TITLE

Waves and associated current – experiences from a five years' measurement campaign in the northern North Sea

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ABSTRACT

To acquire sufficient simultaneous data to establish joint distributions of waves and currents for design, an extensive metocean measurement programme has been performed over a period of approximately five years at several locations in the northern North Sea. A brief description of the measurement programme is given. The measured current data have been found to be more inaccurate than the specified accuracy of the instruments. However, the measured current data still give a good over-all description of the current conditions. At the southernmost locations, wind-driven currents, i.e. inertial oscillations, are the governing current conditions and contribute to larger current speed during summer than in the spring and fall, both operational and extreme. At all locations, year-to-year variation in estimated extreme current speeds based on different individual years are larger than expected, indicating that current measurements for considerably more than one year is required for reliable estimates of extreme current conditions for design of offshore structures. Sensitivity studies of the ultimate limit state (ULS) load on a jacket suggest the possible gain of accounting for the simultaneous occurrence of metocean parameters. The Norwegian design regulations seem to be conservative, at least regarding ULS. These results highlight the need for a better understanding of the current conditions in order to account for the uncertainties associated with these in design of offshore structures.

KEY WORDS

Current measurements; Wave measurements; Northern North Sea; Jackets.

1 INTRODUCTION

Characteristic meteorological and oceanic (metocean) loads and load effects are defined in terms of their annual probability of exceedance, q. The requirements for ultimate limit state (ULS) and accidental limit state (ALS) for characteristic metocean actions are $q \leq 10^{-2}$ and $q \leq 10^{-4}$, respectively. This requirement refers to the resulting metocean load, i.e. the characteristic metocean load obtained by accounting for the simultaneous occurrence of environmental parameters such as wind, waves and current. These parameters are not fully correlated and to utilize this for design, simultaneous data of both good quality and sufficient length are required.

In lack of sufficient simultaneous data, the Norwegian design regulations [1], recommend a combination of metocean parameters assumed to be conservative, but the degree of conservatism is not very well known. To utilize that the occurrence of extreme wind, waves and currents are not fully correlated in design of offshore structures, the latest edition of NORSOK STANDARD N-003 Edition 3 (N-003) [1] recommends at least three years of simultaneous wind, wave and current data.

In order to perform a more accurate analysis of marine structures, joint probability distributions of different environmental parameters have received an increasing interest during the last decade, facilitated by improved availability of reliable joint environmental data. Many recent studies have explored different bi- and multivariate statistical models for environmental parameters. For simplicity, bivariate statistical models are often presented rather than the multivariate generalizations, but these are easily extended beyond two dimensions to multivariate models.

Joint distributions of different environmental parameters based on a marginal distribution of the primary parameter and a conditional distribution for the associated parameters are frequently used and also adopted in design codes. Joint distributions of significant wave height and wave period, both zero up-crossing and peak period, are extensively studied and numerous approaches for Norwegian waters are available in the literature [2-7]. However, the joint environmental model proposed by Haver [8, 9] based on a marginal hybrid lognormal-Weibull distribution of significant wave height and a conditional lognormal distribution of spectral peak period is widely accepted and used. Later, this joint description of significant wave height and spectral peak period was extended to include wind speed, storm surge and current speed, all these parameters conditional on significant wave height and modelled with a normal distribution [10].

The semi-parametric conditional extremes model introduced by Heffernan and Tawn [11] has been strongly recommended for estimation of joint distributions of metocean parameters through a series of studies where this model has been adopted and applied in different ocean basins, including the northern North Sea [12-16]. Bivariate modelling of different combinations of environmental parameters have been performed based on a wide range of bivariate parametric probability distributions, see for instance [17-22]. The use of copula techniques has become increasingly popular and a number of studies has proposed bivariate models for different pairs of metocean parameters based on different copula techniques in different worldwide ocean basins [23-27], including the North Atlantic [28].

There are few available studies of the joint probability of waves and currents in the surface of the water column, probably due to the lack of simultaneous measured wave and current data and the complicated, far from fully understood, wave-current interaction mechanisms. However, based on simultaneous wave and current measurements at Tromsøflaket, both Gordon, Dahl [29] and Heideman, Hagen [30] investigated the relationship of extreme waves and currents and established very simplified joint distributions to be used in design and load calculations for offshore structures. Wen and Banon [31] developed a probabilistic methodology that lead to joint probability distributions of hurricane induced winds, waves and currents at a generic site in the Gulf of Mexico. Prior-Jones and Beiboer [32] estimated joint design criteria for current speed and waves in the southern North Sea and highlighted the need to develop sound design practices for application of the joint environmental probability factors. Based on simultaneous metocean measurements in the Northern North Sea, joint probabilistic models has been proposed for waves and current [33] and wind and waves [34].

However, there still seems to be no general consensus with regard to the approach of estimating the joint probability distributions of environmental parameters and several different approaches are put forward. Jonathan and Ewans [35] gave a good theoretical overview of multivariate modelling of extreme ocean environments and guidelines for validity, but pointed out that “unfortunately there is as yet no unifying approach, and the literature is rather confusing”. Ewans and Jonathan [15] concluded that specification of joint design criteria has often been somewhat ad hoc, based on experience and intuition and thus fairly arbitrary combinations of independently estimated extreme values. Vanem [28] demonstrated that there were large variabilities and thus large uncertainties in the estimated joint models due to different modelling choices, even for one the same data set, and concluded that multivariate modelling of metocean conditions remains a challenge, even in the bivariate case.

For the Norwegian waters, wind and waves data covering several decades are available, but currents are rarely measured for a period longer than one year. Following this, the limiting factor for a robust joint consideration of wind, waves and currents is the short duration of available current data. To secure simultaneous wave and current data for estimation of joint distributions for design of offshore structures, a metocean measurement programme at five locations in the northern North Sea was initiated early 2011 and completed late 2015.

This paper provides a brief description of the metocean measurement programme and highlights the challenges related to the quality of measured current data. Next, the variations in current conditions in this part of the northern North Sea are described. The possible conservatism in the Norwegian design regulations and thus the potential in utilizing simultaneous waves and currents is illustrated for a selected platform case based on the measured wave and current data from the northern North Sea. At last, a summary is made.

2 MEASUREMENTS

A metocean measurement programme of simultaneous waves and current profiles at five locations in the northern North Sea was initiated early 2011, see Figure 1.

First, a pilot phase was performed at Location 1 from January to May 2011, before the main phase with measurements at all five locations started in May 2011. At Location 3, the measurements were ended late 2013 and will not be considered in this paper, but at the other locations the measurement were completed in October 2015, i.e. a total duration of about 4.5 years. An overview of the water depths and data returns are given in Table 1.

The measurements at each location have been performed with the same generic mooring design, which consisted of one surface mooring and one seabed mooring. Based on experiences from the pilot phase at Location 1, the mooring design was changed before the main phase of measurements commenced. The surface mooring consisted of a surface buoy measuring surface waves and near-surface current speed (*Cs*) and direction (*CsDir*). The seabed mooring consisted of *Cs* and *CsDir* measurements throughout the entire water column and near seabed. Sea temperature and salinity were also measured. A schematic outline of the mooring configurations and instrument types are given in Figure 2.

The waves were measured every 30 minutes and the currents were measured every 10 minutes. All measured data were transferred in real-time by satellite.

3 DATA QUALITY OF MEASURED CURRENT DATA

During post processing of the measured current data basic routine quality checks were applied. Nevertheless, the upper levels of the current data measured by the upward looking current profiler placed in the seabed mooring

(Teledyne RD Instruments 150kHz Quartermaster ADCP, QM ADCP) contained fluctuations in subsequent measured 10-minutes *Cs*. This resulted in large spikes in the data, as illustrated in the upper panel of Figure 3. These fluctuations were too large to be real variations in *Cs* from one 10-minutes interval to the next and were thus considered to be noise in the measured current data. The spikes were most apparent down to between 40 m and 50 m water depth. Traces of this noise were also seen in measured data at larger water depths, but clearly decreasing with increasing water depths. This may be taken as an indication that the noise in measured near-surface current data was related to waves. However, filtering of the data by applying a 70-minutes running mean improved the quality in terms of reduced noise/spikes in the data and was implemented as part of the quality control. An example of time histories of *Cs* without and with a 70-minutes running mean applied is shown in Figure 3.

Discrepancies were observed between overlapping current data, i.e. *Cs* measured at the same water depth by the downward-looking current profiler placed in the hull of the surface buoy (Nortek 600 kHz Aquadopp, AQD) and the QM ADCPs placed in the seabed moorings. This is illustrated in the lower panel of Figure 3, where a time history extract from 12^{th} to 19^{th} of August 2014 of *Cs* measured by the two instruments at 30 m water depth at Location 4 is shown. Measured significant wave height (*Hs*) is also given.

This short time history extract captures some important features of the dominating current conditions at Location 4 and also the observed discrepancy between the current measurements. During the first three days, i.e. 12^{th} to 15^{th} of August, the measured *Cs* by the two different current meters corresponded quite well. Regular oscillations in *Cs* and large values of *Cs* up to nearly 60 cm/s are observed, believed to be so-called inertial oscillations. In the same period, *Hs* decreased from 4 m to around 2 m. During the next days, i.e. 15^{th} to 18^{th} of August, the inertial oscillations were disturbed and although measured *Cs* was less than 30 cm/s, deviations in the measured *Cs* were seen clearly. *Hs* was also low and varied around 2 m. The last day, i.e. 18^{th} of August, the measured *Hs* increased from 2 m towards 6 m. Large deviations were seen in measured *Cs*, with the *Cs* measured by the upward-looking QM ADCP significantly lower than the *Cs* measured by the downward-looking AQD. However, the wave conditions alone cannot explain all the differences seen in this time history extract of measured current data by the AQD and the QM ADCP, as the discrepancies were also evident when *Hs* was low.

As a preliminary, preventive measure until more insight is acquired, the *Cs* and *CsDir* data measured by the AQD and by the QM ADCP from 10 m to 40 m water depth are not considered to have a sufficient quality to be included in any further analyses. Thus, only current data measured by the QM ADCP from 40 m and below and the current data measured near seabed (Teledyne RD Instruments 1200 kHz Workhorse ADCP, WH ADCP) from all available water depths have been considered for analysis. A 70-minutes running mean was applied to these measured data. This approach to the measured current data might change as new insight is gained through further investigations. Additional considerations of the quality of the measured current data can be found in Bruserud and Haver [36].

Motivated by the amount of noise seen in the QM ADCP data and the discrepancies found between the current measured by the AQD and QM ADCP, another current measurement project, called Current Verification Study (CurVeS), was initiated. To date, CurVeS consists of three different phases. For a more thorough description of all phases of and the obtained results in CurVeS and consideration of the current measurement data quality, see Bruserud and Haver [36].

The first phase of CurVeS was carried out during 2014, where the over-all aim was to compare *Cs* and *CsDir* data from multiple instruments to provide recommendations for optimal current measurements. Another important aspect was to assess the quality of the measured data of the on-going metocean measurement programme and to quantify the uncertainties prior to further analyses of these data. The new measurements were undertaken in conjunction with the on-going measurements at Location 4. Close to the existing seabed mooring another mooring was deployed for around 2 months. This mooring contained an upward-looking current profiler near seabed (Teledyne RD Instruments 75 kHz Long Ranger ADCP, LR ADCP) and three single-point current meters placed at 20 m, 30 m and 100 m water depths (Aanderaa Recording Current Meters 7, RCM7). In addition to the AQD already deployed in the hull of the surface buoy, the existing surface mooring was equipped with another downward-looking AQD deployed in a modem cage (Nortek 400 kHz Aquadopp, suspended AQD). The deviations between different current meters measuring the *Cs* at the same location and water depth were found to be much larger than expected, especially at 30 m. Thus, no clear recommendation on how current measurements best could be performed was possible to make.

To continue to assess the performance of different current instruments, a natural supplement to the first phase of CurVeS was a second phase where existing current data collected by different acoustic and mechanical instruments at the same time and location were investigated and compared. This desk study was carried out by the Norwegian Deepwater Programme (NDP) and is confidential to NDP's members, but the executive summary has been released for reference. These data have been collected at different worldwide locations, water depths and environmental conditions, but common for all the measured current data sets is that one of the current meters compared is the RPS Metocean CM04 (CM04). The main finding of the study was that "differences in observed *Cs* are usually much larger than the specified accuracies of the instruments, suggesting that the accuracy achieved in the field are often much less than the user might expect”. Measured current data from two CM04s at the same location and water depth were also compared and “showed very good agreement”.

Motivated by the very good agreement found between the two CM04s at the same location and water depth in the second phase of CurVeS, a third phase of CurVeS was started in October 2015. A new mooring was deployed at Location 4, with the same design and instruments (AQD, QM ADCP and WH ADCP) as during the main measurement programme. In addition, the mooring was equipped with two CM04 deployed at 50 m and 90 m water depths. These measurements were completed in March 2016, i.e. a total duration of 6 months. The CM04 deployed at 50 m water depth did not work at all during the measurement period and no comparison between the Aquadopp and the CM04 could be made. The QM ADCP only worked for 6 days during this 6 months’ period and sufficient data for a proper comparison of the measured current data by the CM04 and QM ADCP were not available. Thus, no additional knowledge can be gained through this phase of CurVeS either.

During the last decade, there has been an increasing focus on current conditions for design of offshore structures at the Norwegian Continental Shelf (NCS). Correspondingly, the way of performing current measurements has improved. In the early 1980ties, current measurements were typically performed during a couple of months at a few different water depths. Today, the state-of-the-art current measurements to be utilized in design is at least one year of current measurements through the entire water column. As current measurements are expensive to perform and thus in most cases proprietary, comparative studies focused current measurements are rarely published and relatively few, i.e. very little information about the quality and uncertainties of measured current data is available. Prior to this metocean measurement programme and all three phases of CurVeS, the possibility of such large discrepancies between different current meters and/or profilers, supposed to measure the same *Cs* at the same water depth and location, were not anticipated. In contrast to these findings, the few previous, comparable studies of overlapping current measurements performed with different current meters and/or profilers, reviewed in Bruserud and Haver [36], all reach the same conclusion; different current meters and/or profilers measuring *Cs* at the same location and water depth compare well.

At present, no obvious or plausible explanation for such an amount of noise in the QM ADCP data and the discrepancies between the current measured by different current meters can be offered. Additional efforts are required to gain more knowledge on (I) how current can be measured more accurately for design of offshore structures and (II) how the uncertainties of measured current data can be addressed. For further investigations of the actual current measurements, it would be appropriate to do a more extensive and systematic assessment of mooring configurations, i.e. surface compared to sub-surface moorings, instrument types, i.e. acoustic compared to mechanical current meters, and sampling intervals, i.e. 10-minutes compared to a longer time interval. A natural supplement would be to review how the data quality control of the measured current data is done and also to consider to correct the measured current data for wave orbital velocities. Before more detailed knowledge about the limitations of the available current meters and some sort of specific measure of the uncertainty in measured current data are available, it would be difficult to account for the uncertainties in measured current data in design of offshore structures. However, uncertainties like these are important to be aware of and consider in design of offshore structures, but how such uncertainties best could be implemented in analysis of current speed data still remains to be determined.

4 VARIATIONS IN CURRENT CONDITIONS

In addition to the anticipated investigation of joint distribution of waves and currents, the extensive current data set from the metocean measurement programme can also be used to describe, investigate and gain further knowledge about the current conditions in this part of the northern North Sea.

4.1 Spatial variations

At all the four locations, the directional distribution of measured *Cs* varies very little with water depth and the *Cs* decrease with increasing depth. At Location 1 most of the currents is toward a south-easterly direction, whereas the dominating *CsDir* at the other locations is towards south. At Location 4 and 5 currents towards north are also prominent. Thus, the directional distribution at Location 1 stands out from the three other locations. As Location 1 is further north and thus not sheltered by the Shetland Islands for Atlantic inflow to the same extent as the three other locations further south, see Figure 1, this can explain the observed difference in directional distribution of currents. In addition, Location 1 is in an area with steeper bottom topography and larger water depths, i.e. the westside of the Norwegian Trench, and in such areas currents are known to follow the bottom topography.

Regarding maximum *Cs*, this is found to be larger at Location 1 than at the three other locations. The maximum *Cs* at Locations 2 and 4 are similar, but the maximum *Cs* at Location 5 are significantly larger. The largest *Cs* at Location 5 are caused by an episode of large *Cs* during 24th and 25th of December 2012. During the same period, *Cs* are less than 20 cm/s at the other locations. This indicates a spatial variation in current conditions, also for locations near each other and with approximately the same water depth.

4.2 Seasonal variations

Seasonal variations in both *Cs* and *CsDir* have also been investigated. In general, the magnitudes of mean and maximum *Cs* at all water depths are largest during winter, decrease in the spring, are lowest during summer and increase again in the autumn. However, at Locations 4 and 5 the seasonal maximum *Cs* in the summer is larger than in the spring and autumn. The estimated extreme *Cs* values follow this trend. The reason for this is two episodes with large *Cs*, in August 2011 and 2014, respectively. Time series of *Cs* at 40 m, 80 m and 3 m above the seabed at Locations 4 and 5 during the latter of these episodes are shown in Figure 4. As seen in Figure 3, regular oscillations in *Cs* with large *Cs* values, believed to be inertial oscillations, are seen. At both Locations 4 and 5, relatively large wind speeds in the range 15 m/s to 25 m/s and a change in wind direction are observed just before the oscillations in *Cs* are initiated. The magnitude of *Cs* of inertial oscillations is essentially controlled by the depth of the mixed layer. During summer and autumn when the mixed layer is relatively thin, currents associated with inertial oscillations can be reasonably large. Thus, it is not surprising that inertial oscillations generating large *Cs* are observed in August. The *Cs* values during these two episodes are larger at Location 5 than at Location 4.

At all locations, the *CsDir* vary very little with season. In accordance with the annual directional distributions, the *CsDir* at all locations shows only marginal variation between 40 m and 80 m water depth, but some variations are seen near seabed.

4.3 Inter-annual variations

To study the year-to-year variability of extreme *Cs*, the extreme *Cs* have been estimated for each individual year of current measurements. In Table 2 the estimated *Cs* with annual probability of exceedance 10^{-1} and 10^{-2} are given at 40 m water depth at all four locations for each year. In Figure 5 an illustration of the variation in estimated *Cs* with annual probability of 10^{-2} based on each individual year of measurements is shown.

The year-to-year variability of extreme *Cs* is large at all locations. In general, the largest estimated extreme *Cs* are found in 2011 and the smallest in 2013. At Location 1, the difference between the largest and smallest *Cs* with annual probability 10^{-2} is approximately 20 – 25 cm/s for the different water depths, i.e. the between 20 and 35% (for the smallest relatively to the largest *Cs* with annual probability 10^{-2}). Comparable numbers are found for Location 2.

Both at Locations 4 and 5, this difference is seen to be even larger. At Location 4, the difference is approximately 40 – 50 cm/s, i.e. between 30 and 50 %, while even larger at Location 5 where the difference is approximately 65 – 80 cm/s, i.e. over 50 %.

Previously, very little inter-annual variability in current conditions has been anticipated. Based on that assumption, only one year of current measurements is recommended when extreme current conditions for design are to be established. Current measurements lasting for more than one year are rarely available. The shown year-to-year variations in estimated extreme current conditions suggest large uncertainties when based on one year of current data only. This uncertainty can go in both directions; the estimated extreme current conditions may be conservative or, more important, non-conservative. To account for the observed year-to-year variability and reduce this uncertainty and thus obtain more robust estimates of extreme current conditions, more extensive current data covering several years, are necessary when extreme current conditions for design are to be estimated. However, considering the discussed uncertainties in measured current data, performing current measurements for several years might not be the ideal either.

According to Bruserud and Haver [37], current hindcast of good quality have recently been developed for the northern North Sea. It is pointed out that the quality of this current hindcast is not as good as the quality of the available wind and wave hindcast for the NCS and must be used with caution. Nevertheless, this constitute a very promising starting point for further development of an even better current hindcast for the northern North Sea. Rather than performing current measurements for several years, development of high-quality current hindcast covering several years, validated with a shorter period of current measurements, could prove to be a more appropriate and prosperous approach to obtain more reliable estimates of extreme current conditions for design. In order to have any confidence in such an approach, the problem of how to perform high-quality current measurements with well-defined uncertainty bands still remains to be solved.

5 CASE STUDY

In lack of more detailed and verified joint models of metocean actions, N-003 Edition 3 [1] recommends a conservative approach to combination of metocean processes (see section 10.3, Table 7). However, the degree of conservatism is not very well known. Two case studies have been performed on different combinations of wave and currents to estimate characteristic metocean loads, i.e. ULS load, on a jacket. Both case studies are based on the same simplified load model, but the first comprised simplified metocean data and the other was based on the measured wave and current data from the northern North Sea.

5.1 Methodology

Load estimation

For a jacket, the governing load process is the hydrodynamic load caused by waves and currents. A simple parametric model for overturning moment of a jacket, which neglects the effect of dynamics, was developed by Heideman [38]. The model can be used to estimate a generic, static load (overturning moment), *L [MN]*, on a jacket and is given as

$$L = K_1(H + K_2 Cs)^{K_3} \quad (1)$$

where *H* is individual wave height [m], *Cs* is depth integrated current speed [m/s] and K_1, K_2 and K_3 are empirical constants. For a drag dominated jacket platform in about 100 to 200 m water depth, the following parameters are expected to give reasonable quasi static loads; K_1 set to 0.03, K_2 set to 5.5 and K_3 set to 2.2 [39]. It is obvious from the empirical constants that the waves will be of most importance for the loads.

Two main approaches were considered when the ULS load was to be estimated:

1. ULS load estimated according to N-003 (see section 10.3, Table 7, [1]) where *H* of annual probability of exceedance 10^{-2} and *Cs* of annual probability of exceedance 10^{-1} are combined in the load model given in Equation (1) to obtain the ULS load. Since waves are most important for the estimated loads and will result in the largest loads, the combination of *H* of annual probability of exceedance 10^{-1} combined with *Cs* of annual probability of exceedance 10^{-2} is not considered.
2. ULS load estimated directly from a load time series where (1) time series of *H* and *Cs* were combined by Equation (1) into a time series of the load, (2) a probability distribution was fitted to the load time series and (3) the extreme load with annual probability of exceedance 10^{-2} was estimated.

ULS load estimated according to N-003

For estimation of the extreme *H* both the all-sea states (initial distribution) and peak-over-threshold approaches were considered.

For the all-sea states approach, the long-term distribution *H* during *T* hours is given by

$$F_H(h) = \iint_{hs\,tp} F_{H|Hs,Tp}(h|hs,tp) f_{HsTp}(hs,tp)\, dhs\,dtp \qquad (2)$$

where

$F_{H|Hs,Tp}(h|hs,tp)$ is the short-term distribution of H during T hours based on Forristall's distribution for individual waves [40]:

$$F_{H\S Hs,Tp}(h|hs,tp) = \left(1 - exp\left[-2.263\left(\frac{h}{Hs}\right)^{2.126}\right]\right)^{\frac{T\cdot 60\cdot 60}{0.77Tp}} \qquad (3)$$

and

$f_{HsTp}(hs,tp)$ is long-term variation of wave climate described by the joint probability density distribution for *Hs* and *Tp* based on a lognormal-Weibull distribution for *Hs* and a lognormal distribution for *Tp*|*Hs* [8].

For the peak-over-threshold approach, according to the method proposed by Tromans and Vanderschuren [41], the long-term distribution of storm maximum wave heights, H_M, in a random storm can be given by

$$F_{H_M}(h) = \int_{\tilde{h}} F_{H_M|\tilde{H}}(h|\tilde{h}) f_{\tilde{H}}(\tilde{h}) d\tilde{h} \qquad (4)$$

where

$\tilde{H}$ is the most probable maximum storm wave height given in a specific storm by given by, see for instance [42],

$$F_{\tilde{H}|storm}(\tilde{h}|storm) = \prod^{i} F_{H_i}(\tilde{h}) = 0.37 \qquad (5)$$

where i is the number of storm steps exceeding the selected threshold of storm peak *Hs* and F_{H_i} is the short-term distribution of H during each storm steps i, given by Forristall's distribution for individual waves (Equation (3)). $\tilde{H}$ is estimated for all the storms with storm peak *Hs* exceeding the selected threshold of *Hs*. The long-term distribution of $\tilde{H}$, $f_{\tilde{H}}(\tilde{h})$, is assumed to be well modelled by a Weibull 3-parameter distribution.

and

$F_{H_M|\tilde{H}}(h|\tilde{h})$ is the short-term distribution of H_M, given in terms of a new variable $V = \frac{h}{\tilde{h}}$ assumed to follow a Gumbel distribution

$F_{H_M\|\tilde{H}}(h\|\tilde{h}) = exp\left(-exp\left[-\left(\frac{\left[\frac{h}{\tilde{h}}\right]-1}{\beta_v}\right)\right]\right)$	(6)

The extreme *Cs* can be estimated the traditional way by fitting a 3-parameter Weibull distribution to all the measured current data.

ULS load estimated directly from a load time series

Before a load time series can be calculated from Equation (1), a time series of *H* must be calculated based on the short-term sea state, i.e. the *Hs* and *Tp* data. Two approaches are chosen, both based Forristall's distribution for individual waves (Equation (3), please note that for simplicity $F_{H|Hs,Tp}(h|hs,tp)$ is shortened to $F_H(h)$ and *T ·60·60/0.77Tp* to *n*):

1. The most probable value of *H*

   When Equation (3) is inverted, *H* will be given as

$$H = Hs\left[-\frac{1}{2.263}\left(ln\left[1-F_H(h)^{\frac{1}{n}}\right]\right)\right]^{\frac{1}{2.126}} \tag{7}$$

   H will have its most probable value when $F_H(h)$ is approximately 0.37 [42]. The short-term variability of *H* within the sea state is neglected.

2. Monte Carlo simulated *H*

$$H = Hs\left[-\frac{1}{2.263}\left(ln\left[1-R^{\frac{1}{n}}\right]\right)\right]^{\frac{1}{2.126}} \tag{8}$$

   where *R* is a random number between 0 and 1, representing a possible realization of $F_H(h)$. This is done for every time step of the wave data and a possible time series of *H* is established. Then the procedure is repeated 100 times and hence 100 different possible time series of *H* are established. This approach is a way to include short-term variability in *H.*

Time series of the load, *L,* can be estimated based on Equation (1) with the different time series of *H* and *Cs*. The long-term distribution of *L* and corresponding extreme values are modelled in terms of a 3-parameter Weibull distribution. For the load time series based on Monte Carlo simulated *H,* 3-parameter Weibull distributions are fitted to the 100 different realizations of the time series of *L* and a mean value of the 100 Weibull parameters and corresponding estimated extreme loads are given.

For further details on the methodology of the case study, the reader is referred to Bruserud and Haver [43].

5.2 Case study – example location

Bruserud and Haver [43] indicated the possible conservatism in the Norwegian design regulations for estimation of quasi-static metocean loads on a jacket based on the methodology described in section 5.1. In addition, the effect of a longer time step for current data than the standard 10-mintues *Cs*, i.e. 3 hours as for wave, was studied. The following three time steps for the current data were defined

- **10-min *Cs****;* the standard time interval current measurements are performed, i.e. 10 minutes
- **3-hrs mean *Cs***; averaging all 18 measured 10-minutes *Cs* values during 3 hours
- **3-hrs max *Cs***; selection of the largest 10-minutes *Cs* value during 3 hours

Thus, the possible variations in the load estimation according to N-003 based on different approaches to the data and data analysis were assessed.

The wave and current data utilized in that study was from a deep-water location on the Norwegian Continental Shelf where good quality measured current data was available for the longest period. Assumptions were made, so the current data could be adjusted and made representative for current conditions at a typical jacket location. For waves, hindcast data from the Norwegian reanalysis archive (NORA10) [44] was used. The time step for wave data was 3 hours and for current data 10 minutes.

Table 3 summarizes the most important results from this sensitivity study for this example location [43] and gives the different estimated ULS loads, normalized to ease comparison. When the extreme waves and currents are estimated based on a peak-over-threshold approach, the corresponding estimated ULS load is reduced compared to all-sea states approach. The reduction is approximately 10 %. When a 3-hrs averaging of *Cs* is utilized, the estimated ULS load is somewhat reduced. This is seen both for the all-sea states and peak-over-threshold approaches. The reduction is of similar size, typically a few percent. As expected, the 3-hrs mean *Cs* gives a slightly smaller ULS load than the 3-hrs max *Cs.* When the ULS load is estimated directly from a time series of the load, the ULS load is reduced significantly. Uncertainties apply to this result since the effective length of the joint wave and current data and hence the load time series, is 47 months.

5.3 Case study – northern North Sea

Another case study was performed where the load model described in section 5.1 is applied to estimate the ULS loads based on the recent wave and current measurements at the four locations in the northern North Sea. The water depths at these locations are approximately 100 m, 120 m, 130 m and 190 m (see Table 1), i.e. typical water depths where jackets would be placed. Based on the results from the case study at the example location (previous section), only one sensitivity case was selected for each of the two main approaches for estimation of ULS load

- according to N-003 with an all-sea states approach for estimation of extreme values and 3-hrs max *Cs*
- directly from a time series of the load based on most probable *H* for each 3-hour sea-state, i.e. neglecting short-term variability within the sea-state, and 3-hrs max *Cs*

The parameters for the joint distribution of *Hs* and *Tp* and corresponding estimated extreme values for *H* are given in Table 4 and the Weibull parameters and the corresponding extreme values of *Cs* are given in Table 5.
Estimated values of the ULS load according to N-003, based on the estimated extreme *H* and *Cs,* are given in Table 3. The Weibull parameters and corresponding extreme values of *L* estimated directly from a time series of the load are given Table 6. Please note that the values have been normalized to ease comparison.

At all the four locations, when these two approaches for estimation of ULS load are compared, a significant reduction in estimated ULS load directly from a time series is seen, ranging from around 25 % to 40 %.

Uncertainties apply to the results presented here, mainly due to the length of the measured current data. However, these results are considered to give a reliable indication of the ULS load when sufficient joint data are available; i.e. reductions in ULS load.

6 CLOSING REMARKS

Motivated by the potential in simultaneous metocean data for design of offshore structures and to acquire data of sufficient length to establish joint distributions for waves and currents, a metocean measurement programme of waves and current profiles at five locations in the northern North Sea has been performed for nearly five years.

The main experiences and most important learnings from the metocean measurement programme can be summarized as follows:

- **Quality of current measurements**

Despite quality control, the accuracy of the measured current data was found to be less than expected. Differences in measured current speeds were much larger than the specified accuracy of the instruments. Despite efforts to improve knowledge on different methods and currents meters to perform current measurements for design of offshore structures, further work is required to address and account for the uncertainties of the measured current data.

- **Governing current conditions**

  At Location 2, 4 and 5 inertial oscillations have been observed in the measured current data and found to generate many of the largest observed current speeds. Thus, inertial oscillations seem to be the governing current conditions in this part of the northern North Sea.

- **Operational current conditions**

  In general, the expected seasonal variation in current speeds with the current speeds largest during winter, decreasing during spring and summer before increasing during the autumn, is confirmed. However, at Locations 4 and 5, the maximum current speeds are larger in the summer than the spring and autumn, due to inertial oscillations during the summer.

- **Extreme current conditions for design**

  The variation in estimated extreme current speeds based on different individual years of data is large and larger than assumed previously. This suggest that current measurements of longer duration than one year will give more reliable estimates of extreme current conditions for design of offshore structures.

- **Potential in simultaneous wave and current data**

  When the ULS load for a jacket is estimated directly from a time series of the load, the ULS load is reduced significantly compared to the more traditional approach according to N-003. Although the results are intended to be illustrative and not suitable for design, these results are considered to give a reliable indication of the ULS load when sufficient simultaneous metocean data are available.

The most important experience from this metocean measurements programme is considered to be the new insight regarding the accuracy of the measured current data. No additional knowledge was gained through the three phases of the Current Verification Study, aimed to give guidance on how the accuracy of current measurements could be improved and further work is necessary. Both good quality and sufficient length of simultaneous metocean data are required to establish joint distributions. If either of the wave and current data, in this case the measured current data, do not have adequate quality, it will not be appropriate to establish joint distributions of simultaneous data as the reliability of such will be deteriorated by the data quality.

To utilize that the occurrence of extreme wind, waves and currents are not fully correlated in design of offshore structures, Norwegian design regulations presently recommends at least three years of simultaneous wind, wave and current data. For wind and waves, both measured and hindcast data are of sufficient quality and length. For currents, measured current data has mainly been used and none of the available current hindcast for the Norwegian Continental Shelf (NCS) are considered to hold the required quality. Considering the quality of measured current data presented and discussed in this article, it might be more appropriate and prosperous to develop alternatives to measured current data for design of offshore structures and utilization of simultaneous occurrence of metocean parameters. Rather than to measure current simultaneously with wind and waves for a long period, development of high-quality current hindcasts, validated with a shorter period of current measurements, could prove to give more reliable estimates of extreme current conditions for design of offshore structures. However, to have any confidence in such an approach, the challenge of how to perform high-quality current measurements with well-defined uncertainty bands still remains to be solved.

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TABLES

Table 1. Data overview of current measurements made by the QM ADCP at each location.

Location	**Water depth [m]**	**Data coverage**					
		2011	**2012**	**2013**	**2014**	**2015**	**Total, [%]**
1	190						79
2	100						88
4	118						92
5	125						89

Table 2. Extreme values for year-to-year *Cs* at 40 m water depth at all four locations.

Location	**Period**	**Annual probability of exceedance, [cm/s]**		
		0.63	**10^{-1}**	**10^{-2}**
1	2011	104.2	115.2	128.4
	2012	88.6	97.7	108.5
	2013	87.1	96.0	106.5
	2014	90.9	100.9	113.0
	2015	107.4	117.6	129.5
2	2011	88.8	99.4	112.2
	2012	78.5	86.1	95.1
	2013	66.6	72.4	79.3
	2014	76.5	83.9	92.7
	2015	68.4	74.7	82.3
4	2011	61.6	68.2	76.0
	2012	84.3	96.0	110.5
	2013	49.3	53.6	58.6
	2014	64.7	71.5	79.8
	2015	57.2	62.7	69.1
5	2011	88.1	99.7	113.9
	2012	113.7	132.4	156.1
	2013	62.7	69.1	76.6
	2014	104.9	120.7	140.3
	2015	88.6	100.4	114.8

Table 3. Normalized ULS load according to N-003 and directly from a load time series.

Location	Waves	Current	ULS load
Example	All-sea states *H*	10-min *Cs*	1.00
		3-hrs mean *Cs*	0.95
		3-hrs max *Cs*	0.97
	Peak-over-threshold *H*	10-min Cs	0.89
		3-hrs mean *Cs*	0.86
		3-hrs max *Cs*	0.88
	Most probable *H*	10-min *Cs*	0.54
		3-hrs mean *Cs*	0.52
		3-hrs max *Cs*	0.56
	Monte Carlo *H*	10-min Cs	0.62
		3-hrs mean *Cs*	0.60
		3-hrs max *Cs*	0.64
1	All-sea states *H*	3-hrs max *Cs*	1.00
	Most probable *H*		0.66
2	All-sea states *H*	3-hrs max *Cs*	1.00
	Most probable *H*		0.73
4	All-sea states *H*	3-hrs max *Cs*	1.00
	Most probable *H*		0.64
5	All-sea states *H*	3-hrs max *Cs*	1.00
	Most probable *H*		0.61

Table 4. Parameters for the joint distribution of *Hs* and *Tp* and estimated extreme values for *H* [m].

Location	Distribution	Parameters					Annual probability of exceedance, [m]		
							0.63	10^{-1}	10^{-2}
1	lognormal-Weibull for *Hs*	γ	β	α	ϑ	θ	21.9	25.3	28.8
		2.763	1.534	0.553	3.941	0.862			
	lognormal for *Tp*|*Hs*	a_1	a_2	a_3	b_2	b_3			
		5.193	-1.857	0.219	0.299	-0.046			
2	lognormal-Weibull for *Hs*	γ	β	α	ϑ	θ	19.3	22.2	25.1
		2.822	1.658	0.553	3.436	0.862			
	lognormal for *Tp*|*Hs*	a_1	a_2	a_3	b_2	b_3			
		2.377	0	8.314	0.220	-0.225			
4	lognormal-Weibull for *Hs*	γ	β	α	ϑ	θ	19.6	22.7	25.8
		2.800	1.603	0.553	3.646	0.862			
	lognormal for *Tp*|*Hs*	a_1	a_2	a_3	b_2	b_3			
		13.956	-11.395	-0.003	0.135	-0.003			
5	lognormal-Weibull for *Hs*	γ	β	α	ϑ	θ	19.1	22.1	25.0
		2.819	1.648	0.553	3.470	0.862			
	lognormal for *Tp*|*Hs*	a_1	a_2	a_3	b_2	b_3			
		4.320	-1.670	0.021	0.103	-0.050			

Table 5. Weibull parameters and corresponding extreme values for *Cs* [cm/s].

Location	**Weibull parameters**			**Annual probability of exceedance**		
	γ	***β***	***α***	**0.63**	**10^{-1}**	**10^{-2}**
1	1.450	18.28	6.79	86	98	112
2	1.579	15.79	6.17	67	75	85
4	1.323	10.06	8.14	59	67	76
5	1.065	9.52	9.24	80	94	112

Table 6. Weibull parameters and corresponding extreme values for L [MN].

Location	Weibull parameters			Annual probability of exceedance		
	γ	β	α	0.63	10^{-1}	10^{-2}
1	0.741	1.51	0.53	27.40	35.59	46.58
2	0.661	0.79	0.30	20.21	27.14	36.74
4	1.507	6.32	-2.54	23.49	27.13	31.39
5	0.668	0.74	0.23	18.26	24.46	33.02

FIGURES

The figure captions are listed below.

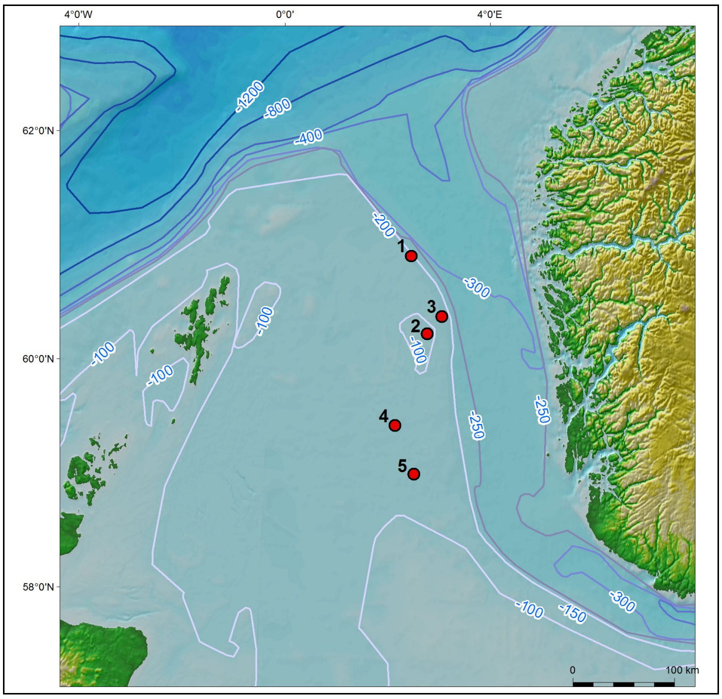
Figure 1. Measurement locations in the northern North Sea.

Figure 2. Schematic outline of mooring configurations and instrument types for the pilot phase at Location 1 (left) and main phase at all locations (right).

Figure 3. Illustration of the data quality issues related to measured current data; “noise” in measured current data before filtering compared to filtered current data (upper panel) and discrepancies observed between overlapping current data (lower panel).

Figure 4. Time series of *Cs* at Location 4 and 5 during one of the two episodes with large *Cs* in August 2014.

Figure 5. Variation in 100 year extreme *Cs* based on individual years at 40 m water depth at all four locations.



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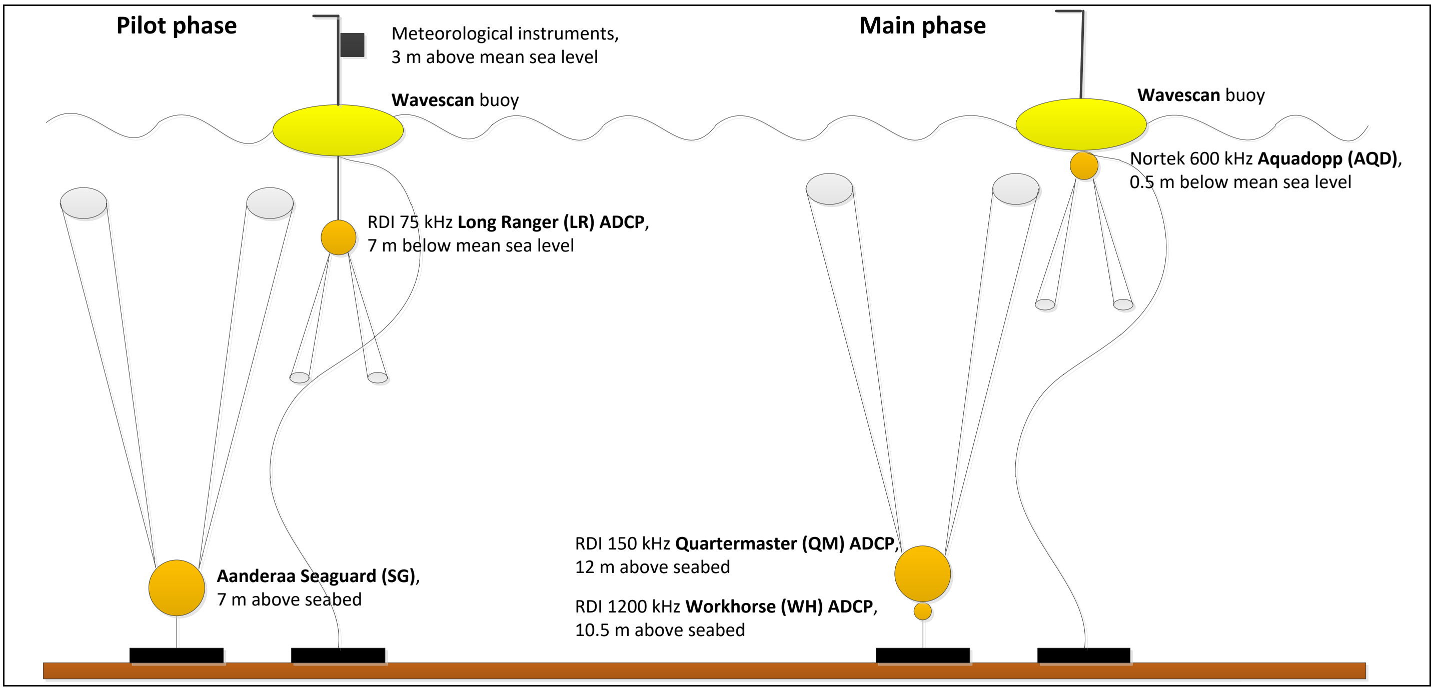

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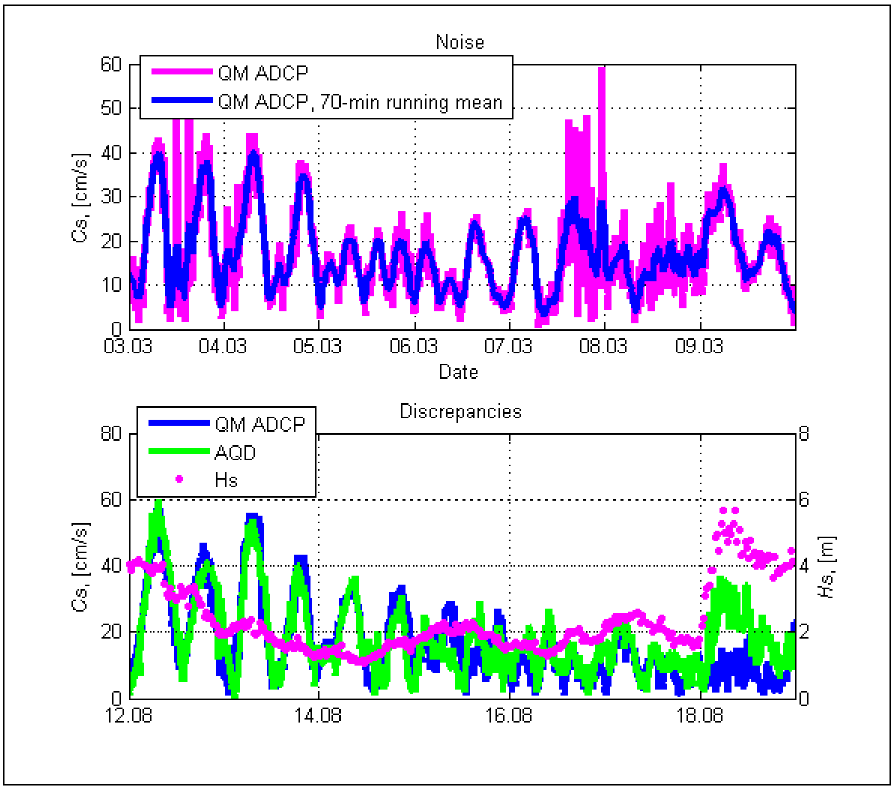

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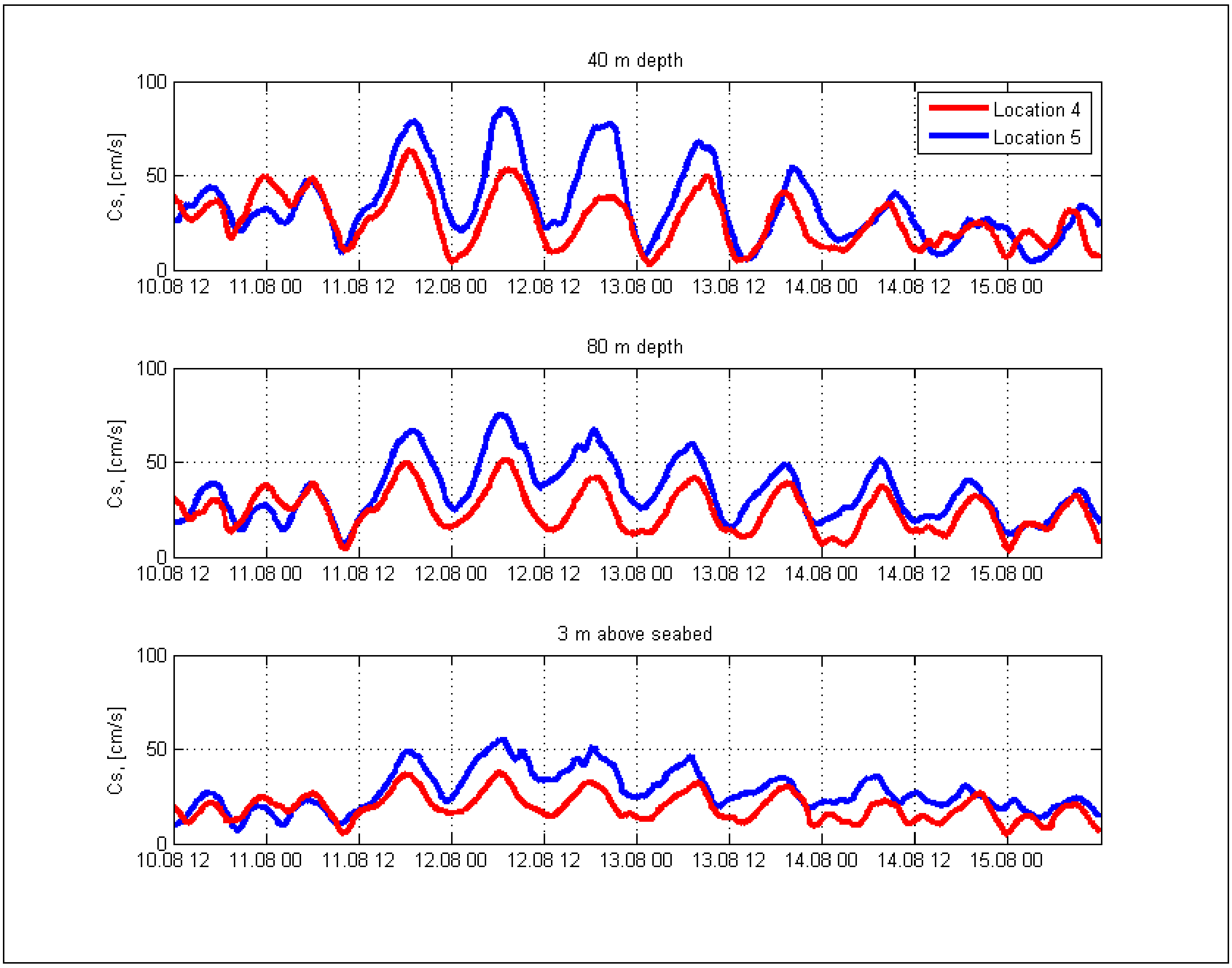

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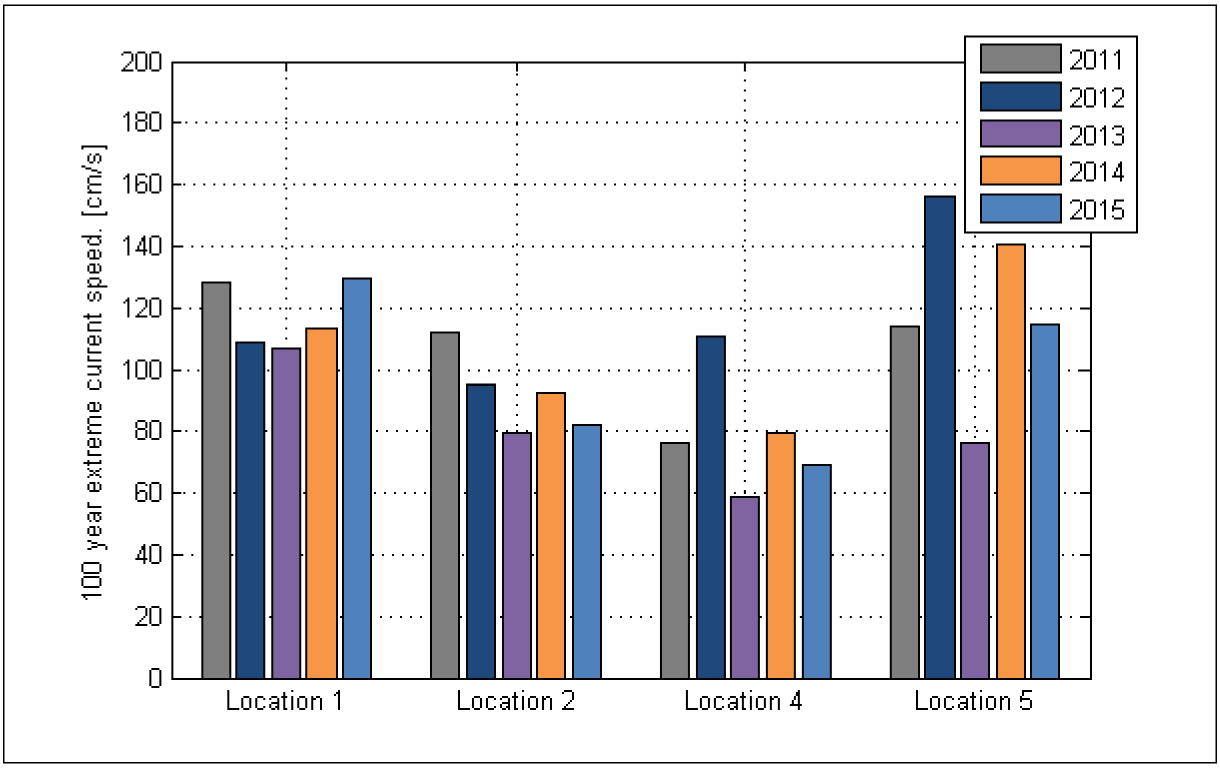

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