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COMMITTEE I.1

ENVIRONMENT

COMMITTEE MANDATE

Concern for descriptions of the ocean environment, especially with respect to wave, current, wind, and sea level, 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.

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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.

CONTENTS

1. INTRODUCTION

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

The mandate of the 2006 ISSC I.1 Committee has been adopted, which accords ice an equal status with traditional interests such as wind, wave, current and sea water level, and which 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. In this respect, extensive descriptions of remotely sensed, satellite-based data sources are given, as they form a large proportion of available data.

The Committee consisted of members from academia, an oil company, research laboratories and classification societies. The Committee met three times: in Brest (May 2007), Washington (March 2008) and in Reykjavik (November 2008). Additionally two telephone conferences were held, in October 2007 and July 2008.

The organisation of this report is an evolution of the outline used by the preceding Committee in their report to the 16th ISSC. Section 2 focuses on sources of environmental data for wind, waves, current 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, long waves in shallow water, and uncertainty.

Rogue waves have been a topic of increasing interest over the past two decades, and 2008 saw the third international Rogue Waves Workshop in France. The previous Committee dealt with them as a special, topic, however this Committee felt that they 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 25-27th

International Offshore Mechanics and Arctic Engineering (OMAE) conferences held in Hamburg (Germany), San Diego (US) and in Estoril (Portugal), the 16-18th International Offshore and Polar Engineering (ISOPE) conferences held in San Francisco, CA (USA), Lisbon (Portugal) and in Vancouver BC (Canada), and the International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH), taken place July 2008 in Banff, Alberta (Canada). Papers from those sources have been reviewed and those of particular relevance are cited here.

Within the subject of current, a highlight is the Global Ocean Data Assimilation Experiment (GODAE) which was initiated in 1998 as an international effort to provide a practical demonstration of real-time operational global oceanography; this is now in its consolidation phase and the status is reviewed in the present report.

A number of Joint Industry Projects (JIPs) are also contributing to the world's knowledge base, from which results are released in the form of academic papers. Several EU, JIP and ESA (European Space Agency) projects have reported during the course of this Committee, including: GlobWave, WAG, CresT, CFOSAT, OSIRIS, HANDLE WAVES, ADOPT, Safe Offload, GOMOS, HAWAI, COSMAR, OADC, and Deepstar.

Climate change has also been a topic of worldwide interest. The previous Committee reviewed this subject as a special topic and the current Committee has also done so, in section 4. In particular, the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) was issued in 2007. The report concludes that warming of the climate system is unequivocal. According to the report there is very high confidence that the net effect of human activities since 1750 has been one of warming causes.

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 (storm intensity and frequency, sea-level rise, sea ice extent, natural variability versus climate change contribution). Particular attention is given to the Arctic and the tropical hurricanes. On the positive side, potentially of great interest to the marine community is the emergence of significant opportunity 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 the tropical cyclone has caused devastating damage to the offshore industries in the Caribbean in the past 5 years, which may be due to climate warming, in which case these effects would be anticipated to continue in the warming climate.

Enhancing safety at sea through specification of uncertainties related to environmental description is also dealt with as a special topic. The GlobWave project, making satellite derived data more widely available, is reviewed; it is expected to contribute significantly to improving description of data uncertainties. The project, initiated by the European Space Agency in 2008, is to improve the uptake of satellite-derived wind-wave and swell data by the scientific, operational and commercial user community.

Given such a wide ranging subject area and limited space, this Committee report cannot be exhaustive; however, the Committee believes that the reader will gain a fair and balanced view of the subjects covered.

2. SOURCES OF ENVIRONMENTAL DATA

2.1 Wind

The three main sources of surface wind data are in-situ measurements (buoys, ships and platforms), remote sensing data (satellites and aircraft) and outputs of numerical models

2.1.1 Locally Sensed Wind Measurements

While identified as an important development in local measurement, sonic anemometers have not yet become widely used in the offshore industry, primarily because of the unavailability of intrinsically safe units. Nevertheless, further evidence of the quality and reliability of these anemometers was provided by Howden *et al* (2008), who reported a buoy-mounted sonic anemometer surviving a hurricane while the mechanical anemometer on the same buoy did not. The sonic anemometer continued to measure winds faithfully through the peak of storm recording 10-minute gust winds of nearly 50 m/s.

Nevertheless, because of the intrinsically safe requirement, mechanical anemometers were used in Phase 3 of the West Africa Gust (WAG) Joint Industry Project. The primary objective of the measurement programme was to quantify the vertical and horizontal structure of squall winds. The measurements were undertaken on the Total Likouala platform, approximately 40km off the coast of the Congo, commencing in December 2006 and concluding in September 2008.

With the completion of the measurement programme, the focus is now on the analysis of the data. An extensive quality control of the data has been undertaken, particularly with respect to understanding the effect of sheltering of the platform for some directions and anemometers. Modelling is being undertaken to understand the sheltering better and most importantly the likely influence on the measurements. This work will be followed by analyses of the data, to quantify the spatio-temporal distribution of the wind field within the squalls.

2.1.2 Remotely Sensed Wind Measurements

Satellite wind data are retrieved from measurements made using scatterometers, radiometers, altimeters and Synthetic Aperture Radars (SAR). Past and present satellite programmes dedicated to wind measurements are described in the following sub-sections.

In the future, the main projects will be the METOP programme (in the EUMETSAT Polar System (EPS)) with a series of 3 satellites to be launched over 14 years and dedicated to operational meteorology. The first one, with ASCAT (see below) on-board, was launched in October 2006.

A second project is the Chinese-French Ocean Satellite CFOSAT (CNES, NSOAS and CNSA) with an estimated launch date of 2012-2013. Two payloads are on-board: the French SWIM (Surface Waves Investigation and Monitoring), a real-aperture radar with a low-incidence conical-scanning beam for directional wave spectra and wind, and a Chinese wind scatterometer with a rotating fan-beam antenna.

In the USA, the Extended Ocean Vector Winds Mission (XOVWM) is under discussion as a means to provide continuity with QuikScat. It is listed as a priority mission and recommended by the National Research Council, in its decadal review, for launch between 2013 and 2016. The XOVWM concept tries to use the best from all existing technologies. It includes a Ku-band scatterometer using synthetic aperture radar processing to achieve wind retrieval at 5km resolution or better. The high wind speed limitations of Ku-band measurements are removed by adding a horizontally polarized C-band channel, which is able to retrieve winds at high wind speeds. Finally, an X-band polarimetric radar is included in the instrument suite to remove rain contamination effects.

Scatterometers. Wind scatterometers are radars that transmit microwave pulses down to the Earth's surface and then measure the power that is scattered back to the instrument (Bragg scattering). This backscattered power, characterized by the backscatter coefficient, σ0, is related to surface roughness. For water surfaces, the surface roughness is highly correlated with the near-surface wind speed and direction. Hence, the scatterometer performs measurements of σ0 at two or three different azimuths (the angle between the antenna beam and the wind direction) to estimate wind speed and direction using empirical models.

The various satellite scatterometers (see Table 1) differ mainly by the radar frequency band and by the type and geometry of the antennas. The two main frequency bands are Ku-band (14 GHz, 2 cm radar wave length) and C-band (5 GHz, 6 cm). At Ku-band the sensitivity of the backscatter coefficient to wind fluctuations is higher than at C-band, which could increase the accuracy of the scatterometer measurements. However, at Ku-band the signal attenuation by rain is also much larger than at C-band, which contaminates the measurement. This can induce large errors in wind retrieval in equatorial regions or in particular areas of deep low pressure meteorological systems or hurricanes, where heavy rain occurs.

Scatterometers use either fan-beam antennas (in general at most three antennas on either one or both sides of the satellite, at different azimuths relative to the satellite track), or a rotating dish antenna with two spot beams that sweep in a circular pattern.

The first Ku band scatterometer was flown on-board of the U.S. satellite SeaSat in 1978. Although the mission was reduced to 3 months, it demonstrated the feasibility of measuring surface wind speed and direction from space, over a large swath with relatively good accuracy.

Thirteen years later the European Space Agency (ESA) launched C-band scatterometers (Active Microwave Instrument), on-board of ERS-1 on July 1991, followed by ERS-2 on April 1995. The ERS AMI scatterometers measure the surface wind vectors over a 500 km wide swath (one side of the satellite) with a nominal resolution of 50 km.

Coverage and resolution were then improved on the Ku-band NSCAT scatterometer flown by NASA on-board Japan's Midori-I (ADEOS-I) spacecraft in August 1996. NSCAT was measuring with 6 fan-beam antennas, 3 on each side of the satellite, leading to two 600 km wide swaths (one each side of the satellite), separated by 330 km, with a 25 km resolution. The mission ended prematurely, 10 months later (June 1997), and was rapidly followed by the launch of QuikScat (SeaWinds instrument) on the Quickbird satellite in June 1999. A similar SeaWinds instrument was then launched on ADEOS II in December 2002 and was operating for only 10 months. SeaWinds scatterometers use a Ku-band rotating dish antenna with two spot beams, covering a 1800 km wide swath, with 25 km resolution.

The most recent scatterometer, the ESA EUMETSAT ASCAT on METOP, was launched in October 2006. Like ERS scatterometers, the ASCAT system geometry is based on C-band fan-beam antennas. With the 6 antennas (only 3 for ERS), ASCAT covers two 550 km swaths, which are separated from the satellite ground track by about 336 km. The nominal resolution is 25 km. Description of the instrument can be found in Figa-Saldaňa *et al* (2002). The wind retrieval accuracy was investigated recently (Bentamy (2008)), during the commissioning phase of the satellite.

Table 1
Some characteristics of the main scatterometer missions

Sensor	Satellite	Data availability [yyyy/mm/dd]	Swath	Resolution	Accessibility
AMI	ERS-1	1991/08/04-1996/06/02	500 km	50 km	http://cersat.ifremer.fr
AMI	ERS-2	1996/03/19-2001/01/17	500 km	50 km	http://cersat.ifremer.fr
NSCAT	ADEOS-I	1996/09/15-1997/06/30	2 x 600 km	25 km	http://podaac.jpl.nasa.gov
SeaWinds	QuikScat	1999/07/19-Current	1800 km	25/ 12.5 km	http://podaac.jpl.nasa.gov
SeaWinds	ADEOS-II	2003/04/10-2003/10/24	1800 km	25/ 12.5 km	http://podaac.jpl.nasa.gov
ASCAT	METOP	2007/03-Current	2 x 550 km	25 / 12.5 km	http://www.osi-saf.org
WindSat (radiometer)	CORIOLIS	2003/02/01-current	1000 km	30 km (frequency dependent)	http://www.cpi.com/datacenter

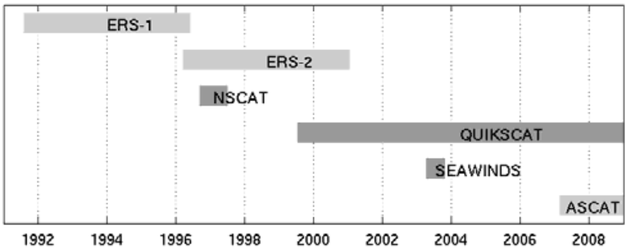

Figure 1: Scatterometer wind data availability

Thus, since July 1991 (ERS-1 launch) there has been an almost continuous coverage of surface wind measurements from scatterometers. Merging the data of the various sensors enables construction of daily, weekly and monthly wind fields. Information on the various missions and available products are given in Table 1 and Figure 1.

Ku and C-band scatterometer wind model functions have been steadily improved along the different missions (Hersbach *et al* (2007)).

Validation of scatterometer wind measurements is not straightforward because it cannot be simply achieved by comparison with in-situ measurements. Indeed, the scatterometer measures the effect not only of the wind but also of the air-sea stability conditions, which are difficult to take into account in the scatterometer wind models (Kara *et al* (2008)). Another difficulty is that the scatterometer retrieves the wind speed relative to the sea surface, which differs from the absolute 10 m wind speed in the presence of oceanic surface current (Kelly *et al* (2005)). The impact of the variabilty of wind within a scatterometer measurement cell on the wind retrieval accuracy is discussed by Portabella and Stoffelen (2006).

Maturity of scatterometer data has been demonstrated, and these data are now assimilated in real time by the meteorological offices in numerical weather models. They are also useful to assess the quality of numerical weather models (Chelton and Freilich (2005), Leslie and Buckley (2006), Suzuki *et al* (2007)), particularly for strong winds (Chelton *et al* (2006)), to study local wind events (Moore and Renfrew (2005)) and wind climatology (Monahan (2006a,b)). Applications to oceanic circulation modelling (improvement of surface forcing) were also developed (Tokmakian 2005). Most recent developments were achieved in the following fields.

- Improvement of the spatial resolution, from 50 km with ERS to 12.5 km for SeaWinds and ASCAT, with higher noise measurement at high resolutions.
- Improvement of rain detection to de-contaminate the wind signal (Tournadre and Quilfen (2005), Allen and Long (2005), Nie and Long (2007)).
- Merging of scatterometer measurements and numerical model output. In fact the combined time and space sampling of scatterometers is not sufficient to get both high temporal resolution and global coverage of the wind data, for instance global 50 km wind fields every 6 hours, as needed for wave hindcast or mesoscale oceanic circulation modelling. Thus the idea of merging the scatterometer measurements (locally high spatial resolution) and numerical model analyses (global coverage, medium resolution) was developed to improve accuracy and resolution of surface wind speed (Milliff *et al* (1999), Zhang *et al* (2006), Bentamy *et al* (2007)). Merged high resolution wind products are presently available; see for instance:
- http://www.cora.nwra.com/~morzel/blendedwinds.qscat.ncep.html, http://www.ncdc.noaa.gov/oa/rsad/seawinds.html, http://cersat.ifremer.fr .
- Study of high wind and wave conditions. During the simultaneous occurrence of high wind and wave conditions, there is a change in the nature of the interaction of the radar waves with the sea surface, for example due to the modification of the surface kinematics induced by breaking waves and spray. In such conditions the measurement accuracy was previously not deemed satisfactory. An effort has been made to improve the situation, investigating the high resolution domain, using information from bi-frequency measurements available on TOPEX, Jason and ENVISAT altimeters (Quilfen *et al* (2006)) and a combination of active and passive sensors (Yueh (2006)) (see WindSat in the radiometer subsection below). Obtaining more information from remote sensing in high wind and wave conditions is paramount because numerical weather models tend to underestimate highest wind speeds (due to smoothing of spatial high frequencies), which of course has a strong impact on wave hindcast accuracy. Improvement of parametric wave models for hurricanes also needs this kind of information.

Finally, it should be noted that QuikSCAT is in its 10th year and that despite its immense impact on many areas such as tropical cyclone detection and diagnosis, wave hindcasting, operational marine forecasting and warning, and numerical weather prediction (most centres now assimilate QuikSCAT data in real time), there is no immediate follow up planned, and passive microwave systems have not been nearly as useful.

Radiometers. Major improvements in satellite radiometer wind speed estimates came from the WindSat system, launched on January 6, 2003. The surface wind speed is estimated from the polarimetric measurements at 10.7, 18.7 and 37 GHz (Gaiser *et al* (2004)). A particular interest is in the retrieval of wind direction information which was not provided by other satellite radiometers, as for instance the Special Sensor Microwave/Imager (SSM/I) series of instruments, operated by the Defence Meteorological Satellite Program (DMSP). An additional interesting aspect is the good performance of the instrument at high wind speed, when active sensors, such as altimeters or scatterometers, exhibit some limitations (Yueh (2006, 2008), Quilfen *et al* (2007)). The measuring swath is about 1000 km wide; with resolution of the order of 30 km (the spatial resolution ranges from 40 km x 60 km at 6.8 GHz to 8 km x13 km at 37.0 GHz). WindSat data are useful for hurricane wind field structure studies (Turk *et al* (2006)) and numerical weather predictions (Le Marshall *et al* (2007)).

Altimeters. The main objective of altimeters is to estimate the sea surface level, highly correlated with large scale and mesoscale oceanic currents, and the significant wave height. Nevertheless the backscatter coefficient σ0, which is a measurement of the ratio of the altimeter emitted power to the power reflected by the sea surface, was observed, as predicted by the theory, to depend on wind speed and wave height. For a long time an altimeter wind speed algorithm was used, only based on the wind σ0 relationship and known as the modified Chelton-Wentz algorithm of Witter and Chelton (1991). Further observations of the σ0 behaviour as a function of wind speed, wind-sea and swell enable the improvement of the estimate of the surface wind speed from σ0 and Significant Wave Height (SWH) (Gourion *et al* (2002)). Recent developments use the opportunity of bi-frequency altimeters (such as TOPEX, Jason at C- and Ku-band, and ENVISAT at S- and Ku-band (Labroue and Tran (2007))). However, it still seems that the altimeter measurement is closer to the friction velocity than to the wind speed. Nevertheless altimeter wind speed estimates are of relatively acceptable accuracy over the medium wind speed range (3 -16 m/s). Note that the altimeter measurement has a very narrow footprint (a few km wide) at the nadir, but with high along-track resolution, and that no information is available for the direction.

SAR. The σ0 information characterizing the surface roughness correlated with wind speed and direction, can be extracted from the SAR image with a spatial resolution much higher than that of a scatterometer. Thus wind speed could be retrieved from this information. However, to obtain speed and direction, at least two σ0 measurements are needed (at two different azimuth angles, as in the case of the scatterometer). To solve this problem, methods were developed to estimate the wind direction from the SAR image itself (Koch and Feser (2006), Zou *et al* (2007)). An alternative method to obtain this parameter is through use of a numerical weather model. The primary reason for interest in SAR wind estimates is to get a high spatial resolution (10- 100m) and to be able to obtain information close to the coasts, which is not possible with scatterometers (Danielson *et al* (2008)).

2.1.3 Numerical Modelling to Complement Measured Data

Cardone and Cox (2007) discuss sources of uncertainty in modelling the wind field in hurricane hindcasts. Uncertainties in the application of a steady state planetary boundary layer (PBL) primarily arise in the uncertainty in the natural variability in the shape of the radial pressure profile; but storms may exhibit even more complex radial pressure and wind distributions and may require double exponential representation of the radial pressure profile. Cardone and Cox (2007) comment that apart from failure to model non-steadiness and the inability to model transient convectively induced changes in the inner core wind field (e.g. diurnally varying convective bursts) the scaling of peak surface winds in a steady PBL model in terms of the pressure field is most sensitive to the specification of surface friction though the drag or surface roughness parameterisation. Recent studies make a compelling case for saturation of the drag coefficient to values of the order of 2.0 x 10^{-3} at wind speeds in excess of about 30 m/s (e.g. Chen *et al* (2007)), but it remains to be demonstrated that a similar saturation effect occurs in shallow water.

2.2 Waves

The 2006 ISSC I.1 report discussed available wave datasets, particularly the on-going global visual observations made from ships in normal service; the Voluntary Observing Fleet (VOF). In addition to these data, hindcast datasets with both global and basin-scale coverage and earth observation satellite datasets were discussed. Despite the extensive coverage of these datasets, it was suggested that the proprietary nature of hindcast studies, the lack of complete calibration of hindcast programs and similar inconsistency in the calibration of satellite data, prevents the possibility of establishing reliable global design criteria. This situation is unchanged. Design criteria must largely be determined on a site-by-site basis, for which site-specific measured data are also an important source of data; but for some locations measured data series are too short or non-existing, and model data may be the only resource.

Although satellite data have recently become more available and used, there is still not full acceptance of their application in industry, often due to lack of knowledge about their accuracy. There are several ongoing projects aiming at further specification of satellite data accuracy, e.g. the ESA project OSIRIS http://elib.dlr.de/55502/

2.2.1 Locally Sensed Wave Measurements

In the last few decades a large amount of in-situ wave data have been collected in different parts of the world, mostly by oil companies, allowing reliable wave statistics to be produced. Some data series are up to 30 years long. In the exploration for new oil and gas fields, new wave data acquisition programmes are initiated for new locations, extending the coverage for which measured data are available. Although long time period datasets exist for selected locations, the data are often proprietary and not available for general research and design projects.

Generally, the offshore industry regards instrumentally recorded data as superior to model derived data, and recommends using them for establishing design and operational criteria. In particular, wave buoys are regarded as accurate instruments for providing integrated wave parameters.

It should be mentioned however that highly accurate measurements of the spatial and temporal wave field remain a major challenge for the industry. Wave buoys reliably provide accurate estimates of power spectra and integrated parameters, and enough information on directionality to allow accurate estimates of the mean and spread in direction as a function of frequency, but they are unable to provide details of the absolute surface elevation. Fixed platform sensors such as downward looking radars and lasers suffer from frequent signal degradation, the source of which remains a subject of investigation. The signals from sub-surface sensors that measure wave kinematics require application of a particular wave theory to be transformed to a surface elevation, with obvious limitations. However, it should be noted that such systems when equipped with an Acoustic Surface Tracking (AST) capability, which uses a fourth acoustic beam to directly measure the water surface elevation, appear to provide a reliable method for directly measuring critical wave statistics over a long-term deployment even during large wave events (Puckette and Gray, 2008). Sensors based on navigation radar systems appear to provide the capability to monitor the sea state in time and space, allowing spatial estimates of sea surface elevation and wave number spectra to be made. However, there are limitations on the frequency range and resolution, and conditions in which measurements can be made due to the necessity for the existence of sea clutter but the absence of other targets.

Nevertheless, the surface wave following buoy remains the most widely used instrument for making in-situ measurements. For many years several national wave buoy networks have been set up and maintained at sea. Significant effort is deployed to give easy access for users (on the internet) to real time measurements and historical validated data. Free access is the rule for some of these networks, for example, the U.S. National Data Buoy Center (NDBC) http://www.ndbc.noaa.gov and the Canadian Marine Environmental Data Service (MEDS)
http://www.meds-sdmm.dfo-mpo.gc.ca/MEDS/Databases/Wave/WAVE_e.htm.

In addition to these resources, many countries provide users with wave buoy data on request through national meteorological or marine institutes. Though wave buoys generally provide accurate spectra and integrated parameters, careful attention must be paid to validation of the buoy measurements. Even when validated, considering the buoy data as a reference is not straightforward, as illustrated by the recent observations of a systematic difference, of the order of 10%, in the significant wave height estimates from the NDBC and MEDS network, over a recent time period (Durrant *et al* (2009)).

Such issues were discussed at a recent workshop on wave measurements from buoys, organised by JCOMM Data Buoy Cooperation Panel (DBCP), and the JCOMM Expert Team on wind Waves and Storm Surges (ETWS) (http://www.jcomm.info/index.php?option=com_oe&task=viewEventRecord&eventID=319).

In particular, it recognised and supported the recent work carried out in the development of the US IOOS Operational Wave Observation Plan (September 2007) and its related documents, including the March 2007 US Wave Sensor Technologies Workshop, that the success of a directional wave measurement network is dependent in large part on reliable and effective instrumentation (e.g. sensors and platforms), a thorough and comprehensive understanding of the performance of existing technologies under real-world conditions is currently lacking, and independent performance testing of wave instruments is required.

Shih (2008) summaries the technology used by the US National Oceanic and Atmospheric Administration (NOAA). With regard to directional wave measurement the paper notes the two main sensors used in NOAA buoys, the Seatex MRU and MicroStrain 3DM-G. The popular waverider buoy uses a Hippy motion sensor. That paper also describes briefly the development of GPS based wave buoys mentioned in the 2006 ISSC I.1 report. Differential GPS is reliant on being within 10-20km of a stationary (land based) reference location. Datawell's GPS wave buoy is said to be able to operate anywhere, without the reference station, but only limited verification of its performance has been made (Jeans *et al* (2003), De Vries *et al* (2003), Harigae *et al* (2005)). It should be noted that some of these references are from trade publications rather than refereed journals.

Experiments reporting wave data (with spreading measurements) gathered on the East and West Indian Coast are reported by Sanil Kumar (2006). Work (2008) gives results of a 3 month comparison between a TriAxys wave buoy and directional spectra derived from an Acoustic Doppler Current Profiler (ADCP); the two systems, both using Maximum Entropy Method algorithms, gave generally similar results, although the ADCP tended to give more concentrated energy around the spectral peak.

Particular attention has been given to measuring the directional and spatial properties of waves using electromagnetic sensing techniques. One example, is the increasing interest in the use of the navigation radar in the X- or S-band for acquiring wave data. X-band radar is turning out to be an interesting sensor to measure the wave fields in the vicinity of ports, platforms and ships. Two EU projects HANDLE WAVES and ADOPT have used a marine radar to collect on board ships' data. Marine radars (e.g.

WAVEX, WAMOS) provide directional wave spectra but infer wave height indirectly. Technology used by marine radars for recording the sea surface is under continuous development and accuracy is being continuously improved. However, recent analysis of WAVEX data shows that it may significantly over-estimate wave heights for swell-dominated conditions (Yelland *et al* (2007)).

Venugopal *et al* (2005) used altimeter results from three closely separated North Sea platforms to derive directional spectra for ten storms (which were subsequently reproduced in a basin). Williams *et al* (2005) give directional wave spectra derived from an airborne digital camera system surveying an ocean area of 7km², for studies of shoaling between deeper water and the shoreline. Sun *et al* (2005) used a laser altimeter to measure the directional properties of a surveyed area. The results compared well with on-site buoy measurement; the technique was sensitive to the encounter frequency of the aircraft with the waves in a way analogous to ships.

The use of stereo-photogrammetry (using triangulation to obtain the wave surface profile from two perspectives) was pioneered in the 1960s, but despite the advantages of accuracy and its non-contact nature, it has been little used in practice. Kinsman (1965), referring to the single example from the Stereo Wave Observation Project (SWOP) of stereo analogue photographs taken from separate aircraft, writes in his text book “the wave–number energy spectrum can be measured by the method used in SWOP, but I doubt that it will ever become habit forming” with a footnote “Dr. Pierson disagrees with me”. The advent of digital photography has allowed the technique, alongside applications such as artificial vision for autonomous vehicles, to be revisited. Demonstration of wave measurement with digital photogrammetry was first reported by Redweik, (1993); however the technology, affordability and motivation are such that the measurements are indeed becoming more routine.

Single point wave measurements have dominated ocean wave measurements for several decades. In order to understand ocean waves Liu *et al* (2008b) argue that four dimensional (x, y, z, t) wave measurements are needed. They present the emerging ocean wave measurement system, the Automated Trinocular Stereo Imaging System (ATSIS) developed by Wanek and Wu (2006). The system is designed for measuring the temporal evolution of three dimensional wave characteristics.

Wave Acquisition Stereo System (WASS) utilises stereo vision based on two calibrated camera views. These provide time series of scattered 3-D points of a water surface, e.g. Santel *et al* (2004), Benetazzo (2006), Gallego *et al* (2008) and Fedele *et al* (2008). The stereo processing uses a pyramidal pixel-based correlation method, and has been derived from methods within the field of computer vision and imaging. Until now, only small scale experiments have been conducted, but in the future there are plans to carry out experiments covering fixed offshore platforms. The main advantages of WASS are believed to be that it reconstructs the water surface densely (i.e. with no “holes” corresponding to unmatched image regions), and that it yields reliable statistics of ocean waves due to the rich information content of video data. However, a main disadvantage of the methodology is that a fixed position relative to the moving surface is required for mounting the system; that is, ships can for example not be used for installation since an accurate, real-time determination of the ship motions is needed in order to extract the absolute motion of the water surface.

Santel *et al* (2004) used a two camera system to survey a 200m² area of a beach surf zone, and obtained good results compared with wave gauges, that were within the expectations of a relatively short stereo baseline.

Gallego *et al* (2008) also used a two camera system and demonstrated the system at two different coastal locations, validating against data recorded from an ultrasonic wave probe. The area surveyed was about 70m². They were not able to process the data in real time, but had not attempted to optimise the processing code nor used particularly high CPU power for the time of writing. The processing was based purely on the image seen by the cameras, wave kinematics models might be used in the future to enhance the solution.

Wanek and Wu (2006) describe a three camera system which they demonstrated from a shore based platform, surveying an area of approximately 16m² on a lake. They recorded and processed several frames, including a wave breaking event, and validated against the point measurement from a capacitance type wave gauge.

The digital stereo-photogrammetric technology is of great interest to the maritime community both from the point of view of source data for wave modellers and basins (high quality measurement of wave spatial and temporal development) and also the future possibility of ship mounted systems.

HF scanning radar systems are also being used with some success; Wyatt *et al* (2008) report use of a shore mounted phased array system to derive directional wave spectra, which showed good agreement with buoy height data, though less successful agreement with period and direction data. The performance of the system for a particular water wave height depends on the HF radio frequency (and therefore electromagnetic wavelength) chosen to sample the sea surface; at the moment frequency selection is a manual process. Hisaki (2005, 2007) also reports use of an HF system to estimate directional spectra using a wind-wave model.

Wave data can also be obtained from ship motion using the wave-ship-buoy analogy. This method is discussed in detail in Section 5.2

2.2.2 Remotely Sensed Wave Measurements

For wave measurement, the main satellite borne sensors are altimeters and SAR. Past and present satellite programmes dedicated to wave measurements are described in the following sub-sections.

In the future, remote sensing of waves will be supported through various programs of operational oceanography in two particular ways: firstly in the continuity with altimeter programs for sea level monitoring and secondly in the development of SAR missions to assume the continuity with ERS, ENVISAT and RADARSAT.

Monitoring of the sea level has probably become the most important justification for continuing high accuracy altimeter missions. Following TOPEX and Jason-1&2, Jason-3 is scheduled for 2013-2014, with a priori the same payload as Jason-2 but this is still open to change. The whole funding for the mission is as yet unconfirmed. Note that CRYOSAT-2, the altimeter dedicated to ice monitoring, is also equipped with an ocean mode and will be launched by ESA in November 2009. A new approach has been developed with SARAL (Satellite with ARgos and ALtika), a joint CNES ISRO mission, involving a high resolution and high accuracy Ka Band (35 Ghz) altimeter (scheduled for 2010). The Ka altimeter could also be combined with the U.S. Wide Swath Ocean Altimeter (WSOA) within the NASA CNES Surface Water Ocean Topography project, scheduled for 2013-216. WSOA is an interferometric radar instrument providing high resolution measurements across a 200 km wide swath. The ESA Sentinel-3 Ocean mission (scheduled for 2012) is devoted to operational oceanographic services and includes a radar altimeter, with aperture synthesis processing for increased along-track resolution. It consists of a series of 3 operational satellites, deployed within the European Global Monitoring for Environment and Security (GMES) programme.

Continuity of C-band SAR instruments (ERS-1&2, ENVISAT) will be carried out with the ESA Sentinel-1 series of 2 satellites, with a multi-mode C-band radar, at very high resolution. The first one should be launched before the end of the ENVISAT mission (2011).

Future high resolution altimeters will also answer the need of the community of coastal wave measurements. Classical altimeter products are not available for coastal applications in general, because the land presence within the altimeter footprint contaminates the signal measurement and the tracking processing fails in such conditions, i.e. in the order of 10 km off the coast or less. New tracking modes, and specific re-processing of some of the past altimeter missions, will enable recovery of the altimeter data close to the coastline. More information is given on the web site of the 2nd Coastal Altimetry Workshop, Pisa 6-7 November 2008 (www.coastalt.eu/pisaworkshop08/).

Altimeters. Retrieval of SWH from altimeter measurements is well understood. The accuracy is low at very low sea state (less than 0.5m SWH), and almost unknown at very high SWH (above 12m) because of a lack of in-situ references at very high sea state. Between these extremes the altimeter SWH accuracy is approximately a few percent of SWH. In general the altimeter tends to overestimate low SWH and to underestimate high SWH, this tendency depending on the sensor. From buoy and cross-altimeter comparisons, corrections were proposed for this (Queffeulou (2004)).

Presently there are more than 17 years of SWH altimeter data available from the following satellites (Table 2, Figure 2): ERS-1, ERS-2, TOPEX-Poseidon, Jason-1, ENVISAT, GEOSAT Follow-On and Jason-2, the last altimeter successfully lauched by NASA and CNES on June 20th, 2008.

The data are distributed by the various space agencies, with the drawback that they use different data format, structure and flags. Some databases exist that gather the measurements from the various satellites (e. g. the SWH database of Cersat available on ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves and the Radar Altimeter Database System of Delft University http://www.deos.tudelft.nl). Note that ESA started the GlobWave project in 2008, with the aim of improving the access to wave data.

Table 2
Some characteristics of the main altimeter missions

Satellite	Data availability [yyyy/mm/dd]	Accessibility
ERS-1	1991/08/01 - 1996/06/02	http://cersat.ifremer.fr
ERS-2	1995/05/15 – current	http://cersat.ifremer.fr
TOPEX	1992/09/25 - 2005/10/08	http://www.aviso.oceanobs.com
GEOSAT Follow-On	2000/01/07 - 2008/09/13	http://ibis.grdl.noaa.gov/SAT/gfo/
ENVISAT	2002/09/27 – current	http://www.aviso.oceanobs.com
Jason-1	2002/01/15 – current	http://www.aviso.oceanobs.com
Jason-2	2008/07/12 – current	http://www.aviso.oceanobs.com

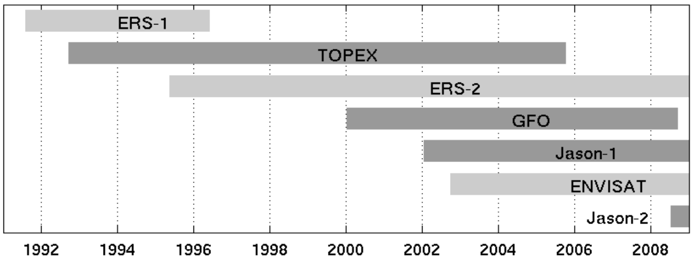

Figure 2: Altimeter wind data availability

Extraction of other wave parameters from altimeter measurements has been investigated; particularly the mean wave period (Quilfen *et al* (2004), Mackay *et al* (2008)) and the skewness (Gomez-Enri *et al* (2007)). But these parameters are not presently available on a routine basis.

One drawback of altimeter data is that the measurement is available only at the nadir of the satellite over a narrow footprint (a few km wide) along-track, so that local coverage can be poor on some occasions. One solution for a better sampling is to merge the data from several satellites, but the relative phasing of the orbits is a strong constraint. However the along-track sampling is high: in operational products the SWH data are estimated every one second in time, i.e. every 5 to 7 km, depending on the satellite.

A major interest in altimeters is that they sample waves in remote areas where no other wave measurements are available. This has many applications. It has been shown that altimeters are very useful to provide regional wave statistics (Challenor *et al* (2006), Queffeulou and Bentamy (2007)), with application to wave energy assessment (e. g. Mackay and Retzler (2008)). In wave modelling, altimeter data are used in two ways. Firstly, the real time measurements are assimilated in numerical wave models on an operational basis by many Meteorological Offices (e. g. Abdalla *et al* (2005), Janssen (2006)). This was clearly shown to have a strong positive impact on the quality of the wave analysis, and also of the forecast (Skandrani *et al* (2004)). Secondly, altimeter data are uniformly distributed over the ocean making them very useful for estimating wave model errors, at global as well as regional scales (Greenslade and Young (2005), Janssen *et al* (2007) and Rascle *et al* (2008)). They are the only data providing a synoptic view of wave model behaviour.

SAR. There is a considerable amount of literature on SAR processing. The 2006 ISSC I.1 report discussed many references which are useful to document the main aspects of SAR data. In the present report we only recall some basic aspects and then give information on new developments for applications in the fields of surface current (Section 2.3.2) and of wave modelling, particularly for SAR data assimilation in wave models and estimation of the dissipation of storm swells (Section 3.2.1).

SAR data analysis is characterized by various processing methods with significant limitations due to non-imaging of the high frequency part of the spectrum. Interpretation and use of the data is not straightforward for non-specialist users. There is an ongoing ESA project investigating the homogeneous reprocessing of all the SAR wave mode data from ERS-1, ERS-2 and ENVISAT, to give easier access to the products and to the interpretation of the data. Note the effort to retrieve integral wave parameters (SWH, mean period, wave power) for applications (Schulz-Stellenfleth *et al* (2007)).

2.2.3 Numerical Modelling to Complement Measured Data

Several hindcast studies have been carried out in the last decade and some of them are reported in the 2006 ISSC I.1 report. Some hindcast studies have been carried out for periods of 40 years or more, e.g. at the European Centre for Medium Range Forecasting (ECMWF). The most recognized and widely used wave models are: 3G WAM, WAVEWATCH and SWAN.

Nested models WAVEWATCH (versions 1.1.8, 2.22) and SWAN (versions 40.11, 40.31) have been applied for hindcasting waves for the Barents, Caspian, Baltic, North, Okhotsk, Black, Azov and Mediterranean Seas. The data are published by the Russian Maritime Register of Shipping (Lopatoukhin *et al* (2003, 2006)) in two Handbooks. In both editions extreme wave statistics is given and in the last one, some information about rogue waves is also included.

When making use of hindcast data, a user can still be faced with some unresolved issues.

- Different hindcasts can give considerable discrepancies in the prediction of extremes as demonstrated by Bitner-Gregersen and Guedes Soares (2007). In order to assess the quality of design wave parameters from a hindcast systematically, errors in both the local hindcast data and in the extrapolation from these data need to be addressed. The overall idea and some building blocks for such an approach are discussed by Bitner-Gregersen and de Valk (2008), whilst realising that there will not be one simple recipe applicable in all situations. Some of the issues are:
    - the selection and use of observational data in quality control;
    - the use of co-located data for calibration, and
    - the use of different datasets for calibration and validation of a database. Satellite wave data are an attractive data source for this purpose.
- Most of the calibrations of the wave model data do not include significant wave heights over 12 m due to lack of measurements beyond 12m. Furthermore, it is becoming increasingly clear that the drag coefficient may not be well specified in extreme situations such as hurricanes, Cavaleri *et al* (2007). These limitations will be investigated by the ongoing CresT Joint Industry Project (JIP).
- Inclusion of current in wave forecasting is still lacking. Today, current taken into account in practical wave forecasts is limited to that caused by tidal flow. A proper description of wave propagation over current is important not only for the forecasting of waves but also for the interpretation of remote-sensing observations (Cavaleri *et al* (2007)). This will also produce better wave hindcasts.
- Poor performance of the Discrete Interaction Approximation (DIA) in wave models, gives inconsistent estimates in hurricanes.

Numerical wave data and satellite data have been utilized in the development of global wind and wave databases (some also provide current and/or sea water level data) e.g. Guedes Soares *et al* (2002), Barstow *et al* (2003), Cardone *et al* (2000) and de Valk *et al* (2004). The databases include numerical data calibrated by measurements (in-situ data, satellite data), a mixture of numerical and instrumental data or pure instrumental (satellite) data.They are under continuous development and improvement.

The HIPOCAS project ("Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe") generated high-resolution homogeneous 44-years (1958-2002) wind, wave and sea level hindcasts covering the entire North Atlantic as well as the Seas around Europe, i.e Mediterranean, Black, Baltic and North Seas, Guedes Soares *et al* (2002). The state-of-the-art wave model WAM was used for the wave hindcast in the version that allows for two-way nesting (Lahoz, and Albiach (1997)). Satellite and in-situ data were used for calibration of the model data. The sampling interval was 3 hours. Accuracy of the HIPOCAS database has recently been improved (Sebastião *et al* (2008), Pilar *et al* (2008), Rusu *et al* (2008), Ponce de León and Guedes Soares (2008), Cherneva *et al* (2008)).

The Fugro-OCEANOR data (Barstow *et al* 2003, 2008) were generated by the WAM model in the EuroWaves project (the forerunner of WorldWaves), the database from operational runs of the WAM model at ECMWF was selected as the best available. The WorldWaves model data are quality controlled as well as validated, and the bias is corrected relative to the satellite and in-situ measurements. The data recorded by the Topex/Poseidon satellite are used for calibration. The data cover world-wide oceans, for some areas the period is up to 20 years (1984-2003) and they are sampled each 6th hour. Recently the WorldWaves software package was updated with the latest version of the SWAN model and with capability for full directional spectra input and output, Barstow *et al* (2008). The WorldWaves offshore database has been updated every month in 2008 and full directional spectra data can now be provided in most areas back to 1957.

The ARGOSS database was established originally for a 5-year period (de Valk *et al* (2004)) and extended recently to 13 years (1990-2002). It includes satellite data received from the European Space Agency (ESA) and data simulated by global and regional hindcast models. The WAVEWATCH-III model (Tolman (1999)) was used. Wind fields and ice data from the National Center of Environmental Prediction (NCEP) were used for the global run, while for the regional models high resolution ECMWF wind fields were applied. The data generated by the WAVEWATCH-III model were calibrated as well as validated by buoy data from NOAA. The satellite data which were calibrated by in-situ measurements, have a fairly complete spatial coverage and are regarded as highly accurate. The data are sampled at three-hourly intervals.

The three wave databases mentioned above provide important information for design and are already used by industry. However, there is still need for further investigations of the databases' accuracy and specification of uncertainties related to the data before they can be fully utilized in engineering applications, as demonstrated by Bitner-Gregersen and Guedes Soares (2007). Although further improvement of the databases took place recently, predictions given by the databases need to be compared and differences in the predictions identified.

A new addition to the library of wave atlas information developed by Soukissian *et al* (2008) is welcome. Their study focused on the Hellenic Seas around Greece, Crete and West of Turkey. The atlas was compiled from 10 year's hindcast data (1995-2004), using the 3rd Generation wave model WAM-Cycle 4, and was made at a spatial resolution of 0.1 degrees longitude/latitude, which is much greater than previous works.

The hindcast model was also calibrated against buoy data from six locations in the area of interest. It was found, in common with previous studies in limited fetch areas, that the wave model underestimated the wind and wave intensity. The authors calculate correction factors of 15% for significant wave height, H_s, 7% for spectral peak period, T_p and 6% for wind speed,U_w for this particular area. Topex/Poseidon and JASON altimeter data are specifically excluded because of its sparse coverage in this restricted area and because of fears concerning their reliability in these seas with multiple island groups. In common with other atlases, wave spreading information is not reported, though charts do give the three most probable wind and wave dominant directions.

The wind and wave atlas of the Mediterranean Sea (Medatlas Group 2004) was also established using model hindcast data corrected by comparison with altimeter measurements.

Several proprietary hindcast datasets have become available over the last few years.

- A new West African hindcast covering a continuous 15-year period (1992-2006), was completed. The basin model domain included the entire North Atlantic Ocean and a fine mesh grid was nested within this domain at high resolution, employing shallow water physics to cover the entire domain of offshore West Africa between Senegal and Namibia. Two alternative versions were used; a hybrid model that employed 3G physics on the basin grid and 2G physics on the fine mesh nest, and a 2G/2G model (which was found to offer potential skill advantages for some response applications). Extension backward of the production hindcast to cover a 25-year period is planned but only after a serious discontinuity in the background winds produced by the NCEP/NCAR reanalysis project is addressed and corrected.
- A new South China Sea hindcast dataset has recently been finalised. The hindcast covers a continuous 50-year period (1956-2006) with reanalysis of approximately 100 storms. A third generation wave model is used throughout the 25 km (coarse) and 6 km (fine) model domains.
- The Gulf of Mexico Oceanographic Study (GOMOS) was offered in 2002 as an upgrade and update of Oceanweather’s quartet of GMEX metocean JIPs carried out between 1988 and 1995, known as GUMSHOE (hurricane extremes), GUMSHOE2 (high-resolution hurricane extremes south of the Mississippi delta), WINX (winter storm extremes) and GLOW (long term normal weather statistics). The hurricane hindcast part of GOMOS was later updated to include storms through the hurricane season of 2005. GOMOS-USA includes all model grid points in all existing and potential areas of offshore exploration and development in Gulf of Mexico waters under U.S. Federal and State jurisdiction. A full update of GOMOS-USA has recently been carried out to take advantage of new advances in measurement technologies, historical data analysis, and interpretation and hindcast methodologies developed since GOMOS was completed, and it includes the most recent hurricanes.

The performance of wave models in very high sea states has been the subject of some debate in recent years. Forristall (2007) made an assessment of the GOMOS hurricane wave hindcasts of hurricanes Lili, Ivan, Katrina and Rita. Data from the National Data Buoy Center, the Naval Research Laboratory, and oil industry platforms were compared with the hindcast data. The bias between simultaneous hindcast and measured significant wave heights of -0.11 m for wave heights greater than 6 m, and the scatter index of 0.15 show that the overall quality of the hindcasts in these extreme storms is at least as good as in other high quality hindcasts. The peak wave heights of 15.96 m in Ivan and 16.91 m in Katrina at NDBC Buoy 42040 were however underestimated. This together with the fact that there were no hindcasts above 14m indicates that more research is needed on wave generation in the most extreme conditions.

Additional hindcasting of selected hurricanes in the Gulf of Mexico will be conducted within the CresT project. This work will be completed in 2009.

Accuracy of wave model data is still discussed in literature. Ardhuin *et al* (2007) show comparison of wave measurements and models in the Western Mediterranean Sea. Inter-comparison of operational wave forecasting systems is reported by Bidlot *et al* (2007). Examples of the use of satellite data for validation of wave model predictions are reported in Rascle *et al* (2008).

SWAN derived from the third generation WAM model is still commonly used to transform waves from deep water to the near shore. It is often applied to generate data for design of wind farms, see e.g. Trumars (2006).

There is also significant interest in how the wave profiles are modified by surface and subsurface features; papers in this field usually refer to civil engineering projects, for example Huang *et al*. (2005) found that a detached breakwater could be of use to shield a fishing harbour, they made experiments and they developed semi-empirical theory. Losada *et al* (2008) report a model of the effects of rubble mound breakwaters. Lee *et al* (2007) report the effect of submarine pits using velocity potential methods, and also Lee and Kim (2006) report on the effect of a semi-infinite breakwater in finite depth. Oliveira (2007) considered the effect of an elliptically shaped bottom shoal on the directional wave spectra and particularly the wave breaking. More general diffraction problems are also receiving attention; for example, Walker and Eatock-Taylor (2005) report on the effects of systems of up to 19 vertical cylinders on the wave field. There are many other examples of papers considering the effects of such submerged and partially submerged bodies on the wave field

2.3 Current

2.3.1 Locally Sensed Current Measurements

Acoustic measurement techniques (both coherent and incoherent) for in-situ sensing of ocean current offer an excellent space-time resolution of the velocity profile. However, the number of reliable and productive commercial systems based on Doppler acoustic measurement is limited when it comes to practical applications, e.g. Pinkel (2008) and Lohrmann and Nylund (2008). This fact leads Pinkel (2008) to underline the importance of exploring new systems. A fundamental problem of Doppler acoustic measurement is the inherent speed ambiguity problem. This problem is studied by e.g. Hay *et al* (2008), and they show that the problem can be dealt with using a dual (or multiple) pulse repetition interval. Specifically, Hay *et al* (2008) present a new approach, in prototype form, in which multiple acoustic frequencies are used simultaneously, allowing a nearly five-fold increase in ambiguity velocity with no reduction in profile sample rate. In the reference, results from laboratory tests with a turbulent wall jet are presented, and the measured velocities reveal detailed coherent structure within the flow and agree well in the mean with independent (point measurements) made with a Vectrino ADV. A somewhat similar approach is presented by Jakobsen *et al* (2008). They show that by transmitting an acoustic pulse of several distinct frequencies, the data quality of the Doppler current measurements can be improved significantly without increasing the power drain, measurement time, or the pulse length. To close on the Acoustic Doppler current profiling techniques, it is evident that there are still challenges to be overcome, a message which was also reported at The IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology, Charleston, SC, USA, in March 2008.

Another type of in-situ measurement of ocean current profile is based on autonomous underwater gliders, Merckelbach *et al* (2008), where differences between successive GPS positions, obtained when the glider surfaces, and dead-reckoned displacements when the glider is submerged, are compared. In this way it is possible to estimate depth averaged horizontal currents and also surface drift. With this technique it is important to be aware of the calibration of the attitude sensor. In the same study, it is also shown that the gliders can be equipped with Conductivity Temperature Depth (CTD) sensors, which provide data used to calculate geostrophic horizontal velocity.

2.3.2 Remotely Sensed Current Measurements

Satellite altimetry, for sea surface topography measurement, has been progressing for more than 30 years. The sea level height information can be used to directly estimate geostrophic oceanic currents. The altimeter information is also assimilated in numerical oceanic circulation models with other parameters (e.g Sea Surface Temperatures (SST), in-situ salinity measurements...) to provide estimates of currents; a further discussion is given in Section 2.3.3. Nevertheless, a key limitation is the unresolved scales shorter than about 300 km in wavelength and 20 days in period (depending on the number of altimeters in flight).

An alternative estimate of short scale local surface currents has been developed using SAR measurements. In particular conditions the interaction between waves and current can be mapped through SAR images, determining surface current boundaries. A more qualitative method has demonstrated the feasibility of estimating surface current velocity, based on the Doppler shift of SAR echoes, due to surface wind and currents (Chapron *et al* (2005)). Accuracy of the method was not well estimated due to the complexity of the combined effects of the wind and currents patterns on the SAR image measurement, but improvements are going on (Johannessen *et al* (2008)).

A demonstration of current measurements from space was carried out by the Shuttle Radar Topography Mission (SRTM) in February 2000 (Romeiser *et al* (2005)). Despite unfavorable system parameters, the combined XTI (cross-track interferometry) / ATI (along-track interferometry) system on space shuttle Endeavour with an along-track antenna separation of 7 m was shown to permit current measurements with an accuracy of 0.1 m/s at a spatial resolution of about 1 km.

The German satellite TerraSAR-X, launched on June 17th 2007, is equipped with the along-track interferometric synthetic aperture radar (along-track InSAR) and offers ATI capabilities in experimental modes of operation. Similar to the SRTM case, the system parameters are clearly suboptimal, but TerraSAR-X will provide the first opportunity to test repeated along-track InSAR image acquisitions from space during a period of about five years. Experiments carried out up till now indicate that the current measuring capabilities of TerraSAR-X should be sufficient for many applications.

A coherent marine radar with 6 m resolution has been developed that measures the radial component of the orbital wave velocity of ocean waves, as well as the mean radial ocean surface velocity. Typically, 256 images are used, covering periods of the order of ten minutes, allowing a modest number of wave groups to be measured. A pair of such radars operated at a coastal site, separated by a few hundred meters along the coastline, allows the different radial components to be combined into a mean current vector field. Results from first testing of the radar are presented for a field site at the U.S. Army Corps of Engineers Field Research Facility (FRF), Duck, N.C. Real time results can be viewed at the FRF website http://frf.usac.army.mil/radar.

HF radars are widely used as a means for measuring ocean surface current systems, and systems have become operational in several locations worldwide so that continuous maps of current are available. A status on the area was given at The IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology, Charleston, SC, USA, in March 2008. In particular, a number of papers reported on the advances in networks of current measuring systems in terms of HF radars, e.g. Heron *et al* (2008), Pettigrew and Neville (2008), Roarty *et al* (2008), Harlan *et al* (2008) and Kohut *et al* (2008). A comparison study of surface current measured by HF radar and by ADCP has been made by Skarke *et al* (2008). The results of the study indicate a strong correlation between HF radar and ADCP measurements of velocity and direction.

Another comparison of measuring techniques for remote sensing is given by Perkovic *et al* (2008), where microwave radar surface velocity estimates are compared to the estimates derived from video observations in the surf zone. The radar estimates are inferred from the Doppler shift of the backscattered radiation while video velocity estimates were produced using the Particle Image Velocimetry (PIV) technique. In the study it is reported that there is a reasonable agreement between PIV and radar estimates, throughout most of the surf zone, for the spatial velocity of alongshore velocity, but that the spatial comparisons of near cross-shore velocities show greater discrepancies.

2.3.3 Numerical Modelling to Complement Measured Data

The Global Ocean Data Assimilation Experiment (GODAE) was initiated in 1998 as an international effort to provide a practical demonstration of real-time operational global oceanography. Learning from the experience of numerical weather prediction and its Global Atmospheric Research Program, the GODAE has set forth an objective, to provide regular and comprehensive description of the ocean circulation at high temporal and spatial resolution, consistent with a suite of remote and in-situ measurements and appropriate dynamical and physical constraints (the International GODAE steering team). The GODAE's main operational and research institutions are from 9 nations and regions (Australia, Japan, the United States, the United Kingdom, France, Norway, European Community, Canada and China).

GODAE set a time-line for the programme composed of; the conceptual development phase (1998-2000), the prototype development phase (2000-2003) and the main demonstration and consolidation phase (2004-2008). Five workshops and symposia were held over the years and in November 2008, the final symposium was held in Nice, France (The Revolution in Global Ocean Forecasting: GODAE 10 years of achievement, 12-15 November 2008). The GODAE products are intended to be applied to Global warming, climate and seasonal forecasting, weather, fisheries and fishery management, offshore industry, maritime security and marine safety, navies, coastal applications, ocean and ecosystem research and others.

Despite the success of Satellite Altimetry in the 90's providing sea level anomalies, in-situ hydrography observation necessary to determine the mean state of the dynamics topography was clearly inadequate. In 1998, GODAE in cooperation with Climate Variability and Predictability (CLIVAR) initiated the Argo project that aims to deploy around 3000 autonomous profiling floats globally every 3 degrees (300 km). Under the initiative of GODAE, various high resolution SST products (GHRSST-PP, NGSST) were developed as well. Simultaneously, modelling and data assimilation capacities were nurtured and several assimilation centres were established in the beginning of the 2000s. GODAE also established several product servers, so the GODAE product gets delivered to the users in a timely manner after appropriate quality control. Finally, a number of applications were demonstrated using the products in global and regional aspects.

Table 3
List of official GODAE products; Reg: regional, Atl.: Atlantic, G: Global,
R: Regional, z: z-coordinate, h: hybrid coordinate, d: days, w: weeks, m: months

Title	Domains	Horizontal Resolution	Vertical Grid	Forecast Range	Update Frequency	Hindcast Length
BLUELINK[1]	Global	1/10-1	47 z	7 d	2 w	11 d
C-NOOFS[2]	Canada Atl.	¼	50 z	6 d	1 d	None
ECCO[3]	Global	1x0.3-1	46 z	None	10 d	
FOAM[4]	Global+Reg	1/4G - 1/12R	50 z	5 d	1 d	1 d
HYCOM[5]	Global	1/12	32 h	7 d	1 d	5 d
NLOM/NCOM[6]	Global	1/32 - 1/8	7-42 h	4 d (30 d)	1 d	3 d
NMEFC[7]	Tro. Pacific	2x1	14 z	None	m	
MERCATOR[8]	Global+Reg	1/4G-1/12 R	50 z	7 d (14 d)	1 d (1 w)	14 d
MFS[9]	Mediterranean	1/16	71 z	10 d	1 d	7 d
MOVE/MRI[10]	Global+Reg	1G-1/2-1/10	50 z	30 d	5 d	10 d
RTOFS[11]	North Atlantic	4-18 km	26 z	5 d	1 d	
TOPAZ[12]	Atl+Arctic	11 - 16 km	22 z	10 d	1 w	7 d

For the end users, what is most important is that the data are available in a timely manner and that there is easy access to data at the desired temporal and spatial resolution, at the specific site of their interest and at the user defined arbitrary dimension. To meet such requests, GODAE implemented the data and product serving capability and standardization. These GODAE products are intercompared and validated for a specified metric and are standardised. Table 3 summarises the official GODAE products that have reached completion.

Further details of the products (ocean model, data assimilation scheme, forcing field etc) can be found in their specific websites. Also, a paper will appear in the Oceanography special edition reviewing the GODAE systems in operation (Dombrowsky *et al* (2008)), and the data assimilation systems employed (Cummings *et*

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[1] BLUELINK (Australia) http://www.bom.gov.au/oceanography/forecasts
[2] C-NOOFS (Canada) http://www.c-noofs.gc.ca/viewer/
[3] ECCO (USA JPL) http://ecco-group.org
[4] FOAM (UK) http://lovejoy.nerc-essc.ac.uk:8080/Godiva2
[5] HYCOM (USA NAVOCEANO) http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html
[6] NLOM/NCOM (USA NAVOCEANO) http://www7320.nrlssc.navy.mil/global_nlom32 /skill.html
http://www7320.nrlssc.navy.mil/global_ncom/
[7] NMEFC (China) http://dell1500sc.nmefc.gov.cn/argo-sz/argo7n.asp
[8] MERCATOR (French) http://bulletin.mercator-ocean.fr/html/welcome _en.jsp
[9] MFS (Italy) http://gnoo.bo.ingv.it/mfs
[10] MOVE/MRI.COM (Japan) http://godae.kishou.go.jp/onlineregist.html
[11] RTOF (USA NOAA/NCEP) http://polar.ncep.noaa.gov/ofs
[12] TOPAZ (Norway) http://topaz.nersc.no/Knut

al (2008)).

In addition to providing ocean observational data (remote sensing satellites or in situ instruments) and analyses and forecasts data, GODAE puts an emphasis on data management and communication to deliver reliable and comprehensive information on the state of the ocean as well. The data include temperature, currents, sea level, salinity, wind/wave and sea ice, at various spatio-temporal resolutions. The data are categorised from raw instrument data (Level 0) to ocean indicator such as nino3 index (Level 5). Table 4 summarises several sites suitable for accessing regular gridded products (Level 3). (Blanc *et al* (2008))

Table 4
List of URLs that allow graphical product searching

Page Title	Purpose	URL
NAVOCEANO	Product search	https://oceanography.navy.mil/legacy/web/ops.htm
GHRSST	Product search	http://ghrsst.jpl.nasa.gov/data_search.html
BLUELINK	Product search	http://www.bom.gov.au/oceanography/forecasts/index.shtml
AVISO	Product search	http://atoll.cls.fr/atoll-web/navigation/go.htm?locale=en
GCMD	Product search	http://gcmd.nasa.gov/
OSMC	Product search	http://osmc.noaa.gov:8180/Monitor/OSMC/OSMC.html
SeaDataNet	Product search	http://seadatanet.maris2.nl/v_cdi_v0/search.asp?search=yes?screen=0
NCOP	Product page	http://www.ncof.co.uk/Deep-Ocean-Forecast.html#forecastsTab
ECCO	Product page	http://ecco.jpl.nasa.gov/external/
MERCATOR	Product page	http://bulletin.mercator-ocean.fr/html/produits/psy2v3/psy2v3_courant_en.jsp
Mersea/MyOcean	Product page	http://bulletin.mersea.eu.org/html/produits/mersea_vs/
Mersea Dynamic	Product page	http://behemoth.nerc-essc.ac.uk/ncWMS/mersea.html
Coriolis	OPeNDAP	http://www.coriolis.eu.org/cdc/opendap-dods_distribution.htm
Mersea	FTP Client	http://www.mersea.eu.org/Information/DownloadService.html
APDRC	Data Search	http://apdrc.soest.hawaii.edu/w_data/data3.html

These sites guide the users to find the product that meets their requirements. The data, can then be downloaded by ftp, http, OPeNDAP/Thredds and other means. There are numerous web browser programmes developed as part of the GODAE initiative and a variety of gridded numerical model outputs are served throughout the web. Table 5 lists selected URLs that use the Live Access Server (LAS) as the data server (http://ferret.pmel.noaa.gov/LAS).

One of the specific objectives of GODAE was to apply state-of-the art ocean models and assimilation methods to produce short-range open-ocean forecasts and boundary conditions to extend predictability of coastal and regional subsystems. The global or basin scale operational models (Table 3) provide boundary conditions to the smaller but higher resolution sophisticated downscale-models. Those products were then used for the practical applications listed below.

- Modelling oil flow after a spillage (Hacket *et al* (2008)) e.g. the PRESTIGE accident.
- Support for the oil industry.
- Providing data for sailing race navigation.
- Fisheries applications (e.g. larval dispersion and fish stock and recruit area management).
- Search and rescue.

Table 5

URLs for the products served by the Live Access Server

Title	Product	URL
USGODAE	Variety	http://usgodae1.usgodae.org/las/servlets/dataset (not working)
APDRC	Variety	http://apdrc.soest.hawaii.edu/las/servlets/dataset
ECCO-JPL	Assimilated field	http://ecco.jpl.nasa.gov/las/servlets/dataset
ECCO-MIT	Assimilated field	http://mit.ecco-group.org:8080/las/servlets/dataset
HYCOM	Assimilated field	http://hycom.coaps.fsu.edu/las/
ESSC Godiva	Assimilated field	http://www.nerc-essc.ac.uk/godiva/
MERCATOR	Assimilated field	http://las.mercator-ocean.fr/ (needs permission)

The GODAE Coastal and Shelf Seas Working Group (CSSWG) have identified 39 independent developments of the coastal or regional model. Examples to demonstrate how these GODAE products are used are listed below.

- Impact assessment of sewage release or fish farming management (with downscaling from 1 km resolution to approximately 150 m, resulting in improved representation of the small scale features due to increased model resolution and the addition of tide, improving the representation of effects caused by tidal mixing).
- Tropical cyclone prediction with local air/sea interaction.
- Maritime safety, e.g. numerical modelling of iceberg track.
- Decision support for environmental management.
- Forecasting jelly fish and larval transports (De Mey *et al* (2008)).
- Search and Rescue operations e.g. the use of Lagrangean tracers (Davidson *et al* (2008)).

Naval applications include estimation of acoustic properties, such as sonar capability and acoustic stealthiness. This can be done using the high resolution products that resolve fronts (Jacobs *et al* (2008)). Current fields are also used for tracing drifting objects. GODAE products have been used for diver operation safety and evaporation duct height estimation.

Rayner and Stevens (2008) discuss the use of GODAE products in offshore industries. There is therefore a requirement that GODAE products provide combined metocean statistics for weather, seastate and vertical current profiles suitable for all these applications (e.g. hindcast, nowcast and forecast fields are needed). Important remaining challenges include coupling the atmosphere, ocean and wave models and the incorporation of decadal and climate changes.

The Committee perceives the launch of the GODAE products as a significant improvement in the resolution, range and availability of numerical models of ocean current physics for the researcher or practitioner. With time, to the Committee's knowledge, further literature will become available presenting both examples of applications of the GODAE products and more detailed critical review of the quality of the assimilated data (Bell and Le Traon (2009)).

2.4 Ice

Depending on the season the sea ice in the South Polar Sea covers between 4 and 19 Mill. km^2. This ice does not constitute a homogeneous surface it changes locally with respect to its properties like age, porosity, thickness, salinity, snow cover, rheology and roughness. Sea ice in the Arctic or Antarctic represents a highly variable boundary layer between the ocean and the atmosphere which significantly affects the transfer of energy or mass.

The exchange of energy is hampered and a significant part of the solar radiation is reflected by sea ice Brandt *et al* (2005). So-called ice-albedo-feedback therefore plays an important role in the energy and radiation balance of the earth's surface. Compared to ice, snow has an albedo which is even higher and further increases this feedback effect. Snow influences the growth and melting of sea ice in several ways, as it reduces the energy transfer from the ocean to the atmosphere which also reduces the growth rates of ice. On the other hand, snow ice can contribute some 25% of the total sea ice.

Due to its vital importance for the earth's climate, the extension of sea ice and some of the ice's properties are regularly monitored. While sea ice extension shows some inter-annual variability, the trend shows a reduction. In August 2008 both the North-East and the North-West Passage have been reported clear of sea ice for the first time and the United Nations Climate Council predicts a further reduction of sea ice in the upcoming years (IPCC (2007)).

The need for more detailed data on the environmental conditions in arctic regions was recognized by many in the offshore industry and beyond. Since the collection of these environmental data is a costly and time consuming process, collaboration in teams is essential. Wiencke and Vassmyr (2007) give results from the Offshore Arctic Data Collaboration (OADC), a JIP between five oil companies. The objective of the project is to ensure that the vast amounts of publicly accessible environmental data, and knowledge related to petroleum development offshore in the Arctic and Barents Sea, are made easily available to the industry. Within the project the available data are reviewed and validated and shared using secure internet (Arctic Web).

2.4.1 Locally Sensed Ice Measurements

Up until now, in-situ measurements are important in the understanding of the variability of meteorological, glaciological and oceanographic variables. Several attempts have been made to estimate sea ice thickness. The oldest and most accurate method of measuring sea ice thickness is by drilling. Nansen did the first systematic measurements of ice thickness in the Arctic during the expedition in 1893–1896. Since then, several techniques have been developed. Manual drilling is still the most exhausting method, but supported by a battery-powered head, semi-manual drilling is the safest approach. Gasoline-powered head drills and hot water drills are faster but sometimes tricky and difficult to handle. Before the hole refreezes, a tape measure with a weight is sent down the hole to read off ice and snow depth. Drilling is a suitable tool for determining the mean ice thickness at a small scale and it is still essential for validating any other method. However, used as a stand-alone technique, these in-situ measurements are time consuming and spatially limited and thus lack the necessary investigation of regional variability.

Annual ice research expeditions in the north eastern Barents Sea performed by the Arctic and Antarctic Research Institute are described by Naumov *et al* (2007). One of the main goals of these surveys is to investigate the ice cover characteristics necessary for design of offshore structures. This work is devoted to investigation of ridged features of the Barents Sea and construction of a design ice ridge.

Since sea ice coverage hinders offshore activities in arctic regions, especially the extraction of hydrocarbons, Zubakin *et al* (2007) analysed the ten seasons with the most severe ice conditions between 1950 and 2007 in the North-Eastern part of the Barents Sea shelf. During this period, a significant amount of data on the environmental conditions is available which allows for a reliable assessment of the ice conditions. The severity of winter conditions depends on several factors, the two main reasons being; the presence of residual ice from the previous winter season and the heat flow coming from the water in the Nordkapp Current to the Barents Sea. Specific data from this research can be found in Zubakin *et al* (2008).

2.4.2 Remotely Sensed Ice Measurements

For a long time, the large extent of sea ice and the relatively sparse net of observation points in polar regions posed a major problem for the observation of sea ice and its properties. Comprehensive monitoring of sea ice was not possible until the onset of satellite observation techniques. Systematic studies of sea ice coverage started in 1978 with the start of the satellite NIMBUS-7. Measurements on this platform were taken by microwave sensors. After the start of ERS-Satellites in 1991 the data were complemented by radar scans. Over the years, several studies addressed the onset of the melting of sea ice by means of aeroplane and satellite measurements. Using these data for the northern hemisphere during the period from 1979 to 2001, a tendency towards longer melting periods has been found (Belchansky *et al* (2004)).

Compared to Arctic regions, the sea ice in the Antarctic shows a higher coverage of snow. Satellite measurements show that the thickest snow cover of sea ice is to be found in the Weddell Sea, Ross Sea, Bellingshausen Sea and the Amundsen Sea, all of which show a high variability between 1992 and 2003 according to Markus *et al* (2007). A combination of in situ and remote measurements showed the metamorphosis of snow due to the daily cycle of melting and freezing (Willmes *et al* (2006)). As a consequence, the emissivity of microwaves is reduced while the backscatter is increased. Persistent melting over the period of several days was found only in the outer regions of the sea ice which are influenced by warmer humid air. Recent studies show various Antarctic ice drainage basins to be strongly out of balance (van den Broeke *et al* (2006)).

Measurements of surface elevation have been performed by means of laser altimetry and differential GPS (DGPS) using a helicopter suspended sensor (Göbell (2007)). Surface elevation is derived from the difference between the laser range measurement above the snow surface and the instrument's height above the ground elevation (geoid) determined by DGPS (GPS height). This yields the geolocated elevation above the geoid. Results show that thickness/surface elevation ratios are smaller over sea ice in the Weddell Sea than in the Lincoln Sea according to a thicker snow cover in the Antarctic. This has fundamental consequences for ice thickness retrieval from space-borne altimeter missions.

Studies with impulse radar sounding of sea ice, also called ground-penetrating radar (GPR) started in the mid 1970s. This technique is suitable for freshwater ice but for sea ice its use is rather limited due to the brine content of the ice (Otto (2004)). The brine content decreases the permittivity of the ice and thus limits the propagation distance of radio-frequency energy. Since the early 1980s, the technique of electromagnetic (EM) induction sounding from airborne platforms has been tested. The first ground-based thickness profiles obtained with the Geonics EM31 looked very promising, especially, after the comparisons with drill-hole measurements. A combination of the EM31 and a laser altimeter allows EM sounding from onboard ice-breakers during voyages through the Arctic and Antarctic oceans to yield regional ice thickness distributions. Thus, the characteristics of different ice regimes can be clearly distinguished and studied. The ship-based measurements, however, suffer from the fact that the easiest route through the ice is always chosen, which means that thicker, older ice is statistically underrepresented. Therefore, the idea of a fully digital airborne sensor platform was adopted again.

Another possibility is the profiling of the ice underside by upward looking sonar (ULS) from submarines or moorings, from which the ice thickness distribution can be inferred. First measurements for the Arctic were obtained in the middle of the 20th century but precise tracks and systematic repeated measurements were not available until the 1980s.

Experiments with moored ULS were conducted in shallow water in the Beaufort Sea (Melling (2005)) and in deeper water in the Fram Strait, the Weddell Sea, and in East Antarctica.

Laser profiling of the visible sea ice height above sea level is the equivalent to sonar profiling from the air. A major issue in laser profiling has been the removal of the aircraft motion from the obtained laser range. With the GPS becoming more popular due to increasing accuracy, a new approach considering the removal of aircraft motion was used by taking the difference between the height derived with GPS and the laser range. Most recently, an improved Arctic geoid model has been derived, combining terrestrial gravity data with the GRACE geoid model (Forsberg and Skorup (2006)). Today, the use of GPS together with a precise geoid model is a common method to derive surface elevation. Besides single-beam laser altimeters, laser scanning systems have also been used successfully. With this technique, cross-track scans are possible, covering a wider path on the ground and thus allowing more measurements than with a single-beam laser. Generally, ice thickness is determined from sea ice surface elevation by multiplying it with a factor derived from a study in climatology.

With the launch of NASA's ICESat satellite in January 2003, laser altimetry was possible on a large-scale for the first time, covering most of the Arctic (Kwok *et al* (2004, 2006)). The height of the snow surface above sea level is derived by comparing measurements over sea ice with measurements over water. The measurement is averaged over 60 m diameter laser footprints spaced at 172 m along-track. To derive ice thickness, the local sea level was estimated by identifying open water or thin ice along the ICESat tracks with RADARSAT imagery (Kwok *et al.* (2004)). The established freeboard height at the leads is used as a reference to level the ICESat elevation profiles. The remaining uncertainty in converting the derived sea ice surface elevation to ice thickness is the snow depth.

As opposed to satellite-borne laser altimetry, radar altimetry from satellites has been conducted since the launch of SEASAT in 1978, followed by several other satellite missions. CryoSat-2 will be the first satellite equipped with a radar altimeter that enables sea ice freeboard measurements covering the polar regions, due to its near-polar orbit. The purpose of the CryoSat-2 (Wingham *et al* (2006a), Drinkwater *et al* (2004)) mission is to determine trends in the ice masses of the Earth. The advantage over ICESat is that transforming freeboard to sea ice thickness is less sensitive and less dependent on snow depth. Very narrow across-track strips are formed, which reduce the footprint size to 250 m. The SAR-Interferometric mode provides improved elevation estimates over ice sheets with variable topography. Generally, the surface is not planar over ice sheets, and a method for determining the echo location is required. A second radar antenna is added and used to form an interferometer across the satellite track.

In anticipation of the ICESat and CryoSat mission, experiments with a special delay-doppler phase-monopulse (D2P) radar took place to demonstrate the use of two enhancements to satellite radar altimetry. In 2002, a joint campaign of laser and radar (LaRa) altimetry was conducted in northern Greenland. The aircraft carried two D2P radar altimeters and a laser scanner. The aim was to assemble critical measurements of land and sea ice in order to help scientists understand and quantify the best methods for retrieving ice thickness by using a combination of laser and radar altimeter measurements. To validate the radar measurements of CryoSat-2, an airborne version was developed by the European Space Agency (ESA). The Airborne Synthetic Aperture and Interferometric Radar Altimeter System (ASIRAS) instrument came into use for the first time during a campaign over the Greenland Ice Sheet in 2004 (Hawley *et al* (2006)).

A comparison of different sea ice-ocean coupled models and the validation with buoy and remote-sensing data for the period 1979–2001, on the basis of monthly averages is presented in Martin (2007). The sea ice concentrations derived from passive microwave imagery are affected by errors due to atmospheric absorption and emission and wind roughening over open water (Andersen *et al* (2007)), as well as anomalous ice and snow emissivity.

Fissel *et al* (2008) address the extent of sea ice and focus on the vertical dimensions. While the areas covered by ice have been monitored extensively over the past 30 years, there is significantly less information on ice thickness: only a limited number of datasets from the past 15 years are available. For two locations, the Fram Strait and the Canadian sector of the Beaufort Sea, long time period measurements of ice thickness are available. Fissel *et al* describe the use of ULS for the investigation of ice thickness. These instruments are moored to the sea floor and can operate independently for more than a year. Thus, the sea ice coverage as well as its growth or melting can be monitored closely with high temporal and spatial resolution.

Wadhams *et al* (2008) show the results of measurements taken by an autonomous underwater vehicle. The Autosub-II carried out multibeam digital terrain mapping of the underside of the sea ice off the coast of Greenland. The implications for the sea ice thickness are discussed. The authors also address the experiments with a second AUV, Gavia, and how the measurement can be compared. The authors discuss how AUV techniques can be applied to problems such as mapping rubble fields around drilling platforms, oil containment by sea ice and other topics of interest to the offshore industry.

Fujisaki *et al* (2007) present a numerical model for 7-day forecasts of sea ice produced by the Japan Meteorological Agency. Their ice dynamic model takes discrete characteristics of ice floes into account. The grid size is 5 x 5 km for high resolution forecasts. The sea surface current data are found to influence sea ice movement significantly and the ocean heat flux at the ice-ocean interface is refined.

Johnston and Timco (2008) describe the development of a guide which could explain the factors of multi-year ice hazardous to ships and structures. They also illustrate the key parameters that can be used to identify different types of sea ice using observations from ships, offshore platforms, aerial reconnaissance and satellite imagery.

A wide range of services of ice data is available via the internet such as the National Snow and Ice Data Center (http://nsidc.org/data/g01360.html), which provides datasets of upward looking sonar collected by submarines of the U.S. Navy and Royal Navy in the Arctic Ocean. Statistics files include information concerning ice draft characteristics, keels, level ice, leads, un-deformed and deformed ice.

The Finnish Institute of Marine Research (FIMR, http://haavi.fimr.fi/polarview/charts.php) publishes SAR-based ice thickness charts showing ice conditions in a 2-25 km scale. An ice thickness chart is operationally produced after a SAR image has been received, using the latest available ice chart as an input. Then the ice field boundaries are refined, and the thinnest and the thickest ice areas inside each ice chart segment are identified based on the SAR signal statistics. The resulting thickness chart is then colour coded according to navigation restrictions based on ice thickness.

The Ocean and Sea Ice Satellite Application Facility (OSI SAF, http://www.osi-saf.org/index.php) also publish meteorology and oceanography information on the ocean-atmosphere interface online. The EUMETSAT data are provided in near real-time.

A consortium of organisations from Canada, Denmark, Germany, Italy, Norway and United Kingdom delivers ice data in the Polar View Programme (http://www.polarview.aq/iceshelf/iceshelf.php). Polar View is an earth observation (EO) or satellite remote-sensing program, focused on both the Arctic and the Antarctic. Polar View is supported by the European Space Agency (ESA) and the European Commission with participation by the Canadian Space Agency. Envisat ASAR data are used to provide regular images of Antarctic ice shelves and coastline. These images are extracted from the regular 3-day rolling mosaic of the entire continent and have a pixel spacing of 1 km.

Continuous Arctic sea ice drift maps from 1992 are provided by IFREMER/CERSAT (http://cersat.ifremer.fr/news/scientific_results/global_mapping_of_arctic_sea_ice_drift_a_unique_database). It combines sea ice data and maps from various scatterometers (microwave radar) and radiometers onboard earth observation satellites (ERS-1, ERS-2, ADEOS-1, QuikSCAT, SSM/I, AMSR-E).

2.4.3 Numerical Modelling to Complement Measured Data

Climate models predict an increased snow fall over the South Polar Sea. This is due to the increased air temperature which causes a higher capacity of water vapour (Trenberth and Shea (2005)). Satellite measurements (Markus (2007)) already show a small increase in the snow cover between 1992 and 2003. In summer, the snow cover does not melt completely but it undergoes a cyclic change of melting and re-freezing.

This cycle changes the shape and size of snow crystals over the course of the summer (Nicolaus *et al* (2007), Willmes *et al* (2007)).

For calibration and validation of forthcoming radar altimetric satellite missions, such as ESA's Cryosat, the knowledge of backscattering properties in dependence of snow morphology is of high relevance. The snow accumulation in the Arctic was investigated by Rotschky (2007). This study shows the potential for satellite-radar observations to reduce inaccuracies in the interpolation of field data over long distances. Also, the results support ongoing ice sheet modelling and the interpretation of ice core data.

The accumulation of ice rubble is investigated by McKenna *et al* (2008). They describe an empirical approach to model the rubble height and extent of ice adjacent to offshore structures. The build-up of rubble against the structure during an event is modelled on a regular grid, with rubble extent and height based on measured data, thereby ensuring a realistic representation.

3. MODELLING OF ENVIRONMENTAL PHENOMENA

3.1 Wind

Wind is the most important driving force for ocean waves and it also causes significant lateral loads on tall structures. For a long time, the effects of wind were only accounted for in empirical formulas for example, using the measured wind velocities or the fetch in classical descriptions of wave spectra. The recent development of offshore wind parks changed this significantly: not only were more precise measurements of the wind speed and direction needed, but also the systematic investigation of wind by means of numerical models became more important.

3.1.1 Analytical and Numerical Description of Wind

The effect of humidity fluxes on stability corrected wind speed profiles is investigated by Barthelmie *et al* (2007). The effect on wind speed profiles is found to be important in stable conditions where the inclusion of humidity fluxes forces conditions towards neutral. Neglecting humidity fluxes leads to an over-estimation of the wind speed profile at 150 m by approximately 5%. With increasing heights of wind turbines in offshore wind parks, the marine boundary layer (between 100-200 m above the surface) can become significant, for which there are few measured data available. The authors examine the role of humidity fluxes from the sea-surface caused by evaporation/condensation of water vapour on the vertical profile of offshore wind speeds. They conclude that understanding the impact of humidity fluxes may also have other applications such as a consideration of how wind speed profiles may change in areas which currently experience sea ice during winter but may become ice free under global climate change, and the retrieval of wind speeds from satellite images.

A CFD model of the wake of an offshore wind farm as a complement to measurements is proposed by Réthoré *et al* (2007). The method is based on the Navier Stokes equations in a large domain downstream of an offshore wind farm. The inflow of the domain is estimated using existing met mast measurements from both free stream and directly in-wake positions. A comparison between the simulation results and measurements from a met mast are presented. The article focuses on a method extending the data available from the existing wind farms, using a CFD analysis. The procedure includes the measurements of two met masts placed at a relatively short distance from the farm, one in the free stream, and one directly downstream of the park. The free stream mast is used to define the region of the inlet, where the wind is undisturbed by the wind farm, and the downstream met mast is used to model the wake region of the inlet.

The variability of wind is discussed by Burton *et al* (2001). As the power in a wind field changes with the cube of the wind speed, so an understanding of the characteristics of the wind resource is critical to all aspects of wind energy exploitation. From the point of view of wind energy, the variability of the wind is its most striking characteristic. This variability persists over a very wide range of scales, both in space and time. On shorter time-scales, the predictability of the wind is important for integrating large amounts of wind power into the electricity network, to allow the other generating plant supplying the network to be organised appropriately.

Modelling of wind power applications is addressed by Lange (2002). For different measurement sites in the Danish Baltic Sea Lange estimates the wind climate. The approach combines different models which also include sea surface roughness and thermal effects. Thermal effects due to the coastal discontinuity, which limit the applicability of the theory, are identified. Their significance for the wind regime at the site is analysed. The importance of the different effects is investigated by comparison with the measured wind speed. To quantify the effect of thermally induced flow modifications in the coastal zone a simple correction method for the vertical wind speed profile is developed.

Broquet *et al* (2008) address the topic of model errors. Effective data assimilation into open-ocean and shelf-seas models requires proper estimates of the error statistics generated by imperfect atmospheric forcing in regional models. The model they investigate describes the Bay of Biscay in a basin-scale North Atlantic configuration. The model used is the Hybrid Coordinate Ocean Model (HYCOM). The spatial structure of the model error is analysed using the representer technique, which allows for the anticipation of the subsequent impact in data assimilation systems. The results show that the error is essentially anisotropic and inhomogeneous, affecting mainly the model layers close to the surface. Even when the forcings errors are centred on zero, a divergence is observed between the central forecast and the mean forecast of the Monte Carlo simulations as a result of nonlinearities. The 3D structure of the representers characterises the capacity of different types of measurement (sea level, sea surface temperature, surface velocities, subsurface temperature, and salinity) to control the circulation.

The research of Shaikh and Siddiqui (2008) focuses on the structure of the airflow near the surface region over the wind-sheared air-water interface. The two-dimensional velocity field in a plane perpendicular to the water surface was measured by PIV. The results show a reduction in the mean velocity magnitudes and the tangential stresses when gravity waves appear on the surface. An enhanced vorticity layer was observed immediately above the water surface. The vorticity was increased by an order of magnitude, and the energy dissipation rate was increased by a factor of 7 in this layer at all wind speeds. The results in this study show that the flow dynamics in a layer immediately adjacent to the water surface, whose thickness is of the order of the significant wave height, is significantly different from that at greater heights.

Dynamical processes at the Iroise Sea are investigated by Muller *et al* (2008). They use a regional 3D model, the so-called Model for Applications at Regional Scale (MARS). The horizontal resolution of the configuration in use is 2 km with 30 vertical levels. The 3D model of the Iroise Sea is embedded in a larger model providing open boundary conditions. As the air surface temperature is highly sensitive to the sea surface temperature, a regional climatologic sea surface temperature is taken into account when determining the meteorological parameters. By allowing a better coherence between the temperature of the sea surface and the atmospheric boundary layer while giving a more realistic representation of heat fluxes exchanged at the air/sea interface, this forcing constitutes a noticeable improvement of the Iroise Sea modelling. The different sensitivity tests discussed pinpoint the importance of entering, in Weather Research and Forcasting (WRF), sea surface temperature data of sufficiently high quality, before the computation of meteorological forcing.

Boreal winter wind storm situations over Central Europe are investigated by Leckebusch *et al* (2008) using an objective cluster analysis. Their analysis considers different clusters of weather patterns in order to achieve an optimum separation of clusters of extreme storm conditions. The authors identify four primary storm clusters which feature almost 72% of the historical extreme storm events and add only to 5 % of the total relative frequency. These clusters show a statistically significant signature in the associated wind fields over Europe. An increased frequency of Central European storm clusters is detected with enhanced GHG conditions, associated with an enhancement of the pressure gradient over Central Europe. Consequently, more intense wind events over Central Europe are expected. The presented algorithm will be highly valuable for the analysis of large data amounts as is required for e.g. multi-model ensemble analysis, particularly because of the large data reduction.

Wium (2005) addresses the simplification of complex wind profiles for practical purposes: while some cases allow for the use of simplified formulas, Wium discusses why some cases require the use of more detailed analysis. The author describes a variety of problems which are being solved, and which can be handled with current knowledge.

3.1.2 Experimental Description of Wind

Xi *et al* (2006) develop a real-time hurricane wind forecast model by incorporating an asymmetric effect into the Holland hurricane wind model. They use hurricane forecast guidance by the NOAA and the National Hurricane Center (NHC) for prognostic modelling. The model's initial wind field also takes real-time buoy data from the NDBC into account. The method is validated using all 2003 and 2004 Atlantic and Gulf of Mexico hurricanes. The results show that 6-h and 12-h forecast winds obtained using the asymmetric hurricane wind model are statistically more accurate than those obtained using a symmetric wind model. Although the asymmetric model performed generally better than the symmetric model, the improvement in hurricane wind forecasts produced by the asymmetric model varied significantly for different storms.

Durante and de Paus (2006) model the wind profiles in the lower Boundary Layer and compare their results with measured profiles. The test sites are Cabauw, The Netherlands and Wilhelmshaven, Germany. They use different numerical schemes in order to calculate the 21 day-averaged vertical wind profiles. Their numerical results which correspond well to the measured profile reveal that the horizontal resolution plays a minor role for the given terrain conditions.

The West Africa Gust (WAG) JIP was initiated in 2004 to make best use of available industry data for characterisation of squalls in engineering design. The initial work highlighted the need for further measurement to address uncertainties in the horizontal and vertical structure of squall winds. Consequently a measurement system was installed on the Total operated Likouala LAFP platform 40 km offshore Congo. Measurements of simultaneous wind speed and direction at elevations ranging from 10 m to almost 40 m above sea level have been made.

3.1.3 Statistical Description of Wind

The gustiness of wind is also considered by Payer (2004). An extreme value model is used in order to take extreme wind speeds and their direction into account simultaneously. Extreme quantiles and exceedance probabilities are estimated. The authors also include the corresponding confidence intervals. A common difficulty with wind data, known as the masking problem and related to the measurement strategy, is that over a time interval, only the largest wind speed of all directions is recorded, while occurrences in all other directions remain unrecorded. To improve estimates, Payer suggests an improved model to handle the masking problem. The performance is compared with the original model and measured wind data. Also, a multivariate extreme value model is introduced which allows for a broad range of dependence structures.

The uncertainty of wind power predictions is also investigated by Lange (2003). The uncertainty is defined as the typical range in which deviations between what was predicted and the real situation are likely to occur. The majority of today's wind power forecasting systems are based on numerical weather prediction models, so it is important to know when and how forecast errors occur. Lange describes the overall behaviour of deviations between predictions and measurements in terms of statistical distributions, as well as the decomposition of the forecast error in amplitude and phase errors. The error reduction in the prediction of the combined power output of many wind farms in a region compared to a single wind farm is analysed and the benefits of a regional wind power prediction are quantitatively assessed.

Böttcher (2005) considers the proper characterization of atmospheric turbulence. The markedly intermittent statistics of velocity differences (the velocity increments) are examined and their relevance with respect to the estimation of extreme events is discussed. The statistics of the increments approach those of stationary, homogeneous and isotropic turbulence. A model is presented in which the atmospheric increment statistics are explained as a superposition of different subsets of homogeneous and isotropic turbulence. It is shown that these subsets are distributed according to a Weibull distribution which is commonly considered to be the annual distribution of averaged wind speeds.

Sanabria and Cechet (2007) present a statistical model for the investigation of severe wind hazard. Wind hazard is assessed by calculating return periods of maximum wind gust (generally considered as 1-3 second duration gusts) from observational data. The return periods for these wind gust speeds were obtained using the application of statistical extreme value distributions. Parameters to fit these distributions were calculated from data provided by the Australian Bureau of Meteorology.

The Grid to Eulerian Extreme Wind Speed Transformation (GUEST) JIP was a proprietary study performed for the North West Approaches Group (NWAG) that addressed the suitability of gridded wind speed products of hindcast studies for the specification of site-specific extreme wind speed design data in the form needed for engineering purposes. The focus of GUEST is offshore northwest Europe because of its availability of new hindcast datasets and high quality measured in-situ marine wind time series of a continuous nature sufficient for the sampling of true Eulerian storm peaks. However, it is expected that the results will be applicable to most mid and high-latitude open ocean areas where design wind speeds are associated with extratropical cyclones. The result of GUEST is a recommended algorithm to transform the wind speed storm peaks and extremes typically derived from the products of metocean hindcast studies to the engineering wind speed design data for the "base" Eulerian averaging interval of 20 minutes, as a function of elevation and boundary layer thermal stratification.

3.2 Waves

Accuracy of the wave spectral models is under continuous improvement. In 2008 the

GlobWave project was initiated by the European Space Agency to improve the uptake of satellite-derived wind-wave and swell data by the scientific, operational and commercial user community. The project covers the development of an integrated set of information services based on satellite wave data, and the operation and maintenance of these services for a demonstration period. It is expected that the GlobWave project will contribute to further progress on improving wave models' uncertainties.

A number of extreme wave studies have been conducted theoretically, numerically, experimentally and based on the field data in the last years, which has significantly advanced our knowledge of ocean waves. It has been demonstrated that the contribution from higher-order and fully nonlinear solutions, compared with the second order wave models may be significant. Several new wave records including extreme waves have been collected in the field and in laboratories allowing verification of wave model predictions. The Rogue Waves 2008 Workshop in Brest organized by Ifremer October 13-15, 2008 has contributed to further increase in our knowledge about extreme and rogue waves and suggested some directions for future research. http://www.ifremer.fr/web-com/stw2008/rw/.

More systematic investigations of mechanisms for the generation of rogue waves, such as bimodal seas, directional energy spreading, spatial description, effects of water depth and wave-current interaction, are still lacking. There are also limited field data applicable to study frequency of occurrence of rogue waves in the ocean.

Statistics of wave height and crest and trough elevations (including the highest steep waves), have been established based on higher-order model simulations, laboratory tests and field data.

Some progress has been made on long-term description of sea states including joint environmental modelling, and in particularly spatial and seasonal distribution of wave data.

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. A review of improvements to the physics of the wave spectral models which have taken place over the last decade is given by Cavaleri *et al* (2007). The WAM model, (WAMDI Group (1988), Komen *et al* (1994)) and the WAVEWATCH-III model (Tolman (1999)) are the most generalized and tested wave prediction models used for both hindcasting and forecasting purposes. Recent improvement of the wave physics in WAVEWATCH-III can be found in Ardhuin *et al* (2008a). 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. The fact that these two, the most popular models operational at two of the most prominent meteorological centres, use different approaches to the problem is in itself an indication that a single "best" solution has not yet been accepted (Cavaleri *et al* (2007)).

Utilisation of wave information collected by satellites in wave models has increased significantly. For example Aouf *et al* (2006) show assimilation of synthetic SWIMSAT directional wave spectra in the wave model WAM, and also assimilation of SAR data (Aouf *et al* (2008)).

Ardhuin *et al* (2008b) and Collard *et al* (2008) used four years of ENVISAT SAR data to track oceanic storm swells and to improve the estimation of the swell dissipation term.

SWAN is commonly utilised to describe shallow water wave climate. The three 3G wave models WAM, WAVEWATCH-III and SWAN use different solution methods, with associated differences in numerical outcome, Cavaleri *et al* (2007). SWAN uses the WAM Cycles 1-3 limiter, so growth rates are very sensitive to the time step size. The present version of SWAN is able to apply curvilinear grids allowing for finer resolution near the coast. In shallow water the higher resolution and stronger refraction require smaller time steps when conditionally stable Eulerian advection schemes are used. Recently, there has been some impetus to push exclusively non-stationary models such as WAM and WAVEWATCH-III closer to shore, since this avoids learning, maintaining, and running multiple wave models at a given operational centre.

As pointed out by Cavaleri *et al* (2007) for future development of the wave models a stronger interaction between the wave and the circulation modelling community is an important and expected development.
Wave models describing short-term variations of sea surface may be categorized into three classes:

- linear wave models;
- second order wave models, and
- higher-order wave models.

Linear and second order wave models (e.g. Prevosto (1998), Forristall (2000)) are well established and have commonly been used in design in the last years. Recently some investigations demonstrating applicability of the second order models to describe extreme wave events have been carried out.

Jensen (2005) used the second order Sharma and Dean finite-water wave theory to derive the mean second order short-crested wave pattern and associated wave kinematics, conditional on a given magnitude of the wave crest. The analysis accounted for wave spreading as well as finite water depth. A comparison with a measured extreme wave profile, the Draupner New Year Wave, has shown a good agreement in the mean, indicating that this second order wave can be a good identifier of the shape and occurrence of extreme wave events.

Toffoli *et al* (2006a) used a second order wave model to investigate the effects of spectral distribution on the statistical properties of the sea surface elevation. Single and double peaked directional wave spectra have been considered at different water depths. For unimodal seas (i.e. single peaked spectrum) the presence of directional components has reduced the effects of the second order interactions in deep water, while it has increased them in shallower depths. For bimodal seas (i.e. double peaked spectrum) a large angle between the wave trains has systematically decreased the vertical asymmetry of the wave profile. The nonlinear interaction seems to reach maximum strength when the two wave spectra are slightly separated in direction (35^o). It has been shown that increase of the wave train's angle produces lower wave crest height (up to 7% lower at the 10^{-4}probability level) than a unimodal sea condition while reduced angles produce significantly higher crest heights than unimodal sea.

The second order, three-dimensional, finite-depth wave theory was compared with field data from Lake George, Australia, Toffoli *et al* (2006b). For small nonlinearities, the second order model approximates the field data very accurately. By low-pass filtering the Lake George time series, there is evidence that some energetic wave groups are accompanied by a setup instead of a setdown when directional spreading is included. In particular, the coupling coefficient of the second order difference contribution predicts a setup as a result of the interaction of two waves with the same frequency but with different directions. Bispectral analysis, furthermore, indicates that this setup is a statistically significant feature of the observed wave records.

Groups of second order waves with high elevation were studied by Arena and Soares (2008) for wind wave unimodal and for bimodal spectra. The three highest waves (the highest one and the waves that precede and follow it), when a large crest occurs, have been considered. The analysis showed that the profile of these three waves depends upon the bandwidth of the wave spectrum.

The higher-order wave models include solutions of the nonlinear Schrödinger (NLS) equation (see Osborne *et al* (2004)) and the Dysthe equation (Dysthe (1979)), and some direct numerical simulation techniques applicable to a physical experiment conducted in a wave flume. These models and the ones developed on the basis of the Boussinesq equation are well reviewed in the 2006 ISSC I.1 Report. The NLS approach has bandwidth constraints (e.g. Socquet-Juglard *et al* (2005)) unlike direct numerical simulation techniques.

Boussinesq models have been used by several authors to study evolution of wave profiles. Furhman and Madsen (2006) have conducted a numerical study of quasi-steady doubly periodic monochromatic short-crested wave patterns in deep water using a high-order Boussinesq model. Simulations using linear wave maker conditions in the nonlinear model have initially been used to approximate conditions from recent laboratory experiments. The numerical simulations share many features with those observed in wave tanks like bending (both frontwards and backwards) of the wave crests, dipping at the crest centrelines, and a pronounced long modulation in the direction of propagation. A new and simple explanation for these features has been provided.

A high-order Boussinesq model has been used by Furhman *et al* (2006) to numerically simulate deep-water short-crested wave instabilities, arising from two quartet resonant interactions so-called Ia and Ib. A series of the class Ia short-crested wave instabilities covering a wide range of incident wave steepness has shown a close match with theoretical growth rates near the inception of instability. Further, the unstable evolution of these initially three dimensional waves led to an asymmetric evolution, even for weakly nonlinear cases. This led to an energy transfer. At larger steepness, a permanent downshift of both the mean and peak frequencies has been observed. Similar results have been obtained for a single case involving a class Ib short-crested wave instability at relatively large steepness.

Madsen and Furhman (2006) have presented a new third-order solution for bichromatic bidirectional water waves in finite depth. Earlier third-order theories in finite depth were limited to the case of monochromatic short-crested waves. The work of the authors generalises these earlier works. The solution suggested includes explicit expressions for the surface elevation, the amplitude dispersion and the vertical variation of the velocity potential, and it incorporates the effect of an ambient current with the option of specifying zero net volume flux. The nonlinear dispersion relation has been generalized to account for many interacting wave components with different frequencies and amplitudes. The model has been verified against classical expressions from the literature.

The second order approximation does not include effects of dynamics of free waves. To include the dynamics of free waves the time evolution of the random surface elevation can be calculated by integrating numerically the Euler equations by use of the Higher Order Spectral Method (HOSM), which was independently proposed by West *et al* (1987) and Dommermuth and Yue (1987). A comparison of these two approaches (Clamond *et al* (2006)) has shown that the formulation proposed by Dommermuth and Yue (1987) is less accurate. Use of a variable step size when performing simulations by HOSM is more efficient than a constant time step as in this way a consistent level of accuracy is maintained. In the literature, however, a number of studies performed with the HOSM have been carried out using a constant time step (e.g., Tanaka (2001), Onorato *et al* (2001), Tanaka, (2007)).

A number of physical mechanisms to explain the extreme and rogue wave phenomena have been suggested in the last decade; these include:

- wave-current interactions;
- linear Fourier superposition (frequency or angular linear focussing), and
- nonlinear interaction and modulational instability.

Zakharov and Dyachenko (2008) show that a rogue wave can be identified with a giant breather or “oscillating soliton” that can propagate on the surface of deep fluid for a long time without losing energy, similar to the breather for the NLS equation. These breathers are localised wave groups with very high local steepness ($ka \geq 0.5$) Existence of such solitons for the Euler equation is not supported by any analytical theory. According to Zakharov and Dyachenko (2008) it is indirect indication of complete integrability of free-surface hydrodynamics in deep water, but stability of such a breather needs further investigation. Alternatively, Tayfun and Fedele (2008) argue that large surface displacements and large wave heights arise from the constructive interference of spectral components with difference amplitudes and phases.

Attention has recently been given to the study of modulational instability of free wave packets (Onorato *et al* (2001,2006), Janssen (2003)). This instability can develop when waves are long crested, i.e. unidirectional, narrow banded and in infinite water depth. As a result, the properties of surface gravity waves can significantly diverge from the ones described by second–order theory (e.g., Mori and Yasuda (2002), Onorato *et al* (2006a), Gibson *et al* (2007), Toffoli *et al* (2008a)). The findings suggest that the spectral evolution of long-crested waves in deep water is governed by non-resonant wave-wave interaction. Free waves may increase the probability of occurrence of extreme events, provided the Benjamin–Feir Index (BFI) is sufficiently high. BFI is defined as the ratio between the wave steepness and the spectral bandwidth (see also Mori and Janssen (2006)). The existing wave forecasting models (i.e. the 3G wave models) do not include the non-resonant interaction.

For the more realistic case of short crested waves, where wave components with different directions of propagation coexist, the non-resonant interaction is inactive and the effect of the modulational instability is reduced (Onorato *et al* (2002a), Socquet-Juglard *et al* (2005), Waseda (2006), Gramstad and Trulsen (2007), Toffoli *et al* (2008b)). Instead Hasselman's resonant interaction (Hasselman *et al* (1985)) governs the evolution of the directionally broad random waves.

Mori *et al* (2008) suggested a modified theory for rogue wave prediction which includes directional effects. The theoretical relationship between kurtosis, BFI, and directional spread σy has been provided. The theory shows good agreement with numerical simulations of the cubic NLS equation.

Didenkulova *et al* (2007) proposed a theoretical model for run-up of nonlinear asymmetric waves on a plane beach, assuming that waves do not break. The model can be applied to prediction of tsunami wave height.

Osborne *et al* (2008) have conducted a new theoretical and numerical analysis of directionally spread shallow water waves. A nonlinear Fourier decomposition of shallow water wave trains based on many directional cnoidal wave trains (at leading order they are solutions to the Kadomsev-Petvishivili or the 2+1 Gardner equations) nonlinearly interacting with one another has been developed. The fully spread directional spectrum has been based upon a Riemann matrix formulation. This formulation uses multi-dimensional Fourier series to compute the surface elevation out to the Boussinesq approximation. It has been found that a new type of rogue wave is observed, in shallow water, which is not related to the Benjamin-Feir instability. These waves arise at the locus of two crossed cnoidal waves. The authors found the actual cnoidal waves that cause the rogue event in a random sea state. Further, the developed numerical algorithm runs about 1000 times faster than typical Boussinesq simulations.

Importance of more detailed investigations of meteorological and oceanographical conditions in which extreme and rogue waves occur have been pointed out by several authors at the ROGUE WAVES 2008 Workshop (e.g., Rosenthal (2008), Liu *et al* (2008a), Tamura *et al* (2008), Badulin *et al* (2008), Leblanc *et al* (2008), Ma and Yan (2008), Annenkov and Shira (2008), Papadimitrakis and Dias (2008), Resio and Long (2008)).

Liu *et al* (2008a) have tried to answer the question of whether rogue waves occur during hurricanes, typhoons or severe storms. The authors analysed wave measurements made near Taiwan during Typhoon Krosa in October 2007. The data showed that there were more rogue waves during the build up of the storm than they anticipated.

The generation mechanism of a narrow-banded wave spectrum under a realistic forcing field of winds and currents in the Kuroshio Extension region east of Japan is presented by Tamura *et al* (2008), where a fishing boat accident on 23rd June 2008 is analysed. The analysis of the spectral evolution showed that nonlinear coupling of swell and wind sea created a sea state with the narrow wave spectrum favourable for rogue waves occurrence.

The state-of-the-art review on extreme and rogue waves can be found in two recent review papers: Kharif and Pelinovsky (2003) and Dysthe *et al* (2008). The physical mechanisms explaining the rogue waves may provide satisfaction of the simplified rogue wave height criterion (i.e., $H_{fr} / H_s > 2$). Difference remains between other wave characteristics, such as the time scale of the rogue wave, wave shape, fluid velocity within the wave and occurrence of breaking.

The conventional FFT-based power spectral density has provided substantial insight into wave processes over many years. More recently a number of authors have emphasised the additional insight to the time dependent spectral characteristics that can be gained. Ewans and Buchner (2008) applied wavelet analysis to the New Year's wave at the Draupner platform (Haver and Anderson (2000)) and to the spatial measurements of a basin wave, as presented by Buchner *et al* (2007). The complex Morlet wavelet (see for example Krogstad *et al* (2006)) has been chosen for the analyses. Examination of the spectral characteristics of the wave field has shown that spectral levels are substantially elevated over all frequencies during the extreme event, and second order phase coupling is strong during the event, but the coupling is localised in the wave field to the vicinity of the peak. The frequency components in the region of the peak of the wave spectrum appear to be largely freely propagating (obeying the linear dispersion relation), whereas the higher frequency components do not. There is evidence for higher-order nonlinear interactions during the extreme crest. An extended comparison with fully nonlinear predictions of focussed events is reported by Buchner *et al* (2008).

Alternative approaches to examining temporal spectral characteristics include the Short-Time Fourier Transform (STFT) and the Hilbert-Huang Transform (HHT). The HHT (Huang *et al* 1998) is a data-adaptive technique. Firstly, an empirical mode decomposition (EMD) is performed, which identifies the specific local time scales and extracts them into intrinsic mode functions (IMFs). A Hilbert transform of the IMFs is then performed, allowing an instantaneous frequency with which embedded events can be identified. Accordingly, the HHT is not affected by limited precision in the same way as STFT does. Veltcheva and Guedes Soares (2007) demonstrated the value of the technique in the examination of records with large wave events. Ortega and Smith (2008) showed that the amount of energy associated with different IMFs varies with the sampling rate and also that the number of IMFs needed for the empirical mode decomposition changes with record length.

3.2.2 Experimental Description of Waves

A number of experiments have been conducted in laboratories to investigate extreme wave events, primarily through changing various wave spectral parameters and utilising a directional wave generator.

The existence of non-resonant interaction and the correspondence of the BFI and statistics were first verified by Onorato *et al* (2004) who have observed the evolution of a uni-directional random wave with a JONSWAP type wave spectrum. Waseda (2006) extended the experimental work of Onorato *et al* (2004) to include directionality of the JONSWAP spectrum. His experiments were performed at the University of Tokyo in a facility 50m long, 10m wide and 5m deep. He found that the occurrence of extreme waves is significantly reduced when the directionality broadens. When the spectrum became directionally broader the wave height distribution fitted better to the Rayleigh distribution.

Experiments in a wave basin have also been performed by Denissenko *et al* (2007). The tank size was 12m x 6m x 1.5m. Their conditions can be characterised by large directional spreading. The analysis showed that the wave crest statistics were consistent with the second order Tayfun distribution.

The spatial analysis of extreme waves in a model basin by Buchner *et al* (2007) showed that linear dispersion and second order theory could not explain the wave propagation towards a rogue wave crest.

A wave basin experiment has been performed in the MARINTEK laboratories (one of the largest existing three-dimensional wave tanks in the world), Onorato *et al* (2008a, 2008b). The aim of this experiment has been to investigate the effects of wave directionality on the statistical properties of surface gravity waves. A directional spread of $\pm 30^{\circ}$ at the spectral peak has been considered. The results have shown that for long-crested, steep and narrow-band waves, the second order theory underestimates the probability of occurrence of large waves. With increased directional spreading, weak deviations from Gaussian statistics have been observed for the sea surface.

The evolution of random directional surface gravity waves was also investigated by Waseda *et al* (2008) at the wave tank of the University of Tokyo, Institute of Industrial Sciences. The experiment has shown that when directional energy spreading broadens, the occurrence of rogue waves rapidly diminishes. The significance of the non-resonant interaction (instability) increases when the directional spreading narrows. Further, the results have suggested that the occurrence of rogue waves is high when a rare situation of directionally confined wind-sea is realised due to abnormal forcing (i.e. wind and current). A new five-year project has been initiated to conduct coordinated wave observations in the Kuroshio Extension area and to study the occurrence of rogue waves.

Petrova and Guedes Soares (2008) have studied irregular deep water sea states generated in a tank and represented by a JONSWAP spectrum. The crests and heights of the maximum observed waves have been fitted by linear and second order statistical models. The results showed that the largest crests are well described by the models with the coefficient of kurtosis. The maximum wave heights and the observed abnormal extremes agree well with the second order theory, although the linear predictions have not deviated much from the observations either. The laboratory results have been compared with results for full-scale data gathered during a storm at the North Alwyn platform in the North Sea. The storm data have shown different statistical behaviour.

Shemer *et al* (2008) carried out an experiment in the Large Wave Channel in Hanover, which is 300 m long, 5 m wide and 7 m deep (water depth 5 m). Numerous realisations of a wave field that has identical initial frequency energy spectra for the free wave components, but random frequency components' phases in each realisation were generated. The analysis has shown that high probability of extreme events is closely related to the width of the free wave part of the spectrum. The initial narrow spectra underwent widening, attained maximum width and became narrow again. Maximum values of kurtosis as well as maximum deviations of the wave height distribution from a Rayleigh distribution all occurred at those locations along the tank which are characterized by a relatively wide spectrum. Further, the probability of extreme events varied with distance from the wave maker.

Experience from model tests done in the MARINTEK basin has shown that high impact of extreme waves on marine structures is correlated with steep and energetic waves, characterized by high crests, wave heights, orbital velocities, slope or a combination of all these properties. Stansberg (2008) proposed a new time-varying impact alter parameter $\psi(t)$, derived directly from a wave record, unifying these properties in a physically consistent way. The idea is based upon a time domain Hilbert transform analysis and an assumption that a second order description of sea surface gives a good indication of possible critical wave events. The parameter $\psi(t)$ is a function of the time-varying phase velocity $Cp(t)$ and wave steepness $kA(t)$ (where k denotes wave number and A the wave amplitude). Application to numerical and laboratory wave records show promising results. Note that the suggested alter parameter does not account for structure dependent effects.

3.2.3 Statistical Description of Waves

Short-term statistics. The Gaussian linear wave model, which has been successfully used in ocean engineering for more than half a century, is well established, and there exists both exact theory and efficient numerical algorithms for calculation of the statistical distribution of wave characteristics. One drawback is its lack of realism under extreme or shallow water conditions, in particular its crest-trough symmetry. The first order Lagrangian wave model describing both the horizontal and vertical movements of individual water particles is more realistic and has got attention recently. The model gives crest-trough asymmetric waves with peaked crests and shallower troughs. Åberg (2007) investigated wave intensities and slopes in Lagrangian seas while Lindgren and Åberg (2008) studied crest-trough wave height and wave front-back slopes.

Today it is common practice to describe the surface elevation by taking into account bound modes up to the second order, i.e. second order wave theory (Hasselmann (1962), Longuet-Higgins (1963)), from which probabilistic models for the sea surface, crests and troughs can be developed (for example, Tayfun (1980), Forristall (2000), Prevosto *et al* (2000), Tayfun and Fedele (2007b)). Among them, the wave crest distributions proposed by Forristall (2000) are frequently used for engineering applications. They represent a two–parameter Weibull fit for unidirectional as well as directional numerically generated waves. The parameters of the Weibull distributions have been defined as functions of the average wave steepness and the Ursell number.

The theoretical crest model of Tayfun (1980) assumes narrow-banded unidirectional waves in deep water. The results of Socquet-Juglard *et al* (2005) indicate that the Tayfun distribution may also describe satisfactory distributions of wave crests and troughs in broad-banded directional seas. Recent findings of Tayfun (2006) and Tayfun and Fedele (2006, 2007a,b), based on the second order quasi-deterministic theory, show that for large waves the Tayfun model is an exact second order model for describing the crests and troughs of wind waves under general conditions at deep or finite water depths, irrespective of any directional and bandwidth constraints. Large waves are defined by the authors as waves characterised by a>>m01/2 (a=H_s / 2, where H_s denotes the significant wave height and m_0 is the zero-spectral wave moment).

A new stochastic model of wave groups for the non-Gaussian statistics of large waves in oceanic turbulence has been suggested by Fedele (2008). The model leads to a new asymptotic distribution of crest heights in a form that generalises the Tayfun model. The model can explain deviations from the Tayfun distribution observed in flume experiments of narrow-banded waves. For realistic sea states its improvements, when compared to the Tayfun model predictions, appear to be insignificant.

Arena and Ascanelli (2008) propose a nonlinear second order wave crest height distribution applicable in three dimensions and arbitrary depth. The authors generally find very close agreement, both in long and short-crested waves, with the Forristall (2000) second-order model also giving high quality measurements. Though there is a little departure in shallow water, both the Forristall model and reported theory give significantly lower probability of particular crest heights than the pure Rayleigh expectation.

Mori and Janssen (2006) developed a distribution for the individual wave heights, based on the Gram-Charlier approximation for the sea surface displacements, called a modified Edgeworth-Rayleigh distribution. The distribution assumes weakly nonlinear random waves and a narrowband spectrum.

Although second order wave models have already proved relatively good agreement with observations, there are measurements that clearly show significant discrepancies, especially at low probability levels (Bitner-Gregersen and Magnusson (2004), Petrova *et al* (2006)).

When waves are long crested, and in infinite water depth, the modulational instability of free wave packets can develop and statistical properties of surface gravity waves can significantly diverge from the ones calculated by second order theory (e.g. Mori and Yasuda (2002), Onorato *et al* (2006a), Gibson *et al* (2007)). Gibson *et al* (2007) investigated the wave crest distribution by combining a fully nonlinear wave model with reliability methods (used traditionally in structural engineering), to find the most likely event leading to a response that exceeds the design limitations. Using direct numerical simulation of the truncated potential Euler equations, Toffoli *et al* (2008a) have demonstrated that the effects related to free wave modes can enhance the crest height up to 20%, at probability levels as low as 0.001, if BFI ≥ 0.80. Toffoli *et al* (2008a) use the HOSM considering a third–order expansion so that the four–wave interaction is included (see Tanaka (2001b, 2007)); note, however, that the solution is not fully nonlinear.

Moreover, Toffoli *et al* (2008a) have shown that the modulational instability of deep water long-crested wave trains influences the wave troughs, which tend to be deeper than in second–order profiles. Using the truncated potential Euler equations, the troughs have been measured to be about 20% deeper than second–order troughs at low probability levels. It is interesting to note that the lower tail of the probability density function of the surface elevation relaxes on the normal distribution for moderate and low values of the BFI; the wave troughs have therefore the same amplitude as when estimated using a Gaussian random process.

The numerical simulations of the truncated potential Euler equations performed by

Toffoli *et al* (2008a) indicate also that higher-order effects of bound waves as well as the nonlinear interaction between free modes provide a very limited contribution to the vertical asymmetry of the wave profile. Thus, the asymptotic value of the skewness λ_3 does not change significantly with the BFI; λ_3 was, in fact, observed to vary from 0.18, for BFI 0.25, to 0.20, for BFI 1.10. These values are consistent with the second order simulations. Further, the authors show that nonlinear effects also result in a deviation of the fourth-order moment of the probability density function, i.e. the kurtosis λ_4, from the value expected for a Gaussian random process ($\lambda_4=3$). For low BFI the kurtosis ($\lambda_4=3.14$) is in agreement with the equation suggested by Mori and Janssen (2006) under the narrow-band approximation: $\lambda_4=24\varepsilon^2$, where $\varepsilon=k_p(m_0)^{1/2}$, and m_0 is spectral variance.

As demonstrated by Toffoli *et al* (2008a) for low degrees of nonlinearity the difference between the second order wave height distribution and the simulations of the truncated potential Euler equations is limited (<4%), while for moderate and high degrees of nonlinearity (BFI ≥ 0.55) the deviation becomes more relevant (>9% at low probability levels). For these conditions, the tail of the distribution is close to the Rayleigh density function. The latter, however, tends to slightly underestimate the simulated heights as BFI ≥ 0.80 (see also Mori and Yasuda (2002)). For these degrees of nonlinearity, and low probability levels (0.001), the wave heights are observed to be approximately 13% higher than in second order theory.

When directional wave components are considered, however, the deviation from the second order statistics is reduced. Numerical simulations of the truncated potential Euler equations carried out by Toffoli *et al* (2008b) show that the coexistence of different directional components reduces the skewness and kurtosis of the surface elevation. The latter, in particular, does not significantly depart from the value expected for Gaussian linear processes. Further, the reduction of magnitude of the statistical moments leads to a significant modification of the wave crest distribution which follows the second order theory–based Tayfun (1980) and Forristall (2000) distributions. These findings are consistent with the results presented by Socquet-Juglard *et al* (2005). In other words, the occurrence of extreme events in broad-banded directional wave fields in infinite water depth seems to be neither more frequent nor higher than the second–order wave theory predicts.

The simulations of Toffoli *et al* (2008b) were limited to one case of broad-banded directional wave field (i.e. wind sea). The effect of varying directional energy spreading on the modulational instability, and consequently on the statistical properties of the surface elevation, was investigated by Bitner-Gregersen *et al* (2008) using numerical simulations of the truncated potential Euler equations. The analysis concentrated primarily on the wave crest distribution. The results confirm that the distributions based on second order theory provide a good estimate for the simulated crest when short-crestedness (i.e. directionality) is accounted for. The findings are consistent with previous simulations of the modified NLS equations and the laboratory investigations of Onorato *et al* (2008a), and are in agreement with recent field observations.

Toffoli *et al* (2006b) compared the second order, three-dimensional, finite-depth surface wave simulations with the statistical properties of the surface elevation and wave crest heights of field data from Lake George, Australia. The results showed that for small nonlinearity the second order model describes the statistical properties of field data very accurately. The ongoing CresT project is investigating the topic further using wave measurements from the Gulf of Mexico.

Comparisons between commonly applied wave and crest height distributions and field data have been presented at the Rogue Waves 2008 Workshop. Olagnon (2008) has analysed the Alwyn (North Sea) dataset. The techniques used to validate applicability of the data for the study were detailed, on the grounds of physical limits on the water velocity, accelerations and other qualities. The study has shown that extreme waves are not more frequent than commonly applied in engineering practice statistics would predict. Further, due to limited knowledge the extreme waves are still unpredicted at present. As suggested by the author the problem, which should be addressed, is precise time of occurrence and location of extreme waves.

Krogstad *et al* (2008) presented a preliminary analysis of the crest height distributions using measured data from the Ekofisk oil field in the central North Sea. The occurrence of rogue waves under various directional conditions was considered. Simultaneous directional spectra from the Laser Array (LASAR) were used. The study has shown that the crest distributions fitted well the second order crest distribution of Forristall (2000). The study has concluded that the observed rogue waves do not appear come from a different population, but rather are rare occurrences within the 2nd order stochastic model.

New field data including extreme events have been analysed to provide an improved statistical description of rogue waves. Lopatoukhin and Boukhanovsky (2008) show stereo wave measurements in the South Pacific. The analysis has been carried out in connection with the loss of the ship Aurelia in February 2005. The importance of a spatial description of rogue waves, using contra fixed point measurements, has been demonstrated by the authors. It has been recommended to use multi-dimensional joint probabilities where several wave parameters characteristic for rogue wave occurrence are included. Tayfun and Fedele (2008) have used WACSIS data collected from the Meetpost Noordwijk platform in 18 m water depth in the southern North Sea (Forristall *et al* (2002)) to study the theoretical distribution of wave phases and amplitudes. It has been shown that the wave-phase distribution assumes two distinct forms depending on whether envelope elevations exceed the significant envelope height or not. The study shows that when wind waves are characterized by the second order nonlinearities, large surface displacements can occur only above the mean sea level. Third-order nonlinearities including quasi-resonant interactions between free waves do not seem to affect the observed statistics in any discernable way. The fourth-order cumulants estimated from the data were shown to be rather unstable and spiked occasionally above the overall averages. Due to the highly unstable nature of statistics associated with the largest waves, a sample population of about 5000 waves collected at a fixed point in time may not always, according to the authors, give reliable estimates of frequency of occurrence of very large waves.

Rogue waves are not just an offshore phenomenon. Didenkulova *et al* (2006) found that 2/3 of the rogue wave events occurring in 2005 were observed onshore. E.g., a rogue wave attacked the breakwater in Kalk Bay (South Africa) on August 26, 2005 and washed people off the breakwater.

The effect of finite water depth on the occurrence of extreme waves has still not been sufficiently investigated. An assessment of this effect, using a direct numerical simulation of the truncated potential Euler equations, has been carried out by Toffoli *et al* (2008c). It has been shown that in water of arbitrary depth third-order nonlinearity is suppressed by finite depth effects if waves are long-crested, while it can be triggered by transverse perturbation in short crested seas. Further, the results have demonstrated that random directional wave fields in intermediate water depths weakly deviate from Gaussian statistics despite the degree of directional spreading of wave energy.

Long-term statistics. The existing joint long-term environmental models have been developed by fitting distributions to data from the actual area. Different approaches can be found in the literature. The Maximum Likelihood Model (MLM) suggested by Prince-Wright (1995), and the Conditional Modelling Approach (CMA), e.g. Bitner-Gregersen and Haver (1991), utilise the complete probabilistic information obtained from simultaneous observations of the environmental variables. If the available information about the simultaneously occurring variables is limited to the marginal distributions and the mutual correlation, then the Nataf model (Der Kiuregihan and Liu (1986)) can be used. Generally, for all three approaches both global models (all data from long series of regular observations) and event models (e.g. POT data) can be applied. However, the Nataf model should be used with great care as it can easily give biased results as already shown by Bitner-Gregersen and Hagen (1999) and confirmed by Sudati Sagrilo *et al* (2008).

Progress on long-term statistical description of waves includes the study of Myrhaugh and Fouques (2008). The authors applied CMA to develop a bivariate long-term distribution of significant wave height and characteristic wave steepness using North Sea data. The characteristic wave steepness in deep water was defined in terms of the significant wave height and spectral peak period. Further, Myrhaugh and Fouques (2008) developed a bivariate long-term distribution of significant wave height and characteristic surf parameter. The characteristic surf parameter is defined as a ratio between the slope of a beach, or a structure, and the square root of the characteristic wave steepness in deep water (defined in terms of the significant wave height and spectral peak period). The distribution can be used to characterise surf zone processes and is relevant for e.g. wave run-up on beaches and coastal structures.

Estimating the maximum wave or crest height that will occur in a long return interval is one of the fundamental problems for ocean engineers. Long time series of individual wave heights are not available therfore the calculations must start with measured or hindcast time series of significant wave heights. An extreme value distribution is fitted to those data. The resulting long term distribution is then combined with a short term distribution for the individual heights. The basic approach is the Borgman integral, but it has been applied in many different ways. Forristall (2008) evaluated methods for estimating maximum wave and crest heights using two types of simulations. In the first, six hour records with a specified distribution of significant wave heights were simulated while in the second, triangular storms with a specified distribution of peak significant wave heights were simulated. Rayleigh short term distributions were used for the wave heights in each record. He has found that the method proposed by Tromans and Vanderschuren (1995) agreed with the results from the simulations and has recommend using it to calculate the distribution of heights given a storm.

Baxevani *et al* (2005) present a new method for modelling the space variability of significant wave height in world oceans, using data obtained from satellite measurements. The model presents the variation of a fitted significant wave height (estimated by mean and covariance functions) as a random surface in space and time that can be assumed to be stationary in limited regions of space, for a fixed time. The proposed model is validated along the TOPEX-Poseidon satellite tracks by computing distributions of different quantities for the fitted model and comparing these to empirical estimates. In Baxevani *et al* (2008), the model is used to estimate parameters of every area in the world to construct maps of the median and the correlation structure. These maps are then used to compute, globally, the probability of the significant wave height exceeding a predefined level, and to compute the distribution of the length of a storm.

The treatment and application of directional properties of the waves in the shipping industry have tended to lag behind the offshore industry. This is partly because offshore sites are usually fixed and can be subject to long term monitoring and measurement, whereas ships have a larger area of operation to deal with; the hindcast wave statistics atlas has been the traditional source of wave information, and this does not offer spreading information.

Readers of technical works should be aware of the use of the term ‘directionality’ when applied to waves. In some cases, ‘directionality’ refers to the probability of waves from particular compass directions, but the treatment of the waves is still long crested. In other cases, ‘directionality’ refers to the spreading of the waves, and their description is short crested

Interest in the directional properties of the waves is increasing, partly as advanced modelling of extreme waves is departing from the purely unidirectional, and partly as the directional spreading of the wave energy is recognized as a source of uncertainty in the probabilistic risk assessment procedures advocated by the classification societies.

Sea state design criteria for offshore facilities are frequently provided by direction. For example, it is typical for return-period values of the significant wave height to be specified for each of eight 45^o sectors in addition to the omni-directional case. However, it is important that these criteria be consistent so that the probability of exceedance of a given wave height from any direction derived from the directional values is the same as for the omni-directional value. As recently demonstrated by Forristall (2004) it is not sufficient simply to scale the directional values so that the value of the wave height from the most severe sector is the same as the omni-directional value. Jonathan and Ewans (2007) develop an approach for establishing appropriate directional criteria and an associated omni-directional criterion for a specific location. The inherent directionality of sea states has been used to develop a model for the directional dependence of distributions of storm maxima. The directional model is applied to the GOMOS data, and the distributional properties of the 100-year significant wave height are estimated.

Jonathan *et al* (2008) consider the effect of the wave direction when considering the statistics of storm events for offshore design. They show that the direction has a strong effect when developing operating criteria and that even if omnidirectional criteria are required, they are better derived from directional modelling than from omnidirectional modelling. The need to consider co-variate effects, such as direction, can be extended to time-dependencies, such as seasonality. Jonathan and Ewans (2008) developed seasonal design criteria for the Gulf of Mexico, based on GOMOS data, and demonstrated that estimates for monthly cumulative distribution functions of the 100-year Hs, based on a seasonal model, showed more variability with season than those which ignore seasonal effects on extreme values, concluding that incorporating seasonality more adequately reflects underlying physical processes.

3.2.4 Spectral Description of Waves

The sea states of a single component wind-sea system represent the basic situation resulting from the effect of the wind. Consequently, much work has been published on the form of single peaked wave spectra. The Pierson-Moskowitz and JONSWAP are the most well known spectral descriptions of this type. In 1993, Torsethaugen suggested a double peaked spectrum for the open ocean, where waves are dominated by local wind sea but also exposed to swell. The model was later simplified by Torsethaugen and Haver (2004). This spectrum was established primarily for one location (Statfjord Field) at the Norwegian Continental Shelf but in qualitative terms is expected to be of much broader validity, and is currently used by the Norwegian industry for other locations in the North and Norwegian Sea. It is well reviewed by the 2006 ISSC I.1 Committee. Being a design approach, the Torsethaugen spectral description is a good option for use whenever there is not information available about the specific nature of two-peaked spectra for a given location (Ewans *et al* (2006a)). However, the model needs to be used with care outside the Norwegian waters as demonstrated by the ongoing EU project Safe Offload. There is still an ongoing discussion in academia and industry about which type of wave spectrum is the most suitable for description of a swell spectrum.

To be able to describe two or more wave systems from the spectral information available, a separation procedure for the wave components needs to be adopted. The partitioning methods involve separating the wave spectrum into two frequency bands: a low-frequency peak, the swell, and a high-frequency peak, the wind-sea. Two approaches are commonly applied: using only the frequency spectrum or the full directional spectrum (including information about frequency and directional energy spreading). Both methods can produce components that overlap in frequency. Ewans *et al* (2006a) compared the methods for bimodal wave spectra with reference to wave spectra from directional wave measurements made at the Maui location off the west coast of New Zealand. The basic approach of Guedes Soares (1984) was used for separation of frequency spectra. The results were also compared with the Torsethaugen separation procedure based on integrated wave parameters of the total sea. The frequency domain partition and the adopted fitting method for bimodal spectra (Guedes Soares and Henriques (1998)) gave a more accurate representation of the bimodal frequency spectrum than the model derived from fitting multi-peaked spectra in the frequency-direction domain (Hanson and Phillips (2001)). All three methods accurately reproduce the original significant wave height. However, on average they all produce spectra with longer mean periods than are typically measured; this effect is most pronounced with the Torsethaugen spectral description. It should be noticed that the partitioning method, using the data in the frequency domain, cannot separate sea states coming from different directions if they have similar peak frequencies.

Nunes *et al* (2008) recently proposed a method for constructing time sequences of the first and second peak sea states under bimodal conditions where the basic approach of Guedes Soares (1984) was adopted for separation of spectra. The data from the southeast Brazilian offshore region showed that the methodology was able to find the correct time sequence of sea states under bimodal wave conditions.

The 2006 ISSC I.1 Committee reported that “as regards the directional spreading, no new models have been proposed since 2002” and this Committee has also found no new spreading models suggested. Below, some currently used directional spreading models are reviewed with particular attention given to the directional spreading of swell.

It is standard engineering practice to use $\cos^2$ spreading in design, often applied as frequency independent, which is adequate for many applications, but the frequency dependence in wave spreading in real sea states should be recognised. Further, $\cos^2$ is a unimodal spreading. In an active wind-sea the spreading can be bimodal, even when the frequency spectrum is unimodal. It should be noted that application of the Poisson distribution for directional spreading of the swell component is recommended by DNV RP-205 (2007).

Bitner-Gregersen and Hagen (2002) suggested a general procedure for including directional spreading in two-peak spectra by weighting directional statistics for the swell and the wind-sea components. The method is illustrated for the two-peak Torsethaugen frequency spectrum for a given sea state, and the model predictions are shown to correspond reasonably well with measured statistics.

Research continues in the field of the character of the directional spectra. For example Boukhanovsky *et al* (2007) propose a classification of five separate spectral types, with continuous evolution between them. They demonstrate the approach with North Sea buoy data.

3.3 Current

A number of JIPs have recently been initiated or proposed for modelling of currents. In the Gulf of Mexico, topographic Rossby waves (TRWs) can generate currents of 1 m/s over much of the water column along the Sigsbee Escarpment (Hamilton 2007). A Deepstar project within the RPSEA Environmental Programme aims to improve models for predicting TRWs.

In recognition of shortcomings in existing methods for modelling current profiles for the design of structures that are sensitive to currents, such as catenary risers, riser towers and export lines, a new JIP: Worldwide Approximation of Current Profiles (WACUP) has been proposed and will likely begin during 2009. The goal of the project is to find methods that appropriately describe current profile statistics for design.

3.4 Ice

The International Polar Year, organized through the International Council for Science (ICSU) and the World Meteorological Organization (WMO), is a large scientific programme focused on the Arctic and the Antarctic from March 2007 to March 2009. The fundamental concept of the IPY is an intensive burst of internationally coordinated interdisciplinary scientific research and observations focused on the Earth's polar regions.

ISO is currently developing a new standard, 19906, on ice loads, which is expected by the end of 2009. This International Standard specifies requirements and provides guidance for the design, construction, transportation, installation and decommissioning of offshore structures related to the activities of the petroleum and natural gas industries, in arctic and cold regions environments. The objective of the document is to ensure that arctic and cold region's offshore structures provide an appropriate level of reliability with respect to personal safety, environmental protection and asset value to the owner, the industry and to society in general. The document is currently a Committee Draft, and is in the process of being updated following national review, before being issued later in 2009.

3.4.1 *Analytical and Numerical Description of Ice*

The effect of ice on waves is investigated by Vaughan and Squire (2008). They describe how ice-coupled waves travelling beneath solid ice sheets experience decay arising from both scattering and damping. The inclusion of scattering and damping in one model is necessary in order to simulate reality accurately. They describe a model that assimilates these mechanisms, which is used to reproduce waves under two dimensional ice sheets of variable thickness. Damping is more significant for lower period waves and scattering causes a reduction in the observed decay rate.

A coupled ice-ocean model is investigated by Tang and Dunlap (2007). It describes the annual variation of sea ice which is mainly determined by meteorological conditions and ocean currents. The investigation is based on the so-called Princeton Ocean Model and it uses a second order turbulence closure to account for the vertical mixing. The ice model is based on the viscous-plastic rheology of Hibler and contains multiple ice categories defined by thickness range. The model domain encompasses Baffin Bay and the Labrador Sea with a grid resolution of 1/3 degree longitude and variable latitude to maintain approximately square grid cells. The simulations reveal the changes in the ice cover over the course of a year. The concentration and thickness in western Baffin Bay are higher than those in eastern Baffin Bay due to the influence of the warm East Greenland Current flowing into Baffin Bay. The ice velocities are relatively high in the northern straits, off the Baffin Island coast and in western Davis Strait, reflecting the seasonal wind conditions and surface circulation. The modelled ice distribution is compared with satellite data and good agreement is obtained.

Iceberg deterioration is investigated by Kubat *et al* (2007). Different mechanisms contribute to melting or calving of icebergs including; solar radiation, buoyant convection, forced convection and wave erosion. The work includes a sensitivity study that examines the role of environmental and model parameters. The main parameters addressed include; the water temperature, wind and current velocities, iceberg size and wave height. The results indicate that wave height plays a major role in iceberg deterioration. While the model shows that water current has little effect on the iceberg, the other parameters affect it significantly.

3.4.2 *Statistical Description of Ice*

Affected by the Arctic climate warming, the extent of the Arctic sea ice cover has shrunk by roughly 2.8–4.5% per decade in the last 30 years (Johannessen *et al* (2004)). Since 2000 a new record September minimum in ice extent was set each year according to Stroeve *et al* (2004) and NSIDC (2005). The decrease in sea ice extent is associated with an increasing duration of the summer melt season. Although the sea ice retreat is strongest in summer, the negative trend is independent of season. However, the winter ice cover was found to be comparatively stable until recently, when a considerable decline in ice area was also recorded for the winter season Comiso (2006).

The massive multi-year ice has even been reduced by 7–9% per decade. Though this ice type is more resistant to melting than the thinner first-year ice, changes in the Arctic ice drift pattern have lead to a major and persistent net loss of older ice (age ≥10 years) with a trend of -4.2% per year in the period 1989–2003 (Belchansky *et al* (2004)). More recently, a doubled decrease in multi-year ice area of 14% between 2005 and 2006, most prominent in the Eurasian part of the Arctic Ocean, was observed by Nghiem *et al* (2006). According to Comiso and Parkinson (2004), dynamic processes play a large role, amplifying climate feedback processes that have been initiated thermodynamically and accelerating their progression. Those climate model experiments which are forced by observed CO2 concentrations predict a further retreat of the Arctic sea ice cover of roughly 15% within the next 50 years. The negative trend is expected to be a stable feature with major implications for the Arctic and also global climate.

The connection between sea ice cover and climate change is strong because the global sea ice area accounts for more than a quarter of the total cryospheric surface and contributes to short positive feedback cycles, intensifying, for example, existent natural variations and also global warming. Sea ice that is thicker than 10 cm has a high albedo α of 0.7, whereas the open ocean absorbs about 90% of this energy. Falling snow accumulates on top of the large solid surface offered by the sea ice cover and intensifies the surface albedo to 0.75–0.85. This means that the observed increase of air temperature in the Arctic of about 0.5°C per decade within the last 25 years causes not only the retreat of the snow and ice cover but is also amplified by the diminished ice cover. This allows the ocean to absorb more incoming solar radiation and results in a further temperature rise, accelerating the ice melt Comiso and Parkinson (2004).

A further contribution to sea ice melt is a decrease in surface albedo which is caused by the formation of melt ponds in summer (α = 0.15–0.45) as well as the sedimentation of natural and anthropogenic aerosols (α = 0.4–0.6). Arctic-wide remote sensing results show an average summer albedo of 0.5–0.7 decreasing by up to 50% towards the ice edge in the Arctic marginal seas (Laine (2004)). The sea ice-albedo feedback mechanism is a positive feedback cycle which in general supports sea ice growth as well as reduction.

The most intense change in the sea ice cover is reported for the Eurasian part of the Arctic Ocean by Nghiem *et al* (2006). Model results (Lindsay and Zhang (2005)) show a decrease in mean ice thickness of 43% (1.31 m) within the 16 year period of 1988–2003. While the level ice thickness has a negative trend during the entire simulation period 1948–2003, the ridged ice features a positive trend until 1988, followed by a negative trend which is stronger than that of the level ice for the rest of the simulated period. This observation leads the authors to the conclusion that possibly a tipping-point has been passed and the Arctic ice-ocean system has since entered a new era of thinning sea ice, which is dominated by internal thermodynamic processes related to the positive ice-albedo feedback rather than external forcing. Based on in-depth statistical analyses of sea-ice roughness, two classification methods are investigated regarding their potential to separate different ice types (von Saldern (2007)).

4. SPECIAL TOPICS

4.1 Climate Change and Variability

Controversial views of climate change have developed, as a result of regionality of the impact and the difference in social and economic situation of each nation. The political decisions made by each nation in response to climate change can therefore differ from proaction to inaction. The Intergovernmental Panel on Climate Change (IPCC) has produced a series of Assessment Reports (1990, 1995, 2001 and 2007) to provide scientific basis for policy makers. The IPCC was jointly established in 1988, by the World Meterological Organization (WMO) and the United Nations Environment Programme (UNEP), with the mandate to assess scientific information related to climate change, to evaluate the environmental and socio-economic consequences of climate change and to formulate realistic response strategies. The assessments provided by IPCC have since then played a major role in assisting governments to adopt and implement policies in response to climate change. In particular the IPCC has responded to the need for authoritative advice of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), which was established in 1992, and its 1997 Kyoto Protocol.

The IPCC Fourth Assessment Report on Climate Change (AR4) was issued in 2007 and consists of the following sub-reports:

- the AR4 Synthesis Report;
- the Working Group I Report “The Physical Science Basis”;
- the Working Group II Report “Impacts, Adaptation and Vulnerability” and
- the Working Group III Report “Mitigation of Climate Change”

The reports provide the state-of-the-art information and condensed summaries of the current understanding of scientific, technical and socio-economic aspects of climate change. A summary of the findings of the three Working Group reports is given in the AR4 Synthesis Report, which also provides a synthesis that specifically addresses the issues of concern to policymakers in the domain of climate change.

The four scenarios considered by the IPCC are based on emissions and concentration of CO_2 and their impacts. These scenarios have been used to project climate changes in the 21st century and beyond. The A* scenarios are pessimistic ones while the B* scenarios are optimistic ones. Particular attention has been given to the scenario A1B and B1.

The AR4 report provided, for the first time with little uncertainty, a consensus of the science community on the anthropogenic causes of the global warming. The IPCC, in recognition of their activity, has received the Nobel Peace Prize in 2007, together with Al Gore who authored the bestselling novel "An Inconvenient Truth." In 2007, the economic impact of climate change has been reported in "The Stern Review," as an estimated annual cost of between 5 % and 20 % of the global GDP. Unlike the AR4 report, the Stern Review is as yet not a consensus opinion among economists.

In this section, impacts of climate change that are relevant to the ocean industries will be highlighted. These will be taken mostly from IPCC AR4, but will be supplemented by information from other sources. We first define climate change and climate variability. Then the state of knowledge about the possible impacts of climate change/variability will be discussed, with particular focus on consequences to wind and wave climates. The changes to wind and wave climates are not independent, and are closely related to the changes in storms in mid-latitude and the tropics. Intensified hurricanes in the Gulf of Mexico, Cyclones in the Bay of Bengal and Typhoons in the Pacific were reported in the last 3 years. There was also a report on hurricanes in the Southern Hemisphere. In particular, tropical hurricanes in the North Atlantic will be discussed in detail.

The term 'climate', defined as the mean state of the weather system, originates from the Greek word "climata (κλιματα)." Millenniums ago, people were already aware of the difference in "climate" due to the land 'inclination' or latitude as it is now called. The earth climate system consisting of ocean, atmosphere, land, ice, vegetation, volcanic activity and so forth maintains its thermal state by solar energy input. The uneven distribution of solar radiation due to the earth's geometry is moderated by perpetual circulation in the oceans and atmosphere that mixes cold and warm water/air at high and low latitudes. Thus at time scales distinct from the astronomical and tectonic changes, the climatic condition is stationary, but can be classified largely by the location (e.g. Koppen-Gaiger). It is only in the last few decades that people became aware of the natural variation of the climate system attributed to interaction between the atmosphere and oceans. The local warming of the sea water off the coast of Peru called the El Nino is now well understood to be a consequence of quasi-oscillation of the tropical Pacific atmosphere and ocean coupled system, and affects the global weather due to tele-connection.

The local impacts due to climate variation (such as a hot-summer in a particular year at a specific location) are quite often confused with impacts due to climate change. While climate variation originates from the internal dynamics of the earth's system, climate change can be attributed to changes of external forcing (solar radiation, volcanic activity) and human activity. The time scales of climate variations are inter-seasonal, decadal and multi-decadal whereas the time scales of climate change due to external forcing (such as solar radiation) is much longer (millions of years). Climate change due to human activity would occur at a higher rate (time scales of hundreds of years). Because of the relative proximity between these timescales, to differentiate climate change due to human activity and climate variation requires careful analysis (e.g. one hot summer is not evidence of global warming).

4.1.1 Specific Climate Modes

Under the initiative of the World Climate Research Programme, Climate Variability and Predictability (CLIVAR) has fostered research "to observe, simulate, and predict the earth's climate system, with a focus on ocean-atmosphere interaction, enabling better understanding of climate variability, predictability and change, to the benefit of society and the environment in which we live". The progress achieved until 2006 is summarised in the documented reports in the special section of the Journal of Climate (Busalacchi and Palmer (2006)) of the First International CLIVAR Science Conference "Understanding and Predicting our Climate System," which hosted 640 scientists from 56 countries. The issues addressed include: seasonal-to-interannual climate prediction, monsoons, decadal prediction, anthropogenic climate change and paleoclimate, as well as applications. Special attention was given to climate variation in the tropics and its global influence.

The climate system is very complex and its mechanism is still not fully understood. Uncertainty related to climate prediction can not be ignored when impacts of climate change on design are discussed. In particular, the differentiation between climate change due to human activity and natural climate variation requires careful consideration.

The following are the recognised main modes of climate perturbation: El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), Tropical Atlantic Variability (TAV) and North Atlantic Oscillation (NAO), and Indian Ocean Dipole (IOD). A short description of these modes demonstrating their complexity and the uncertainty related to their prediction is given below.

ENSO and PDO. In the tropical Pacific, ENSO is the dominant mode of climate perturbation to the mean state. The east-to-west Sea Surface Temperature (SST) gradient is in a dynamical balance with the trade winds (Walker circulation). When this equilibrium condition is weakened due to reduction of the trade wind, the equatorial upwelling at the eastern boundary decreases, the SST gradient relaxes and the trade wind is weakened further (Bjerknes' positive feedback hypothesis). ENSO repeats with a 2 to 7 year interval and lasts for 12-18 months, phase locked to the Boreal winter. Kelvin and Rossby waves in the equatorial waveguide, or those with modification due to air-sea coupling, play a crucial role in the adjustment process of ENSO. Because heat exchange between the eastern and western Pacific by the Kelvin/Rossby wave is much faster than the ENSO cycle, Jin (1997) suggested that a repeated wave transmission recharges and discharges the equatorial heat content. Other theories exist such as stochastic forcing, which may trigger the equatorial Kelvin wave.

Uncertainty in the predictability of ENSO was addressed based on three different mechanisms (Chang *et al*. 2006):

- the unstable ENSO mode nonlinearly couples with the annual cycle or other coupled modes, therefore uncertainty in the initial condition leads to chaotic behaviour;
- the damped coupled mode is maintained by stochastic weather forcing but uncertainty arises when non-modal growth is enhanced;
- ENSO is considered as a self-sustained oscillator but is perturbed by stochastic forcing.

Despite these uncertainties, predictability of ENSO has improved. Luo *et al* (2008) demonstrated with an ocean-atmosphere coupled General Circulation Model (GCM) that the past ENSO events were predictable with a two-year lead time. The precondition is forced through SST nudging but without any flux correction. While resorting to intensive computational load, the GCM-based seasonal climate forecast is free of empiricism.

As we are gaining further knowledge about tropical Pacific ocean-atmosphere interaction, new types of climate variability are discovered. Unlike the classical El Nino, the anomalous warming of the central Pacific in 2004 was identified as a climate mode orthogonal to El Nino, characterised by anomalous twin Walker circulation cells and tripole SST anomalies (Ashok *et al* (2007)). This pseudo-El Nino was coined “El Nino Modoki” where the Japanese term “Modoki” meaning “a similar but different thing” was used. As an independent climate mode, El Nino Modoki exerts global influence different from those of the dominant tropical Pacific climate modes El Nino and La Nina such as; northern Indian droughts and severe drought and heat wave in Japan and Korea, during boreal summer. It should be noted that El Nino itself has been redefined as indicating anomalous warming of the Nino 3.4 region (5N-5S, 170W-120W), and is sometimes referred to as the “Date-line El Nino”, Larkin and Harrison (2005).

Decadal changes in ENSO are associated with the meridional exchange of heat between subtropics and the tropics via shallow overturning ocean circulation known as the subtropical cell (STC). The discovery of the STC dates back to the 1990s (McCreary and Lu (1994), Johnson and McPhaden (1999)). The STC consists of known upper-ocean circulations: North Equatorial Countercurrent (NECC, eastward at 3^{o}-10^{o}N), North and South Equatorical Current (NEC, westward, north of 10^{o}N and SEC, westward, south of 3^{o}N), and Equatorial Under Current (EUC, eastward and 150 m subsurface at the equator). The possible connection of these circulations implies that the oceanic heat sink in the Kuroshio Extension region and the oceanic heat source in the equatorial cold tongue are connected through a pathway in the surface and the interior ocean. Because of large heat transport by the STC, its modulation was considered to be the cause of the decadal variation of the Pacific climate (the PDO), as well as modulation of the tropical ENSO (Gu and Philander (1997), Kleeman *et al* (1999)). The former and other works suggest that the cause of the decadal variation is the temperature anomaly whereas the latter and other works suggest that it is the variation of the circulation itself (Nonaka *et al* (2002)).

As such, the existence of ENSO-like modal structure of the PDO and the feedback mechanism between the ocean and the atmosphere is well understood, but what regulates the oscillation is not well understood. Yasuda *et al* (2006) presented a possibility that the bi-decadal oscillation of the North Pacific is correlated with the 18.6-year oscillation of the diurnal tide due to oscillation of the moon's orbital surface to the equator. The enhanced tidal mixing in the straits of the Kuril Islands, that connects the Sea of Okhotsk and the Pacific, increases the poleward oceanic heat transport. The suggested mechanism, of coastal baroclinic Kelvin wave in the North Western Pacific enhancing the thermohaline circulation, was verified by a coupled ocean-atmosphere model outlining a process that also involves Equatorial Under Current (Hasumi *et al* (2008)). These studies suggest that the PDO is possibly regulated by astronomical forcing while the intrinsic variability of the ocean-atmosphere coupled system still remains valid.

TAV and NAO. TAV is not dominated by a single mode, as in the Pacific ENSO and/or the Pacific Decadal Oscillation, but is likely governed by a combination of a few modes: the first is the meridional mode and the second is the zonal mode also termed as the equatorial mode or the Altantic Nino (Chang *et al* (2006)). On the other hand, in the mid-to-high latitudes, there is a well defined climate variability called the North Atlantic Oscillation (NAO). The NAO is an atmospheric phenomenon indicating the oscillation of the sea-level pressure between the Icelandic Low and the Azores High, and is considered nowadays as part of the Arctic Oscillation (AO). The change in the NAO phases indicates a shift of westerly winds in Europe thereby changing the storm track. In the positive phase of NAO, pressure difference is larger than average and so the moist air brought in by the westerly wind causes warm and wet winters in Europe, cold and dry winters in northern Canada and Greenland, and mild and wet winter in the eastern US. In the negative phase of NAO, the pressure gradient reduces and consequently there are fewer and weaker winter storms than in average years and their route is more West to East. The storms bring moist air into the Mediterranean, cold air to northern Europe, and increase the frequency of cold air outbreaks on the US East coast.

The correlated change of the SST gradient between the off-equatorial and the equatorial Atlantic and the ITCZ (Inter Tropical Convergence Zone) position, is called the Meridional Mode (MM). Although far less established than in the tropical Pacific, there is an indication that the tropical zonal SST gradient is coupled with the atmospheric pressure gradient through the Bjerknes feedback mechanism (Merle (1980)). Despite considerable lack of observational evidence, the various numerical models including atmospheric GCM (Okumura and Xie (2004)) suggest that, during boreal summer, the reponse of the atmosphere to the equatorial Atlantic SST anomalies is consistent with the Bjerknes feedback.

There is some evidence of the relevance of ENSO and NAO to TAV. In addition, the Atlantic equivalent to the Pacific subtropical cell (STC) will connect the extra-tropics and the tropics via oceanic pathways. Such processes are still not well understood and raise questions as to whether the oceanic bridge is important or the atmospheric bridge is important for these communications (Chang *et al* (2006)). Of particular interest is the impact of these climate variations to the Atlantic Hurricane activity. Because TAV is likely governed by a combination of a few climate modes, the year-to-year change of the Hurricane activity is also rather complicated. More effort is needed to distinguish its natural variation from changes due to global warming.

IOD. The SST of the Indian Ocean is characterised by warmer surface water in the eastern basin and the colder surface water in the western basin. Associated with this zonal SST gradient, air descends in the cool water off the Somali coast and westerly wind accelerates along the equator in the lower atmosphere, forming a Walker circulation in an opposite sense to the Pacific. The ocean circulation is rather complicated and is driven by the monsoonal wind system in the northern Indian Ocean. In summer time, strong southwest monsoons drive the Somali current off Eastern Africa, and the southwest monsoon current along the equator. During winter time, the reversed Northeast monsoon wind weakens the Somali current, and the westward North Equatorial Current is formed. In transition times, less affected by the monsoon wind, an eastward Equatorial Jet forms at the equator (Tomczak and Godfrey (2003)). Normally, the precipitation is largest in the Eastern Indian Ocean near the maritime continent and reduces in the western side. Precipitation varies depending on the Monsoon system.

The IOD mode, a term first used by Saji *et al* (1999), is an ocean-atmosphere coupled phenomenon, similar to ENSO in the Pacific. The discovery of the IOD is one of the remarkable progresses made in the recent study of climate variability (Yamagata *et al* (2003), Webster *et al* (1999)). The anomalous SST is closely associated with the surface wind anomaly; in the positive IOD mode, equatorial wind reverses from westerlies to easterlies as the SST in the east cools and warms in the west. The basin-wide Walker circulation is weakened during the positive IOD and is considered to be independent of the Pacific Ocean. The development of IOD is phase-locked with the seasonal cycle and its onset coincides with the summer monsoon in May/June. The IOD peaks during boreal autumn (September/October) and diminishes in the winter (December/January). During the positive IOD event, the thermocline deepens towards the West. In the eastern Indian Ocean, coastal upwelling caused by the anomalous southeasterly wind further cools the SST, and in the western Indian Ocean a combination of Ekman pumping and a Rossby wave enhances the SST warming (Xie *et al* (2002)). This positive feedback between the atmosphere and the ocean is in accordance with the Bjerknes-type feedback mechanism (Bjerknes (1969)).

A remarkable feature of the IOD is its global influence via atmospheric bridges or teleconnection. During the positive IOD events, the Far East (Japan and Korea) experiences warm and dry summers whereas during negative IOD events it experiences cold and wet summers (Saji and Yamagata (2003)). The mechanism of such remote influence of the IOD is rather complicated and involves three geographically isolated regions, the Eastern Indian Ocean, Eastern Europe and the Mediterranean Sea, and the

Far East. Through atmospheric bridges, the IOD can influence the Southern Oscillation in the Pacific (Behera and Yamagata (2003)), rainfall variability of the Indian summer monsoon (Ashok *et al* (2001)), the summer climate in East Asia (Guan and Yamagata (2003)), African rainfall (Rao and Behera (2005)), the Sri Lankan Mahara rainfall (Zubair *et al* (2003)), and the Australian winter climate (Ashok *et al* (2003)).

As of 2006, a number of Coupled General Circulation Models (CGCMs) have already succeeded in reproducing the IOD; SINTEX-F1 (Yamagata *et al* (2004)), CSIRO-Mark3 (Cai *et al* (2005)), GFDL-CGCM (Lau and Nath (2004)), and NSIPP-CGCM (Wajsowicz (2005)). In recent years, the understanding of how ENSO and IOD interact in the Indo-Pacific basin, what triggers the initial wind and SST anomalies, influence of the barrier layer (thin surface layer with low salinity) and the roles of the Indonesian through flow in the decadal variation of the IOD, has been improved. The SINTEX-F 9-member ensemble forecast with SST-nudging successfully predicts the IODs at around 3-4 months lead time (Luo *et al* (2007)).

The year 2007 was unusual from a historical perspective (Behera *et al* (2008)). The positive IOD developed concurrently with La Nina in the Pacific, which is a rare event that occurred only twice in the last hundred years. In addition, consecutive positive IOD events in 2006 and 2007 are comparatively unusual. This unusual pIOD (positive IOD) event in 2007 occurred following the El Nino Modoki during the boreal spring (Ashok *et al* (2007)). Tozuka *et al* (2008) suggests that the El Nino Modoki event is more likely under the global warming condition. It is therefore conceivable that more consecutive pIODs will occur in the 21st century. As of now, we are seeing a third consecutive pIOD event in 2008 (http://www.jamstec.go.jp/frsgc/research/d1/iod/). This is a historically rare occasion and much more is expected to be learned numerically and observationally in the coming years. Finally, a remarkable discovery was made from the analysis of the coral geochemical records from the equatorial eastern Indian Ocean, displaying the IOD events over the last 6500 years (Abram *et al* (2007)). The study reinforces the presumption that IOD is independent of the ENSO, and further suggests possible connection of the IOD and the monsoon.

Climate Change. There are both natural and anthropogenic drivers of climate change. IPCC (2007) has analysed the chain including greenhouse gas (GHG) emissions and concentrations, radiative forcing and resultant climate change and has evaluated whether observed changes in climate and in physical and biological systems can be attributed to natural or anthropogenic causes. It has been concluded that warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. According to the IPCC report there is very high confidence that the net effect of human activities since 1750 has been one of warming causes. Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. It was concluded by the IPPC that anthropogenic warming would continue for centuries due to the time scales associated with climate processes and feedbacks, even if GHG concentrations were to be stabilised. According to IPCC (2007), the climate is already changing and will continue changing with the following predicted trends:

- temperature will increase;
- extreme temperatures will increase even more;
- high latitudes will get wetter;
- subtropics will get drier;
- ice will continue melting;
- sea level will continue rising;
- wind regimes will move, and
- increased intensity of hurricanes/storms both in the tropics and outside the tropics.

The results presented by the IPCC primarily address air and ocean temperature, sea water level and ice. The discussion about wind and waves is not as comprehensive, due to more limited current knowledge about effects of climate change on these phenomena.

Projected changes in waves and wind climate are expected to have the largest impact on marine structure design in comparison to other environmental phenomena. Changes in sea level have little potential to affect ship design directly but may impact offshore and coastal installations, depending how significant they are. Secondary effects, such as changes in tidal range, harbour depths and offloading heights may need to be taken into account. Increase of temperature and ice melting will affect sea transport in the Arctic regions as well as it may affect design of marine structures operating in the Arctic areas.

The 2009 ISSC I.1 Committee recognises the significance of the IPCC findings and the conclusions drawn by the Panel. However, as pointed out by the IPCC Report, the results presented are affected by various types of uncertainties which influence accuracy of a climate model's simulation of past or contemporary climate and the accuracy of climate change projections. The topic receives ever increasing attention, e.g. the Workshop on Climate Change which was organized by WMO and OGP (International Association of Gas and Oil Producers) in Geneva in May 27-29, 2008, and in which some members of this Committee participated. The uncertainties involved in climate change projection need to be taken into account in discussions concerning impacts of climate change on design of ships and offshore structures.

4.1.2 Wind

Changes in atmospheric circulation imply associated changes in winds, wind waves and surface fluxes. Surface wind and meteorological observations from the VOF became systematic around 150 years ago and are assembled in ICOADS (Worley *et al*, (2005)). These observations have been used by the IPCC Panel (2007) to study climatic variations of winds in the past. As pointed out by the IPCC apparent significant trends in scalar wind should be considered with caution, as VOF wind observations are influenced by time-dependent biases (Gulev *et al.* (2007)), resulting from the rising proportion of anemometer measurements, increasing anemometer heights, changes in definitions of Beaufort wind estimates (Cardone *et al*,(1990)), growing ship size, inappropriate evaluation of the true wind speed from the relative wind (Gulev and Hasse (1999)) and time-dependent sampling biases (Sterl (2001), Gulev *et al* (2007)). Consideration of time series of local surface pressure gradients (Ward and Hoskins (1996)) does not support the existence of any significant globally averaged trends in marine wind speeds, but reveals regional patterns of upward trends in the tropical North Atlantic and extra-tropical North Pacific and downward trends in the equatorial Atlantic, tropical South Atlantic and subtropical North Pacific.

A number of recent studies suggest that cyclone activity over both hemispheres has changed over the second half of the 20th century. General features include a poleward shift in storm track location, increased storm intensity and a decrease in total storm numbers (e.g. Simmonds and Keay (2000), Gulev *et al* (2001), McCabe *et al* (2001)).. In particular, Wang *et al* (2006) found that the North Atlantic storm track has shifted about 180 km northwards in winter during the past half century. The above findings are confirmed by Paciorek *et al* (2002), Simmonds and Keay (2002) and Zhang *et al* (2004). However, Emmanuel (2005) indicated that there has been no perceptible change in the frequency of occurrence of tropical cyclones over the past 30-40 years.

Models also project a poleward shift of storm tracks in both hemispheres by several degrees of latitude. In the extra-tropics, variations in tracks and intensity of storms reflect variations in major features of the atmospheric circulation, such as the North Atlantic Oscillation (see Woolf *et al* (2002), Chang *et al* (2002), Wolf and Woolf (2006)). The intensity of storms is linked to sea temperatures, and an increase of 0.5°C in tropical sea surface temperatures can be correlated to an increase in maximum wind speeds of around 2-3 ms^{-1}.

For extra-tropical areas the picture is complicated by spatial variations and coastal influences. Pirazzoli *et al* (2004) analysed up to 100 years of coastal wind and surge measurements in Brittany and found both increases and decreases in the frequency of stronger winds, depending on the locations that were analysed and the wind directions.

The observed changes reported by the IPCC (2007) are summarised below.

- Mid-latitude westerly winds have generally increased in both hemispheres. These changes in atmospheric circulation are predominantly observed as ‘annular modes’ which strengthened in most seasons from the 1960s to at least the mid-1990s.
- Wind regimes move. There are observed changes in winter storm tracks and related patterns of precipitation and temperature anomalies, especially over Europe.
- Intense tropical cyclone activity has increased since about 1970. Variations in tropical cyclones, hurricanes and typhoons shows decadal variability, which result in a redistribution of tropical storm numbers and their tracks, so that

increases in one basin are often compensated by decreases over other oceans. Globally, estimates of the potential destructiveness of hurricanes show a significant upward trend since the mid-1970s, with a trend towards longer lifetimes and greater storm intensity.

- A large increase in numbers and proportion of hurricanes reaching categories 4 and 5 globally has been observed since 1970 even as the total number of cyclones and cyclone days decreased slightly in most basins. The largest increase was in the North Pacific, Indian and southwest Pacific Oceans. However, numbers of hurricanes in the North Atlantic have also been above normal (based on 1981–2000 averages) in 9 of the 11 years 1996-2007, culminating in the record-breaking 2005 season. Moreover, the first recorded tropical cyclone in the South Atlantic occurred in March 2004 off the coast of Brazil.

It should be noted that the two last findings by the IPCC have been toned down by the International Workshop on Tropical Cyclones – VI (IWTC-VI December 2007), which states in its Summary:

> "Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date, no firm conclusion can be made on this point."

Reasons for difficulties in detecting trends include significant changes in hurricane observation methods over time, as well as strong multi-decadal variability in hurricane activity (Knutson (2007)).

4.1.3 Wave

The observed changes in wind imply associated changes in wind generated waves. Increases in wave heights over the North Atlantic were first signalled in 1994 by Hogben (Hogben 1994), the main author of the Global Wave Statistics atlas, used currently as a basis for ship design.

The IPCC experts' group has used visual observations to study the observed changes of the wave height. The changes in observational practice have affected wave observations less than wind, although the observations may suffer from time-dependent sampling uncertainty. Linear trends in the annual mean SWH (Significant Wave Height) from ship data (Gulev and Grigorieva (2004)) for 1900 to 2002 were positive almost everywhere in the North Pacific, with a maximum upward trend of 8 to 10 cm per decade (up to 0.5% per year). These observations are supported by buoy records for 1978 to 1999 (Allan and Komar (2000), Gower (2002)) for annual and winter (October to March) mean SWH and confirmed by the long-term estimates of storminess derived from the tide gauge residuals (Bromirski *et al* (2003)) and hindcast data (Graham and Diaz (2001)). Regional model hindcasts (e.g., Vikebo *et al* (2003), Weisse *et al* (2005)) show increasing SWH in the northern North Atlantic over the last 118 years. This result was also confirmed by Sterl and Caires (2006). The potential changes expected for waves are listed below.

- There is evidence from modelling studies that future tropical cyclones could become more severe, with greater wind speeds and more intense precipitation (IPCC (2007)). This would result in more severe waves. Studies suggest that such changes may already be underway. Some modelling studies have projected a decrease in the number of tropical cyclones globally due to the increased stability of the tropical troposphere in a warmer climate, characterised by fewer weak storms and greater numbers of intense storms.
- A number of modelling studies have also projected a general tendency for more intense but fewer storms outside the tropics, with a tendency towards more extreme wind events and higher ocean waves in several regions, in association with those deepened cyclones (IPCC (2007)).
- In one of few studies of potential changes in wave heights, Debernard *et al* (2002) found small changes between the periods 1980-2000 and 2030-2050 for the northern North Atlantic, with important exceptions for a significant increase in the Barents Sea and significant reductions North and West of Iceland.
- The increase in storm intensity may lead to more nonlinear waves and increased frequency of occurrence of extreme wave events (extraordinarily steep and/or high waves, breaking waves).
- More intense swell might also be expected.
- The frequency of occurrence of combined wave systems like wind sea and swell (one, or several swell components) is expected to increase in some ocean areas due to increase of storm intensity and change of storm tracks.
- Combination of wind sea and swell may consequently lead to more frequent extreme events (Onorato *et al* (2006b), Shukla *et al* (2006)).
- Vulnerability to hurricane storm-surge flooding will increase if the projected rise in sea level due to global warming occurs.

It should be noted that the current atmospheric and global climate models are unable to provide reliable regional quantitative estimates of the impact of climate change on metocean parameters. Nevertheless, Grabemann and Weisse (2008) report reasonable skill in a high resolution wave modeling study with control climate simulations for the North Sea.

4.1.4 Hurricanes, Cyclones & Typhoons

In 2004, three major hurricanes hit the United States with the total cost related to the destruction of more than $40 billion (Klotzbad and Gay 2006). This record was immediately broken in 2005 where 5 major hurricanes hit the U.S. including 3 hurricanes of category 5 intensity (Katrina, Rita and Wilma). Among them, Katrina was the most devastating and the estimated damage caused by it alone amounts to $100 billion and 1300 deaths (Curry, Webster and Holland (2006)). According to Webster *et* *al* (2005), the total number of hurricanes has not increased globally since 1970, but the number of category 4 and 5 hurricanes has doubled, so that the distribution of hurricane intensity has shifted towards greater intensity. With consecutive years of hurricane disasters, it is natural to hypothesize that "Greenhouse warming is causing an increase in global hurricane intensity"; SST increases due to green house warming, average hurricane intensity increases with increasing SST, and therefore the frequency of the most intense hurricane increases globally (Curry, Webster and Holland (2006)).

This hypothesis, however, was not immediately accepted in the scientific community, as apparent from the open debate about "Hurricanes and Global Warming" between Pielke *et al* (2005, 2006) and Anthes *et al* (2006). Their debate highlights the following uncertainties in connecting global warming and hurricanes:

- whether climate change caused by human activities, and characteristics and impacts of the hurricane, are connected or not;
- whether the consequences of tropical hurricane intensification and the trend of rainfall, sea level and storm surge in the global warming scenario are related or not or
- whether the recent trends and variation in the tropical storms can be explained or not.

The first and the second points are related to the passive and active roles of the tropical cyclone whereas the third point is related to the developing new field of study called the "paleotempestology".

Elsner (2008), summarises the state of understanding of the passive and active roles of the tropical cyclone and the paleotempestology in his report on the International Summit on Hurricanes and Climate Change (May of 2007). The 77 academics and stakeholders from 18 countries discussed various issues including:

- how to project the estimated environmental conditions, such as SST and wind shear, to the potential intensity of the hurricane (i.e. passive role);
- how to understand the mechanism by which the tropics and the mid-latitude communicate at biennial to inter-seasonal time scales via hurricanes carrying heat and moisture (i.e. active role);
- how paleotemptestology utilizes proxies or historical records from geological and biological evidence (e.g. sediment cores, tree rings, cave deposits).

Some results suggest that current warmness is not needed for increased storminess. They also indicate that the intervals of more hurricanes corresponds to fewer ENSO periods, but problems with distinguishing the storm track changes and the overall activity casts uncertainty in the analyses. Finally, future projection is discussed in the context of high-resolution numerical modelling. The results are mixed. While most show decreases of the total number of storms, the basin scale tendency differs among predictions. A second summit is planned for 2009.

While the goal is to predict how future environmental conditions will affect storm intensity, duration and frequency, the analysis of historical storms serve as a means to verify the existing theories of hurricane activity (Hoyos *et al* (2006)). Based on Emanuel (1987), the potential intensity (PI) theory correlates the local SST and the profile of temperature through the troposphere and lower stratosphere to the hurricane intensity (Bister and Emanuel (2002)). Hurricane intensity may be defined in different ways: Power Dissipation Index (PDI) is the cube of the maximum wind speed integrated over the life of all storms in a given season (Emanuel (2005)), Accumulated Cyclone Energy (ACE) sums the squares the maximum sustained wind speed (Bell and Chelliah (2006)). It is plausible to utilize the PI to project the SST variation onto the hurricane intensity distribution, but other factors affecting the general circulation patterns need to be taken into consideration to predict frequency and duration of the hurricane variability (Kossin and Vimont (2007)). The tropical cyclone activity is a function of the magnitudes of the following environmental parameters:

- the shear of the horizontal wind through the depth of the troposphere;
- SST;
- low-level vorticity and
- humidity of the lower and middle troposphere.

Incorporating these factors, Emanuel (2008) has extended the PI to an empirical index of the frequency of the cyclogenesis in the tropics, the Genesis Potential Index (GPI). According to Emanuel (2008), "a good theoretical understanding of the environmental control of storm frequency is lacking".

Despite deficiency of the PI theory, progress has been made simulating cyclone activity using historical and forecast climate models. Dynamical methods are used as well. Knutson *et al* (2007) modelled the Atlantic Hurricane with regional downscaling model outputs of 18 km resolution for the past 27 seasons. Utilizing the large scale model outputs as boundary conditions and constraints (SST, lateral boundary condition and large scale interior atmospheric state), they have successfully reproduced the frequency of the tropical storms in the last 27 years. An alternative method of random seeding, the beta-and-advection model, and numerical modelling was used to downscale the AR4 global warming simulations (Emanuel *et al* (2008)). Their result indicates that the global frequency of the hurricane reduces but the intensity may increase in some regions. The accuracy of these downscaling methods depends on the accuracy of the predictability of the environmental parameters of the global model such as those incorporated in the GPI (Genesis Potential Index).

In the recent review by Vecchi, Swanson and Soden (2008), the SST of the Atlantic main development region, relative to the mean tropical Atlantic SST, is suggested to control the hurricane activity (Vecchi and Soden (2007), Knutson *et al* (2007)). If this is the case, they claim that the recent increase in hurricane activities is not discernible from that due to climate variation. Additional empirical study, together with dynamical downscaling from the global climate models with improved regional SST projection, is necessary to determine whether absolute SST or relative SST is the causal link to the enhanced hurricane activity (Vecchi, Swanson and Soden (2008)).

4.1.5 Sea Water Level

Predictions from global climate models indicate that the rise in average sea water level, observed in the past, will continue during the next 100 years. The consensus of scientists regarding the sea level rise is reported in the IPCC AR4 and a brief summary will be provided below. Reference to the IPCC AR4 is omitted as most information comes from the report.

Combination of land and marine instrumentation records and proxy-based reconstruction of global or northern hemispheric surface temperatures suggests that the average northern hemisphere temperature since the mid 1900s is likely to be the warmest 50-year period in the past 1300 years. The rate of surface warming increases in the mid-1970s and since then, the ocean temperature rises at about half the rate of the land surface temperature. The last 12 years contained 11 years that are among the 12 warmest years since 1850. It is robust to state that the global heat content of the ocean has increased since 1955. The increase of the upper 3000 m ocean heat content is estimated to be around 2×10^{23} J ($0.3\ \mathrm{W\ m^{-2}}$) for the last 50 years (Levitus *et al* (2005)). This corresponds to an average temperature increase of about 0.06 degrees, which amounts to a steric sea level change of about 37.8 mm (2.1×10^{-4} 1/° rate of thermal expantion at 20°C).

The global mean sea level change reconstructed from tide gauges suggests a similar increase in the last 50 years (Church and White (2006)). It is robust to state that the global average sea level increased in the 20th century, and with confidence we can state that the rate has increased between the mid-19th and mid-20th centuries and further accelerated between 1993 and 2003. The cause of the increase is thermal expansion and the loss of mass from glaciers and ice caps, but the increase during 1961 to 2003 appears to be even larger than that resulting from such an estimation.

The sea level change has been geographically non-uniform in the past and is also expected to be so in the future. While observed total sea level rise was 1.8 ± 0.5 mm per year during 1961-2003, and 3.1 ± 0.7 mm per year during 1993-2003, regionally the values differ. A few examples are provided in AR4. In the northeast Atlantic, the sea level change is affected by the decadal change of air pressure and wind due to NAO. In the Russian Arctic Ocean the sea level rise in the recent decades is about 1.85 mm per year. In the Pacific Islands, considered to be most vulnerable to sea level rise, the rate of increase was around 1.6 mm per year in the last 50 years and 0.7 mm per year in the last 25 years. In Kwajalein, the sea level rise is estimated to be around 1.9 ± 0.7 mm per year and in Tuvalu, 2.0 ± 1.7 mm per year. As can be seen from the large error limits, the sea level in the Pacific Islands is largely affected by poorly quantified vertical land motion and the interannual variability (ENSO).

Sea level observations by tide gauges are restricted to the coastal region and because of the natural geographical inhomogeneity of the sea level rise, the global average sea level estimates become errorneous. Satellite altimetry provides a means to measure directly the global sea surface topography. The accuracy of the sea level height depends on the spatial scale. A key limitation of altimetry is the unresolved scales shorter than about 300 km in wavelength and 20 days in period. The use of altimetry is limited in coastal waters as well (no closer than 10 to 20 km from the coast). Although altimetry is not able to provide local short scale sea level monitoring, it provides the long-term mean sea level change at global scale. Numerous estimations from Topex/Poseidon and Jason, and multi-satellites are available for the period 1993-present day (see for example Cazenave *et al* (2008)). The estimated range of sea level rises are between 2.9 and 3.6 mm per year with an error margin of 0.4 mm per year (Andersen *et al* (2006), Nerem *et al* (2006), Scharroo and Miller (2006)).

Global mean surface air temperature rise is estimated for different emission scenarios. The IPCC AR4 compares around 20 different models projecting temperature rise. Surface air temperature rise during 2011 to 2030 compared to 1980 to 1999 ranges between 0.064°C and 0.069 °C and so the dependence on emission scenarios is indistinguishable. The difference becomes more significant in 2046-2065; 1.3°C (B1), 1.8°C (A1B) and 1.7°C (A2) increase, of which a third is due to climate change that is already committed. By 2090-2099, the differences are large and 20% is due to climate change already committed. The surface air temperature rises are: e.g. 1.1°C to 2.9°C (mean 1.8°C) for B1, 1.7°C to 4.4°C (mean 2.8°C) for A1B and 2.0°C to 5.4°C (mean 3.4°C) for A2. Therefore, the difference among models is about ±40 % of the multi-model mean.

Geographical differences in the surface-air temperature pattern are evident from the projection. For example, greater increase of temperature over land, relatively large increase in temperature for the Arctic and the equatorial eastern Pacific ocean but with less warming in the Northern Atlantic and Southern Ocean. Such a pattern is common among different scenarios, and its magnitude is enhanced for the A1B cases. For the worst temperature increase case A2, increases in aerosols cause a modest cooling in the northern hemisphere.

Corresponding to the surface-air temperature increase, sea level rises and the thermal expansion rate of the ocean water is projected to be around 1.3 ± 0.7 mm per year for all the cases during 2000 to 2020. Just as surface air temperature, the differences among scenarios are minimal. During 2080 to 2100, the thermal expansion rate is 1.9 ± 1.0, 2.9 ± 1.4, 3.8 ± 1.3 mm per year for B1, A1B and A2 emission scenarios respectively. The global average sea level rise is 18 cm to 38 cm for the B1 scenario, 21 cm to 48 cm for the A1B scenario, and 23 cm to 51 cm for the A2 scenario. The largest contributing factor to sea level rise is thermal expansion (75 %), and the rest is from other factors such as melting glaciers and ice caps and Greenland and Arctic ice sheets. Of those, the most uncertain is the sensitivity of the ice sheet mass balance due to lack of observational constraints and model error. The increase of sea level in the 21st century is certain and will continue for hundreds to thousands of years due to loss of ice sheet even if radiative forcing is stabilized.

Local sea level rise depends on both thermal expansion and ocean circulation, and therefore, corresponding to changes in the atmospheric and oceanic circulation, the sea level rise becomes geographically nonuniform. The median of the spatial variance from different models is around 8 cm, but the spatial pattern is quite different among models.

Pheffer *et al* (2008) proposed that an accelerated melting of the ice sheet will potentially contribute to about 1-2 m sea level rise.

The IPCC AR4 does not assess the likelihood nor provide a best estimate or an upper bound for sea level rise, due to limited understanding of some important effects driving sea level rise. In particular, the full effects of changes in ice sheet flow are not included and none of the climate models used to date takes account of such major features as ice streams, nor incorporates an accurate representation of the bottom of an ice sheet.

There are three large ice sheets, one on Greenland and two on Antarctica,(the East and West Antarctic Ice Sheet divided by the Transantarctic Mountains). These three ice sheets hold 99 percent of the ice that would raise sea levels if global warming caused them to melt or become afloat. If they disappeared entirely, the sea level would rise by nearly 6 m, 7 m, and 52 m respectively. Greenland and the West Antarctic Ice Shelf (WAIS) are losing mass. Both have disappeared in the geologically recent past, possibly as recently as 400,000 years ago; this is not the case for the much larger East Antarctic Ice Shelf (EAIS), which has apparently persisted for much longer (Bell (2008)).

The stability of the ice shelves in a warming climate was highlighted by the collapse of the Larsen B Ice Shelf in 2002 off the northern Antarctic Peninsula (Bentley *et al* (2007)). Ice cores indicate that this scale of collapse is unprecedented since the end of the last ice age. According to Domack *et al* (2005) the cause was the long-term thinning of the ice shelf, combined with the modern half-century-long warming in the Antarctic Peninsula region. Subsequently, glaciers that fed the former ice shelf have increased in speed by factors of between two and eight, following the collapse. In contrast, glaciers further south did not accelerate as they are still blocked by an ice shelf.

Detailed high-resolution satellite imagery revealed the simultaneous rise and compensating fall of patches on the Antarctic Ice Sheet (Gray *et al* (2005)), reflecting extensive water movement under the ice and pointing to the potentially destabilizing effect of subglacial water (Wingham *et al* (2006b)). The observations reveal a widespread, dynamic subglacial water system, which may have enormous potential for the instability in the ice movements, and hence on the mass balance of the entire ice sheet. This effect is also a likely reason for the acceleration of the Greenland ice sheet (Zwally *et al* (2002)).

4.1.6 Ice

A thorough examination of the impact of climate change on ice can be found in the 2006 ISSC I.1 report. Attention was paid to the findings of the Arctic Climate Impact Assessment (ACIA (2004,2005)). This particular programme of work was concluded with the NOAA State of The Arctic report (Richter-Menge *et al* (2006)), which represents a significant consensus on the impact of climate change on ice, in the period up to the 2009 ISSC I.1 report, as well as providing an update to some of the records of processes discussed in the previous ACIA reports.

Whilst the arctic system is reported to generally show signs of continued warming, specific findings included:

- that, although the temperature trend from 2000-2005 showed new hotspots, measurements in late boreal winter 2006 followed a pattern consistent with earlier winters;
- that the sea ice extent in March (typically its time of annual maximum thickness) 2006 was a new winter minimum, consistent with the reduction in extent seen in previous years;
- that the permafrost temperature continues to increase, but that there is a ‘barely noticeable’ increase in the thickness of the active layer (the ground beneath the permafrost which undergoes seasonal freezing and thawing) and
- that some of the environment parameters in the arctic region, measured in 2006, showed a return to previous climatology, against the trend observed from 2000-2005.

4.2 Long Waves in Shallow Water

Infragravity waves are long waves with periods of 30 to 300 seconds. They are most apparent in shallow-water and were first reported by Munk (1949), who coined the term “surf beat” to describe them. Since then, they have received much attention from the coastal engineering community, in the design of coastal structures and in coastal morphology. In addition, the waves can induce significant motions in ships moored in shallow-water, such a LNG carriers, and large associated mooring loads. Accordingly, with increasing interest in the development of LNG terminals at coastal locations, infragravity waves have also become of interest to the offshore engineering community, and several JIPs that involved investigations of infragravity waves have been undertaken in recent years. Included are the West African Swell Project (WASP), the Safe Offload project, and the sHAllow WAter Initiative (HAWAI) project.

4.2.1 Description of Infragravity Waves

When ocean wind waves propagate into shallow water and become steeper, triad interactions become significant, resulting in the transfer of wave energy to low frequencies. Accordingly, two wind wave or primary components, with frequencies f_1 and f_2 propagating into shallow-water interact to produce a wave having a frequency f_3 equal to the difference between the frequencies of the two components – i.e. $f_3 = f_1 - f_2$. The interaction is strongest when both the frequencies and directions of the primary wave components are nearly the same. The third wave is bound to the primary wave group and can constitute a large proportion of the shallow water infragravity wave field (Herbers *et al* (1994)).

As the primary waves are dissipated through breaking, the bound wave is released as a free wave, reflected from the beach, and radiated seaward as a free wave. Depending on the direction of propagation, the free wave may be refracted back to shore, in which case it is said to be trapped and is referred to as an edge wave. Alternatively, it may radiate into the deep ocean, in which case it is referred to as a leaky wave. Longuet-Higgins and Stewart (1962) indicated that the shoaling of the bound infragavity wave height ($h^{-5/2}$) is much stronger than the leaky infragravity wave ($h^{-1/4}$). However, Herbers *et al* (1995) found a much stronger h^{-1} variation in the free wave energy with increasing water depth. They also found the free wave component to be consistently much larger than the bound wave component.

In the deep ocean, the leaky waves from all coastlines of the ocean basin contribute to a ubiquitous infragravity wave field (Webb *et al* (1991)). At a given coast location, free waves from distant, transoceanic sources may propagate into shallow water, but are typically low amplitude and only observed when the local wave field is low (Herbers *et al* (1995)).

Edge waves propagate alongshore but have standing wave characteristics cross-shore. Different modes of the standing wave can occur simultaneously, but their amplitude decays seawards, resulting in the largest wave heights being close to shore where the first few modes dominate (Oltman-Shay and Guza (1987), Elgar *et al* (1992)). While the bound waves are a function only of the incoming (primary) wave field and the bathymetry, the edge wave intensity is also determined by the local coastal features and surrounding shelf.

4.2.2 Measurements of Infragravity Waves

The measurement of infragravity waves demands a good low-frequency response in the instruments. Typically, surface-following wave buoys have response functions that roll off at low frequency and are unsuitable. The exception is the Datawell directional GPS buoy that can measure waves with periods up to 100 seconds, and although not providing comprehensive coverage of the infragravity frequency band, it appears to provide coverage across the more energetic infragravity frequency band (Masterton and Ewans (2008)).

Pressure transducers and to a lesser extent near-bottom mounted current meters have traditionally been used to measure waves in the shallow-water zone. Both instruments are limited by inherent system noise at high frequency where the wave signal is small due to hydrodynamic filtering, but at low-frequency, in the infragravity wave frequency band, hydrodynamic filtering is not significant and the signal to noise ratio is usually not an issue. The U.S. Corp of Army Engineers maintains a permanent array of pressure transducers at their Field Research Facility, at Duck, North Carolina. This array and other pressure transducer systems deployed at Duck from time to time, have provided valuable data for research and consequently to the fundamental understanding of infragravity waves (Van Dongeren *et al* (2003)). Similar experiments have been conducted on the west coast of the USA, with comparable success (Oltman-Shay and Guza (1987)).

Unfortunately, pressure transducer systems are difficult to deploy and maintain, and are usually only employed in specific research campaigns. Accordingly, operational measurement programmes involving the measurement of shallow-water waves, have resorted to instruments that are more easily deployed and serviced, such as the Datawell directional GPS buoy but also bottom-mounted ADCPs operating in wavemode, such as the AWAC (Jeans and Feld (2003)). In principle, Datawell directional GPS buoys and ADCPs are capable of providing information on the directionality of infragravity waves, though it is first necessary to separate the free wave component that obeys the dispersion relation from the bound wave component that does not.

In the deep-ocean, differential pressure transducers are needed to adequately overcome the comparatively small pressure fluctuation associated with infragravity waves, compared with the enormous static head of water.

4.2.3 Modelling of Infragravity Waves

Practically, there are only two types of model that are suitable for modelling infragravity waves in the coastal zone; Boussinesq-type models and so-called surf beat type models. Boussinesq models are complex and generally require very long computational times; as a result, they do not usually include complex bathymetry and coastal features, and they are often restricted to moderate water depths. Nevertheless, these models can be used to study specific sea state conditions (Madsen *et al* (1997)).

Surf beat models have been more widely used for studying infragravity waves in the coastal zone. These models compute infragravity waves by combining a wave driver model, which provides forcing on the scale of the wave groups of the primary waves, and a shallow-water model used for calculating the generation and the propagation of infragravity waves. Phase information is available for the infragravity waves, but the individual primary wind waves are described spectrally and are not phase resolved. Due to their computational efficiency, these models lend themselves to more comprehensive scales. Van Dongeren *et al* (2003) found good agreement with the infragravity wave predictions using this type of model and measured data, and Groenewegen *et al* (in prep.) used a linearised surf beat model developed by Reniers *et* *al* (2002) and found good predictions and measurements over an extended period.

4.2.4 Consequences for Design and Prediction

Infragravity waves can be significant in shallow-water and have impact on engineering facilities such as LNG terminals. Naciri *et al* (2004) demonstrated the sensitivity of LNG carriers moored in shallow-water to long-period waves.

It is standard practice to account for the bound infragravity wave component in design, through the computation of 2nd order wave forces on vessel surge or offset, starting with a particular wind wave design spectrum. However, this does not take the free wave component into account, which may contribute the majority of the infragravity wave energy. In recognition of this, the HAWAI JIP was initiated. This involved a major review of infragravity waves themselves and the response of LNG carriers in shallow-water. While this study is proprietary, it is expected that results will be presented at the OMAE conference in 2009.

Specification of the free wave component, and particularly the edge waves, is paramount to properly accounting for infragravity waves in design. Consideration of this is given in the Safe Offload project, in which the surf beat model IDSB of Reniers *et al* (2002) has been evaluated for locations off the West (Duck) and East (Baja) coasts of the USA. The model has performed well in predicting the infragravity wave levels by comparison with measurements (e.g. Groenewegen *et al* (in prep.), Bijl *et al*, 2009), and this bodes well for enabling long-term infragravity wave datasets to be established. The IDSB model allows prediction of both the free and bound infragravity wave spectrum as a function of water depth and a particular input wind wave frequency-direction spectrum. Accordingly, a long-term hindcast database of spectra can be converted into an equivalent infragravity wave spectral database from which design criteria can be established.

4.3 Uncertainty

The oceanographic community has always been concerned with providing environmental models and data which approximated the physics of the ocean in the most accurate way. Industry, on the other hand, needs accurate data and models for design purposes. Although uncertainties of data and models were discussed before the 1980's, they were not systematically quantified. Further development of the reliability methods (Madsen *et al* (1986)) and their implementation by some parts of the industry in the 1980's has brought much focus onto the uncertainties associated with environmental description. Det Norke Veritas (DNV) had a world leading role in further development of the reliability methodology, as well as software that performs reliability analysis. The PROBabilistic Analysis program PROBAN® developed by DNV at the end of the 80's, and continuously improved since then (Tvedt (2002)), is still one of the leading software packages for reliability calculations and is used by academia as well as industry. Reliability methods allow quantification, in a probabilistic way, of the uncertainties in the different parameters that govern structural integrity.

4.3.1 Definition of Uncertainties

In 1990 Bitner-Gregersen and Hagen have suggested classification of uncertainties for environmental description. The proposed definitions were later generalised and in 1992 included in DNV Rules (DNV (1992)).

Generally, uncertainty related to an environmental description may be divided into two groups: aleatory (natural) uncertainty and epistemic (knowledge) uncertainty. Aleatory uncertainty represents a natural randomness of a quantity, also known as intrinsic or inherent uncertainty, e.g. the variability in wave height over time. Aleatory uncertainty cannot be reduced or eliminated.

Epistemic (knowledge) uncertainty represents errors which can be reduced by collecting more information about a considered quantity and improving the methods of measuring it. In accordance with Bitner-Gregersen and Hagen (1990), this uncertainty may be classified into: data uncertainty, statistical uncertainty, model uncertainty and climatic uncertainty.

1. Data uncertainty is due to imperfection of an instrument used to measure a quantity, and/or a model used for generating data. If a quantity considered is not obtained directly from the measurements but via some estimation process, e.g. significant wave height, then the measurement uncertainty must be combined with the estimation or model uncertainty by appropriate means.
2. Statistical uncertainty, often referred to as estimation uncertainty is due to limited information such as a limited number of observations of a quantity (sampling variability) and is also due to the estimation technique applied for evaluation of the distribution parameters. The latter can be regarded as the model uncertainty.
3. Model uncertainty is due to imperfections and idealisations made in physical process formulations as well as in choices of probability distribution types for representation of uncertainties.
4. Climatic uncertainty (or climatic variability) addresses the representativeness of measured or simulated wave history for the (future) time period and area for which design conditions need to be provided.

To characterise the accuracy of a quantity, e.g. significant wave height H_s, or H_{m0}, it is necessary to distinguish systematic error (bias) and precision (random error) with reference to the true value τ, which usually is unknown.

4.3.2 Consequences for Design

Generally, environmental description will be affected by all types of epistemic uncertainties to varying degrees. Identification of uncertainties and their quantification represents important information for risk assessment in design and operation of marine structures. High uncertainty of environmental description may lead to over-design or under-design of marine structures, with significant economic/risk impact. Several authors have demonstrated in the past the importance of uncertainties for calculations of load and responses. Offshore industry had a leading role here. The shipping industry has tended to lag behind the offshore industry in these investigations. Recently also the shipping industry, as well as academia, has focused more to study sensitivity of ship load and responses to adopted uncertainties, e.g. Nielsen *et al* (2008).

Enhancing safety at sea through specification of uncertainties related to environmental description is today one of the main concerns of the shipping industry in general and the Classification Societies in particular. The offshore industry is also much concerned with it. This is reflected in the present I.1 Committee report. All sections of the report include recent papers discussing environmental uncertainties.

Specification of uncertainties for environmental description is not an easy task because the true value τ is usually unknown and needs to be assumed. For the integrated wave parameters, for example, the values provided by wave rider buoys are commonly adopted as the true values. The situation is even more difficult for environmental models where experimental tests or the average values of recognized models are used as the reference values today. Further discussion on how to specify the true value τ is still called for.

Several investigations aiming at specification of uncertainties of environmental description have been carried out in the last three decades and the results are reported in the literature. Recently the focus has been given to the following type of uncertainties which importance has less been recognized earlier: spatial variability, seasonality, new aspects of sampling variability and time dependent statistics. Uncertainties have got also a central place in the climate debate because they influence climate model's simulation of past or contemporary climate and accuracy of climate change projections. The topic was discussed by the Workshop on Climate Change organized by the WMO and the OGP in Geneva in May 27-29, 2008.

Extreme crest heights are usually calculated from single point statistics, but the designer of a platform is really interested in the probability of a wave crest reaching any part of the deck area. Ocean waves are dispersive and directionally spread, and their size and shape are changing as they propagate. As a result the maximum crest height over an area in a given length of time will be larger than the maximum crest at a single point, Forristall (2006). Forristall (2006) has developed statistics for the maximum crest over an area using a combination of analytic theory and numerical simulations. The resulting crest heights are significantly higher than given by point statistics even for relatively small areas.

Jonathan and Ewans (2008) adopted non-homogenous Poisson model to characterise storm peak events with respect to season for two Gulf of Mexico locations. The behaviour of storm peak significant wave height over threshold has been approximated by a generalized Pareto model. The rate of occurrence of storm peaks has been also modelled by a Poisson distribution with a rate varying with season. Characteristics of the 100-year storm peak significant wave height, estimated using the seasonality have been examined and compared to those estimated ignoring seasonality. The analysis has shown that estimates for monthly variability functions of the 100-year significant wave height based on the seasonal model show more variability with season than those based on the model which ignores seasonal effects. As pointed out by the authors, one consequence of it is that for temporary ocean structures a materially smaller design value can achieve the same non-exceedence probability than a materially larger omni-seasonal design value.

Hagen (2007) has studied the effect of sampling variability on the predicted extreme individual wave height and crests height for long return periods, such as for the 100-year maximum wave height and 100-year maximum crest height. He has shown that the effect of sampling variability is different for individual crest or wave height as compared to for significant wave height. The short Forristall crest height distribution (Forristall, 2000) and the Forristall wave height distribution (Forristall, 1978) has been adopted in the analysis. Samples from the 3-hour Weibull distribution have been simulated for 100000 years period, and the 100-year extreme values for wave heights and crest heights have been determined for respectively 20 minute and 3 hour sea states. The results have been compared with the ones obtained by probabilistic analysis. It has been demonstrated that direct application of the Forristall distributions for 3-hour sea state parameters give long term extremes that are biased low. Further, it has been shown how the short term distributions can be modified such that consistent results for 20 minute and 3 hour sea states are obtained.

Today, time-independent statistics are used in design. For climate change projections the non-stationary character of the current climate, in terms of both climate change trends and natural variability cycles, needs to be taken into account. Caires *et al* (2006) used the non-homogeneous Poisson process to model extreme values of the 40-yr ECMWF Re-Analysis (ERA-40) significant wave height. The model parameters have been expressed as functions of the seasonal mean sea pressure anomaly and seasonal squared sea pressure gradients index. Using three scenarios, projections of the parameters of the non-homogeneous Poisson process have been made; trends to these projections were determined and return-value estimates of the significant wave height up to the end of the twenty-first century have been projected. Comparison has been made between the uncertainty of estimates associated with the non-homogeneous Poisson process estimates and the homologous estimates using a non-stationary generalized extreme value model.

5. DESIGN AND OPERATIONAL ENVIRONMENT

5.1 Design

Sections 1-4 of this report present the state-of-the-art of environment parameter measurement and modelling. However, new designs and operational decisions must be assessed/made relative to recognised codes and standards, for which the authority (e.g. classification societies, users) will depend on the design and its application. To achieve recognition, an environment parameter's climatology must be demonstrated as robust and of adequate accuracy and consequently, such codes and standards may lag behind the state-of-the-art.

The majority of ocean-going ships are designed today 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. IMO (1997, 2001) 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 are not explicitly used by classification society rules for general ship design they are used in rule calibration when FSA methodology is applied. British Maritime Technologies (BMT) data (Hogben *et al* (1986)) are adopted. For some less typical designs, classification society rules require or recommend some type of dynamic load analysis that makes use of wave climate data. For these analyses the BMT data are also applied.

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 of high speed vessels 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 of the requirement to remain in the same position offshore platform design and operational conditions need to be based on location specific metocean climate. Measured and/or hindcast data are usually applied.
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 appropriate to the task.

This section describes the most recent developments in published metocean data and its application.

5.1.1 Metocean Data

The need for improving the availability, quality and reliability of environmental databases for specification of marine structures' design and operating criteria has been one of the main concerns of various international professional organisations as well as

Classification Societies and offshore companies in particular.

Visual observations (from the VOF) of waves collected from ships in normal service and summarized in the BMT Global Wave Statistics (GWS) atlas (Hogben *et al* (1986)) are currently used for ship design. 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 IACS (Recommended Practice 34).

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. Hindcasts are also commonly used. Different hindcasts can give considerable discrepancies in prediction of extremes as demonstrated by Bitner-Gregersen and Guedes Soares (2007). The overall idea and some building blocks for assessing the quality of design wave parameters from a hindcast are discussed by Bitner-Gregersen and de Valk (2008), while realising that there will not be one simple recipe applicable in all situations.

It should be noted that neither measurements nor wave models can be entirely relied upon to provide unbiased and error-free estimates under all conditions. Utilisation of numerical data and measurements (including satellite data) seems to be the best way of providing a reliable metocean database for engineering applications and design.

There is still need for further discussion about the accuracy of the recently developed databases, and uncertainties related to them, before they can be fully utilized in engineering applications. Using data from a global database for design purposes, the uncertainties related to these datasets should be identified and, if relevant, considered in the analysis.

Further, replacement of the GWS design basis by more reliable data is today one of the main concerns of classification societies.

5.1.2 Design Environment

In the design process, ship structural strength and ship stability are calculated, following international standards, in extreme events with an occurrence of once in every 20 years (Ultimate Limit State, ULS). Recently an increase of the return period to 25 years has been suggested and applied. ALS (Accidental Limit State) checks cover grounding, collision and fire and explosion. ALS does not include a check for severe weather events. Limited knowledge about rogue waves and particularly ship behaviour in these waves, as well as a lack of information about the probability of ships encountering such waves, precludes their explicit inclusion in operational and design practice for ship structures.

Offshore structures (including FPSOs) follow a different approach to design of ship structures and are designed for the 100-year return period (ULS). The Norwegian offshore standards (NORSOK Standard (2007)) takes into account extreme severe wave conditions by requiring that a 10000-year wave does not endanger the structure integrity (ALS). However, extended knowledge about extreme and rogue waves and marine structures' behaviour in them is necessary to reach consensus within the offshore industry on wave models for the prediction of extreme and rogue waves and design scenarios to be included in a possible ALS check.

Joint long-term environmental models are required for a consistent treatment of the loading in a level III reliability analysis (Madsen *et al* (1986)) and for assessment of the relative importance of the various environmental variables during extreme load/response conditions and at failure. Development of joint models was limited in many years by lack of simultaneous environmental data. Since the 1990's, reliable simultaneous databases have been established and use of joint probabilities has started to be permitted in design (e.g. DNV RP-C205 (2007)).

Relatively little attention has been given in the last decade to directional effects and combined seas. So far consensus has not been reached within the industry concerning directional criteria. For omnidirectional data, a joint model including possibility of environmental effects approaching from different directions was proposed by Bitner-Gregersen (1996). Fit of distributions to directional band data may easily provide extremes which are lower, or higher, than an omnidirectional extreme value. The problem has been pointed out by Forristall and Shaw (1995) who underlined that uncritical application of the directional data could lead to structures with lower reliability than the target probability level. Sørensen and Stenrdorff (2001) proposed coupled stochastic models for the annual values of the ominiderctional and directional significant wave heights and individual wave and crest heights. Recently, Forristall (2004) has suggested a simple method for assuring consistency between omnidirectional and directional criteria. According to this procedure, the product of non-exceedance probabilities of all directional sectors is equal to the omnidirectional probability. The procedure is of particular importance for a reliability analysis of marine structures.

Jonathan and Ewans (2007) have proposed an objective risk-cost approach for optimising directional criteria, while preserving overall reliability. Simulation studies are performed, using realistic extreme value assumptions, to quantify the uncertainties.

The use of metocean parameters and models for the design and operation of marine structures continues to develop. One of the most significant developments over the last several years has been the work undertaken under the auspices of the American Petroleum Institute's (API) committee on metocean. This work is described in two Offshore Technology Conference papers and is included in several guides which have recently appeared or are about to appear. In addition, these API documents will also become International Standards under the new policy. Much of this work was stimulated by the wave of extreme hurricanes which the Gulf of Mexico has experienced over the last several years. This experience has promoted a reassessment of the previous procedures. Previously, much of the Metocean data for the design of offshore platforms has been hidden inside the API RP-2. As API has expanded the number of guides that exist for fixed and floating offshore structures' overall design and system specific design (e.g. mooring systems, risers, etc.), these data have been separated from this document into a series of stand alone documents. This has had two effects, in that the data are more available to designers of vessels and systems other than fixed platforms and in addition these data have also expanded.

5.1.3 Design for Rogue Waves and Climate Change

An extended knowledge about extreme and rogue waves, in particularly their probability of occurrence and ship structures behaviour in them is mandatory for evaluation of possible revision of classification society rules, see Bitner-Gregersen *et al* (2003). So far, consensus about the probability of occurrence of rogue waves has not been reached.

Further, a consistent approach combining new information about extreme and rogue waves in a design perspective has not been proposed. This is one of the objectives of the ongoing CresT JIP (Cooperative Research on Extreme Seas and their impacT). The CresT project involves identifying the meteorological and oceanographic conditions in which extreme crests are likely to occur, numerical and physically modelling of these conditions, an examination of the loading and response to these extreme waves of a TLP platform, and a risk and reliability analysis.

To be able to design for climate change, time-dependent statistical description needs to be adopted. Statistical extreme value analysis, as currently used in the metocean community, has to be upgraded to take into account the non-stationary character of current climate, in terms of both climate change trends and natural variability cycles. This development is currently in process (Caires *et al* (2006), Jonathan *et al* (2008)).

5.2 Operations

5.2.1 Real-Time and Near-Real-Time Wave Data

Real-time knowledge of sea state parameters at a specific position is fundamental to almost all marine and ship operations. In many operations it is also of vital importance to associate/supply wave as well as weather forecasts. In regards to the required data it is therefore useful to make a distinction whether the data concerns marine and/or ship operations in a short term sense (the next 1-5 hours) or in a long term sense (> 5-10 hours). In the latter case it is appropriate to talk about planning, where it is of less importance to have access to real-time wave information but more important to possess good and reliable weather forecasts and (for very long term planning) wave statistics. For short term operations, on the other hand, there is a clear advantage in having access to real-time or near-real-time wave data.

Wave estimation based on ship responses. In recent years significant research efforts have been dedicated to evaluate the possibility of estimating real-time directional wave spectra on the basis of measured ship responses. The assumption is thus to use the analogy between the excited (by waves) ship hull, and a traditional wave rider buoy. In this way, the idea is to provide real-time estimations of sea states by means of simple low-cost onboard instrumentation installed on offshore units, such as ships and floating production storage and offloading (FPSO) systems. Some of the first practical investigations and applications were made by Iseki and Ohtsu (2000), Iseki and Terada (2002), Waals *et al* (2002), Tannuri *et al* (2003), Nielsen (2005) and Pascoal *et al* (2005), which all introduce a theoretical relationship between the measured ship responses, the unknown wave spectrum and the known, calculated, responses in terms of response amplitude operators (RAOs). Conceptually, two methods are considered:

- parametric modelling which assumes the wave spectrum to be composed of parameterised wave spectra, so that the underlying wave parameters are sought from an optimisation problem and
- non-parametric modelling, sometimes known as Bayesian modelling, where the directional wave spectrum is found directly as the values in a completely discretised frequency-directional domain.

Independent of the method, the main assumption is that of a linear relationship between wave excitations and ship responses, which facilitates the use of complex-valued frequency response functions (i.e. RAOs). The wave-buoy analogy is made complicated due to two main reasons, not to mention onboard and online use of full-scale measurements. Firstly, as discussed by e.g. Simos *et al* (2007), Nielsen (2007) and Pascoal and Guedes Soares (2008), the use of RAOs introduces the interesting physical phenomena of a spatial wave filter due to the finite vessel size and a frequency filter due to the mass-spring-damper equivalent model. Thus, a ship is, in general, only sensitive to wave excitations characterised by wave lengths in a certain range. Means to accommodate this type of problem has been studied by Nielsen (2008b). Secondly, the wave-buoy analogy is made complicated since the speed-of-advance problem needs to be taken into account for ships having speed, which leads to a triple-valued function problem in following seas; e.g. Iseki and Ohtsu (2000), Iseki (2004), Nielsen (2006) and Nielsen (2008a). Some applications are, however, restricted to the consideration of FPSOs, whereby the speed-of-advance problem is avoided, so that more efficient calculation procedures can be applied for the estimation algorithm(s), e.g. Sparano *et al* (2008) and Pascoal and Guedes Soares (2008). The literature also discusses which kind of responses the sea state estimation should be based on. In general, it is agreed that a set of three global responses (e.g. sway, heave, pitch) is the best compromise to obtain accurate estimations from, since fewer responses lead to ambiguities in the solution, and more responses do not necessarily increase the accuracy much, although the computational costs are increased significantly. The literature also mentions the importance of using at least one response with port/starboard asymmetry such as e.g. sway and roll in order to estimate the direction of propagation of the waves. In this relation, the literature also comments on issues with respect to using sway in favour of roll with attention to FPSOs, since roll is a more nonlinear response than sway. On the other hand, sway will be affected by the automatic rudder control for a ship underway.

In the literature there exist procedures which differ from the two concepts, parametric and non-parametric modelling, mentioned above. Although Fukunaga *et al* (2007) introduces RAOs as known information about the ship, similar to parametric and non-parametric modelling, the actual estimation of sea state parameters is conducted on the basis of comparisons of ratios of significant values of measured and calculated response amplitudes. Johnson and Wilson (2005) considers the estimation problem from a purely statistical point of view, and has as the objective to deduce a relationship between root-mean square ship motions and significant wave height. A somewhat similar concept is introduced by Jiang and Li (2005) where RAOs of a ship, as well as a wave spectrum, are estimated on the basis of blind deconvolution of response measurements. Based on more simple instrumentation, the actual encountered wave record may also be established by a combination of accelerometers and relative wave measurements from direct measurements, without any modelling. Hence, a double integration of the vertical acceleration yields the vertical displacement at a fixed position in the ship and, thereby, the actual wave height may be extracted with due account given to the relative wave height. A report is given by, e.g. Stredulinsky and Thornhill (2007).

The wave-buoy analogy is of considerable interest when dealing with onboard, in-service monitoring systems, since the response measurements, which are the basis for the estimation methodology, are readily available. The combination of response measurements, as well as response calculations, and the onsite sea state can be used to provide operational and navigational decision support in terms of online, real-time decision support systems (DSS). However, it is important to mention that the wave-buoy analogy needs to be further elaborated before the methodology can be applied in risk-based DSS (e.g. Bitner-Gregersen and Skjong (2008), Nielsen *et al* (2008)), since it is not yet possible to precisely associate the uncertainty with which the sea state is estimated. It should be noted that this type of problem has yet to be fully resolved for both wave radars and any other real-time wave estimation.

It is interesting to note that in the future it is likely to see an integration of different sources of information with respect to estimating wave environment by the wave-buoy analogy. Currently, there are thus ongoing projects in e.g. Denmark and Japan, where the possibility of integrating data from satellites and data from wave radars, respectively, is being investigated.

Due to the inherent problem of filtering that applies to the wave-buoy analogy, in addition to the fundamental assumption about linearity between wave and ship, as well as the speed-of-advance problem, the estimated spectral energy distribution (with frequency and direction) may, in some cases, not necessarily compare well with similar estimations from, say, a traditional wave rider buoy. Therefore, it can be argued that the collected data should be used with care for oceanic statistics. However, it needs to be emphasised that the wave-buoy analogy is capable of estimating exactly those waves which are of importance to the ship, in the operational and navigational sense. That is, the wave-buoy analogy estimates the waves to which the ship responds.

Wave estimation based on marine radar. Several reports have been made in the past on the estimation of directional spectra of ocean waves by marine radar (cf. Section 2; Hutchison *et al* (2006); Kahma *et al* (2005)). In the same area, inversion schemes have also been studied for the extraction of 2-D sea surface elevation maps; e.g. Nieto-Borge *et al* (2004) and Hessner and Reichert (2007). With regards to ship and marine operations, reliable and real-time measurements of the surrounding ocean surface can be of paramount importance. Not to mention the spatial and temporal foreseeing of e.g. rogue waves, many ship operations (helicopter landings and takeoff, ship-to-ship operations etc) will benefit positively if a 'deterministic picture' of the waves-to-be-expected could be provided. In particular, the ship master could adjust heading and speed to avoid the impact of single, extreme waves or wave groups (Clauss *et al* (2008)).

Wave estimation based on remote sensing techniques. Almost all recent satellite missions provide near-real-time data. The nominal maximum time delay is generally 3 hours. The near-real-time data are used on a routine basis by the meteorological offices and are available on the Global Transmission System or via ftp. The available data are the significant wave height and surface wind speed from altimeters (ERS-2, Jason 1 and 2, ENVISAT), some wave spectrum parameters from SAR (ERS-2, ENVISAT, RADARSAT), and surface wind vectors from scatterometers (Quikscat, METOP). Details on the satellite measurements can be found in section 2.

5.2.2 Planning, Weather Routing and Warning Criteria

In the planning of marine operations, in general, there is a need for waves and weather statistics, including the seasonal variability; e.g. Hutchison *et al* (2006). In addition, the wave statistics may be supplemented by different kinds of modelling to better include the spatial variation. This has been investigated specifically by Baxevani *et al* (2005) and Baxevani *et al* (2008), where the space variability of significant wave height in world oceans was modelled using data obtained from satellite measurements. With regard to the planning of FPSO operations, Ewans *et al* (2006b) mentions that the operability of FPSOs is a function of the long-term variation in sea state parameters. The reference emphasises that estimations of the operability depend both on how the sea state is described in terms of its constituent wind-sea and swell components, and on how the long term variability of the sea state is captured.

To avoid severe and adverse weather situations, ship operations are often assisted by weather routing systems that for specific planned routes basically give information on the weather and waves to be expected on time scales of 5-10 days in advance (e.g. Chen (2002), Cox and Cardone (2002), Payer and Rathje (2004), Hayashi and Ishida

(2006), Hansen and Pedersen (2007) and Padhy *et al* (2008)). One of the implications in using weather routing is reported in Olsen *et al* (2004, 2005), where the analysis of a vast number of observations of wave height from ships in the North Atlantic shows that the encountered wave height distribution is significantly lower than the distribution provided by classification societies for structural assessment. Somewhat similar findings can also be seen in Okada *et al* (2006) and Miyahara *et al* (2006), although these references do not mention weather routing.

As mentioned by Toffoli *et al* (2005), it is of concern to meteorological centres to include sea state related parameters in marine weather forecasts, when the parameters exceed a certain threshold. To contribute towards the definition of adequate warning criteria, an investigation was therefore undertaken by Toffolli *et al* (2005), where 270 ship accidents were analysed, of which all were reported as being due to bad weather. Thus, sea state related parameters at the time of the accidents were analysed and compared to known ship characteristics, and in order to estimate a certain degree of severity, results were compared to wave climate variation. No conclusive evidence could be drawn from the study. However, there are indications that wave trains travelling along different directions with crossing seas should be seen as possibly dangerous conditions. Moreover, it is important to combine the ship characteristics and the information on expected sea state, since accidents, in particular, occurred when the wavelength was systematically above half the ship length. The investigation also indicated that for most of the accidents, the observed sea states were relatively severe when fitted to the climate data for the same location. Therefore, it is suggested to further study the use of quantiles of e.g. significant wave height and wave steepness, to indicate different levels of risk for regional occurrence of dangerous sea states.

There are numerous reports on rogue waves in literature, and some of the most recent overviews are given by Dysthe *et al* (2008) and Didenkulova *et al* (2006). However, there is still an ongoing search for a full understanding of the physical processes responsible for the generation of extreme waves and a search for identifying geophysical conditions in which such waves are most likely to occur (Rosenthal and Lehner (2008)), so that warning criteria can be associated to planning and weather routing.

5.2.3 Decision Support Systems

In recent years there has been increasing focus on supplying onboard, real-time guidance and decision support to the crew on ships as well as offshore structures. Decision Support Sytems (DSS) for ships and offshore structures are studied, developed and applied in a wide range of contexts; e.g. to increase the operational and navigational safety of ships, for improved safety with regards to ship-to-ship operations, and within dynamic modelling of risk-based ship traffic prioritisation. Three examples of ongoing projects dealing with the development of DSS are:

- the EU project ADOPT – Advanced Decision Support System for Ship

Design, Training and Operation under the Sixth Framework Programme;
- the joint knowledge-building project STSOps, Investigating Hydrodynamic Aspects and Control Strategies for Ship-to-ship Operations under the The Research Council of Norway, and
- the EU project Handling Waves, Decision Support System for Ship Operation in Rough Weather.

The ADOPT project (http://adopt.rtdproject.net/), e.g. Tellkamp *et al* (2008), has its main focus on four tasks. The first task is to decide which ship related information is relevant in decision making when navigating a ship, and how to implement this information. The second task is to decide which environment related information is relevant for the behaviour of the ship, and how to generate and implement this information. The third task concerns the selection and translation of other available information such as data from satellite navigation systems, sea charts, radar(s) and ship motion simulation systems. The final task is to integrate the above information into the ADOPT Decision Support Tool, combined with elements such as human factors, and to validate this tool by simulation and onboard monitoring. (The project finished in autumn 2008.)

The STSOps project (http://www.sintef.no/Projectweb/STSOps/) seeks to develop new knowledge and new tools for studies of complex ship-to-ship operations. Specifically, one of the work packages, 'Nautical Aspects and Guidance System Design', e.g. Pedersen *et al* (2008a) and Pedersen *et al* (2008b), has as its overall objective the development of a DSS based on the principles of an automatic control system, for the Mooring Master and ship navigation officers in order to enhance operational safety and efficiency in relation to ship-to-ship operations.

The objective of the Handling Waves project (http://www.mar.ist.utl.pt/handlingwaves/home.aspx) is to develop an on-board decision support system for tactical decisions of ship handling in waves which enables the master to improve ship performance and to minimise the likelihood of structural damage. The system that is being proposed aims at predicting the near term changes in motions and loads that would arise from any change in course and speed by the shipmaster. It is a system for tactical decisions of ship handling, covering, in particular, situations of rough weather. It is not aimed at being a system for long range planning such as the weather route planning systems that use information on weather forecasts and plan the route of the ship during the future days along her voyage

The three mentioned DSS projects deal exclusively with ship operations, however, Prislin and Goldhirsh (2008) highlights the benefits of carrying out operational support, using uninterrupted marine monitoring, with the major goal to make offshore platforms safe and profitable. Eleye-Datubo *et al* (2006) looks into the possibility of setting up a general marine and offshore decision support solution using a Bayesian network technique, and exemplifies the feasibility in the context of a marine evacuation scenario, and that of authorised vessel to FPSO collision. In a somewhat different context, Sadiq *et al* (2004) presents a framework for a decision support system for the selection of the best drilling waste discharge option using a fuzzy synthetic evaluation technique. Ulstein *et al* (2007) develops a model that can identify optimal production patterns of offshore petroleum production and assist in planning of possible shut-downs, demonstrate system robustness to customers and aid in contract negotiations. With regards to intelligent traffic monitoring for oil spill prevention, Eide *et al* (2007a) studies a model which is to facilitate the comparison of ships and to support a risk-based decision on which ships focus attention. Similarly, for prevention of oil spill, Eide *et al* (2007b) presents a model that can be used as a tool to prioritise oil tankers and coastal segments, so that effective risk-based support can be given when positioning tugs in the case of a drifting ship situation. In a more simplistic way, with focus on sloshing, Zalar (2005) develops navigational charts for membrane type LNG carriers. The charts can be used as operating guidance and serve as a guideline for ship operations to avoid critical environmental and navigation conditions, while operating the LNG carrier in the partially filled condition.

Operational decision support systems for ships combine, in general, information on the on-site sea state with various kinds of pre-calculated, or online, response calculations to obtain statistical information about future responses to be expected. Implicitly, the statistical predictions depend on all operational parameters such as speed, metacentric height, relative wave heading, mass distribution, etc. In addition, the predictions will be directly influenced by parameters describing the sea state; e.g. significant wave height and zero-upcrossing period. Under real operational conditions the problem is that none of these parameters are known exactly, which means that the parameters must be described in terms of random variables with related uncertainties. This means that the response calculations must be carried out probabilistic (i.e. risk-based), e.g. Bitner-Gregersen and Skjong (2008), and therefore the calculations need to be integrated with some kind of probability assessment software. Thus, the outcome of the calculations/analyses might be given in terms of, say, the expected mean outcrossing rate. For linear and Gaussian processes the approach is relatively straightforward since closed-form expressions can then be established for the outcrossing rate, e.g. Spanos *et al* (2008). In case of nonlinear and/or non-Gaussian processes, it is not possible to establish closed-form expression but, surely, brute force simulations can be applied, e.g. Ayyub *et al* (2006), Sheinberg *et al* (2007) and Krüger *et al* (2008). Recently, however, Nielsen *et al* (2008) developed a procedure based on work by Jensen and Capul (2006) and Jensen and Pedersen (2006), where concepts from structural reliability are introduced, so that the probabilistic analysis, leading to the expected mean outcrossing rate, is conducted by use of the first order reliability method (FORM) in a so-called parallel system analysis; see also Nielsen (2008c) and Jensen (2008). Whether to choose brute force simulation, e.g. Monte Carlo simulation, or the FORM approach for nonlinear/non-Gaussian processes cannot be concluded since the two approaches should rather be considered complementary with their own advantages and disadvantages. However, since calculations need to be carried out in the order of minutes, to provide the necessary operational and navigational support in time, computational speed is fundamental. With regards to brute force simulation, it is therefore recommended to apply different means for increasing the computational efficiency. Specifically, it is worth mentioning the so-called amplified wave concept, applied to roll simulation of ships by Söding and Tonguc (1986). Naess *et al* (2007) and Naess and Gaidai (2008) look at extreme prediction by Monte Carlo simulation in combination with an optimisation based extrapolation, and the developed technique might be also of interest for short term predictions with a need for efficient calculation algorithms.

As of today, maritime authorities do not approve commercial software used in DSS, and authorities have not issued any kind of mandatory obligation with regards to installation of decision support system(s). In the future, this might change, but as an intermediate stage it is foreseen that maritime authorities may include DSS as recommended practice for marine and ship operations. In particular, it is believed that for ships there might become regulations towards integration of the voyage data recorder with DSS, including some kind of real-time assessment/measurement of the on-site sea state. Such integration and the associated collected (prior) knowledge would be very valuable in the investigation of eventual accidents.

6. CONCLUSIONS AND RECOMMENDATIONS

The demand for reliable meteorological and oceanographic data continues in response to the increasing need to meet the World's resource requirements. Yet, the availability of data remains an issue. Many public domain datasets are difficult to access, while others are proprietary.

Remote sensing is an important source of data. During the last three years the capacity in wind and wave remote sensing was set to a satisfactory level, in continuity with the past developments. For wind measurements two scatterometers are operational: the US QuikScat, and the European ASCAT on-board the first satellite of the METOP series. Wave height measurements were assumed through several altimeters: ERS-2 (restricted coverage, near end of mission), Jason-1 & 2, ENVISAT and GEOSAT Follow-On (end of mission in 2008), and SAR's of ENVISAT and RADARSAT. An effort has been performed to calibrate and validate the data, and to improve their quality.

The increased interest in wind power and subsequent development of offshore wind energy parks have highlighted the lack of appropriate wind data and the need for wind data 100-200 m above ground, as well as the need to model the effect of wind parks on the wind field and possibly other wind parks in their wake. The recently completed measurement programme of the West Africa Gust (WAG) JIP is expected to provide new insight into the temporal and spatial characteristics of squalls, which are important design considerations for many locations.

With increasing interest in the development of LNG terminals at coastal locations, infragravity waves have become of interest to the offshore engineering community. Effort to improve understanding of the impact of these waves on offloading facilities has begun and is expected to continue over the coming years.

Data derived from numerical modeling continues to be the main source of data for design and operational planning. There are however outstanding issues with this source of data. Wave models are not validated for very extreme sea state conditions and give inconsistent estimates in hurricanes. Significant improvements in numerical current modeling are identified as crucially important for reducing uncertainties in design.

The end of GODAE opens a new era of operational oceanography. In the last 10 years, the GODAE scientists were the major driving force to establish global in-situ observational arrays and satellite measurements, and data assimilation systems that synthesise numerical models and observations. From now on, the user demands are crucial to sustaining the established systems. Demonstration of the use of GODAE products by offshore industries will no doubt be the next driving force in the post-GODAE period. The need for establishment of downscale models, shared databases and validation are pressing.

Real-time wave data are highly desirable for marine operations (on a short-term scale), and wave estimations may be provided by e.g. a wave radar. Specifically, in terms of ship operations, it is foreseen that an analogy to the wave rider buoy, using the ship itself as a wave buoy, will also be of interest in the future. Ship and offshore operations can be assisted by decision support systems to improve the operational safety (and efficiency); both in a short-term context and in a long-term (planning) context. Decision support needs to be associated with proper warning criteria to different phenomena. However, for some phenomena, e.g. rogue waves, there is still a need for a better understanding of the actual processes.

Our knowledge of ocean waves has significantly advanced. A number of extreme wave studies have been conducted theoretically, numerically, experimentally and based on the field data. The Rogue Waves 2008 Workshop in Brest organized by Ifremer October 13-15, 2008, has brought further insight into extreme and rogue waves generation mechanisms as well as their modelling http://www.ifremer.fr/web-com/stw2008/rw/ .

So far, consensus about the probability of occurrence of rogue waves has not been reached. Although 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 (Accidental Limit State), consensus has not been reached within the offshore industry on wave models for the prediction of extreme and rogue waves and design scenarios to be included in a possible ALS check. This is the objective of the ongoing CresT JIP (Cooperative Research on Extreme Seas and their impacT).

Uncertainty of data and models is an integrated part of environmental description and specification and understanding of uncertainty is important for improving safety at sea.

It has got a central place in the climate debate. In this respect, consideration of co-variates, such as direction and seasonality, has been identified as important, even when developing omni-directional and all-season design criteria, but has not yet been generally adopted in design practice.

Climate change and its potential impact on offshore and ship design and operations remain subjects of much debate. The release of the latest IPCC Assessment Report in 2007 has provided additional material for consideration, but the impact of climate change on design and operational criteria for future facilities, even for the coming decades, remains unclear.

Devastating damage to the offshore industries by intensified hurricanes in the Atlantic has been reported, but the relation of their intensification to climate change (global warming) is not yet fully understood. Some studies suggest that the recent intensification of hurricanes is still within the bounds of climate variability, which is the natural cycle of the earth system. Other memorable events such as the European heatwave in 2003, are due to climate variability. Thus, for long-term planning for the offshore and shipping industries, the enhanced knowledge of climate variability and its possible impact is essential. The question is how the pattern, strength and frequency of climate variability changes as the basic state of the earth slowly changes due to global warming. On the other hand, sea level rise, considered to be the most obvious impact of global warming, is not fully understood. Improvement of the ice-sheet dynamics in the climate models is crucial for a better estimate of sea-level rise.

This shortfall in knowledge of Atlantic hurricanes, sea-level rise and rogue waves raises a question about whether the design criterion for ships and offshore structures should take a precautionary approach or not. To what extent scientific uncertainty should be eliminated before any preventive approach is taken is debatable but the knowledge about climate change and its relationship to climate variability, weather and local impacts should be enhanced and that mandates further research.

Historically, there are two Arctic sea routes that have posed challenges to explorers: North-West (North of the Russian mainland from the Novaya Zemlya islands in the West to the Bering Strait in the East) and North-East Passage (a series of channels in the Canadian Archipelago from Baffin Bay in the East to the Beaufort Sea and the Bering Strait in the West). The reduction in Arctic ice coverage is however beyond doubt. In August 2008, the North-West and North-East Passage were reported for the first time ever to be simultaneously clear of sea ice, with obvious significance for sea transportation. Clearly the need for ice monitoring and modeling remains an important research topic.

6.1 Advances

In wind, wave and current remote sensing, a major advance has been achieved in high resolution analysis (in altimeter and SAR datasets) in response to demand from users.

This will enable improved definition for near-coastal applications. New altimeter technologies were developed concerning high resolution and accuracy, with Ka band altimeter (SARAL) and wide swath ocean altimeter (WSOA). Near future operational oceanographic services are now defined: the ESA Sentinel-3 programme will use these instruments to provide continuity with present altimeter missions; the Sentinel-1 programme is devoted to high resolution multi-mode C-band SAR.

Utilisation of wave information collected by satellites in wave models has increased significantly. The GlobWave project initiated by the ESA in 2008 will further contribute to it.

A number of extreme wave studies have demonstrated that the contribution from higher-order and fully nonlinear solutions, compared with the second order wave models may be significant. Further, higher-order model simulations, laboratory tests and field data have allowed statistics of wave height and crest and trough elevations (including the highest steep waves) to be established and differences in comparison to commonly applied statistical distributions to be identified. The ongoing EU Marie Curie Network SEAMOCS (Applied Stochastic ModEls for Ocean engineering, Climate and Safe Transportation) has contributed to this and the recently initiated CresT JIP is also investigating the subject. The Rogue Waves 2008 Workshop has confirmed the importance of wave directionality for rogue wave predictions.

The issue of the IPCC Assessment Report in 2007 has brought new knowledge about climate change, in particular about storm intensity and frequency, sea-level rise, sea ice extent, natural variability versus climate change contribution, as well as uncertainties related to their prediction.

6.2 Recommendations

More generally, the need for improving the availability, quality and reliability of wave databases as well as providing wave models approximating wave physics in the most accurate way has always been one of the main concerns of academia as well as classification societies and offshore companies. This situation is unchanged, and any effort to address this concern is recommended.

Though future remote sensing data should be available through operational oceanographic programmes, significant progress has to be encouraged for easier access to satellite wind, wave and current data. There is still not full acceptance for applying satellite data in industry, often due to lack of knowledge about their accuracy. Further marketing of satellite data for industry should continue through international conferences and workshops as well as invitations of industry, as observers or as partners, to participate in international projects investigating/demonstrating satellite data accuracy.

The need for detailed investigations of meteorological and oceanographic conditions in which extreme and rogue waves occur has been pointed out by several authors at the Rogue Waves 2008 Workshop. More systematic investigations of extreme and rogue wave mechanisms such as bimodal seas, directional energy spreading, spatial description, effects of water depth, and wave-current interaction, are still lacking. There is also a need for more field data to study rogue waves in the ocean. These investigations are essential for reaching consensus about probability of occurrence of rogue waves which is mandatory for evaluation of possible revision of classification society rules which do not include explicitly rogue waves today. Further, a consistent approach combining new information about extreme and rogue waves in a design perspective needs to be proposed.

Attention needs to be given to properly accounting for directional effects in design, assuring consistency between omnidirectional and directional criteria, seasonality, spatial and nonstationary statistics.

In order to enhance safety at sea, it is important that consideration be made of uncertainties related to the environmental description. These investigations need to continue. The shipping industry lags behind the offshore industry in these studies.

The industry should continue to develop decision support systems. Their use is recommended in the new DNV Recommended Practice DNV-RP-H103 (DNV, 2009) for modelling and analysis of marine operations developed within the JIP project COSMAR (COSt Effective MARine Operations), if their reliability is documented and approved by an authority, e.g. a Classification Society. The effectiveness of decision support systems is expected to improve with improved knowledge of wave-structure interactions and more accessible real-time wave data and wave statistics.

The 2009 ISSC I.1 Committee recognises the significance of the IPCC (2007) findings and the conclusions drawn by the Panel. However, as pointed out by the IPCC Panel, the results presented are affected by various types of uncertainties which influence accuracy of a climate model's simulation of past or contemporary climate and accuracy of climate change projections. Accordingly, neither Classification Societies nor oil companies have yet initiated revision of their rules and standards to account for climate change. A Workshop on climate change organised by WMO (World Meteorological Organization) and OGP (International Association of Gas and Oil Producers) in Geneva in May 27-29, 2008, was dedicated to uncertainties of climate change projections, which resulted in the identification of several key priorities. The oil/gas industry have indicated their willingness to contribute more effectively to the WMO efforts in reducing uncertainties in climate change and to address the issues raised in the key priorities.

Further, it should be noted that the IPCC Report (2007) presents the results as the average global values. Extreme value estimates needed for design work may be significantly more affected by climate changes than the average values. Further investigations are called for to document these effects. In addition, time-dependent statistics needs to be adopted by the metocean community to be able to design for climate change.

In the case of very dramatic climate change, if the ice disappears completely from the Arctic Ocean in summer and only parts are ice covered in winter, it is conceivable that a third route between Asia and North America and Europe may be introduced – the Transpolar Route (TR). This route will cut distances even more than the two traditional routes and may reduce the political tensions and uncertainties pertaining to these. However, so far none of the models shows that an all-year ice-free Arctic Ocean is a likely scenario in the 21st century, although the ice may consist of mainly first year and become thinner.

Although new investigations are still called for to quantify and reduce uncertainties related to climate change projections, as well as to better understand the effect of climate change on marine structures, a process preparing for the adoption of future climate change needs to be initiated imminently by industry. Any revision of design criteria methodology that accounts for climate change needs to be well founded on good scientific and technological findings.

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REFERENCES

Abdalla, S., Bidlot, J.-R., and Janssen, P. (2005). Assimilation of ERS and Envisat wave data at ECMWF. *Proceedings of the 2004 Envisat & ERS Symposium*, September 6-18, 2004, Salzburg, Austria, ESA SP-572.

Åberg, S. (2007). Wave intensities and slopes in Lagrangian seas. *Advance in Applied Probability*, 39:4, 1027-1035.

Abram, N. J., Gagan, M. K., McCulloch, M. T., Chappel, J. and Hantoro, W. S. (2003). Coral reef death during the 1997 Indian Ocean Dipole linked to Indonesian wildfires. *Science* , 301, 952-955.

Abram, N. J., Gagan, M. K., Liu, Z., Hantoro, W. S., McCulloch, M. T. and Suwargadi, B. W. (2007). Seasonal characteristics of the Indian Ocean dipole during the Holocene epoch. *Nature,* 445, 299–302, doi:10.1038/nature05477.

ACIA (Arctic Climate Impact Assessment). (2004). *Highlights, impacts of a warming Arctic*, Cambridge University Press, Cambridge, UK.

ACIA (Arctic Climate Impact Assessment). (2005). *Eighteen chapter scientific report*, Cambridge University Press, Cambridge, UK.

Allan, J., and Komar, P., (2000). Are ocean wave heights increasing in the eastern North Pacific? Eos, 81, 561–567.

Allen, J. R. and Long, D. G. (2005). An Analysis of SeaWinds-Based Rain Retrieval in Severe Weather Events. *IEEE Trans. Geosci. Rem. Sens.*, 43, 2870-2878.

Andersen, O. B., Knudsen, P. and Beckley, B. (2006). Regional long-term sea level and sea surface temperature characteristics from satellite observations. *Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry*, March 13-18, Venice, Italy, ESA SP-614.

Andersen, S., Tonboe, R., Kaleschke, L., Heygster, G. and Pedersen, L. T. (2007). Intercomparison of passive microwave sea ice concentration retrievals over the high-concentration Arctic sea ice. *J. Geophys. Res.,* 112 , C08004.

Annenkov, A. Y. and Shira, V. I. (2008). Direct numerical simulation of waves subjected to an abrupt change of wind: evolution of spectra and kurtosis. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Anthes, R. A., Correll, R. W., Holland, G., Hurrell, J. W., MacCracken, M. C. and Trenberth, K. E. (2006). Hurricanes and global warming –potential linkages and consequences. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-87-5-617

Aouf, L., Lefèvre, J. M. and Hauser, D. (2006). Assimilation of synthetic SWIMSAT directional wave spectra in wave model WAM. *J. Atmos. Oceanic Technol.*, 23:3, 448–463.

Aouf, L., Lefèvre, J.-M. , Chapron, B. and Hauser, D. (2008). Recent improvements of the assimilation of upgraded ASAR L2 wave spectra in the wave model. *Proceedings of SeaSAR 2008*, January 21-25, 2008, ESRIN, Frascati, Italy, ESA SP-656.

Ardhuin, F., Bertotti, L., Bidlot, Cavaleri, L.J.-R., Filipetto, V., Lefevre, J.-M. and Wittmann, P. (2007). Comparison of Wind and Wave Measurements and Models in the Western Mediterranean Sea. Ocean Engineering, 34:3-4, 526-541.

Ardhuin, F., Collard, F., Chapron, B., Queffeulou, P., Filipot, J.-F. and Hamon, M. (2008a). Spectral wave dissipation based on observations: a global validation. *Proceedings of the Chinese-German Joint Symposium on Hydraulics and Ocean Engineering*, August 24-30, 2008, Darmstadt, Germany.

Ardhuin, F., Chapron, B. and Collard, F. (2008b). Strong decay of steep swells observed across oceans, submitted to *Geophys. Res. Lett.*, available at http://hal.archives-ouvertes.fr/hal-00321581/en/

Arena, F. and Ascanelli, A. (2008). Nonlinear crest height distribution in three-dimensional ocean waves. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008) , June 15-20, 2008, Estoril, Portugal.

Arena, F. and Guedes Soares, C. (2008). On Sequence of High Waves in Nonlinear Groups. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008) , June 15-20, 2008, Estoril, Portugal.

Ashok, K., Guan, Z. and Yamagata, T. (2001). Impact of the Indian Ocean Dipole on the decadal relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett.*, 28, 4499-4502.

Ashok, K., Guan, Z. and Yamagata, T. (2003). Influence of the Indian Ocean Dipole on the Australian winter rainfall. *Geophys. Res. Lett.*, 30:15, 1821, doi:10.1029/2003GL017926.

Ashok, K., Behera, S. K., Rao, S. A. and Weng, H. (2007). El Nino Modoki and its possible teleconnection. *J. Geophys. Res.*, 112:C11007, doi:10.1029/2006/JC003798,2007.

Ayyub, B.M., Kaminskiy, M., Alman, P.R., Engle, A., Campbell, B.L. and Thomas, W.L. (2006). Assessing the probability of the dynamic capsizing of vessels, *Journal of Ship Research*, 50:4, 289-310.

Badulin, A. I., Korotkevich, A. O., Resion, D., and Zakharov, V. E. (2008). Wave-wave interactions in wind-driven mixed sea. Olagnon, M. (2008). About the frequency of occurrence of rogue waves. *Proceedings of the Rogue Waves 2008 Workshop*, Brest, France 13-15 October 2008.

Barstow, S., Mørk, G., Lønseth, L., Schjølberg, P., Athanassoulis, G., Belibassakis, K., Gerostathis, T., Spaan, G. and Stergiopoulos, C. (2003). WORLDWAVES: High quality coastal and offshore wave data within minutes for any global site. *Proceedings of the 22nd International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2003), June 9-13, 2003, Cancun, Mexico.

Barstow, S., Mørk, G. and Lønseth, L. (2008). WorldWaves resource assessments. *Proceedings of the 2nd International Conference on Ocean Energy.* October 15-17, 2008, Brest, France.

Barthelmie, R. J., Sempreviva, A. M. and Pryor, S. C. (2007). The influence of humidity fluxes on offshore wind speed profiles. *e-WindEng*, 005, 01–05.

Baxevani, A., Rychlik, I. and Wilson, R.J. (2005). A new method for modelling the space variability of significant wave height, *Extremes*, 8, 267-294.

Baxevani, A., Borgel, C. and Rychlik, I. (2008). Spatial models for variability of significant wave height in world oceans, *International Journal of Offshore and Polar Engineering*, 18 :1, 1-7.

Behera, S. K. and Yamagata, T. (2003). Influence of the Indian Ocean Dipole on the Southern Oscillation. *J. Meteor. Soc. Jpn.*, 81, 169-177.

Behera, S. K, Luo, J.-J. and Yamagata, T. (2008). Unusual IOD event of 2007. *Geophys. Res. Lett.*, 35, L14S11, doi:10.1029/2008GL034122.

Belchansky, G. I., Douglas, D. C. and Platonov, N. G. (2004). Duration of the Arctic sea ice melt season: regional and interannual variability, 1979-2001. *J. Climate*, 17, 67–80.

Bell, G. D. and Chelliah, M. (2006). Leading tropical modes associated with interannual and mutidecadal fluctuations in North Atlantic hurricane activity. *J. Climate*, 19, 590-612.

Bell, R. E. (2008). The unquiet ice. *Scientific American*, 298:2, 60-67.

Bell, M. and Le Traon, (2009). "The Revolution in Global Ocean Forecasting – GODAE: 10 Years of Achievement", Vol. 22, No. 3, September 2009, Guest Editors: Mike Bell, National Centre for Ocean Forecasting, and Pierre-Yves Le Traon, IFREMER.

Benetazzo, A. (2006), Measurements of short water waves using stereo matched image sequences, Coastal Engineering, 53:12, 1013-1032.

Bentamy, A. , Ayina, H.-L., Queffeulou, P., Croize-Fillon, D., and Kerbaol, V. (2007). Improved near real time surface wind resolution over the Mediterranean Sea. *Ocean Sci.*, 3, 259–271.

Bentamy, A. (2008). Characterization of ASCAT measurements based on buoy and QuikSCAT wind vector observations. *Ocean Sci. Discuss.*, 5, 77–101.

Bentley, C. R., Thomas, R. H., and Velicogna, I. (2007). Global outlook for ice and snow. *United Nations Environmental Programme, 2007*. http:/www.unep.org/geo/geo_ice.

Bertino, L., and Lisæter, K. A. (2008). The TOPAZ monitoring and prediction system for the Atlantic and Arctic oceans. *J. of Operational Oceanography*, 1:2, 15–19.

Bidlot, J.-R., Li, J.-G., Wittmann, P., Fauchon, M., Chen, H., Lefèvre, J.-M., Bruns, T., Greenslade, D., Ardhuin, F., Kohno, N., Park, S. and Gomez, M. (2007). Inter-comparison of operational wave forecasting systems. *Proceedings of the 10th Int. Workshop of Wave Hindcasting and Forecasting*, Hawaii, USA, Nov. 2007. (http://www.waveworkshop.org/10thWaves/Papers/paper 10th workshop Bidlot at al.pdf).

Bijl, M., Reniers, A., Ewans, K.C., Masterton, S., and Huijsmans, R. (2009). Evaluation of a model for estimating infragravity waves in shallow water – accuracy and suitability for long-term climatologies. *Proceedings of OMAE 2009*, 31 May-5 June, 2009, Honolulu, Hawaii.

Bister, M., and Emanuel, K. A. (2002). Low frequency variability of tropical cyclone potential intensity, 1. Interannual to interdecadal variability. *J. Geophys. Res.*, 107, 4801, doi:10.1029/2001JD000776.

Bitner-Gregersen, E. M. and Hagen, Ø. (1990). Uncertainties of data for the offshore environment. *Journal Structural Safety*, 7.

Bitner-Gregersen, E. M., and Haver, S., (1991). Joint Environmental model for reliability calculations, *Proceedings of the 1st International Offshore and Polar Engineering (ISOPE 1991)*, Edinburg, UK Vol. 1, pp. 246-253.

Bitner-Gregersen, E. M., Cramer, E. H. and Korbijn, F. (1995). Environmental Description for Long-term Load Response of Ship Structures. *Proceedings of the 5thInternational Offshore and Polar Engineering (ISOPE 1995)*, June 11-16, 1995, The Hague, the Netherlands.

Bitner-Gregersen, E. M., (1996). Distribution of mulitidirectional environmental effects. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1996)*, June 16-20, 1996, Florence, Italy.

Bitner-Gregersen, E.M. and Hagen, Ø., (1999).Extreme value analysis of wave steepness and crest using joint environmental description. *Proceedings of the 18th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1999)*, St. Johns, Newfoundland, Canada, June, 1999.

Bitner-Gregersen. E. M. and Hagen. Ø. (2002). Directional spreading in two-peak spectrum at the Norwegian continental shelf. *Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2002), June 23-28, 2002, Oslo, Norway.

Bitner Gregersen, E. M., Hovem, L. and Hørte, T. (2003). Impact of freak waves on ship design practice. *Proccedings MAXWAVE Final Meeting*, October 8-10, 2003, Geneva, Switzerland.

Bitner-Gregersen, E. M. and Magnusson, A. K. (2004). Extreme events in field data and in a second order wave model. *Proceedings of the Rogue Waves 2004 Workshop*, October 20-32, 2004, Brest, France.

Bitner-Gregersen, E. M. and Guedes Soares, C. (2007). Uncertainty of average wave steepness prediction from global wave databases. *Proceedings of the MARSTRUCT Conference*, March 12-14, 2007, Glasgow, UK.

Bitner-Gregersen, E. M. and Skjong, R. (2008). Concept for a risk based Navigation Decision Assistant, *J. Marine Structures*, online, 30 August 2008.

Bitner-Gregersen, E. M. and de Valk, C. (2008). Quality control issues in estimating wave climate from hindcast and satellite data. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Bitner-Gregersen, E. M., Toffoli, A., Onorato, M. and Mobaliu, J. (2008), Implications of nonlinear waves for marine safety. *Proceedings of the Rogue Waves 2008 Workshop*, Brest, France 13-15 October 2008.

Bjerknes, J. (1969). Atmospheric teleconnection from the equatorial Pacific. *Mon. Wea. Rev.*, 97, 163-172.

Blanc, F., Clancy, R., Cornillon, P., Donlon, C., Hacker, P., Haines, K., Hankin, S., Pouliquen, S., Price, M., Pugh, T., and Srinivasan, A., (2008). Data & Product serving, an overview of capabilities developed in 10 years. *Observing and Forecasting the Ocean, GODAE Final Symposium*, November 12-15, Nice France (http://www.godae.org/Invited-papers.html).

Borgman, L.E. (1973). Probabilities for highest wave in hurricane, *J. Waterways, Harbors and Coastal Engineering*, ASCE 99 (WW2), 185-207.

Böttcher, F. (2005). Statistische Analyse der atmosphärischen Turbulenz und allgemeiner stochastischer Prozesse. Carl von Ossietzky Universität Oldenburg, Germany. *Ph.D. thesis*, University of Oldenburg.

Boukhanovsky, A. V., Lopatoukhin, L. J. and Guedes Soares, C. (2007). Spectral wave climate of the North Sea. *Applied Ocean Research*, 29:3, 146-154.

Brandt, R. E.,Warren, S. G., Worby, A. P. and Grenfell, T. (2005). Surface albedo of the Antarctic sea ice zone. *J. Climate*, 18, 3606–3622

British Maritime Technology (Hogben, N. Da Cunha, L.F., and Oliver , H.N.) (1986), Global Wave Statistics, Unwin Brothers Limited, London, England.

Broquet, G., Brasseur, P., Rozier, D., Brankart, J.-M., and Verron, J. (2008). Estimation of model errors generated by atmospheric forcings for ocean data assimilation: experiments in a regional model of the Bay of Biscay. *Ocean Dynamics*, 58:1, 1–17.

Bromirski, P.D., Flick, R.E. and Cayan, D.R., (2003). Storminess variability along the California coast: 1858-2000. J. Clim., 16, 982–993.

Buchner, B., Van Dijk, R. R. T. and Voogt, A. J., (2007). The spatial analysis of an extreme wave in a model basin. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2007), June 10-15, 2007, San Diego, USA.

Buchner, B., Christou, M., Ewans, K. and Swan, C. (2008). Spectral of characteristics of an extreme crest measured in a laboratory basin. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Burton, T., Sharpe, D., Jenkins, N., and Bossanyi, E. (2001). *Wind Energy Handbook*. John Wiley and Sons, Chichester.

Busalacchi A., and Palmer T. N. (2006). Preface of the Special Section, *J. Climate*, 19, 4975-4976

Cai, W., Hendon, H. and Meyers, G. (2005). Indian Ocean dipole-like variability in the CSIRO Mark 3 coupled climate model. *J. Climate*, 18, 1449-1468.

Caires, S., Swail, V. R. and Wang, X. L. (2006). Projection and analysis of extreme wave climate. *J. Climate*, 19.

Cardone, V.J., Greenwood, J.G. and Cane, M.A., (1990). On trends inhistorical marine wind data. J. Clim., 3, 113–127.

Cardone, V.J., Cox, A.T. and Swail, V.R. (2000). Specification of the global wave climate: is this the final answer? *Proceedings of the 6th International Workshop on Wave Hindcasting and Forecasting,* November 6-10, 2000, Monterey, California.

Cardone, V. and Cox, A. (2007). Tropical cyclone atmospheric forcing for ocean response models: approaches & Issues, *Proceedings of the 10th International Wind and Wave Workshop*, November 11-16, 2007, Oahu, Hawaii, USA.

Cavaleri, L, Alves, J.-H. G. M., Ardhuin, F., Babanin, A., Banner, M., Belibassakis, K., Benoit, M., Donelan, M., Groenweg, J, Herbers, T. H. C., Hwang, P., Janssen, P. A. E. M., Janssen, T., Lavrenov, I. V., Magne, R., Monbaliu, J., Onorato, M., Polnikov, V., Resion, D, Rogers, W. E., Sheremet, A., McKee Smith, J., Tolman, H. L., Van Vledder, G., Wolf, J. and Young, I.(2007). Wave modelling - the state of the art. *Progress in Oceanography*, 75:4, 603-674.

Cazenave A. *et al* (2008). Present day sea level and climate change. *Ocean Surface Topography Science Team Meeting*, November 9-12, 2008, Nice, France (http://www.aviso.oceanobs.com/index.php?id=1452).

Challenor, P., Woolf D., Gommenginger C., Srokosz M., Cotton D., Carter D. and Sykes, N. (2006). Satellite altimetry: A revolution in understanding the wave climate. *Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry*, March 13-18, 2006, Venice, Italy, ESA SP-614.

Chapron, B., Collard, F. and Ardhuin, F. (2005). Direct measurements of ocean surface velocity from space : Interpretation and validation. *J. Geophys. Res.*, 110, C07008.

Chang, E.K.M., and Fu, Y. (2002). Interdecadal variations in Northern Hemisphere winter storm track intensity. J. Clim., 15, 642–658.

Chang, P., Yamagata, T., Schopf, P., Behera, S. K., Carton, J., Kessler, W. S., Meyers, G., Qu, T., Schott, F., Shetye, S. and Xie, S.-P. (2006). Climate fluctuations of tropical coupled system – the role of ocean dynamics. Special Section, *J. Climate*, 19, 5122-5174.

Chelton, D. B. and Freilich, M. H. (2005). Scatterometer-based assessment of 10-m wind analyses from the operational ECMWF and NCEP numerical weather prediction models. *Mon. Wea. Rev.*, 133, 409-429.

Chelton D. B., Freilich, M. H., Sienkiewicz, J. M. and Von Han, J. M. (2006). On the use of QuikSCAT scatterometer measurements of surface winds for marine weather prediction. *Mon. Wea. Rev.*, 134, 2055-2071.

Chen, H. (2002). Weather routing: a new approach, *Safety at Sea*, Feb. 2002 (downloadable at http://www.ocean-systems.com/pdf_docs/Safety%20at%20Sea.pdf).

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

Cherneva, Z., Andreeva, N., Pilar, P., Valchev, N., Petrova, P., Guedes Soares, C. (2008). Validation of the WAMC4 wave model for the Black Sea. *Coastal Engineering,* 55, 881–893.

Church, J. A. and White, N. J. (2006). A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.*, 33, L01602, doi:10.1029/2005GL024826

Clamond, D., Francius, M., Grue, J., Kharif, C. (2006). Long time interaction of envelope solitons and freak wave formations. *Europ. J. Mech. B/Fluids*, 25:5, 536–553.

Clauss, G. F., Klein, M. and Testa, D. (2008). Spatial revolution of an extreme sea state with an embedded rogue wave. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), Estoril, Portugal.

Collard, F., Ardhuin, F. and Chapron B. (2008). Persistency of ocean swell fields observed from space. Submitted to *J. Geophys. Res.*

Comiso, J. C. (2006). Abrupt decline in the Arctic winter sea ice cover. *Geophys. Res. Lett.,* 33 , S. L18504.

Comiso, J. C. and Parkinson, C. L. (2004). Satellite-observed changes in the Arctic. *Phys. Today*, 57, 38-44.

Cox, A. T. and Cardone V. J. (2002). 20 Years of operational forecasting at Oceanweather. *7th International Workshop on Wave Hindcasting and Forecasting*, Banff, Alberta, Canada.

Cummings, J., Bertino, L., Brasseur, P., Fukumori, I., Kamachi, M., Martin, M., Mogensen, K., Oke, P., Testut, C. E., Verron, J. and Weaver, A. (2009). Ocean Data Assimilation Systems for GODAE. *Observing and Forecasting the Ocean, GODAE Final Symposium*, November 12-15, Nice France (http://www.godae.org/Final-GODAE-Symposium.html).

Curry, J. A., Webster, P. J. and Holland, G. (2006). Mixing politics and science in testing the hypothesis that greenhouse warming is causing a global increase in hurricane intensity. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-87-8-1025.

Danielson, R. E., Dowd, M. and Ritchie, H. (2008). Objective analysis of marine winds with the benefit of the Radarsat-1 synthetic aperture radar: A nonlinear regression framework. *J. Geophys. Res.*, 113, C05019, doi:10.1029/2007JC004413.

Davidson F. J. M., Allen, A., Brassington, G. B., Breivik, O., Daniel, P., Stone, B., Kamachi, M., Sato, S., King, B., Lefevre, F. and Sutton, M. (2008). Safety and effectiveness of operations at Sea. *Observing and Forecasting the Ocean, GODAE Final Symposium*, November 12-15, Nice France (http://www.godae.org/Invited-papers.html).

De Mey P., Craig, P., Edwards, C. A., Ishikawa, Y., Kindle, J. C., Proctor, R., Thompson, K. R., Jiang Zhu, Auclair, F., Beckers, J. -M., Blayo, E., Huthnance, J., Lyard, F.. and the GODAE Coastal and Shelf Seas Working Group (CSSWG) community (2008). Coastal modelling and applications. *Observing and Forecasting the Ocean, GODAE*

Final Symposium, November 12-15, Nice France (http://www.godae.org/Invited-papers.html).

Denissenko, P., Likaschuk, S., and Nazarenko, S. (2007). Gravity wave turbulence in a laboratory flume.*Physical Review Letters,* 99, 014501.

Debernard J., Sætra Ø., Røed L. P. (2002). Future wind, wave and storm surge climate in the northern North Atlantic. Climate Research, 23, 39-49.

de Valk, C., Groenewoud, P., Hulst, S. and Klopman, G. (2004). Building a global resource for rapid assessment of the wave climate. *Proceedings of the 23rd International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2004), June 20-25, 2004, Vancouver, Canada.

de Vries, E. (2005). No longer paddling. Offshore wind developments 2005-2006. *Renewable Energy World,* 8:5, 60–70.

de Vries, J. J., Waldron, J. and Cunningham, V. (2003). Field tests of the new Datawell DWR-G GPS wave buoy. *Sea Technology*, Dec 2003.

Didenkulova, I. I., Slunyaev, A.V., Pelinovsky, E.N. and Kharif, C. (2006). Freak waves in 2005, *Natural Hazards and Earth System Sciences*, 6, 1007-1015.

Didenkulova, I. I., Pelinovsky, E. N., Soomere, T. and Zahilo, N. (2007). Runup of nonlinear asymmetric waves on a plane beach. *Tsunami and nonlinear waves* (Ed. Anjan Kundu), 174-188.

DNV. (1992). DNV CN30.6 Structural reliability analysis of marine structures, Høvik, Norway, July 1992.

DNV, (2007). DNV RP-C205 Environmental conditions and environmental loads.Høvik, Norway, April 2007.

DNV. (2009). DNV Recommended Practice DNV-RP-H103. Modelling and analysis of marine operations. Høvik, will ve issued April, 2009.

Domack, E., Duran, D., Leventer, A., Ishman, S., Doane, S., Mc-Callum, S., Amblas, D., Ring, J., Gilbert, R. and Prentice, M. (2005). Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. *Nature*, 436:7051, 681-685.

Dombrowsky, E., Bertino, L., Brassington, G., Chassignet, E., Davidson, F., Hurlburt, H., Kamachi, M., Lee, T., Martin, M., Mei, S. and Tonani, M. (2008). GODAE systems in operation. *Observing and Forecasting the Ocean, GODAE Final Symposium*, November 12-15, Nice, France (http://www.godae.org/Final-GODAE-Symposium.html).

Dommermuth, D. G. and Yue, D. K. (1987). A high–order spectral method for the study of nonlinear gravity waves. *J. Fluid Mech.,* 184, 267–288.

Drévillon, M., Bourdallé-Badie, R., Derval, C., Drillet, Y., Lellouche, J-M., Rémy, E., Tranchant, B., Benkiran, M., Greiner, E., Guinehut, S., Verbrugge, N., Garric, G., Testut, C-E., Laborie, M., Nouel, L., Bahurel, P., Bricaud, C., Crosnier, L., Dombrowsky, E., Durand, E., Ferry, N., Hernandez, F., Galloudec, O., Le Messal, F. and Parent, L. (2008). The GODAE/Mercator-Ocean global ocean forecasting system: results, applications and prospects. *Journal of Operational Oceanography*, 1:1, 51-57

Drinkwater, M. R., Ratier, R. F. G. and Wingham, D. J. (2004). The European Space Agency's Earth Explorer Mission CryoSat: measuring variability in the cryosphere. *J. Geophys. Res.,* 39, 313–320.

Durante, F., and de Paus, T. (2006). A comparison of MM5 and meteo mast wind profiles at Cabauw, The Netherlands and Wilhelmshaven, Germany. *e-WindEng,* 003.

Durrant, T. H., Greenslade, D. J. M. and Simmonds, I. (2009). Validation of Jason-1 and ENVISAT remotely-sensed wave heights. *J. Atmos. Oceanic Technol.* [submitted].

Dysthe, K. B. (1979). Note on the modification of the nonlinear Schrödinger equation for application to deep water waves. *Proc. R. Soc. London,* A 369, 105–114.

Dysthe, K., Krogstad, H.E. and Müller, P. (2008). Oceanic rogue waves. *Ann. Rev. Fluid*

Mec., 40, 287-310.

Eide, M.S., Endresen, Ø., Brett, P.O., Ervik, J.L. and, Røang, K. (2007a). Intelligent ship traffic monitoring for oil spill prevention: Risk based decision support building on AIS, *Marine Pollution Bulletin*, 54, 145-148.

Eide, M.S., Endresen, Ø., Breivik, Ø., Brude, O.W., Ellingsen, I.H., Røang, K., Hauge, J. and Brett, P.O. (2007b). Prevention of oil spill from shipping by modelling of dynamic risk, *Marine Pollution Bulletin*, 54, 1619-1633.

Eleye-Datubo, A.G., Wall, A., Saajedi, A. and Wang, J. (2006). Enabling a powerful marine and offshore decision-support solution through Bayesian network technique, *Risk Analysis*, 26:3, 695-721.

Elgar, S., Herbers, T.H.C., Okihiro, M, Oltman-Shay, J., and Guza, R.T. (1992), Observations of infragravity waves, *J. Geophys. Res.*, 97:C10, 15,573-15,577.

Elsner, J. B. (2008). Hurricanes and climate change. *Bull. Amer. Meteor. Soc.*,.doi:10.1175/BAMS-89-5-677.

Emanuel, K. A. (1988). The dependence of hurricane intensity on climate. *Nature*, 326, 483-485.

Emanuel, K. A. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, 436, 686-688.

Emanuel, K. A. (2008). The Hurricane-climate connection. *Bull. Amer. Meteor. Soc.*,. doi:10.1175/BAMS-89-5-Emanuel.

Ewans, K. and van der Vlugt, T. (1998). Estimating Bimodal Frequency-directional Spectra from Surface Buoy Data Recorded During Tropical Cyclones. J. Phys. Oceanogr. 28, pp. 495-512.

Ewans, K. (2001). Directional Spreading in Ocean Swell. *Proceedings of WAVE'2001, "Ocean Wave Measurements and Analysis"*, San Francisco, USA.

Ewans, K. and Buchner, B. (2008). Wavelet analysis of an extreme wave in a model Bassin. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Ewans, K.C, Bitner-Gregersen, E. M. and Guedes Soares, C. (2006a). Estimation of Wind-Sea and Swell Components in a Bimodal Sea State. *J. Offshore Mech. Arct. Eng.,* 128:4, 265-270.

Ewans, K.C., Vanderschuren, L. and Tromans, P.S. (2006b). FPSO Conference – Estimating wind-sea and swell for FPSO operability, *J. Offshore Mech. Arct. Eng.*, 128:4, 314-321.

Fedele, F. (2008). Rogue Waves in Oceanic Turbulence. *Proceedings of the 23rd International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2004), June 20-25, 2004. Vancouver, Canada.

Fedele, F., Gallego, G., Benetazzo, A., Yezzi, A. and Tayfun, M.A. (2008). Euler characteristics and maxima of oceanic sea states. *Proceedings of the 31st Italian Congress of Hydraulic*, Perugia, Italia.

Figa-Saldaña J., Wilson, J. J. W., Attema, E., Gelsthorpe, R., Drinkwater, M. R. and Stoffelen, A. (2002). The advanced scatterometer (ASCAT) on the meteorological operational (MetOp) platform: A follow on for European wind scatterometers. *Can. J. Remote Sensing*, 28: 3, 404–412.

Fissel, D. B., Marko, J. R., and Melling, H. (2008). Advances in upward looking sonar technology for studying the process of change in Arctic Ocean ice climate. *Journal of Operational Oceanography*, 1:1,9–18.

Forristal, G. Z. (1978). On the statistical distribution of wave heights in a storm. *J. Geophys. Res.*, 83, 2353-2358.

Forristall, G. Z. and Shaw, C. (1995). The right way to use directional design criteria? *Proceedings European and Petroleum Forum*, London.

Forristall, G. Z. (2000). Wave crest distributions: observations and second order theory.

J.Phys. Oceanogr. ,30, 1931-1943.

Forristall, G. Z., Krogstad, H., Taylor, P., Barstow, S., Prevosto, M. and Tromans, P. (2002). Wave crest sensor intercomparison study: an overview of WACSIS. *Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2002), June 23-28, 2002, Oslo, Norway.

Forristall, G. Z. (2004). On the use of directional wave criteria, *Technical Notes, J. Waterway, Port, Coastal and Ocean Engineering*, ASCE, Setp./Oct., 272-275.

Forristall, G., Z. (2006). Maximum wave heights over an area and the air gap problem. *Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2006), 4–8 June, 2006, Hamburg, Germany.

Foristall, G. Z. (2007). Comparing hindcasts with measurements from hurricanes Lili, Ivan, Katrina and Rita. *International Workshop on Wave Hindcasting & Forecasting*, Oahu, Hawai, November 11-16, 2007.

Foristall, G. Z. (2008). How we should combined longand short term wave height distributions? *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Forsberg, R., Skourup, H. (2005). Arctic Ocean gravity, geoid and sea–ice freeboard heights from ICESat and GRACE. *Geophys. Res. Lett.*, 32, L21502.

Frandsen, E. A. (2006). Analytical modelling of wind speed deficit in large offshore wind farms. *Wind Energy,* 9:1-2, 39–53.

Fujisaki, A., Yamaguchi, H., Fengjun, D., and Sagawa, G. (2007). Improvement of Short-Term Sea Ice Forecast in the Southern Okhotsk Sea. *Journal of oceanography*, 63, 775–790.

Fukunaga, K., Yamamoto, N. and Ikeda, Y. (2007). A Simple Onboard System to Identify Encounter-Wave Characteristic. *Proceedings of the 17th International Offshore and Polar Engineering (ISOPE) Conference*, July 1-6, *2007,* Lisbon, Portugal.

Fuhrmanj, D. R., Madsen, P. A., (2006). Short-crested waves in deep water: a numerical investigation of recent laboratory experiments. *J. Fluid Mech.,* 559, 391–411.

Fuhrmanj, D. R., Madsen, P. A. and Bingham, H. B. (2006). Numerical simulation of lowest-order short-crested wave instabilities. *J. Fluid Mech.,* 557, 369–397.

Gaiser, P. W., St. Germain, K. M., Twarog, E. M., Poe, G. A., Purdy, W., Richardson, D., Grossman, W., Linwood Jones, W., Spencer, D., Golba, G., Cleveland, J., Choy, L., Bevilacqua, R. M. and Chang, P. S. (2004). The WindSat Spaceborne Polarimetric Microwave Radiometer: Sensor Description and Early Orbit Performance. *IEEE Trans. Geosci. Rem. Sens.*, 42, 2347-2361.

Gallego, G., Benetazzo, A., Yezzi, A., Fedele F. (2008). Wave statistics and spectra via a variational wave aquisision stereo system. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Gibson, R. S., Swan, C., Tromans, P. S. (2007). Fully nonlinear statistics of wave crest elevation calculated using a spectral response surface method: application to unidirectional sea states. *J. Phys. Oceanogr.,* 379, 3–15.

Göbell, S. (2007). Determination of sea ice surface elevation with laser and radar altimetry and comparison with ice thickness datasets in the Arctic and Antarctic. Bremen: Universität Bremen / Alfred-Wegener-Institut für Polar- und Meeresforschung (Dissertation).

Gomez-Enri, J., Gommenginger, C., Srokosz, M. A., Challenor, P. G. and Benveniste, J. (2007). Measuring Global Ocean Wave Skewness by Retracking RA-2 Envisat Waveforms. *J. Atmos. Oceanic Technol.*, 24:6, 1102-1116.

Gourion, J., Vandemark, D., Bailey, S., Chapron, B., Gommenginger, C., Challenor, P. G., and Srokosz, M. A. (2002). A Two-Parameter Wind Speed Algorithm for Ku-Band

Altimeters. *J. Atmos. Oceanic Technol.*, 19: 12, 2030-2048.

Gower, J.F.R., (2002). Temperature, wind and wave climatologies, and trends from marine meteorological buoys in the northeast Pacific c. J.Clim., 15, 3709–3718.

Grabemann, I, and Weisse, R. (2008). Climate Change Impact on Extreme Wave Conditions in the North Sea: An Ensemble Study. Ocean Dynamics, 58, 199-212.

Graham, N.E., and Diaz, H.F., (2001). Evidence for intensification of North Pacific c winter cyclones since 1948. Bull. Am. Meteorol. Soc., 82, 1869– 1893.

Gramstad, O. and Trulsen, K. (2007). Influence of crest and group length on the occurrence of group length. *J. Fluid Mech.,* 582, 463–472.

Gray, L., Joughin, I., Tulaczyk, S., Spikes, V.B., Bindschadler, R. and Jezek, K. (2005). Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. *Geophys. Res. Lett.*, 32:3, L03501.

Greenslade, D. J. M., and Young, I.R. (2005). The impact of altimeter sampling patterns on estimates of background errors in a global wave model. *J. Atmos. Oceanic Technol.*, 22:12, 1895–1917.

Groenewegen M. J., Reniers A. J. H. M., Ewans K.C., Masterton S., Stelling G. S., and Meek J. (*in prep.*) Estimation of infragravity waves for vessel motion predictions. *Coastal Engineering*

Gryning, S. E., Batchvarova, E., Brümmer, B., Jørgensen, H. and Larsen, S. (2007). On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer. *Boundary-Layer Meteorology,*124:2, 251-268.

Gu, D. and Philander, S. H. (1997). Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, 275, 805-807.

Guan, Z., and Yamagata T. (2003). The unusual summer of 1994 in East Asia: IOD teleconnections. *Geophys. Res. Lett.*, 30:10, 1544, doi:10.1029/2002GL016831.

Guedes Soares, C. (1986a). Assessment of the uncertainty in visual observations of wave height. *Ocean Engineering,* 13:1,37-56.

Guedes Soares, C. (1986b). Calibration of visual observations of wave period. *Ocean Engineering*, 13:6, 539-547.

Guedes Soares, C. and Henriques, A. C., (1998). Fitting a double-peak spectral model to measured wave spectra. *Proceedings of the 17th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 98), July 5-9, 1998, Lisbon, Portugal. Paper No. OMAE-98-1491.

Guedes Soares, C., Weisse, R., Carretero, J. C. and Alvarez, E. (2002). A 40-years hindcast of wind, sea level and waves in European waters. *Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2002), June 23-28, 2002, Oslo, Norway.

Gulev, S.K. and Hasse, L., (1999). Climate changes of wind waves in the North Atlantic ove the last several decades. Proc. ISOPE'1999 Conf., Brest, France, May 30 - June 4, 1999.

Gulev, S.K., Zolina, O. and Grigoriev, S., (2001). Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. Clim. Dyn., 17, 795–809.

Gulev, S.K., and Grigorieva, V., (2004). Last century changes in ocean wind wave height from global visual wave data. Geophys. Res. Lett., 31, L24302, doi:10.1029/2004GL021040.

Gulev, S.K., Jung, T. and Ruprecht, E., (2007). Estimation of the impact of sampling errors in the VOS observations on air-sea fluxes. Part II. Impact on trends and interannual variability. J. Clim., 20, 302–315.

Hacket, B., Comerma, E., Daniel, P. and Ichikawa, H. (2008). Marine pollution monitoring and prediction. *GODAE Final Symposium*, November 12-15, Nice, France (http://www.godae.org/Final-GODAE-Symposium.html).

Hagen, Ø. (2007). Wave distributions and sampling variabitily. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2007), June 10-15, 2007, San Diego, CA, USA.

Hamilton, P. (2007). Deep-Current Variability near the Sigsbee Escarpment in the Gulf of Mexico. *J. Phys. Oceanogr.*, 37:3.

Hansen, S.V. and Pedersen, E. (2007). On an advanced shipboard information and decision-making system for safe and efficient passage planning. *Proceedings of the TransNav'07*, Gdynia, Poland.

Hanson, J. L., and Phillips, O. M. (2001). Automated analysis of ocean surface directional wave spectra. *J. Atmos. Oceanic Technol.*, 18, pp. 277–293.

Harigae, M., Yamaguchi, I., Kasai, T., Igawa, H., Nakanishi, H., Murayama, T., Iwanaka, Y. and Suko, H. (2005). Open-sea sensor to measure height and direction, *GPS World*, May.

Harlan, J., Terrill, E. and Crout, R. (2008). NOAA IOOS National HF radar network data management: status and plans. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, Charleston, SC, USA, March 2008.

Hasselmann, S., Hasselmann, K., Allender, J. H. and Barnett, T.P. (1985). Computation and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum. Part 2: Parameterization of the nonlinear transfer for application in wave models. *J. Phys. Oceanogr.* 15, 1378-1391.

Hasumi, H., Yasuda, I., Tateba, H. and Kimoto, M. (2008). Pacific bidecadal climate variability regulated by tidal mixing around the Kuril Islands. *Geophys. Res. Lett.*, 35, L14601, doi:10.1029, doi:10.1029/2008GL034406.

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

Hawley, R. L., Morris, E. M., Cullen, R., Shepherd, A. P. and Wingham, D. (2006). ASIRAS airborne radar resolves internal annual layers in the dry–snow zone of Greenland. *Geophys. Res. Lett.,* 33, S. D06107

Hay, A. E., Zedel, L., Craig, R. and Paul, W. (2008). Multi-frequency, pulse-to-pulse coherent doppler sonar profiler. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, Charleston, SC, USA, March 2008.

Hayashi, M. and Ishida, H. (2006). Characteristics analysis of weather routing by practical navigators. *Proceedings of the of Intl. Conference on Systems, Man and Cybernetics*, Taipei, Taiwan.

Herbers, T. H. C., Elgar, S. and Guza, R. T. (1994). Infragravity-frequency motions on the shelf. Part I: forced waves, *J. Phys. Oceanogr.*, 24, 917-927.

Herbers, T. H. C., Elgar, S., Guza, R.T. and O'Reilly, W. C. (1995). Infragravity-frequency (0.005-0.05 Hz) motions on the shelf. Part II: free waves. *J. Phys. Oceanogr.*, 25, 1063-1079.

Heron, M. L., Prytz, A. and Searson, S. (2008). The Australian Coastal Ocean Radar Network (ACORN). *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Hersbach, H., Stoffelen, A., and de Haan, S. (2007). An improved C-band scatterometer ocean geophysical model function: CMOD5. *J. Geophys. Res.*, 112, C03006, doi:10.1029/2006JC003743.

Hessner, K. and Reichert, K. (2007). Sea surface elevation maps obtained with a nautical X-band radar – Examples from WaMos II stations, 10th International Workshop on

Wave Hindcasting and Forecasting, Hawaii, USA.

Hisaki, Y. (2005). Ocean wave directional spectra estimation from an HF ocean radar with a single antenna array: Observation. *J. Geophys. Res.,*110, C11004.

Hisaki, Y. (2007). Directional distribution of the short-wave estimated from HF ocean radars. *J. Geophys. Res.*,112, C11014.

Hogben, N., (1994), "Increases in Wave Heights over the North Atlantic: A Review of the Evidence and some Implications for the Naval Architect", Trans. RINA, V Vol.137, Part A, pp. 93-115.

Howden, S., Gilhousen, D., Guinasso, N., Walpert, J., Sturgeon, M. and Bender, L. (2008). Hurricane Katrina winds measured by a buoy mounted sonic anemometer. *J. Atmos. Oceanic Technol.* 25, 607-616.

Huang, N., Shen, Z., Long, S., Wu, M., Shih, H., Zheng, Q., Yen, N., Tung, C. and Liu, H. (1998). The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc. R. Soc. London,* A 454, 903–995.

Huang, W. P., Chou, C. R. and Yim, J. Z. (2005). On reflection and diffraction due to a detached breakwater. *Ocean Engineering*, 32:14-15, 1762-1779.

Hutchison, B., Appolonov, E.M., Guedes Soares, C., Kleiven, G., Prevosto, M., Rahman, T., Landó, L.R., Shaw, C., Smith, D. and Tomita, H. (2006). Committee I.1 – Environment. *Proceedings of the 16th Intl. Ship and Offshore Structures Congress (ISSC)*, Southampton, UK.

IEA: IEA Wind Energy Annual Report 2005. Boulder, 2006. – Forschungsbericht. – 287 S.

IPCC (2007). *Climate Change 2007. The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2007. ISBN 978-0-521-70596-7.

Iseki, T. and Ohtsu, K. (2000). Bayesian Estimation of Directional Wave Spectra Based on Ship Motions, *Control Engineering Practice*, 8, 215-219.

Iseki, T. and Terada, D. (2002). Bayesian Estimation of Directional Wave Spectra for Ship Guidance Systems, *International Journal of Offshore and Polar Engineering*, 12, 25-30.

Iseki, T. (2004). Extended Bayesian estimation of directional wave spectra. *Proceedings of the 23rd Int. Conf. on Offshore Mechanics and Arctic Engineering*, Vancouver, Canada.

IMO (1997). Interim guidelines for the application of Formal Safety Assessment (FSA) to the IMO rule making process. *Maritime Safety Committee, 68th session, June 1997; and Marine Environment Protection Committee, 40th session*, September 1997.

IMO (2001). Guidelines for Formal Safety Assessment for the IMO Rule making process. *IMO/Marine Safety Committee 74/WP.19.*

Jacobs, G., Woodham, R. H., Jourdan, D. and Braithwaite, J. (2008). Application from GODAE to Navies throughout the world. *Observing and Forecasting the Ocean, GODAE Final Symposium*, November 12-15, Nice, France (http://www.godae.org/Final-GODAE-Symposium.html).

Jakobsen, T., Minken, H. and Furset, H. (2008). Improving Acoustic Current Measurements by ZPulse Technology. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Janssen P.A.E.M. (2006). 15 years of wave height data assimilation. *Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry*, March 13-18, 2006, Venice, Italy, ESA SP-614, July 2006.

Janssen, P.A.E.M., Abdalla, S., Hersbach, H. and Bidlot, J.-R. (2007). Error estimation of buoy, satellite, and model wave height data. *J. Atmos. Oceanic Technol.*, 24:9, 1665-1677.

Jeans, G. and Feld, G. (2003). The measurement and analysis of long-period waves to support coastal engineering. *Proceedings of the 30th IAHR Congress long period waves symposium*, Thessaloniki, Greece, 175, 409-421.http://www.iahr.net/site/index.html.

Jeans, G., Bellamy, I., de Vries, J. J. and van Weert, P. (2003). Sea trial of the new Datawell GPS directional waverider. *Proceedings of the IEEE/OES Seventh Working Conference on Current Measurement Technology*, March 13-15, 2003,145-147.

Jensen, J. J. (2005). Conditional second order short-crested water waves applied to extreme wave episodes. *J. Fluid Mech.,* 545, 29–40.

Jensen, J. J. and Capul, J. (2006). Extreme response predictions for jack-up units in second order stochastic waves by FORM, *Probabilistic Engineering Mechanics*, 21:4, 330-338.

Jensen, J. J. and Pedersen, P. T. (2006). Critical wave episodes for assessment of parametric roll, *Proceedings of IMDC'06*, Ann Arbor, USA.

Jensen, J. J. (2008). Stochastic procedures for extreme wave load predictions – wave bending moment in ships, *Marine Structures* (in press).

Jiang, L. and Li, J-.D. (2005). The prediction of sea wave characteristics based on ship motion information, *Shipbuilding of China*, 46:3 (in Chinese).

Jin, F.-F. (1997). An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.*, 54, 811-829.

Johannessen, O. M., Bengtsson, L., Miles, M. W., Kuzmina, S. I., Semenov, V. A., Alekseev, G. V., Nagurnyi, A., Zakharov, V. F., Bobylev, L. P., Pettersson, L. H., Hasselmann, K. and Cattle, H. P. (2004). Arctic climate change: observed and modeled temperature and sea-ice variability. *Tellus A*, 56:4, 328–341.

Johannessen, J., Chapron, B., Collard, F., Kudryavtsev, V., Mouche, A., Akimov, D. and Dagestad, K. -F. (2008). Direct ocean surface velocity measurements from space: Improved quantitative interpretation of Envisat ASAR observations. *Geophys. Res. Lett.*, 35, L22608, doi:10.1029/2008GL035709.

Johnson, G. C. and McPhaden, M. J. (1999). Interior pycnocline flow from the subtropical to the equatorical Pacific Ocean. *J. Phys. Oceanogr.*, 29, 3073-3089.

Johnson, M. C. and Wilson, P.A. (2005). Sea state estimated from ship motions by a statistical approach, Transactions RINA Part A1. *International Journal of Maritime Engineering*, 147, 53-69.

Johnston, M. E. and Timco, G. W. (2008). Guide for Understanding and Identifying Old Ice in Summer. *ICETECH 2008*, 20-23 July, 2008, Alberta, Canada.

Jonathan, P. and Ewans, K. C. (2006). Uncertainties in extreme wave height estimates for hurricane dominated regions. *Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering*, 4–8 June, 2006, Hamburg, Germany.

Jonathan, P. and Ewans K. C. (2007). The effect of directionality on extreme wave design criteria. *Ocean Engineering,* 34, 1977–1994.

Jonathan, P. and Ewans K. C. (2008). Modelling the seasonality of extreme waves in the Gulf of Mexico. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Jonathan P., Ewans, K. C. and Forristall, G. Z. (2008). Statistical estimation of extreme ocean environments: The requirement for modelling directionality and other covariate effects. *Ocean Engineering,* 35:11-12, 1211-1225, doi:10.1016/j.oceaneng.2008.04.002.

Kahma, K., Hauser, D., Krogstad, H. E., Lehner, S., Monbaliu, J. A. J. and Wyatt, L. R. (2005). Measuring and analysing the directional spectra of ocean waves, *EU COST Action 714*, EUR 21367, ISBN 92-898-0003-8.

Kara, A. B., Wallcraft, A. J. and Bourassa, M. A. (2008). Air-sea stability effects on the 10 m winds over the global ocean: Evaluations of air-sea flux algorithms. *J. Geophys.*

Res., 113, C04009, doi:10.1029/2007JC004324.

Kelly, K. A., Dickinson, S. and Johnson, G. C. (2005). Comparisons of scatterometer and TAO winds reveal time-varying surface currents for the Tropical Pacific Ocean. *J. Atmos. Oceanic Technol.*, 22, 735-745.

Kharif C. and Pelinovsky, E. (2003). Physical mechanisms of the rogue wave phenomenon. Eur. J. Mech. B Fluids, 22, 603–634.

Kinsman, B. (1965). *WIND WAVES Their Generation and Propagation on the Ocean Surface*. Dover Publications Inc, , 1965.

Kleeman, R., McCreary, J. P. Jr. and Klinger, B. A. (1999). A mechanism for generating ENSO decadal variability. *Geophys. Res. Lett.*, 26, 1743-1746.

Klotzbad, P. J. and Gray, W. M. (2006). Causes of the unusually destructive 2004 Atlantic basin hurricane season, *Bull. Amer. Meteor. Soc.*, doi:10.1174/BAMS-87-10-1325.

Knutson, T., (2007). Hurricanes and Climate. Presenattion at the OGP meeting in London. March, 2007.

Knutson, T. R., Sirutis, J. J., Garner, S. T., Held, I. M. and Tuleya, R. (2007). Simulation of the recent multidecadal increase of Atlantic hurricane activity using an 18-km-Grid regional model. *Bull. Amer. Meteor. Soc.*,. doi:10.1175/BAMS-88-10-1549.

Koch, W. and Feser, F. (2006). Relationship between SAR-derived wind vectors and wind at 10-m height represented by a mesoscale model. *Mon. Wea. Rev.*, 134, 1505-1517.

Kohut, J., Roarty, H., Licthenwalner, S., Glenn, S., Barrick, D., Lipa, B. and Allen, A. (2008). Surface current and wave validation of a nested regional HF radar network in the Mid-Atlantic Bight. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Komen, G., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, H. and Janssen, P. (1994). *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge.

Kossin, J. P. and Vimont, D. L. (2007). A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Amer. Meteor. Soc.*,. doi:10.1175/BAMS-88-11-1767.

Krogstad, H. and Barstow, S. (1999). Directional distributions in ocean wave spectra. *Proceedings of the 9th International Offshore and Polar Engineering (ISOPE) Conference*, May 30 - June 4, 1999 , Brest, France.

Krogstad, H., Barstow, S., Haug, O. and Peters, D. (1998). Directional distributions in wave spectra. *Proceedings of WAVE'97, "Ocean Wave Measurements and Analysis"*, November 3-7, 1997, Virginia Beach, Virginia, USA, Vol.2 .

Krogstad, H., Magnusson, A.K., and Donelan, M.A. (2006). Wavelet and local directional analysis of ocean waves. *International Journal of Offshore and Polar Engineering*,16:2, 97-103.

Krogstad, K.E., Barstow, S.F., Mathisen, J.P., Lønseth, L., Magnusson, A.K., Donelan M.A, (2008). Extreme Waves in the Long-Term Wave Measurements at Ekofisk. *Proceedings of the Rogue Waves 2008 Workshop*, Brest, France 13-15 October 2008.

Krüger, S., Kluwe, F. and Vorhölter, H. (2008). Decision support for large amplitude roll motions based on nonlinear time-domain simulations. *Proceedings of COMPIT*, April 21-23, 2008, Liege, Belgium (http://www.anast.ulg.ac.be/COMPIT08/Files/Proceeding_Compit08.pdf).

Kubat, I., Sayed, M., Savage, S. B., Carrieres, T., and Crocker, G. (2007). An operational iceberg deterioration model. *Proceedings of the 17th International Offshore and Polar Engineering Conference,* July 1-6, 2007, Lisbon, Portugal, 652–657.

Kwok, R., Zwally. H. J. and Yi, D. (2004). ICESat observations of Arctic sea ice: A first look. *Geophys. Res. Lett.*, 31, L16401.

Kwok, R., Cunningham, G. F., Zwally, H. J. and Yi, D. (2006). ICESat over Arctic sea ice: Interpretation of altimetric and reflectivity profiles. *J. Geophys. Res.*, 111, C06006.

Labroue, S. and Tran, N. (2007). Envisat RA-2 & MWR Product and Algorithm evolution studies -
WP 1300 report, CLS-DOS-NT-07-257CLS-DOS-NT-07-257, CLS 8-10, Rue Hermès - Parc Technologique du Canal - 31520 Ramonville St-Agne, France.

Laine, V. (2004). Arctic sea ice regional albedo variability and trends, 1982–1998. *J. Geophys. Res.*, 109, C06027.

Lange, B. (2002). Modelling the marine boundary layer for offshore wind power utilization. Carl von Ossietzky Universität Oldenburg, D26111 Oldenburg, Germany.

Lange, M. (2003). Analysis of the uncertainty of wind power predictions. Carl von Ossietzky Universität Oldenburg, D26111 Oldenburg, Germany.

Larkin, N. K. and Harrison, D. E. (2005). On the definition of El Nino and associated seasonal average U. S. weather anomalies. *Geophys. Res. Lett.*, 32, L13705, doi:10.1029/2005GL022738.

Lau, N.-C and Nath, M. (2004). Coupled GCM simulation of atmosphere-ocean variability associated with zonally asymmetric SST changes in the tropical Indian Ocean. *J. Climate*, 17, 245-265.

Leblanc, S., Branger, H., Francius, M., Golay, F., and Kharif, C. (2008). Wind-forced modulations of gravity waves. *Proceedings of the Rogue Waves 2008 Workshop*, Brest, France 13-15 October 2008.

Le Marshall J., Bi, L., Jung, J., Zapotocny, T. and Morgan, M. (2007). WindSat polarimetric microwave observations improve southern hemisphere numerical weather prediction. *Aust. Met. Mag.*, 56, 35–40.

Leckebusch, G. C., Weimer, A., Pinto, J. G., Reyers, M., and Speth, P. (2008). Extreme wind storms over Europe in present and future climate: a cluster analysis approach. *Meteorologische Zeitschrift*, 17:1, 67-82.

Lee, H. S. and Kim, S. D. (2006). A comparison of several wave spectra for the random wave diffraction by a semi-infinite breakwater. *Ocean Engineering*, 33:14-15, 1954-1971.

Lee, H. S., Wang, K. H., Williams, A. N. (2007). Three-dimensional modelling of multidirectional random wave diffraction by rectangular submarine pits. *Ocean Engineering*, 34:5-6, 665-675.

Lefèvre, J.-M., Skandrani, C., Queffeulou, P. and Bentamy, A. (2007), Wave model error analysis from altimetry. *Proceedings of the Ocean Science Topography Science Team meeting*, March 12-15, 2007, Hobart , Australia.

Lefèvre, J.-M., Aouf, L., Ardhuin, F. and Queffeulou, P. (2008). Validation of a set of input source terms based of altimeters data. *Proceedings of the WISE meeting*, June 6-18, 2008, Helsinki, Finland.

Leslie, L. M. and Buckley, B. W. (2006). Comments on "Scatterometer-Based Assessment of 10-m Wind Analyses from the Operational ECMWF and NCEP Numerical Weather Prediction Models". *Mon. Wea. Rev.*, 134, 737-742.

Levitus, S., Antonov, J. I. and Boyer, T. P. (2005). Warming of the World Ocean, 1955-2003. *Geophys. Res. Lett.*, 32, L02604.

Lindgren, G. and Åberg, S. (2008). First order stochastic Lagrange models for crest-trough and front-back asymmetric ocean waves. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Lindsay, R. W. and Zhang, J. (2005). The thinning of Arctic sea ice, 1988–2003: have we passed a tipping point? J. Climate, 18:22, 4879-4894.

Liu, P. C., Chen, H. S., Doong, D.-J., Kao, C. C. and Hsu, Y.-J. (2008a). Freak waves during Typhoon Krosa. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Liu, P. C., Schwab, D. J., Wu, C. H. and MacHutchon, K. R. (2008b). Wave heights in a 4d ocean wave field. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Losada, I. J., Lara, J. L., Guanche, R. and Gonzalez-Ondina, J. M. (2008). Numerical analysis of wave overtopping of rubble mound breakwaters. *Coastal Engineering*, 55:1, 47-62.

Lohrmann, A. and Nylund, S. (2008). Pure coherent Doppler systems - How far can we push it? *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Longuet-Higgins, M. S. and Stewart, R. W. (1962). Radiation stress and mass transport in surface gravity waves with application to “surf beats”. *J. Flud Mech.,* 29, 481-504.

Lopatoukhin, L., Boukhanovsky, A., Rozhkov and Degtyarev, A.B. (2003). Wind and Wave Climate of the Barents, Caspian and Okhotsk Seas. Handbook, Russian Maritime Register of Shipping. pp 213 (in Russian).

Lopatoukhin, L., Boukhanovsky, A., Ivanov, S. V. and Chernyshev, E.S. (2006). Wind and Wave Climate of the Baltic, North, Black, Azov, Mediterrannean Seas. Handbook, Russian Maritime Register of Shipping. pp 450, (in Russian).

Lopatoukhin, L. and Boukhanovsky, A. (2008). Extreme and freak waves. Results of measurements and simulation. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Luo, J. J., Masson, S., Behera, S. K. and Yamagata, T. (2007). Experimental forecasts of Indian Ocean Dipole using a coupled OAGCM. *J. Climate*, 20:10, 2178-2190.

Luo, J. J., Masson, S., Behera, S. K. and Yamagata, T. (2008). Extended ENSO predictions using a fully coupled ocean-atmosphere model. *J. Climate*, 21, 84-93, doi:10.1175/2007JCL1412.1

Ma, Q. W., and Yan, S. (2008). Preliminary simulation of wind effects on 3D freak waves. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Mackay, E. B. L., and Retzler, C. H. (2008). Wave energy resource assessment using satellite altimeter data. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Mackay, E. B. L., Retzler, C. H., Challenor, P. G. and Gommenginger, C. P. (2008). A parametric model for ocean wave period from Ku band altimeter data. *J. Geophys. Res.*, 113, C03029, doi:10.1029/2007JC004438.

Madsen, H. O., Krenk, S. and Lind, N. C. (1986). *Methods of structural safety*. Prentice-Hall, Enlewood Cliffs, NJ 07632.

Madsen, P. A., Sørensen, O. R. and Schäffer, H. A. (1997). Surf zone dynamics simulated by a Boussinesq type model. Part I: Model description and cross-shore motion of regular waves, *Coastal Engineering,* 32, 255-287.

Madsen, P. A. and Fuhrmanj, D. R. (2006). Third-order theory for bichromaticbidirectional water waves. J. *Fluid Mech*., 557, 369–397.

Markus, T. and Cavalieri, D. (2006). Interannual and regional variability of Southern Ocean snow on sea ice. *Annals of Glaciology*, 44 , 53–57.

Martin, T. (2007). Arctic sea ice dynamics: drift and ridging in numerical models and observations. Bremen: Universität Bremen / Alfred-Wegener-Institut für Polar- und Meeresforschung (Dissertation).

Masterton, S. and Ewans, K.C. (2008). Characteristics of the infragravity wave climate. *Proceedings of the 27th Int. Conf. on Offshore Mechanics and Arctic Engineering*, June 15-20, 2008, Estoril, Portugal.

McCreary, J. P. Jr., and Lu, P. (1994). On the interaction between the subtropical and the equatorial oceans: The subtropical cell. *J. Phys. Oceanogr.*, 31, 181-244.

McCabe, G.J., Clark, M.P. and Serreze, M.C., (2001) Trends in Northern Hemisphere surface cyclone frequency and intensity. J. Clim., 14, 2763–2768. M

McKenna, R., Marcellus, B., Croasdale, K., McGonigal, D. and Stuckey, P. (2008). Modelling of ice rubble accumulation around offshore structures. *ICETECH 2008.*, 20-23 July, 2008, Alberta, Canada.

Medatlas Group (2004). *Wind and Wave Atlas of the Mediterranean sea*. Western European Armaments Organisation Research cell, ISBN 2 – 11 – 095674 – 7, 420 pp.

Melling, H., Riedel. D. A. and Gedalof, Z. (2005). Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea. *Geophys. Res. Lett.*, 32, L24501.

Merckelbach, L. M., Briggs, R. D., Smeed, D. A. and Griffiths, G. (2008). Current Measurements from Autonomous Underwater Gliders. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Merle, J. (1980). Varibilité thermique annuelle et interannuelle de l'océan Atlantique équatorial Est. L'hypothèse d'un 'El Nino' Atlantique, *Oceanol. Acta*, 3, 209-220.

Milliff, R. F., Large, W. G., Morzel, J., Danabasoglu, G. and Chin, T. M. (1999). Ocean general circulation model sensitivity to forcing from scatterometer winds. *J. Geophys. Res.*, 104:C5, 11337-11358.

Miyahara, K., Miyake, R., Abe, N., Kumano, A., Toyada, M. and Nakajima, Y. (2006). Full-scale measurements on hull response of a large container ship in service. *Proceedings of the 25th Int. Conf. on Offshore Mechanics and Arctic Engineering*, Hamburg, Germany.

Monahan, A. H. (2006a). The probability distribution of sea surface wind speeds. Part I: Theory and SeaWinds observations. *J. Climate*, 19, 497-520.

Monahan, A. H. (2006b). The probability distribution of sea surface wind speeds. Part II: Dataset intercomparison and seasonal variability. *J. Climate*, 19, 521-534.

Moore, G. W. K. and Renfrew, I. A. (2005). Tip jets and barrier winds: A QuikSCAT climatology of high wind speed events around Greenland. *J. Climate*, 18, 3713-3725.

Mori, N. and Yasuda, T. (2002). Effects of high-order nonlinear interactionson unidirectional wave trains. *Ocean Engineering* 29, 1233–1245.

Mori, N. and Janssen, P. A. E. M. (2006). On kurtosis and occurrence probability of freak waves. *J. Phys. Oceanogr.,* 36, 1471–1483.

Mori, N., Janssen, P. A. E. M. and Onorato, M. (2008). Directional effects on freak wave prediction. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Motta, M., Barthelmie, R. J. and Volund, P. (2005). The influence of non-logarithmic wind speed profiles on potential power output at Danish offshore sites. *Wind Energy*, 8:2, 219–236.

Muller, H., Dumas, F., Blanke, B., and Mariette, V. (2007). High-resolution atmospheric forcing for regional oceanic model: the Iroise Sea. *Ocean Dynamics*, 57:4-5, 375–400.

Munk, W. H. (1949), Surf Beats, *Eos Trans. AGU*, 30, 849-854.

Myrhaugh, D. and Fouques, S. (2008). Bivariate distributions of significant wave height with characteristic wave steepness and characteristic surf parameter. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Naciri, M., Buchner, B., Bunnik, T., Huijsmans, R., and Andrews, J. (2004). Low frequency motions of LNG carriers moored in shallow water. *Proceedings of the 23rd Int. Conf. on Offshore Mechanics and Arctic Engineering*, Vancouver, Canada.

Naess, A., Gaidai, O. and Teigen, P. S. (2007). Extreme response prediction for nonlinear floating offshore structures by Monte Carlo simulation. *Applied Ocean Research*, 29, 221-230.

Naess, A. and Gaidai, O. (2008). Monte Carlo methods for estimating the extreme response of dynamical systems. *Journal of Engineering Mechanics*, 134:8, 628-636.

Naumov, A. K., Gudoshnikov, Y. P., and Skutina, E. A. (2007). Determination of the design ice ridge based on data of expedition studies in the northeastern Barents Sea. *Proceedings of the 17th International Offshore and Polar Engineering (ISOPE) Conference*, July 1-6, 2007, Lisbon, Portugal, 735–741.

Nerem, R. S., Chambers, D. P., Leuliette, E. W., Mitchum, G. T. and Cazenave, A. (2006). Satellite measurements of sea level change: where have we been and where are we going, *Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry*, March 13-18, 2006, Venice, Italy, ESA-SP614.

Nghiem, S. V., Chao, Y., Neumann, G., Li, P., Perovich, D. K., Street, T. and Clemente-Colón, P. (2006). Depletion of perennial sea ice in the East Arctic Ocean. *Geophys. Res. Lett.* , 33, L17501.

Nicolaus, M., Haas, C., Bareiss, J., Willmes, S. (2006). A model study of differences of snow thinning on Arctic and Antarctic first-year sea ice during spring and summer. *Annals of Glaciology*, 44, 47–153.

Nie, C. and Long, D. G. (2007). A C-Band wind/rain backscatter model. *IEEE Trans. Geosci. Rem. Sens.*, 45, 621-631.

Nielsen, U. D. (2005). Estimation of directional wave spectra from measured ship responses, PhD Thesis, Department of Mechanical Engineering, Technical University of Denmark, (downloadable at http://www.skk.mek.dtu.dk/English/Publikationer/PHD-rapporter.aspx).

Nielsen, U. D. (2006). Estimations of on-site directional wave spectra from measured ship responses. *Marine Structures*, 19:1, 33-69.

Nielsen, U. D. (2007). Response-based estimation of sea state parameters - Influence of filtering. *Ocean Engineering*, 34, 1797–1810.

Nielsen, U. D. (2008a). Introducing two hyperparameters in Bayesian estimation of wave spectra. *Probabilistic Engineering Mechanics*, 23:1, 84-94.

Nielsen, U. D. (2008b). The wave buoy analogy – Estimation of high-frequency wave excitations. *Applied Ocean Research*, 30, 100-106.

Nielsen, U. D. (2008c). Calculating outcrossing rates used in decision support systems for ships. *Proceedings of the Intl. Mechanical Engineering Congress and Exposition*, Boston, USA.

Nielsen, U. D., Friis-Hansen, P. and Jensen, J. J. (2008). A step towards risk-based decision support for ships – Evaluation of limit states using parallel system analysis, *Marine Structures* [in press].

Nieto-Borge, J. C., Rodríguez, G. R., Hessner, K. and González, P. I. (2004). Inversion of marine radar images for surface wave analysis. *J. Atmos. Oceanic Technol.*, 21:8, 1291-1300.

Nonaka, M., Xie, S.-P. and McCreary, J. P. Jr. (2002). Decadal variations in the subtropical cells and equatorial pacific SST. *Geophys. Res. Lett.*, 29:1116, doi:10.1029/2001GL013717.

NORSOK (2007) Standard N-003: Action and action effects, Rev. 2, http://www.standard.no/pronorm-3/data/f/0/03/78/7_10704_0/N-003d2r2.pdf.

NSIDC (2005): Sea ice decline intensities. In: Joint press release of NSIDC, NASA and Univ. Washington http://www-nsidc.colorado.edu/news/press/20050928/trendscontinue.html 111 (2005), S. D06107

Nunes, L. M. P., Guedes Soares, C. and Lima, J. A. M. (2008). Separation of wave systems in time series of combined sea states. *Proceedings of the 27th International*

Conference on Offshore Mechanics and Arctic Engineering (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Okada, T., Takeda, Y. and Maeda, T. (2006). On board measurement of stresses and deflections of a post-panamax containership and its feedback to rational design. *Marine Structures*, 19, 141-172.

Okumura, Y. and Xie, S.-P. (2004). Interaction of the Atlantic equatorial cold tongue and African monsoon. *J. Climate*, 17, 3583-3601.

Olagnon, M. (2008). About the frequency of occurrence of rogue waves. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Oliveira, F., S., B., F. (2007). Numerical modelling of deformation of multi-directional random waves over a varying topography. *Ocean Engineering*, 34:2, 219-358.

Olsen, A. S., Schrøter, C. and Jensen, J. J. (2004). Encountered wave height distributions for ships in the North Atlantic. *Proceedings of PRADS'04*, Lubeck, Germany.

Olsen, A. S., Schrøter, C. and Jensen, J. J. (2005). Wave height distribution observed by ships in the North Atlantic. *Ships and Offshore Structures*, 1:1, 1-12.

Oltman-Shay, J. and Guza, R. T. (1987). Infragravity edge wave observations on two California Beaches. *J. Phys. Oceanogr.*, 17, 644-663.

Onorato, M., Osborne, A., Serio, M. and Bertone, S. (2001). Freak wave in random oceanicsea states. *Physical Review Letters,* 86:25, 5831–5834.

Onorato, M., Osborne, A. R., Serio, M. (2002a). Extreme wave events in directional random oceanic sea states. *Physics of Fluids*, 14:4, 25–28.

Onorato, M., Osborne, A. R., Serio, M., Resio, D., Pushkarev, A., Zakharov, V. E. and Brandini, C. (2002b). Freely decaying weak turbulence for sea surface gravity waves. *Phys. Rev. Lett.*, 89, 144501.

Onorato, M., Osborne, A. R., Serio, M., Cavaleri, L. (2004). Quasi-resonant interactions and non-gaussian statistics in long crested waves. *Proceedings of the Rogue Waves 2004 Workshop*, October 20-32, 2004, Brest, France.

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

Onorato, M., Osborne, A.R. and Serio, M. (2006b). Modulation Instability in Crossing Sea States: A Possible Mechanism for the Formation of Freak Waves. *J. Phys. Rev. Lett.*, 96, 014503.

Onorato, M., Cavaleri, L., Fouques, S., Gramstad, O., Janssen, P.A.E.M., Monbaliu, J., Osborne, A.R., Pakozdi, C., Serio, M., Stansberg, C.T., Toffoli, A. and Trulsen, K. (2008a). Statistical properties of mechanically generated surface gravity waves: a laboratory experiment in a 3D wave basin. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Onorato, M., Cavaleri, L., Fouques, S., Gramstad, O., Janssen, P.A.E.M., Monbaliu, J., Osborne, A.R., Pakozdi, C., Serio, M., Stansberg, C.T., Toffoli, A. and Trulsen, K., (2008b). Statistical properties of mechanically generated surface gravity waves: a laboratory experiment in a 3D wave basin. *J. Fluid Mech.* [submitted].

Ortega, J. and Smith, G. H. (2008). Empirical assay of the use of the Hilbert-Huang transform for the spectral analysis of storm waves. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Osborne, A. R., Onorato, M., Serio, M., Resio, D. T. (2004). Nonlinear Fourier analysis of deep-water, random wave trains. *8th international Workshop on Wave Hindcasting and Forecasting*, November 14-19, 2004, Oahu, Hawaii.

Osborne, A. R., Onorato, M. and Resio, D. (2008). A New class of rogue waves in shallow water: nonlinear Fourier components and hyperfast numerical simulations in the

Boussinesq approximation. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Otto, D. (2004). Validierung von Bodenradar–Messungen der Eis– und Schneedicke auf ein– und mehrjährigem Meereis in Arktis und Antarktis. Technical University Clausthal.

Paciorek C. J., Risbey J. S., Rosen R. D., Ventura V., (2002). Multiple indices of Northern Hemisphere cyclone activity, winters 1949–99. J. Clim., 15, 1573–1590.

Padhy, C. P., Sen, D. and Bhaskaran, P. K. (2008). Application of wave model for weather routing of ships in the North Indian Ocean, *Natural Hazards*, 44, 373-385.

Papadimitrakis, I. and Dias, F. (2008). Extreme waves in deep waters. Occurrence & breaking through meteorological and other focusing. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Pascoal, R. and Soares, C. G. (2008). Non-parametric wave spectral estimation using vessel motions, *Applied Ocean Research* [in press].

Pascoal, R., Soares, C. G. and Sørensen, A. J. (2005). Ocean wave spectral estimation using vessel wave frequency motions. *Proceedings of the 24th Int. Conf. on Offshore Mechanics and Arctic Engineering*, Halkidiki, Greece.

Payer, H. G. and Rathje, H. (2004). Shipboard routing assistance – Decision making support for operation of container ships in heavy seas, *Trans. SNAME*, 112, 1-12.

Payer, T. (2006). Modelling extrem wind speeds. Ludwig-Maximilians-Universität München, Germany.

Pedersen, E., Shimizu, E., Haugen, T. and Berg, T. E. (2008a). On the development of guidance system design for ships operating in close proximity. *Proceedings of the IEEE-PLANS 2008 Symposium*.

Pedersen, E., Shimizu, E., Haugen, T. and Berg, T. E. (2008b). Application of a short-range distance measurement system in ship-to-ship operations. *Proceedings of the ION National Technical Meeting*.

Perkovic, D., Lippmann, T. C. and Frasier, S. J. (2008). Marine Doppler radar surface current measurements in the surf zone. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Petrova, P., Cherneva, Z. and Guedes Soares, C. (2006). Distribution of crest heights in sea states with abnormal waves. *Applied Ocean Research,* 28, 235–245.

Petrova, P. and Guedes Soares, C. (2008). Maximum wave crest and height statistics of irregular and abnormal waves in anoffshore basin. *Applied Ocean Research,* 30, 144-152

Pettigrew, N. R. and Neville, F. (2008). Gulf of Maine Ocean Observing System (GoMOOS): Current measurement in an integrated ocean observing system. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Pheffer, W. T., Harpe, J. T. and Oneel, S. (2008). Kinetamic constraints on glacier contribution to 21st –century sea-level rise. *Science*, 321:5894, 1340-1343, doi:10.1126/science.1159099.

Phillips, O. M. (1985). Spectral and statistical properties of the equilibrium ranges in wind-generated gravity waves. *J. Fluid Mech.*, 156, 505-531.

Pielke, R. A. Jr., Landsea, C., Maryfield, M., Laver, J. and Pasch, R. (2005). Hurricanes and global warming. *Bull. Amer. Meteor. Soc.*, 86, 1571-1575.

Pielke, R. A., Jr., Landsea, C., Maryfield, M., Laver, J. and Pasch, R. (2006). Reply to "Hurricanes and global warming –potential linkages and consequences". *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-87-5-622.

Pilar, P., Guedes Soares, C. and Carretero, J. C. (2008). 44-year wave hindcast for the North East Atlantic European coast. *Coastal Engineering,* 55, 861–871.

Pinkel, R. (2008). Development of Doppler sonar technology at SIO. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Pirazzoli P. A., Regnauld H., Lemasson L. (2004). Changes in storminess and surges in western France during the last century. Marine Geology, 210 (1-4), 307-323, doi:10.1016/j.margeo.2004.05.015

Ponce de León, S. and Guedes Soares, C. (2008). Sensitivity of wave model predictions to wind fields in the Western Mediterranean sea. *Coastal Engineering,* 55, 920–929.

Portabella, M. and Stoffelen, A. (2006). Scatterometer backscatter uncertainty due to wind variability. *IEEE Trans. Geosci. Rem. Sens.*, 44:11, 3356-3362.

Prevosto, M., Krogstad, H. K., Barstow, S. and Guedes Soares, C. (1996). Observations of the high-frequency range of the wave spectrum. *J. Offshore Mech. Arctic Eng.*, 118, 89-95.

Prevosto, M. (1998). Effect of directional spreading and spectral bandwidth on the nonlinearity of the irregular waves. *Proceedings of the 8th International Offshore and Polar Engineering (ISOPE) Conference,* May 24-29, 1998, Montral, Canada.

Prislin, I. and Goldhirsh, M. (2008). Operational supports for offshore platforms – From system integrity monitoring to marine assurance and safety. *Proceedings of the 27th Int. Conf. on Offshore Mechanics and Arctic Engineering*, Lisbon, Portugal.

Puckette, P. T. and Gray, G. B. (2008). Long-term performance of an AWAC wave gage, Chesapeake Bay, VA. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology.*

Qiu, B. and Chen, S. (2005). Variability of the Kuroshio extension jet, recirculation gyre, and mesoscale eddies on decadal timescales. *J. Phys. Oceanogr.*, 35, 2090-2103.

Queffeulou, P. (2004). Long term validation of wave height measurements from altimeters. *Marine Geodesy*, 27:3-4, 495-510.

Queffeulou, P. and Bentamy, A. (2007). Analysis of wave height variability using altimeter measurements. Application to the Mediterranean Sea. *J. Atmos. Oceanic Technol.*, 24:12, 2078-2092.

Quilfen, Y., Chapron, B., Collard, F. and Serre, M. (2004). Calibration/validation of an altimeter wave period model and application to TOPEX/Poseidon and Jason-1 altimeters. *Marine Geodesy*, 27:3-4, 535-549.

Quilfen, Y., Tournadre, J. and Chapron, B. (2006). Altimeter dual-frequency observations of surface winds, waves, and rain rate in tropical cyclone Isabel. *J. Geophys. Res.*, 111, C01004, doi:10.1029/2005JC003068.

Quilfen, Y., Prigent, C., Chapron, B., Mouche, A. A. and Houti, N. (2007). The potential of QuikSCAT and WindSat observations for the estimation of sea surface wind vector under severe weather conditions. *J. Geophys. Res.*, 112, C09023, doi:10.1029/2007JC004163.

Rao, S. A. and Behera, S. K. (2005). Subsurface influence on SST in the tropical Indian Ocean structures and interannual variabilities, *Dyn. Atmos. Oceans*, 39, 103-135.

Rascle, N., Ardhuin, F., Queffeulou, P. and Croizé-Fillon, D. (2008). A global wave parameter database for geophysical applications. Part 1: wave-current-turbulence interaction parameters for the open ocean based on traditional parametrizations. *Ocean Modelling*, 25 ,154-171.

Rayner, R. and Stephens, R. (2008). Offshore industry applications. GODAE final. *Observing and Forecasting the Ocean, GODAE Final Symposium*, November 12-15, Nice France (http://www.godae.org/Invited-papers.html).

Redweik, G., (1993). Untersuchungen zur Eignung der digitalen Bildzuordnung für die Ableitung von Seegangsparametern. *Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover*, Nr. 194.

Reniers, A. J. H. M., van Dongeren, A. R., Battjes, J. A., and Thornton E. B. (2002). Linear modelling of infragravity waves during Delilah. *J. Geophys. Res.,*107:C10, 3137-3155.

Resio, D. T. and Long, C. E. (2008). Kurtosis and "extreme" wave probabilities in very young wind-generated seas. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Réthoré, P., Bechmann, A., Sørensen, N. N., Frandsen, S. T., Mann, J., Jorgensen, H. E., Rathmann, O., and Larsen, S. E. (2007). A CFD model of the wake of an offshore wind farm: using a prescribed wake inflow. *Journal of Physics: Conference Series*, 75,1–7.

Richter-Menge, J., Overland, J., Proshutinsky, A., Romanovsky, V., Bengtsson, L., Brigham, L.,Dyurgerov, M., Gascard, J. C., Gerland, S., Graversen, R., Haas, C., Karcher, M., Kuhry, P., Maslanik, J., Melling, H., Maslowski, W., Morison, J., Perovich, D., Przybylak, R., Rachold, V., Rigor, I., Shiklomanov, A., Stroeve, J., Walker, D. and Walsh, J. (2006). State of the Arctic Report. *NOAA OAR Special Report*, NOAA/OAR/PMEL, Seattle, USA.

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A. and Thomas, R. (2004). Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophys. Res. Lett.*, 31:18, L18401.

Roarty, H., Kohut, J. and Glenn, S. (2008). The Mid-Atlantic regional coastal ocean observing system: Serving Coast Guard and fisheries needs in the Mid-Atlantic Bight. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, Charleston, SC, USA, March 2008.

Romeiser, R., Breit, H., Eineder, M., Runge, H., Flament, P., de Jong, K. and Vogelzang, J. (2005). Current measurements by SAR along-track interferometry from a space shuttle. *IEEE Trans. Geosci. Remote Sens.*, 43, 2315-2324.

Romeiser, R. (2008). Current Measurements in Coastal Waters and Rivers by TerraSAR-X Along-Track InSAR. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology.*

Rosenthal, W. and Lehner, S. (2008). Rogue waves: Results of the MaxWave project. *Journal of Offshore Mechanics and Arctic Engineering*, 130:2, 1-8.

Rosenthal, R. (2008). Sea state statistics and extreme waves observed by satellite. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France .

Rotschky, G. (2007). Spatial distribution of snow accumulation and snowpack properties in Dronning Maud Land, Antarctica: Observational techniques and methods for surface mass-balance assessments of polar ice sheets. Bremen: Universität Bremen / Alfred-Wegener-Institut für Polar- und Meeresforschung (Dissertation).

Rusu, L., Pilar, P., Guedes Soares, C. (2008). Hindcast of the wave conditions along the west Iberian coast. *Coastal Engineering,* 55, 906–919.

Sadiq, R., Husain, T., Veitch, B. and Bose, N. (2004). Risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique, *Ocean Engineering*, 31, 1929-1953.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature*, 401, 360-363.

Saji, N. H. and Yamagata, T. (2003). Structure of SST and surface wind variability during Indian Ocean dipole mode events: COADS observations. *J. Climate*, 16, 2735-2751.

Sanabria, L. A. and Cechet, R. P. (2007). *A Statistical Model of Severe Winds.* Geoscience Australia Record, Australia.

Sanil Kumar, V. (2006). Variation of wave directional spread parameters along the Indian coast. *Applied Ocean Research*, 28:2, 93-102.

Santel, F., Linder, W., Heipke, C. (2004). Stereoscopic 3D-image sequence analysis of sea surfaces. *Proceedings of the Intl. Soc. Photogrammetry and Remote Sensing (ISPRS)*

Commission V Symposium, vol. XXXV, Part 5. Istanbul, 2004, 708-712.

Scharoo R. and Miller, L. (2006). Global and regional sea level change from multi-satellite altimeter data. *Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry*, March 13-18, 2006, Venice, Italy, ESA SP614.

Schulz-Stellenfleth, J., König, T., and Lehner, S. (2007). An empirical approach for the retrieval of integral ocean wave parameters from synthetic aperture radar data. *J. Geophys. Res.*, 112, C03019, doi:10.1029/2006JC003970.

Sebastião, P., Guedes Soares, C. and Alvarez, E. (2008). 44 years hindcast of sea level in the Atlantic Coast of Europe. *Coastal Engineering,* 55, 843–848.

Shaikh, N. and Siddiqui, K. (2008). Airside velocity measurements over the wind-sheared water surface using particle image velocimetry. *Ocean Dynamics*, 58, 65–79.

Sheinberg, R., Stambaugh, K., Eisele, A. and Leadbetter, R. (2007). Estimating probability of capsize for operator guidance. *International Shipbuilding Progress*, 54:4, 191-205.

Shemer, L., Sergeeva, A. and Slunyaev, A. (2008). Extreme events in unidirectional nonlinear wave groups in a tank. *Proceedings of the Rogue waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Shih, H. H. (2008). Recent advances in in-situ ocean observation. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Shukla, P. K., Kaurakis, I., Eliasson, B., Marklund, M., and Stenflo, L. (2006). Instability and evolution of nonlinearly interacting water waves. *J. Phys. Rev. Lett.*, 97, 094501.

Simmonds, I., and Keay, K. (2000). Variability of Southern Hemisphere extratropical cyclone behavior 1958–97. J. Clim., 13, 550–561.

Simmonds, I., and Keay, K. (2002). Surface fluxes of momentum and mechanical energy over the North Pacific and North Atlantic Oceans.Meteorol. Atmos. Phys., 80, 1–18.

Simos, A.N., Sparano, J.V., Tannuri, E.A. and Matos, V.L.F. (2007). Directional wave spectrum estimation based on a vessel 1st order motions: Field results. *Proceedings of the of the 17th International Offshore and Polar Engineering (ISOPE) Conference*, Lisbon, Portugal.

Skandrani, C., Lefevre, J.-M. and Queffeulou, P. (2004). Impact of multisatellite altimeter data assimilation on wave analysis and forecast. *Marine Geodesy*, 27:3-4, 511–533.

Skarke, A., Lipphardt Jr., B.L., Muscarella, P., Wong, K.C., Trembanis, A. and Badiey, M. (2008). Comparison of HF radar and ADCP surface currents at the Delaware Bay Mouth. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, March 2008, Charleston, SC, USA.

Socquet-Juglard, H., Dysthe, K., Trulsen, K., Krogstad, H. and Liu, J. (2005). Distribution of surface gravity waves during spectral changes. *J. Fluid Mech.,* 542, 195–216.

Söding, H. and Tonguc, E. (1986). Computing capsizing frequencies in a seaway. *Proceedings of the 3rd Intl. Conference on Stability of Ships and Ocean Vehicles STAB'86*, vol. II, Addendum 1, 51-60 , Gdansk, Poland.

Sørensen and Stenrdorff, M. (2001). A Rational procedure for determination of directional individual design wave heights. *Proceedings OMAE'2001 Conference*, Rio de Janeiro, Brazil.

Soukissian, T., Prospathopoulos, A., Korres, G., Papadopoulos, A., Hatzinaki, M. and Kambouridou, M., (2008). A new wind wave atlas of the Hellenic Seas. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), Estoril, Portugal.

Spanos, D., Papanikolaou, A. and Papatzanakis, G. (2008). Risk-based onboard guidance to the master for avoiding dangerous seaways. *Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships*, Osaka, Japan.

Sparano, J. V., Tannuri, E. A., Simos, A. N. and Matos, V. L. F. (2008). On the estimation of directional wave spectrum based on stationary vessels 1st order motions: A new set of experimental results. *Proceedings of the 27th Int. Conf. on Offshore Mechanics and Arctic Engineering*, Lisbon, Portugal.

Stansberg, C. T., (2008). A wave impact parameter. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Sterl, A., (2001). On the impact of gap-filling algorithms on variability patterns of reconstructed oceanic surface fields. J. Geophys. Res., 28,2473–2476.

Sterl, A., and Caires, S., (2005). Climatology, variability and extrema of ocean waves: the Web-based KNMI/ERA-40 wave atlas. Int. J. Climatol., 25, 963−977.

Stern, N. (2007). *Review on the economics of climate change*. Cambridge University Press

Stredulinsky, D. and Thornhill, E. (2007). DRDC experiences with shipboard measurement of seaway wave characteristics. *Proceedings of the 8th Canadian Marine Hydromechanics and Structures Conference*, October 16-17,2007, St. John's, NL, Canada.

Stroeve, J. C., Serreze, M. C., Fetterer, F., Arbetter, T., Meier, W., Maslanik, J. and Knowles, K.(2005). Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. *Geophys. Res. Lett.*, 32, L04501.

Sun, J., Burns, S. P., Vandemark, D., Donelan, M. A., Mahrt, L., Crawford, T. L., Herbers, T. H. C., Crecenti, G. H. and French, J. R. (2005). Measurement of Directional Wave Spectra Using Aircraft Laser Altimeters. *J. Atmos. Oceanic Technol.*, 22:7, 869–885.

Suzuki, N., Donelan, M. A. and Plant, W. J. (2007). On the sub-grid-scale variability of oceanic winds and the accuracy of numerical weather prediction models as deduced from QuikSCAT backscatter distributions. *J. Geophys. Res.*, 112, C04005,doi:10.1029/2005JC003437.

Tambke, J., Lange, M., Focken, U., Wolff, J.-O. and Bye, J.A.T. (2005). Forecasting offshore wind speeds above the North Sea. *Wind Energy*, 8, 3–16.

Tamura, H., Waseda, T. and Miyazawa, Y. (2008), Numerical study of the sea state in the Kuroshio Extension region at the time of an accident. *Proceedings of the Rogue waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Tanaka, M. (2001). Verification of Hasselmann's energy transfer among surface gravity waves by direct numerical simulations of primitive equations. *J. Fluid Mech.*, 444, 199-221.

Tanaka, M. (2007). On the role of resonant interactions in the short-term evolution of deep-water ocean spectra. *J. Phys. Oceanogr.*, 37:4, 1022-1036.

Tang, C. C. L. and Dunlap, E. (2007). Modelling the Annual Variation of Sea-Ice Cover in Baffin Bay. *Proceedings of the 17th International Offshore and Polar Engineering (ISOPE) Conference,* July 1-6, 2007, Lisbon, Portugal, 646–651.

Tanimoto, Y. and Xie, S.-P. (2002). Inter-hemispheric decadal variations in SST, surface wind, heat flux and cloud cover over the Atlantic Ocean. *J. Meteor. Soc. Japan*, 80, 1199-1219.

Tannuri, E. A., Sparano, J. V., Simos, A. N., and Da Cruz, J. J. (2003). Estimating directional wave spectrum based on stationary ship motion measurements. *Applied Ocean Research*, 25, 243-261.

Tayfun, M. (1980). Narrow–band nonlinear sea waves. *J. Geophys. Res.,* 85:C3, 1548–1552.

Tayfun, M. A. (2006). Statistics of nonlinear wave crests and groups. *Ocean Engineering*, 33:11–12, 1589–1622.

Tayfun, M. A. and Fedele, F. (2006). Wave-height distributions and nonlinear effects. *Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2006), June 5-9, 2006, Hamburg, Germany.

Tayfun, M. A. and Fedele, F. (2007a). Wave-height distributions and nonlinear effects. *Ocean Engineering,* 34, 1631-1649.

Tayfun, M. A. and Fedele, F. (2007b). Expected shape of extreme waves in storm seas.

Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2007), June 10-15, 2007, San Diego, CA, USA. Paper No. OMAE 2007-29073.

Tayfun, M. A. and Fedele, F. (2008). Envelope and phase statistics of large waves. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Tellkamp, J., Günther, H., Papanikolaou, A., Krüger, S., Ehrke, K.-C. and Nielsen, J. K. (2008). ADOPT – Advanced decision support system for ship design, operation and training – An overview, *Proceedings of COMPIT*, Liege, Belgium.

Toffoli, A., Lefèvre, J.-M., Bitner-Gregersen, E. M. and Monbaliu, J. (2005). Towards the identification of warning criteria: analysis of a ship accident database. *Applied Ocean Research,* 27:6, 281–291.

Toffoli, A., Onorato, M. and Monbaliu, J. (2006a). Wave statistics in unimodal and bimodal seas from a second–order model. *Europ. J. Mech. B/Fluids*, 25, 649–661.

Toffoli, A, Onorato, Babain, A.V.,M., Bitner-Gregersen, E. M., Osborne, A.R., Babain, A.V. and Monbaliu, J. (2006b). Second order theory and setup in surface gravity waves: A comparison with experimental data. *J. Phys. Oceanogr.*, 37, 2726-2738.

Toffoli, A., Onorato, M., Bitner-Gregersen, E. M., Osborne, A.R. and Babain, A.V. (2008a). Surface gravity waves from direct numerical simulations of the Euler equations: A comparison with second order theory. *Ocean Engineering*, 35:3-4, 367-379.

Toffoli, A., Bitner-Gregersen, E. M., Onorato, M. and Babain, A.V. (2008b). Wave crest and trough distributions in a broad-banded directional wave field. *Ocean Engineering* [in press].

Toffoli, A., Benoit, M., Onorato, M. and Bitner-Gregersen, E. M. (2008c). Assessing the effect of finite water depth on the occurrence of extreme waves using a direct numerical simulation method. *International Conference on Coastal Engineering (ICCE)*, August 29 - September 5, Hamburg, Germany.

Tokmakian, R. (2005). An ocean model's response to scatterometer winds. *Ocean Modelling*, 9, 89–103.

Tolman, H. L. (1999). User manual and system documentation of WAVEWATCH-III version 1.18. *NOAA/NWS/NCEP /OMB Technical Note,* 166.

Tomczak, M. and Stuart Godfrey, J. (2003). Regional Oceanography: an Introduction. Second edition 390p., Daya Publishing House.

Torsethaugen, K. and Haver, S. (2004). Simplified double peak spectral model for ocean waves. *Proceedings of the 14th Int. Offshore and Polar Engineering Conference*, May 23-28, 2004, Toulon, France, 76-84.

Tournadre, J., and Quilfen, Y. (2005). Impact of rain cell on scatterometer data, Part 2: Correction of Seawinds measured backscatter and wind and rain flagging. *J. Geophys. Res.*, 110, C07023, doi:10.1029/2004JC002766.

Tozuka, T., Luo, J.-J., Masson, S. and Yamagata, T. (2008). Tropical Indian Ocean variability revealed by self-organizing maps. *Clim. Dyn.*, 31, 333-343, doi:10.1007/s00382-007-0356-4.

Trenberth, K. and Shea, D. (2005). Relationships between precipitation and surface temperature. *Geophys. Res. Lett.*, 32, L14703.

Trizna, D. B. (2008). Coherent Microwave Marine Radar for Decameter-Scale Coastal Current Mapping. *Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology.*

Tromans, P. S. and Vanderschuren, L. (1995). Response based design conditions in the North Sea: Application of a new method. *Proceedings of the Offshore Tech. Conf.*, OTC 7683, 387-397.

Trumars, J. (2006). *Wave loads on Offshore wind power plants.* Phd Thesis. The Univeristy of Chalmers, June 2006.

Turk, F. J., DiMichele, S. and Hawkins, J. (2006). Observations of Tropical Cyclone Structure From WindSat. *IEEE Trans. Geosci. Rem. Sens.*, 44, 645-655.

Tvedt, L. (2002). *Det Norske Veritas PROBAN, Theory, general purpose probabilistic analysis program, Version 4.4, (L. Tvedt the program author),* Høvik, Norway.

Ulstein, N. L., Nygreen, B. and Sagli, J.R. (2007). Tactical planning of offshore petroleum production, *European J. of Operational Research*, 176, 550-564.

Van den Broeke, M, Van de Berg, W. J. and Van Meijgaard, E. (2006). Snowfall in coastal West Antarctica much greater than previously assumed. *Geophys. Res. Lett.*, 33, L02505.

Van Dongeren, A. J. H. M., Reniers, A. R, and Battjes J. A. (2003). Numerical modelling of infragravity wave response during DELILAH. *J. Geophys. Res.*, 108:C9, 3288-3307.

Vaughan, G. L. and Squire, V. A. (2008). The scattering and damping of ice-coupled waves. *Proceedings of the 18th International Offshore and Polar Engineering (ISOPE) Conference*, July 6-11, 2008, Vancouver, BC, Canada, 610–617.

Vecchi, G. A. and Soden, K. L. (2007). Increased tropical Atlantic wind shear in model projections of global warming. *Geophys. Res. Lett.*, 34, L08702, doi:10.10129/2006GL028905.

Vecchi, G. A., Swanson, K. L. and Soden, B. J. (2008). Whither Hurricane activity? *Science*, 322, 687-689.

Veltcheva, A. D and Guedes Soares, C. (2007). Analysis of abnormal wave records by the Hilbert Huang transform method. *J. Atmos. and Oceanic Tech.*, 24, 1678-1689.

Venugopal, V., Wolfram, J. and Linfoot, B. T. (2005). Wave kinematics factor in real and simulated storms. *Ocean Engineering,* 32 ,623–650.

Visbeck M., Chassignet E. P., Curry R. G., Delworth T. L., Dickson R. R., Krahmann G., (2003). The ocean's response to North Atlantic Oscillation variability. In: The North Atlantic Oscillation: Climatic Significance and Environmental Impact [Hurrell, J.W., et al. (eds.)]. Geophysical Monograph 134, American Geophysical Union, Washington, DC, pp. 113-145.

von Saldern, C. (2007). Bestimmung verschiedener Eisklassen durch statistische Analyse der Rauigkeit von Meereis. Bremen: Universität Bremen (Dissertation).

Waals, O. J., Aalbers, A. B. and Pinkster, J. A. (2002). Maximum likelihood method as a means to estimate the directional wave spectrum and the mean wave drift force on a dynamically positioned vessel. *Proceedings of the 21st Int. Conf. on Offshore Mechanics and Arctic Engineering*, Oslo, Norway.

Wadhams, P., Wilkinson, J. P., and Doble, M. J. (2008). Three-dimensional mapping of the sea ice underside from AUVs and applications to the offshore industry. *ICETECH 2008*.

Wajsowicz, R. C. (2005). Potential predictabilty of tropical Indian Ocean SST anomalies. *Geophys. Res. Lett.*, 32, L24702, doi:10.1029/2005GL024169.

Walker, D. A. G. and Eatock-Taylor, R. (2005). Wave diffraction from linear arrays of cylinders. *Ocean Engineering*, 32:17-18, 2053-2078.

WAMDI Group (1988). The WAM model – a third generation ocean prediction model. J. *Phys. Oceanogr.,* 18, 1775-1809

Wanek, J. M. and Wu, C. H. (2006). Automated trinocular stereo imaging system for three-dimensional surface wave measurements. *Ocean Engineering*, 33, 723-747.

Wang, D. W., Mitchell, D. A., Teague, W. J., Jarosz, E. and Hulbert, M. S. (2005). Extreme waves under hurricane Ivan. *Science*, 309, 5 August 2005.

Wang, X.L., Swail, V.R. and Zwiers, F.W., (2006). Climatology and changes of extratropical storm tracks and cyclone activity: Comparison of ERA-40 with NCEP/NCAR Reanalysis for 1958–2001. J. Clim., 19,3145–3166.

Ward, M.N., and Hoskins, B.J. (1996). Near surface wind over the global ocean 1949–1988. J. Clim., 9, 1877–1895.

Waseda, T. (2006). Impact of directionality on the extreme wave occurrence in a discrete random wave system. *Proceedings of the 9th International Workshop on Wave Hindcasting and Forecasting*, Sept. 24-29, Victoria, Canada.

Waseda, T., Tamura, H. and Kinoshita, T. (2008). Extremely narrow spectrum and freak wave – an abnormal sea state. *Proceedings of the Rogue Waves 2008 Workshop*, October 13-15, 2008, Brest, France.

Webb, S. C., Zhang, X., and Crawford, W. (1991). Infragravity waves in the deep ocean. *J. Geophys. Res.*, 96: C2, 2723-2736.

Webster, P. J., Moore, A., Loshnigg, J. and Leban, M. (1999). Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98. *Nature*, 400, 356-360.

Webster, P. J., Holland, G. J., Curry, J. A. and Chang, H.-R. (2005). Changes in tropical cycylone number, duration and intensity in a warming environment. *Science*, 309, 1844-1846.

Weisse, R., von Storch, H. and Feser, F., (2005). Northeast Atlantic and North Sea storminess as simulated by a regional climate model during 1958-2001 and comparison with observations. J. Clim., 18, 465–479.

West, B. J., Brueckner, K. A., Jand, R. S., Milder, D. M. and Milton, R. L. (1987). A new method for surface hydrodynamics. *J. Geophys. Res.*, 92 :C11, 11803–11824.

Wiencke, M. and Vassmyr, K.-A. (2007). Offshore Arctic Data Collaboration (OADC). *Proceedings of the 17th International Offshore and Polar Engineering (ISOPE) Conference*, July 1-6, 2007, Lisbon, Portugal, 639–645.

Williams, J. Z., Dugan, J. P, Piotrowski, C. C. and Kaihatu, J. M. (2005). Comparisons of remotely-retrieved directional wave spectra over a large area with a shoaling-wave model. *Proceedings of the IEEE Conf. OCEANS2005*, Sept 17-23, 2005, Washington DC, USA.

Willmes, S., Haas, C., Nicolaus, M. and Bareiss, J. (2006). Microwave signatures of different ice regimes in the Weddell Sea and their temporal variability during spring. Deep Sea Research, Special Issue: The Ice Station Polarstern (ISPOL), D06107.

Willmes, S., Bareiss, J., Haas, C. and Nicolaus, M. (2007). The importance of diurnal processes for the seasonal cycle of sea-ice microwave brightness temperature during early summer in the Weddell Sea. *Annals of Glaciology,* 44, 297–302.

Wingham, D. J., Francis, C. R., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., de Chateau-Thierry, P., Laxon, S. W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P. and Wallis, D. W. (2006a). CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields. *Advances in Space Research*, 37, 841–871.

Wingham, D. J., Siegert, M. J., Shepherd, A. and Muir, A. S. (2006b). Rapid discharge connects Antarctic subglacial lakes. *Nature*, 440:7087, 1033-1036.

Witter, D. L. and Chelton, D. B. (1991). A Geosat altimeter wind speed algorithm and a method for wind speed algorithm development. *J. Geophys. Res.*, 96, 18853-18860.

Wium, J. (2005). Wind effect on structures: An introduction. *Structural Engineering International*, 4, 220–227.

Wolf J. and Woolf D. K. (2006). Waves and climate change in the north-east Atlantic. Geophys. Res. Lett., 33, L06604, doi:10.1029/2005GL025113

Woolf, D.K., Challenor, P.G. and Cotton, P.D., (2002). The variability and predictability of North Atlantic wave climate. J. Geophys. Res., 107, 3145, doi:10.1029/2001JC001124.

Work, P. A. (2008). Nearshore directional wave measurements by surface-following buoy and acoustic Doppler current profiler. *Ocean Engineering*, 35:8-9, 727-737.

Worley S. J., Woodruff S. D., Reynolds R. W.,Lubker S. J., N. Lott, 2005: ICOADS release 2.1 data and products. Int. J.Climatol., 25, 823-842.

Wyatt, L. R., Green, J. J. and Middleditch, A. (2008). Signal sampling impacts on HF radar wave measurement. J. *Atmos. Oceanic Technol.* [in press].

Xie, S.-P. and Tanimoto, Y. (1998). A pan-Atlantic decadal climate oscillation. *Geophys. Res. Lett.*, 25, 2185-2188.

Xie, S.-P., Anamalai, H., Schott, F. and McCreary, J. P. (2002). Structure and mechanisms of South Indian Ocean climate variability. *J. Climate*, 15, 864-878.

Xie, L., Bao, S., Pietrafesa, L. J., Foley, K., and Fuentes, M. (2006). A real-time hurricane surface wind forecasting model: Formulation and verification. *Monthly Weather Review*, 134, 1355–1370.

Yamagata, T., Behera, S. K. and Guan, Z. (2003). The role of the Indian Ocean in climate forecasting with a particular emphasis on summer conditions in East Asia. *Proceedings of ECMWF Workshop*, Reading, United Kingdom, ECMWF, 102-114.

Yamagata, T., Behera, S. K., Luo, J.-J., Masson, S., Jury, M. and Rao, S. A. (2004). Coupled ocean-atmosphere variability in the tropical Indian Ocean. *Earth climate: The ocean-atmosphere interaction*, *Geophys. Monogr.*, 147, 189-212, Amer. Geophys. Union.

Yasuda, I., Osafune, S. and Tatebe, H. (2006). Possible explanation linking 18.6-year period nodal tide cycle with bi-decadal variations of ocean and climate in the North Pacific. *Geophys. Res. Lett.*, 33, L08606, doi:10.1029/2005GL025237.

Yelland, M. J., Bjorheim, K., Gommenginger, C., Pascal R. W. and Moat, B. I. (2007). Future exploitation of in-situ wave measurements at Station Mike. Poster at the *GLOBWAVE Workshop*, September 19-21, 2007, Brest, France.

Yueh, S. H. (2006). Combined active and passive remote sensing of hurricane ocean winds. *Proceedings of the International Pan Ocean Remote Sensing Conference*, November 2-4, 2006, Busan, Korea.

Yueh, S. H (2008). Directional signals in Windsat observations of hurricane ocean winds. *IEEE Trans. Geosci. Rem. Sens.*, 46:1, 130-136.

Zakharov, V. E. and Dyachenko, A. I. (2008). Freak waves and giant breather. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering* (OMAE 2008), June 15-20, 2008, Estoril, Portugal.

Zalar, M. (2005). Operating guidance for membrane type LNG carrier in partial filling condition, *Trans. SNAME*, 113, 367-373.

Zhang, H.-M., Bates, J. J. and Reynolds, R. W. (2006). Assessment of composite global sampling: sea surface wind speed. *Geophys. Res. Lett.*, 33, L17714, doi:10.1029/2006GL027086.

Zhang X., Walsh J. E., Zhang J., Bhatt U. S., Ikeda M., (2004). Climatology and interannual variability of Arctic cyclone activity. 1948-2002. J. Clim., 17, 2300-2317.

Zou, Q., He,Y., Perrie, W. and Vachon, P. W. (2007). Wind-vector estimation for RADARSAT-1 SAR images: validation of wind-direction estimates based upon geometry diversity. *IEEE Geosci. Rem. Sens. Let.* ,4, 176-180.

Zubair, L., Rao, S. A. and Yamagata, T. (2003). Modulation of Sri Lankan Maha rainfall by the Indian Ocean Dipole. *Geophys. Res. Lett.*, 30, 1063, doi:10.1029/2002GL015639

Zubakin, G. K., Eide, L., Buzin, I., Lebedev, A. A., and Ivanov, V. V. (2007). Conditions for formation of extremely severe ice seasons in the Barents Sea in the second part of the XX century. *Proceedings of the 17th International Offshore and Polar Engineering (ISOPE) Conference*, July 1-6, 2007,Lisbon, Portugal.

Zubakin, G. K., Egorov, A. G., Ivanov, V. V., Lebedev, A. A., Buzin, I. V., and Eide, L. I. (2008). Formation of the severe ice conditions in the Southwestern Kara Sea. *Proceedings of the 18th International Offshore and Polar Engineering (ISOPE) Conference*, July 6-11, 2008, Vancouver, Canada.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J. and Steffen, K. (2002). Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, 297:5579, 218-222, doi:10.1126/science.1072708.