Uncertainties in Current Measurements in the Northern North Sea

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ABSTRACT

A met–ocean measurement program of waves and current profiles at five locations in the northern North Sea was performed over a period of approximately 5 years. Despite quality control, the measured current speed data contained more noise than expected and large discrepancies were observed between overlapping current speed data measured by different current profilers at the same locations and water depths. Some of the noise and discrepancies can be explained by the influence from surface waves. The current measurements from instruments attached to a surface buoy indicated that these suffered from the influence of surface waves. Further investigations of the uncertainties in current speed data were carried out through three phases of a current verification study, where both additional current measurements and data analysis were done. Comparisons of overlapping measured current speed showed large deviations, suggesting that the accuracy of current measurements is not as good as the user expects. These presented results are in contrast to previous studies of overlapping current measurements.

1. Introduction

Knowledge of the extreme environmental conditions and loading are required for both design and operation of marine structures, such as offshore oil- and gas-producing facilities. Design codes stipulate that offshore structures should be designed to exceed specific levels of reliability. To define extreme environmental loading, extreme meteorological and oceanographic (met–ocean) design criteria—primarily wind, wave, and current—must be specified. Accurate estimates of environmental design conditions, based on measured and/or hindcast data, are of fundamental importance to the reliability of offshore structures over time. Thus, the uncertainties related to the estimates of environmental design conditions are also important to account for.

For the Norwegian continental shelf, Norwegian design regulations NORSOK N-003 (NORSOK 2007)

define the characteristic met–ocean loads and load effects in terms of their annual probability of exceedance q. The requirements for ultimate limit state and accidental limit state for met–ocean actions on an offshore structure are $q \leq 10^{-2}$ and $q \leq 10^{-4}$, respectively. This requirement refers to the resulting met–ocean load, that is, the characteristic met–ocean load obtained by accounting for the simultaneous occurrence of wind, waves, and current. When there is a lack of sufficient simultaneous data, N-003 recommends a combination of met–ocean 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 the design of offshore structures, the new edition of N-003, which is on industry hearing (NORSOK 2017), recommends at least 5 years of simultaneous wind, wave, and current data.

Based on this and in order to be able to establish joint distributions for significant wave height and current speed for the design of offshore structures, a met–ocean measurement program at five locations in

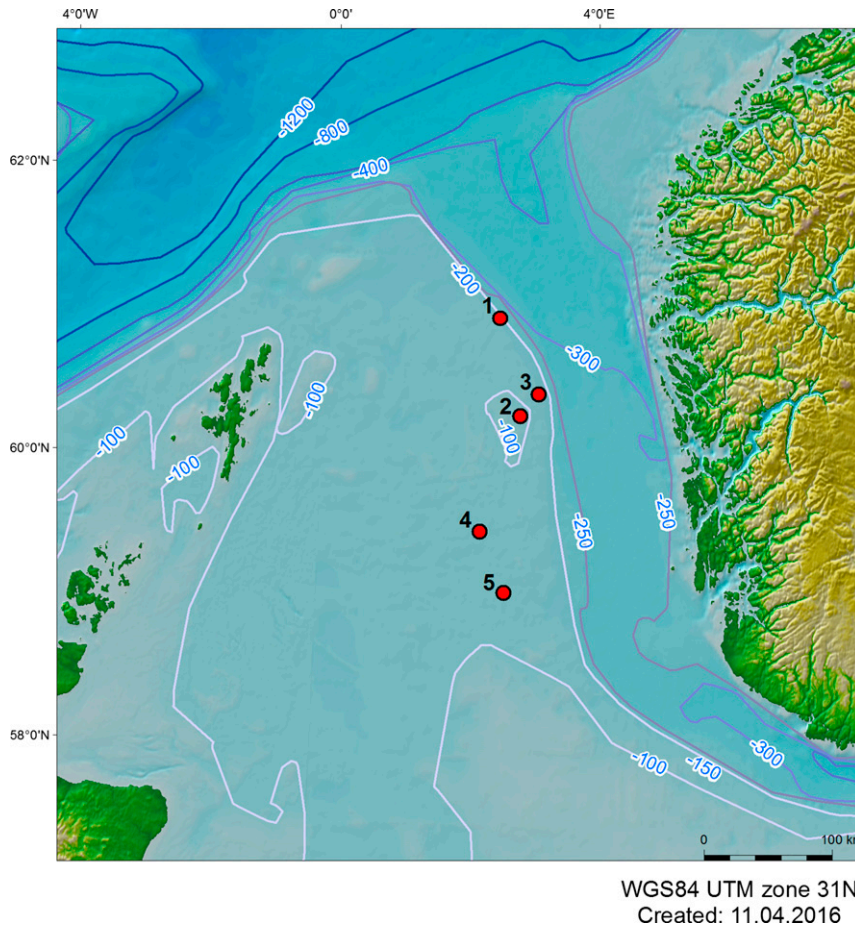*Corresponding author e-mail*: Kjersti Bruserud, kjbrus@statoil.com

FIG. 1. Measurement locations in the northern North Sea.

the northern North Sea (see Fig. 1) was initiated early 2011 and completed in late 2015, that is, a total duration of about 4.5 years. Simultaneous waves and current profiles were measured. Despite data quality control, the measured current speeds were found to contain more noise than expected, resulting in spikes in the data. Discrepancies between overlapping current speeds measured by two different current profilers were also observed.

From a design point of view, it is important to assess— and, if possible, quantify—all types of uncertainties related to the estimated met–ocean design conditions, as these will influence the accuracy of the extreme environmental loading and also the reliability of a structure. In general, only quality-controlled time series of current speeds are available when met–ocean design conditions are to be estimated and not the raw data recovered from current meters. Therefore, further assessment of the uncertainties in the measured current speeds, introduced by the observed noise and discrepancies, was considered necessary.

To gain a better understanding of the noise and discrepancies found in the time series of measured current speeds and to improve the knowledge on different methods of conducting current measurements for estimation of met–ocean design conditions, additional measurements and analysis of data were performed through the Current Verification Study (CurVeS), phases I–III. All three phases of CurVeS emphasized qualitycontrolled time series of current speeds, since estimates of current design conditions are based on this parameter.

This article is outlined as follows: previous intercomparisons of current meters are reviewed in the next section, before a general introduction to the measurement program and the different phases of CurVeS is given. Then the results are presented, and some concluding remarks are given in the final section.

2. Previous intercomparison of current meters

From late 1990s onward, newly developed acoustic instruments have to a large extent taken over for

mechanical current meters for current velocity measurements. When new instruments are to replace older, proven technologies, it is particularly important to test the performance of the current meters. This is most conveniently done by ensuring a certain amount of overlapping data from the different instruments. In addition, confidence in current measurements performed with different instruments and technologies depends on consistency between the instruments. During the 2000s, several studies were conducted where comparisons of different types of current meters were made (Drozdowski and Greenan 2013; Gilboy et al. 2000; Hogg and Frye 2007; Irish et al. 1995; Mayer et al. 2007; Plueddemann et al. 2003; Watts et al. 2013; Wilson and Siegel 2008). Although the motivations and investigations of the studies varied, some relevant and comparable experiences can be extracted from them.

Irish et al. (1995) compared current measurements in U.S. waters in relatively benign current conditions at 87 m in Massachusetts Bay (no exact location), at 2822 m in the North Atlantic (59°35.6′N, 20°57.9′W) and on the northern North Carolina shelf (no water depth and exact location), where surface moorings with acoustic Doppler current profilers (ADCPs) were deployed close to vector-averaging and vector-measuring current meters (VACM and VMCM, respectively); see the appendix for further details about the instruments. The duration of the measurements at the three locations was 13 months: 1990–91, April–September 1991, and November 1988–May 1989. The motivation of the study was to evaluate the quality of the ADCP data obtained in a surface mooring configuration and to identify any systematic differences between the acoustic and mechanical instruments. The ADCPs tended to measure slightly lower speeds than the VACMs and higher speeds than the VMCMs but by only approximately 1%, which corresponds to 1–3 cm s^{-1}. These comparisons were considered as good as any conventional current meter intercomparisons, and the ADCP current speed measurements were concluded to be at least as good as for any other current meter in the same applications.

Gilboy et al. (2000) carried out measurements in 4550-m water depth southeast of Bermuda (31°44′N, 64°10′W) with a VMCM, an ADCP, and a single-point acoustic current meter (ACM) deployed in subsurface moorings, during August–December 1996. The aim of the study was to acquire in situ data and knowledge about the ACM performance compared to the VMCM and the ADCP. The measured current speeds did not exceed 40 cm s^{-1}. Hence, it is reasonable to assume moderate flows in this area. All three instruments had similar measurements; time series comparisons showed excellent agreements and the correlation r was larger than 0.95 for all comparisons and best for the VMCM and the ADCP. The ACM tended to give the lowest current speeds and the ADCP the largest, but the deviation was generally very small and on the order of a few centimeters per second.

Plueddemann et al. (2003) compared current velocity measurements from subsurface moorings with two different types of ACMs: an ADCP and a VMCM in 12-m water depth in Buzzards Bay (Massachusetts, no exact locations) during February–May 2000. A semidiurnal tide dominates the flow in this bay. The current conditions here are very benign, and during the data collection period the measured current speeds did not exceed 20 cm s^{-1}. Good agreement was observed between all instruments, and around the mean speed of 8 cm s^{-1} a variation of only 1.5 cm s^{-1} was seen. As reported by Gilboy et al. (2000), the ADCP was found to measure larger current speeds than the other instruments—here around 10% larger current speeds—and the discrepancy was increasing with speed. Pettigrew et al. (2005) also investigated current measurements in a coastal embayment sheltered from significant wave activity where tides dominate the flow at 32 m (central Maine, no exact location). The general current conditions are benign with measured current speeds less than 30 cm s^{-1}. Two different ADCPs and a string of recording current meter 9 (RCM9) were deployed in surface moorings for two 15-day periods (no exact time periods). Excellent agreement was found between all instruments, and the differences in mean current speeds and the root-mean-square (RMS) values were less than 0.5 and 0.2 cm s^{-1}, respectively. However, some discrepancies were pointed out, but no attempt was made to explain this.

Deepwater current measurements performed southeast of Bermuda (no exact locations) at 4552 m water depth during July–November 2000, at 4370 m during November 2001–February 2004, and at 4300-m water depth during April–May 2002 were investigated by Hogg and Frye (2007). The fidelity of the speed measurements by ACMs, such as RCM11s and other types of ACMs deployed in subsurface moorings, were compared to a mechanical reference instrument, such as VMCM or VACM. The instruments were placed in water depths ranging from 1970 to 4000 m and hence the measured current speeds were very low, that is, always less than 15 cm s^{-1}. When compared to the reference instrument, the RCM11 appeared to have a small, systematic bias amounting to a 10%–25% reduction of the reference current speed, but the other ACMs compared well.

Mayer et al. (2007) compared upward- and downward-looking ADCPs—that is, subsurface and surface moorings—in 20–30-m water depths at five different locations on the West Florida shelf (27°12.0′N, 82°56.75′W; 27°7.7′N, 82°54.0′W; 27°7.9′N, 83°0.35′W; 27°9.9′N, 82°55.5′W; 27°12.7′N, 82°49.2′W) during the period November 1999–August 2001. Good agreements were seen between all instruments, except for measurements in the upper 5–7 m of the water column. Here, the observed velocity, when sampled by the downward-looking ADCPs, was reduced by about 9% compared to the upward-looking ADCPs. The authors stated that there were many potential explanations for this difference, which include in-line instruments, bin size, biological fouling, and bubbles. Many in-line instruments and a small bin size may result in larger variability; for example, algae growth on the surface buoy can attract fish, which may contaminate the ADCP beams, and surface bubbles created by surface wave activity can affect the ADCP observations by reducing the acoustic energy.

Another evaluation of current measurements at a shallow and sheltered location dominated by tidal flow was done by Wilson and Siegel (2008). The performance of a buoy and bottom-mounted ADCP in 7-m water depth in Chesapeake Bay (Maryland, 39°09.114′N, 76°83.472′W) during the period March–April 2008 was explored. The agreement between the two current meters, both in magnitude and direction, was found to be very good. Motivated by the need to verify that ADCPs produce reliable measurements relative to a historical standard, such as RCM8, and a newer ACM, such as RCM11, Devine and Scotney (2008) performed current measurements, with a subsurface mooring, at 155-m water depth on the Scotian shelf (Canada, no exact location) during August–October 2007. In this area, the current conditions consist of low to moderate flows. The RCM8 measured slightly higher current speeds than the acoustic instruments. However, the conclusion was that the current measurements compared well.

Another comparison of current measurements in the same area was done by Drozdowski and Greenan (2013). First, one mooring—including ACMs, a Seaguard (SG) RCM, and a Doppler volume sampler (DVS); an ADCP; and the older, more commonly used RCM8—was deployed in a subsurface mooring at 155-m water depth on the Scotian shelf (44°17.5′N, 63°16.0′W) for the period May–June 2008. Then, a second mooring—including two SGs, an ADCP, and a RCM11—was deployed in 1700-m water depth on the Scotian slope (Canada, 42°44.3′N, 61°34.6′W) for the period October 2008–September 2009. Very good agreement was found;

the RMS of the speed difference was 1.0–1.6 cm s^{-1}, that is, about 3%–6% of maximum observed current speed, and speed differences larger than 4 cm s^{-1} were uncommon. A slight tendency for more disagreement at higher speeds between the DVS and the other current meters was reported.

Watts et al. (2013) compared current meters at about 4000-m depth in an area of the Drake Passage (off Cape Horn, Argentina, no exact location) expected to have strong currents. One subsurface mooring with two VMCM and two RCM11s, two SGs, and one Aquadopp was deployed during November 2009–October 2010. All different current meters agreed well. At low current speeds—that is, less than 35 cm s^{-1}—the RCM11 was 5% low, SG 5% high, and Aquadopp 7% high compared to the VMCM. At high current speeds—that is, larger than 67 cm s^{-1}—the RCM11, SG, and VMCM agreed within 2%.

A brief summary of the described comparisons of current measurements is given in Table 1. The described current meters comparisons cover several variations of different geographical locations, water depths, seasons, wave and current conditions, and current meters. Despite this, all the comparisons reach the same general conclusion—that different current meters compare well. Thus, none of the described comparisons investigate further and discuss potential reasons for discrepancies in the measured current data, such as surface wave motions or biofouling. Problems with the acoustic scatterers are not mentioned specifically, and the quality of the acoustic data studied in these comparisons is assumed to be good.

3. Data

a. Present current measurements

The met–ocean measurement program at five locations in the northern North Sea was initiated early 2011. The main phase with measurements started in May 2011. At location 3, the measurements were ended late 2013, but at the other locations the measurement were completed in October 2015. The measurement locations are shown in Fig. 1, and an overview of the water depths, measurement platforms, number of measurement bins, bin size, and data return for waves measured by the surface buoy, and currents measured by the seabed mooring is given in Fig. 2.

The measurements at each location were performed with the same generic mooring design, which consisted of one surface mooring and one seabed mooring. The surface mooring at each location included a

Wavescan buoy measuring surface waves and a downward-looking Nortek 600-kHz Aquadopp (AQD) measuring near-surface current speed and direction. The seabed mooring was designed to measure current speed and direction throughout the entire water column and near the seabed by two near-bottom upward-looking acoustic current profilers: Teledyne RD Instruments 150-kHz Quartermaster ADCP (QM ADCP) and Teledyne RD Instrument 1200-kHz Workhorse ADCP (WH ADCP), respectively. Sea temperature and salinity measurements were also done near the seabed. A schematic outline of the mooring configuration and the instrument types are given in Fig. 3. All measured data were transferred in real-time by satellite.

Wave measurements were done with a sampling interval of 30 min. The wave sampling was undertaken by measuring buoy heading, heave, pitch, and roll at a frequency of 1 Hz over an ensemble interval of 17 min, that is, 1024 samples per record. The remaining 13 min in every 30-min sampling interval are for the buoy to process and write data. All current meters were set to record samples at 10-min intervals. However, the sampling methods and ensemble intervals were different for the different types of current profilers. The AQDs were configured in a high-power mode with continuous pinging at 2 Hz per ensemble. The QM and WH ADCPs transmitted 28 and 50 pings, respectively, per ensemble. The ping interval was originally set to 10 s—that is, ensemble intervals of 280 and 500 s for the QM and WH ADCPs, respectively—but from October 2013 the ping interval was shortened to 2.5 s, that is, ensemble intervals of 70 and 125 s for the QM and WH ADCPs, respectively. The ping interval was changed in an attempt to reduce the amount of noise observed in the measured current data. Following this change in ping interval, the measured current speeds did not present the same amount of noise as seen before and were considered to be somewhat improved. However, the quality of the measured current data was still not considered to be satisfactory.

Quality control checks of the measured current data were applied at two levels: within the ADCPs and during postprocessing. During postprocessing, basic routine quality checks were applied, including the following:

- Setting measured current speeds less than $0 \, cm \, s^{-1}$ to zero.
- Applying a magnetic deviation of $-1.4°E$ to all directional data to correct from magnetic north to true north.

- Setting of false start and end times to remove invalid measurement records during the instrument's deployment and recovery.
- Producing preliminary plots of observed current speed and direction to inspect the general quality of the data and to identify anomalous data.
- Plotting of time series of pitch, roll, heading, echo amplitude, and percentage of good pings (PGP) to identify periods of excessive pitch and/or roll of the ADCPs, anomalous echo amplitudes, or low PGP.
- Error flagging of records with less than 75% "good pings."
- Plotting time series of error velocities, and flagging the error velocities outside a threshold value of $\pm 5 \, cm \, s^{-1}$.
- Plotting measured current speed and direction for final inspection of the data quality by an experienced oceanographer to identify, examine, and, if necessary, remove any remaining anomalous values.

Nevertheless, the upper levels of the measured QM ADCP data, down to around 50-m water depth, had from the very beginning of the measurements contained a lot of "noise," resulting in spikes in the data. Filtering of the data by applying a 70-min 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 is shown in Fig. 4, where two time slices of the measured current speed at 30-m water depth at location 4 before and after filtering of the data by a 70-min running mean are shown. The number of spikes and the amount of noise in the measured current data are clearly reduced after the measured current data has been filtered.

Discrepancies were observed between overlapping current data, that is, current measured at the same water depth by the AQD mounted in the surface and QM ADCP in the seabed moorings. This is illustrated in Fig. 5 for location 4.

In Fig. 5a scatterplots of the current speed measured by the AQD and QM ADCP at 20- and 30-m water depth during the period October 2013–August 2014 are shown. The scatterplots show a large spread of the measured current speed by the two different acoustic profilers. In general, the spread in the measured current speed seems to be largest for the lowest measured current speeds and decreases with increasing current speed. The spread in the measured current speed seems to be larger at 20-m than at 30-m water depth, although the linear fit to data is closer to the one-to-one line at 20 m than at 30 m. At 20 m, the linear fit deviates approximately 11% from the one-to-one line and at 30 m approximately 15% from the one-to-one line. This means that the difference in the current speed

TABLE 1. Overview of comparison studies of different types of current meters. Acoustic and mechanical current meter types are indicated with (A) and (M), respectively.

Paper	Motivation	Location	Water depth	Flow regime	Duration (months)	Mooring type	Current meters	Result	
								General agreement	Specific measures
Irish et al. (1995)	Evaluate the quality of ADCP data obtained in a surface moored configuration at three locations	Shelf Open ocean Bay	Shallow Deep Shallow	—	13 5 7	Surface	ADCPs (A), VACM (M), VMCM (M)	Good	Difference means: 1–2 cm s^{-1} RMS: ~3 cm s^{-1}
Gilboy et al. (2000)	Acquire in situ data and knowledge about ACM performance compared to VMCM and ADCP	Open ocean	Deep	—	4	Subsurface	ACM (A), ADCP (A), VMCM (M)	Excellent	r: 0.95–0.99
Plueddemann et al. (2003)	Compare velocity measurements from different types of current meters	Bay	Shallow	Tidal	4	Subsurface	ACM (A), ADCP (A), VMCM (M)	Good	r: 0.96–0.98 Difference means: 0.5–1.8 cm s^{-1}
Pettigrew et al. (2005)	Compare two different bottom-mounted ADCPs and a moored string of RCM9	Bay	Shallow	Tidal	2 × 0.5	Surface	ADCP (A) RCM9 (M)	Excellent	Difference means: 0.1–9.4 cm s^{-1} RMS: 2.0–9.9 cm s^{-1}
Hogg and Frye (2007)	Fidelity of speed measurements by several ACMs at three locations	Open ocean	Deep	Low	5 4 2	Subsurface	RCM11 (A), Nortek (A), Falmouth (A) VACM (M), VMCM (M)	Well	Not given
Mayer et al. (2007)	Compare upward- and downward-looking ADCPs at five locations	Shelf	Shallow	Low	22	Surface, subsurface	ADCPs (A)	Good	RMS: ~7–13 cm s^{-1}
Devine and Scotney (2008)	Verify that the DVS produces reliable measurements relative to a historical standard (RCM8) and a newer Doppler-type current meter (RCM11)	Shelf	Deep	Low	3	Subsurface	DVS (A), RCM11 (A) RCM8 (M)	Good	Not given
Drozdowski and Greenan (2013)	Comparison of acoustic single-point current meters SG and DVS to older-generation single-point current meters and ADCPs at shallow and deep-water locations	Shelf	Shallow Deep	Low	2 × 2	Subsurface	SG (A), DVS (A) RCM8 (M)	Very good	RMS: 1.0–1.6 cm s^{-1}
Watts et al. (2013)	Obtain comparisons at speeds in excess of 35 cm s^{-1} to determine whether a speed-correction factor should be applied to RCM11	Open ocean	Deep	Strong	12	Subsurface	RCM11 (A), SG (A), AQD (A) VMCM (M)	Well	r^2: 0.97–0.99

Location	Water depth, [m]	Time period	Instrument					Data coverage					
			Type	Depth, [m]	Platform	Bins No.	Bins Size, [m]	2011	2012	2013	2014	2015	Total, [%]
1	190	5 May 2011 – 4 Oct 2015	Waves	Surface	Surface		-						50
			Aquadopp			20	2						56
			QM ADCP	178	Seabed	20	10						79
			WH ADCP	179.5		20	1						92
2	100	5 May 2011 – 4 Oct 2015	Waves	Surface	Surface		-						83
			Aquadopp			20	1						77
			QM ADCP	98	Seabed	20	10						88
			WH ADCP	99.5		20	1						88
3	138	5 May 2011 – 9 Nov 2013	Waves	Surface	Surface		-						78 [1]
			Aquadopp			20	2						81 [1]
			QM ADCP	126	Seabed	20	10						90 [1]
			WH ADCP	127.5		20	1						96 [1]
4	118	5 May 2011 – 3 Oct 2015	Waves	Surface	Surface		-						87
			Aquadopp			20	2						87
			QM ADCP	106	Seabed	20	10						92
			WH ADCP	108		20	1						80
5	125	5 May 2011 – 3 Oct 2015	Waves	Surface	Surface		-						77
			Aquadopp			20	2						81
			QM ADCP	115	Seabed	20	10						89
			WH ADCP	115		20	1						84

[1] Total data coverage during actual time period of measurements, i.e. 5 May 2011 – 9 Nov 2013, not until Q1 2015.

FIG. 2. Data overview of met–ocean measurements.

measured by two different current meters at the same water depths at the same location is 11% and 15%, respectively, with the current speeds measured by the AQD larger than the corresponding current speeds measured by the QM ADCP. As the specified accuracy of both of these instruments is ±1% of the measured current speed value, or ±0.5 cm s^{-1}, the scatterplots indicate that the accuracy of each current meter might not be as good as specified by the manufacturer and thus expected by the user.

Figure 5b shows a time series extract of the current speed measured by the same two instruments at 30-m water depth from 12 to 19 August 2014. The corresponding measured significant wave height is also shown. Even though the time history extracts of current speeds and significant wave height are short, these capture some important features of both the dominating current conditions and the observed discrepancy between the current speeds measured by the AQD and the QM ADCP. During the first 3 days—that is, 12–15 August—the measured current speeds by the two different current meters corresponded quite well. Regular oscillations in current speeds and large values
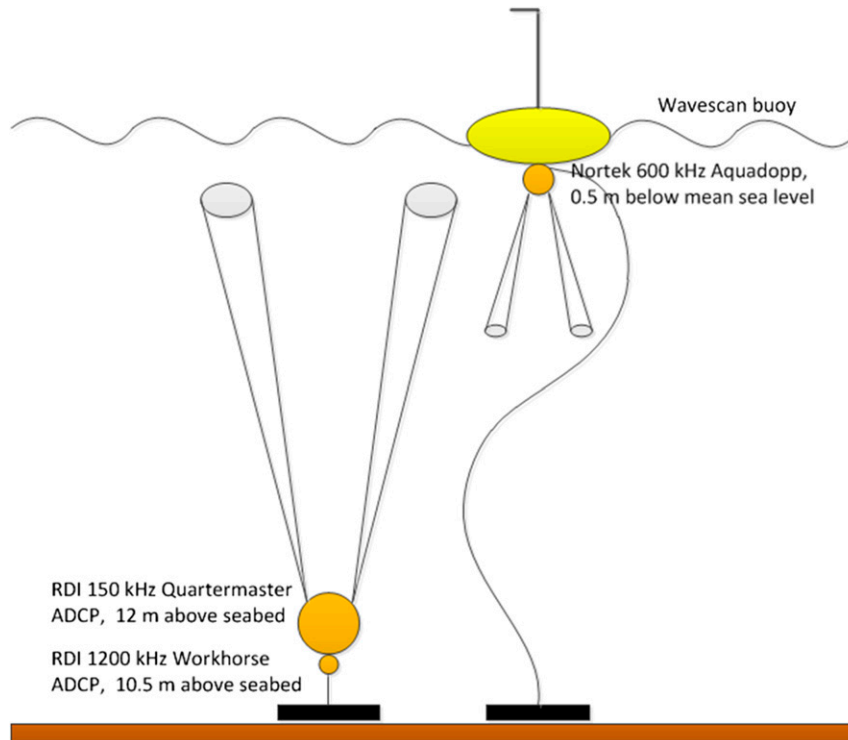

FIG. 3. Schematic outline of mooring configurations and instrument types for the main phase of the current measurements at all locations.
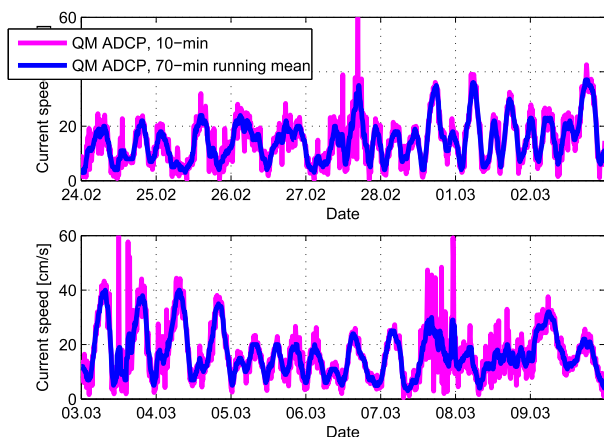
FIG. 4. Illustration of the typical time history of QM ADCP measured current speed (top) before and (bottom) after filtering of the data by a 70-min running mean at 30-m water depth at location 4 during February and March 2014.

of current speeds up to nearly $60\,\mathrm{cm\,s^{-1}}$ are observed, believed to be so-called inertial oscillations. In the same period, the significant wave height decreased from 4 to around 2 m. During the next days—that is, 15–18 August—deviations in the measured current speeds are seen clearly although the measured current speeds were less than $30\,\mathrm{cm\,s^{-1}}$. The significant wave height was also low and varied around 2 m. The last day—that is, 18 August—the measured significant wave height increased from 2 toward 6 m. The largest deviations in the measured current speed are seen here, with the current speeds measured by the QM ADCP significantly lower than the current speed measured by the AQD. This suggests that the rapidly increasing and

large significant wave height was the main reason for this large deviation seen 18 August and that the current measurements made by the AQD deployed in the surface buoy were influenced by the surface waves. The extra Wavescan buoy motion itself caused by the increasing surface waves may explain some of the observed discrepancy in the measured current data. In addition, any current meter moving at surface wave periods—that is, from 2 to 15 s in the northern North Sea—has the potential of aliasing surface wave energy and contaminating the measured current speeds. Another explanation for the observed discrepancies in the measured current speeds could be the existence of surface bubbles created during increased surface wave activity, as discussed by Mayer et al. (2007), which are known to affect the quality of downward-looking ADCP measurements, such as the AQD. However, the wave conditions alone cannot explain all the differences seen in both the scatterplot and time history extract of the measured current speeds by the AQD and the QM ADCP, as the discrepancies were also evident when the significant wave height was low. The good correspondence of large current speeds measured by the two current meters through the inertial oscillations and the poorer correspondence of small, measured current speeds is in accordance with the observations from Fig. 5a.

There can be many potential explanations for the observed discrepancies between overlapping current speed measurements, both related to instrument configurations and environmental factors.

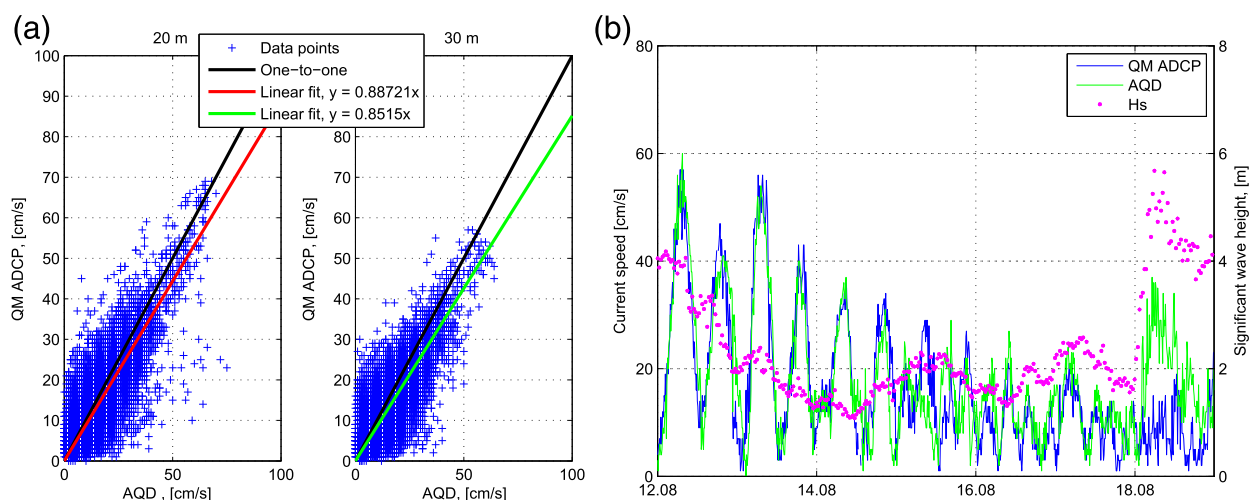The sampling interval for both the AQD and QM ADCP was set to 10 min. According to the instrument

FIG. 5. Illustration of typical discrepancies observed between overlapping current data: (a) scatterplot of current speed measured by the AQD and QM ADCP at (left) 20- and (right) 30-m water depth at location 4 during the period October 2013–August 2014 and (b) time history of current speed measured by the AQD and QM ADCP at 30-m water depth at location 4 during August 2014.

specifications, both instruments should give accurate estimates of the 10-min current speed at the current water depth and location, which again should be directly comparable. However, the ensemble interval and ping interval were different for the two current profilers. Moreover, the bin size for the AQD was set to 2 m and for the QM ADCP 10 m. Such differences in instrument configurations might require more careful analysis before direct comparisons of the measured current data, but it is questionable whether this could explain more than a small part of the larger discrepancies observed between these overlapping current speed data. The instrument compasses and the calibration of these can also influence the measured current data quality. Since the compasses of both the AQD and QM ADCP were calibrated prior to the measurements and have the same specifications (see Table A1), the instrument compasses or compass calibration probably cannot be offered as an explanation to any of the discrepancies in the overlapping current data.

The main environmental factor that can influence the quality of current measurements is surface waves, especially current measurements performed from a surface buoy. As already discussed in this section, surface waves influenced the AQD current measurements and can be offered as an explanation for some of the largest observed discrepancies between the current speed measured by the AQD and QM ADCP, but not all of the smaller observed discrepancies. Biofouling is another environmental factor to which the AQD mounted in the surface buoy might be subject. As part of the operational procedures, all instruments were checked for biofouling during the fieldwork and this was reported not to be a problem.

None of the discussed possible explanations are plausible to alone explain such an amount of noise in the QM ADCP data and thus large discrepancies observed between the overlapping current speeds measured by the AQD and QM ADCP. The main cause of this has yet to be determined. This suggests that further investigations are required.

b. Current Verification Study phase I (CurVeS I)

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, CurVeS, was started early 2014. The overall aim of this project was to compare current speed and direction data from multiple instruments to provide recommendations for optimal current measurements. Other important aspects were to assess the quality of the measured data

of the, at that time, ongoing met–ocean measurement program and to try to quantify the uncertainties prior to further analyses of these data. The new measurements were undertaken in conjunction with the measurement at location 4 and done as close as practically possible to location 4.

Another mooring was deployed at 59°34.750′N, 2°13.609′E—that is, around 400 m from location 4—where the water depth was 107 m. This mooring consisted of a seabed mooring with an upward-looking TeledyneRD Instruments (RDI) 75-kHz Long Ranger acoustic Doppler current profiler (LR ADCP) and three Aanderaa RCM7s at 20, 30, and 100 m below sea mean level, respectively. The LR ADCP was configured with 16 bins of 5-m bin size, measuring currents between 15- and 95-m water depth. The sampling interval for the LR ADCP was 10 min. The LR ADCP transmitted 240 pings with a ping interval of 2.5 s; that is, the ensemble interval was also 10 min. The sampling intervals for the RCM7s were 2 min with samples every 12 s. As the RCM7s sampled every 12 s, the wave orbital velocities will not be well averaged out. In general, the RCM7s are not suitable for near-surface current measurements. Consequently, the current measurements at 20 m were expected to be substantially compromised and have not been considered for further analyses. The measurements at 30 m might be compromised as well. The measurements started 18 February 2014 and ended 6 April 2014, that is, after approximately 7 weeks. During this period, the existing surface mooring at location 4 was equipped with an additional 400-kHz Nortek Aquadopp (suspended AQD) deployed on a modem cage. Schematic mooring configurations and also the instrument types at location 4 during this period are given in Fig. 6.

c. Current Verification Study phase II (CurVeS II)

To further assess the performance of different current instruments, a natural supplement to CurVeS I was to investigate and compare existing current data collected by different acoustic and mechanical instruments at a similar time and location. These data were collected at different locations, water depths, and environmental conditions. This desk study was carried out by the Norwegian Deepwater Programme (NDP), during the summer 2015. Most of the participants in NDP provided appropriate current data. All the compared datasets comprised the single-point current meter RPS Metocean CM04 (CM04). Permission to use these data for this study was contingent on not publishing the metadata because the study is confidential, but the results may be released for publication in the future.
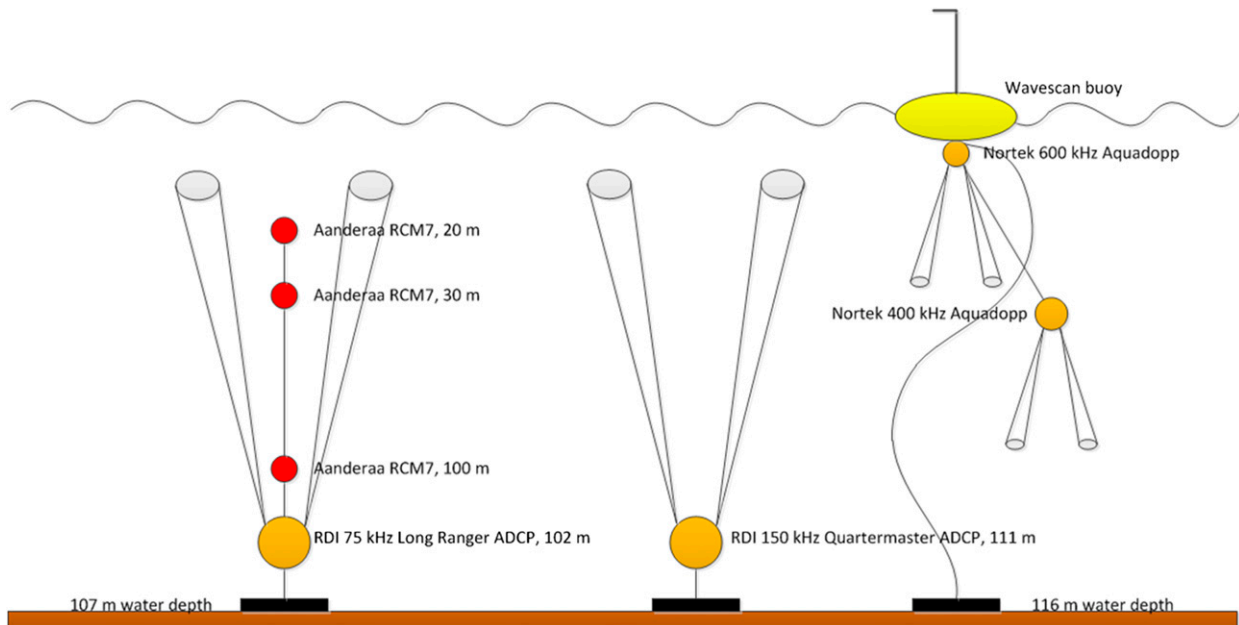
FIG. 6. Schematic outline of mooring configurations and instrument types for CurVes I.

In addition, a dataset with current measurements by two CM04s at the same location and water depth was included in the study. The CM04 showed a reasonable comparison against itself, but this result may not be directly applicable to the northern North Sea.

However, one of the studied datasets is available. The exact measurement location was 40°39.114′N, 19°07.567′E, where the water depth was 180 m. The measurements started the 1 November 2013 and were completed 22 February 2014, that is, 4 months of measurements. This seabed mooring consisted of one downward-looking 2000-kHz Nortek AQD located 8 m above the seabed and a CM04 located 3 m above the seabed. The AQD was set up with seven bins of 1 m, that is, measuring currents at 7, 6, 5, 4, 3, 2, and 1 m above the seabed. The sampling interval for the AQD was 10 min, with an ensemble interval of 1 min. The CM04 was configured with continuous 30-Hz sampling for 1 min. For comparison with current data from the AQD, every tenth data point from the CM04 was used.

d. Current Verification Study phase III (CurVeS III)

Aimed at providing more guidance on how to quantify the uncertainties of the already measured current data in the main phase of the now completed measurement program, a third phase of CurVeS started in October 2015. A surface and seabed mooring with the same design, instruments (AQD, QM ADCP, and WH ADCP), and configurations as during the main measurement program were deployed close to location 4 (see section 3a) where the water depth was around 117 m. In addition, two CM04s and the Aanderaa Seaguards (SGs) were included in the seabed mooring and deployed at 50- and 90-m water depths. The measurements started 13 October 2015 and were completed 27 February 2016, that is, around 4.5 months' duration. The AQD, QM ADCP, and WH ADCP were configured identically as in CurVeS I and the two CM04s as in CurVeS II. Both the sampling and ensemble interval for the SGs were 2 min, with transmittal of 150 pings with a ping interval of 0.8 s. Schematic mooring configurations and the instrument types are given in Fig. 7.

The CM04 deployed at 50-m water depth did not work at all during the measurement period, and no comparison between the AQD and the CM04 at 50-m water depth could be made. The QM ADCP worked for only 6 days during this period, and sufficient data for a proper comparison of the measured current data by the CM04 and QM ADCP at 90-m water depth were barely available. No additional knowledge could be gained through CurVeS III.

4. Results

a. CurVeS I

Time series of the different current speed measurements at 30- and 100-m water depths are given in Fig. 8.
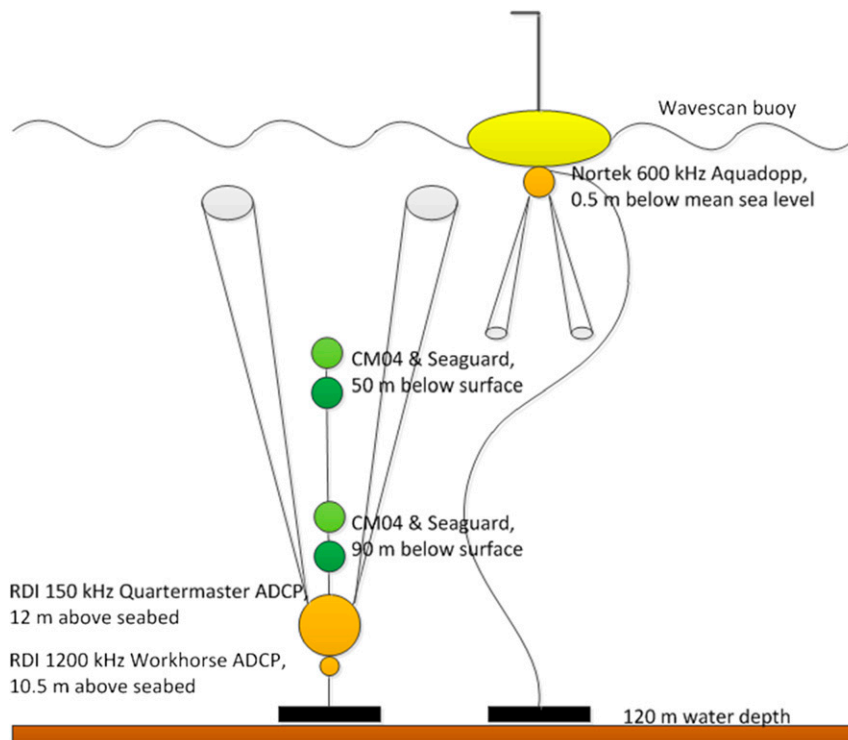
FIG. 7. Schematic outline of mooring configurations and instrument types for CurVes III.

The time series are from one selected week, which is seen to be characteristic and representative for the entire measurement period.

At 30 m, the current speeds measured by the suspended AQD were very different from the current speeds measured by all the other current meters with much larger values of current speed and more noise. Thus, the quality of these data is considered to be very poor. The main reason for this contamination of data is believed to be the motion of the Wavescan buoy, created by surface waves (see discussion in section 3a). Although the AQD mounted in the surface buoy performed considerably better and compared well enough with the RCM7 and LR ADCP, both with regard to current speed values and timing, these current measurements were also influenced by the motion of the Wavescan buoy. The LR ADCP and the RCM7 seemed to be the two current meters that compared best. As expected, the QM ADCP data contained more noise and had larger current speed values than the mounted AQD, LR ADCP, and RCM7. The timing of episodes was quite good. Please note that all these current measurements were performed at the same water depth of 30 m and thus slight deviations in measurement depth or vertical temperature/density gradients cannot explain the observed differences. As some of the compared current speed data were measured at slightly different locations, there could be a small horizontal temperature gradient present explaining some of the observed differences in the measured current speed data. Unfortunately, temperature measurements corresponding to the different water depths and measurement locations are not available for comparison and further investigations cannot be made.

At 100 m, the QM ADCP data were less noisy than at 30 m. This could imply that waves disturbed the upper bins of current measurements by the QM ADCP and influenced the quality of these data. In general, the QM ADCP measured larger current speeds than both the RCM7 and the LR ADCP; the latter instrument measured the lowest current speeds. This is in contrast to the current measurements at 30 m, where the LR ADCP measured larger current speeds than the RCM7. In general, near-seabed current measurements can be influenced by other environmental factors than discussed in section 3a, and they can be sensitive to and affected by local bathymetry. The LR ADCP and RCM7s were placed slightly away from where the QM ADCP was placed (at location 4), and there was a small difference in total water depth between these two locations. One possible explanation for the observed deviations in current speed between the QM ADCP and the two
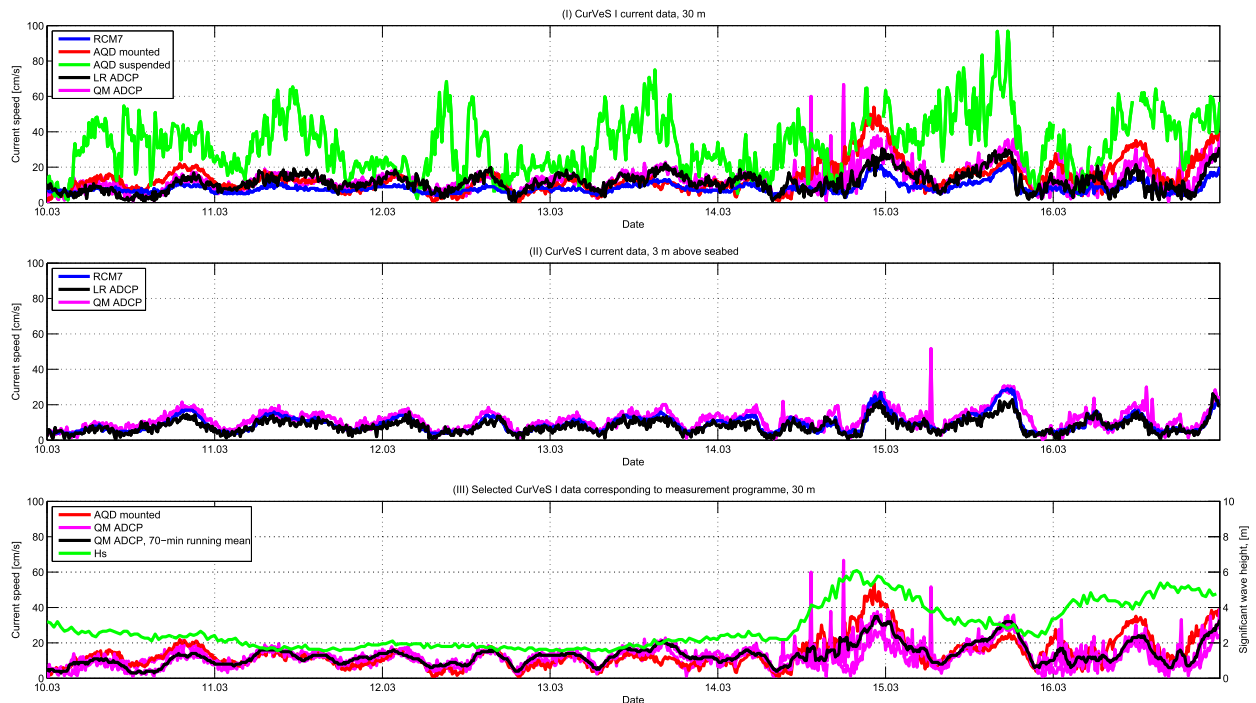
FIG. 8. Time histories of the current measurements in CurVeS I of (top) the different measured current speeds at 30-m water depth, (middle) the different measured current speeds at 100-m water depth, and (bottom) the measured current speeds corresponding to the main measurement program, including QM ADCP data filtered with a 70-min running mean and significant wave height at 30-m water depth.

other instruments could be attributed to slightly different local bathymetry. However, both of these measurement locations were in a relatively flat part of the northern North Sea, the so-called North Sea Plateau, so the local bathymetry effects are expected to be small. As discussed for the 30-m water depth, both vertical and horizontal temperature gradients could have influenced some of the compared measured current data. Another reason for the observed deviations could be slightly different measurement depths. The QM ADCP and RCM7 measured currents at 100-m water depth, but the first bin of the LR ADCP was at 95-m water depth. This might explain some of the deviations seen in the current speeds measured by the LR ADCP and the two other current meters.

It is interesting to note that the measured current speeds by the QM ADCP, LR ADCP, and RCM7 at 30-m water depth and 3 m above the seabed show little variation with measurement depth and are in the very same range, respectively.

Time series of just the two current meters included in the main phase of the measurement program at 30-m water depth—that is, the mounted AQD and the QM ADCP—are also shown in Fig. 8. For comparison, the QM ADCP data filtered with a 70-min running mean are included. The comparison between the

mounted AQD and the filtered QM ADCP data is seen to be significantly improved, but differences were still evident. The corresponding measured significant wave height is also shown in Fig. 8. The amount of noise in the QM ADCP data seemed to increase when the significant wave height increased toward peaks of 6 m—see 14 and 15 March. The largest differences in the measured current speeds between the two current meters were also seen here. However, clear deviations in the measured current speeds were apparent for significant wave heights less than 2 m—see 13 March.

To further investigate the influence of surface waves on differences in the measured current speeds, the difference in the measured current speed by the AQD mounted in the hull of the surface buoy and by QM ADCP at 30-m water depth versus significant wave height is shown in Fig. 9. Large differences in the measured current speeds are seen for all significant wave heights, but there seems to be a tendency for this difference to increase with increasing significant wave height, typically for significant wave heights exceeding 2.5–3 m. This tendency is more evident in the linear fit to data points, which has a clear positive slope. In the northern North Sea at location 4, the significant wave height will exceed 3 m around 30% of the time of the year and wave activity can become a challenge for
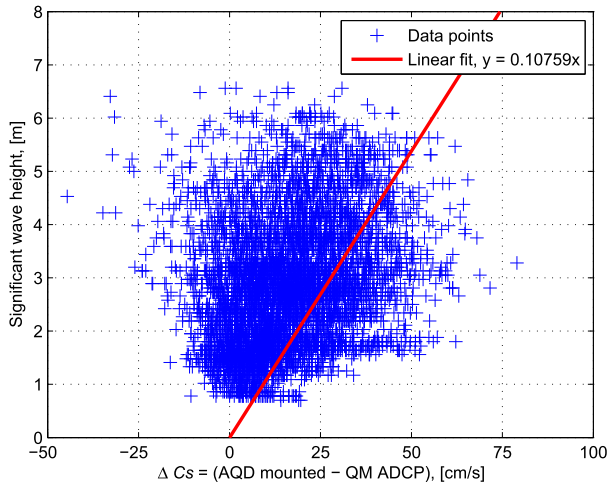
FIG. 9. Scatterplot of difference in measured current speed by the mounted AQD and QM ADCP vs significant wave height.

current measurements collected from instruments attached to surface buoys.

Current speed roses measured by the different current meters are shown in Fig. 10, and summary current statistics are given in Table 2. The form of the directional distributions measured by the RCM7 and QM ADCP correspond best, while the LR ADCP looks most different from the others. The mounted AQD directional distribution form is similar to the RCM7 and QM ADCP but with less distribution of currents toward the south and more toward the southeast. As expected from the current speed time series, larger current speeds are seen in the mounted AQD and QM ADCP current roses. At 30 m, the RCM7 current statistics have lower values than the acoustic current meters. For the acoustic instruments, the mean current speeds are of the same order of magnitude, while the maximum current speeds have a large spread. At 100 m, the mean current speeds and the standard deviations for all current meters are similar, but the maximum values are quite different.

Figure 11 shows the scatter (in current speed) and quantile–quantile (q–q) plots for the different acoustic current meters and the RCM7s at 30- and 100-m water depths. Note that this does not mean that the RCM7 is considered to be better or more correct than any of the other; this is primarily done for the convenience of presenting results. In general, a too-large scatter and a too-low correlation coefficient between the different measured current speeds are seen. Since the q–q plots also deviate from the one-to-one line, distributions fitted to the datasets will for most cases also be rather different.

At 30 m, all the three acoustic instruments recorded larger current speeds than the RCM7. This is also reflected in the linear fits to both the data points and the

quantiles. It is difficult to say whether the RCM7 underestimates or the acoustic current meters overestimate the current speed.

At 100 m, the difference between the acoustic and mechanical current meters is seen to be less pronounced. The QM ADCP recorded larger current speeds than the RCM7, but the LR ADCP now gives lower values than the RCM7, in accordance with the time history in Fig. 8.

b. CurVeS II

The CurVeS II report is confidential, but the executive summary was released for reference. The main finding of the study was that "differences in observed current speed 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" (RPS MetOcean 2015, p. i). Strong evidence that ADCPs have increased noise due to the presence of surface waves that increases with the significant wave height was also found.

As one of the measured current data analyzed in CurVes II is available, the analysis of these data was reproduced. Figure 12 shows time series of the current measurements during one month of each available season. During these three months, much noise is seen in the current data measured by the AQD. During March 2013, the timing and values of current speeds measured by the two instruments were comparable, but both measurements were quite noisy. During June and September 2013 when the current speeds were low, the timing of current speed variations measured by the two instruments was comparable, but the measured current speed values were deviating.

The current speed roses measured by the CM04 and the AQD are shown in Fig. 13, and summary statistics are given in Table 3. The general form of the current roses is quite similar, but there is a difference in the currents toward the north. The mean, maximum, and standard deviation of the current speed for the CM04 and AQD measurements are comparable and correspond well.

Figure 14 shows the scatter and q–q plot for the CM04 and the AQD. Some spread in the current data is evident but much less is than found in CurVeS I, and the consistency between the measured data is considered to be good. This is supported by the estimated correlation coefficient, which has the value 0.87. The linear fit to data and quantiles is very good and implies a deviation between the measurements of a few percent.

c. CurVeS III

A comparison of time series measured by the CM04 at 90-m water depth and QM ADCP at 80-m water depth during the 6 days of available data is given in Fig. 15. The
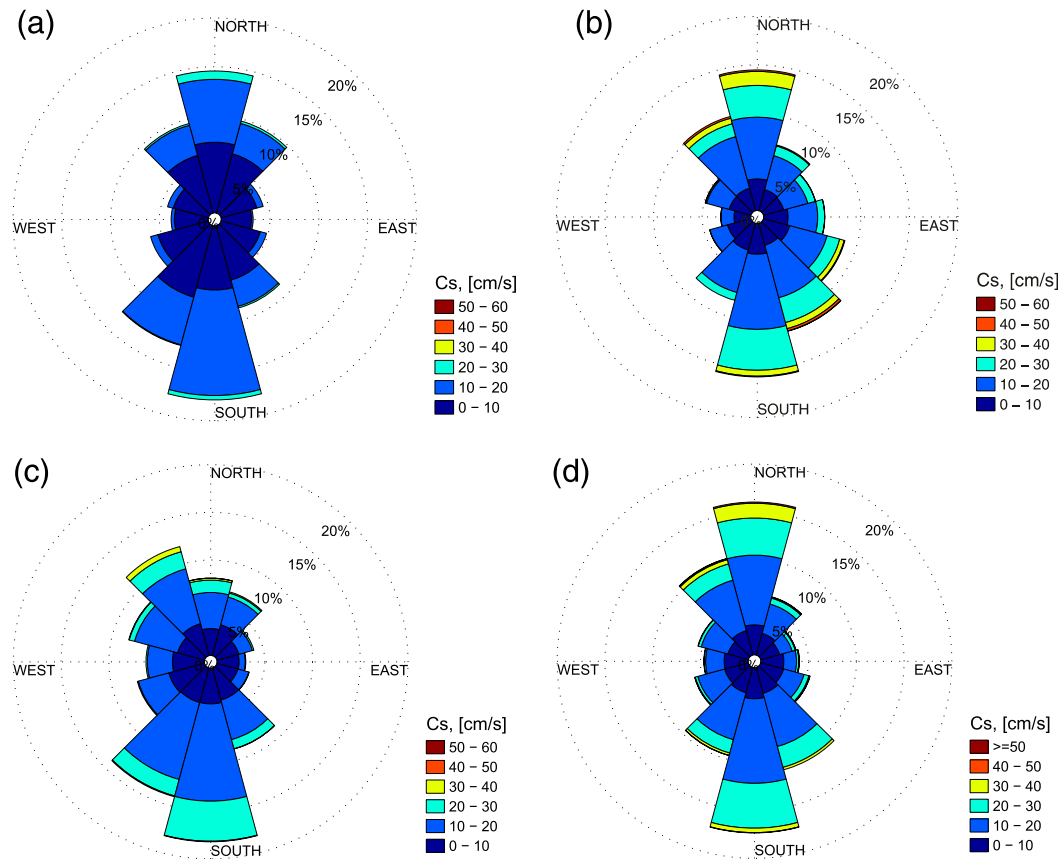
FIG. 10. Current roses for the current meters in CurVes I: (a) RCM7: 30 m, (b) AQD mounted: 30 m, (c) LR ADCP: 30 m, (d) QM ADCO: 30 m, (e) RCM7: 100 m, (f) LR ADCP: 100 m, and (g) QM ADCP: 100 m.

measured current speed by the CM04 was larger than the measured current speed by the QM ADCP, especially during 13–15 October, and the discrepancies were much larger than expected. Oscillations in the measured current speeds were evident both in the CM04 and QM ADCP measurements, and the timing of oscillations corresponded reasonably well.

With only 6 days of measured current data by the CM04 and QM ADCP available for comparison, it is not considered to be a sufficient amount of data to provide current roses and statistics, but the scatter and q–q plot for the CM04 and QM ADCP are shown in Fig. 16. A slight spread is seen in the scatterplot, with the measured current speed by the CM04 larger than the current speed measured by the QM ADCP. Moreover, the correlation coefficient was found to be 0.92. The linear fit to data implies a deviation between the two measured current speed datasets of around 15%. The linear fit to quantiles is better, with a deviation between the measurements of around 2%. However, too much weight to this result should not be given since so little data (only 6 days) were available for comparison.

d. Measures of scattering in measured current data

To do a direct comparison of the scattering and quality of the current data measured and compared in CurVes I–III and the measured current data published and described in the second section of this article, the following different measures of scattering in the compared data were estimated:

- the difference in means, also referred to as mean difference,

$$\text{difference}_{\text{means}} = \overline{X} - \overline{Y}, \tag{1}$$

where $\overline{X}$ and $\overline{Y}$ are the means of the compared measured current speeds

- the correlation coefficient r and r^2,

$$r = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y}, \tag{2}$$

where $\text{cov}(X, Y)$ is the covariance between the different measured current data compared, X and Y, σ_X and σ_Y are standard deviations of X and Y, respectively
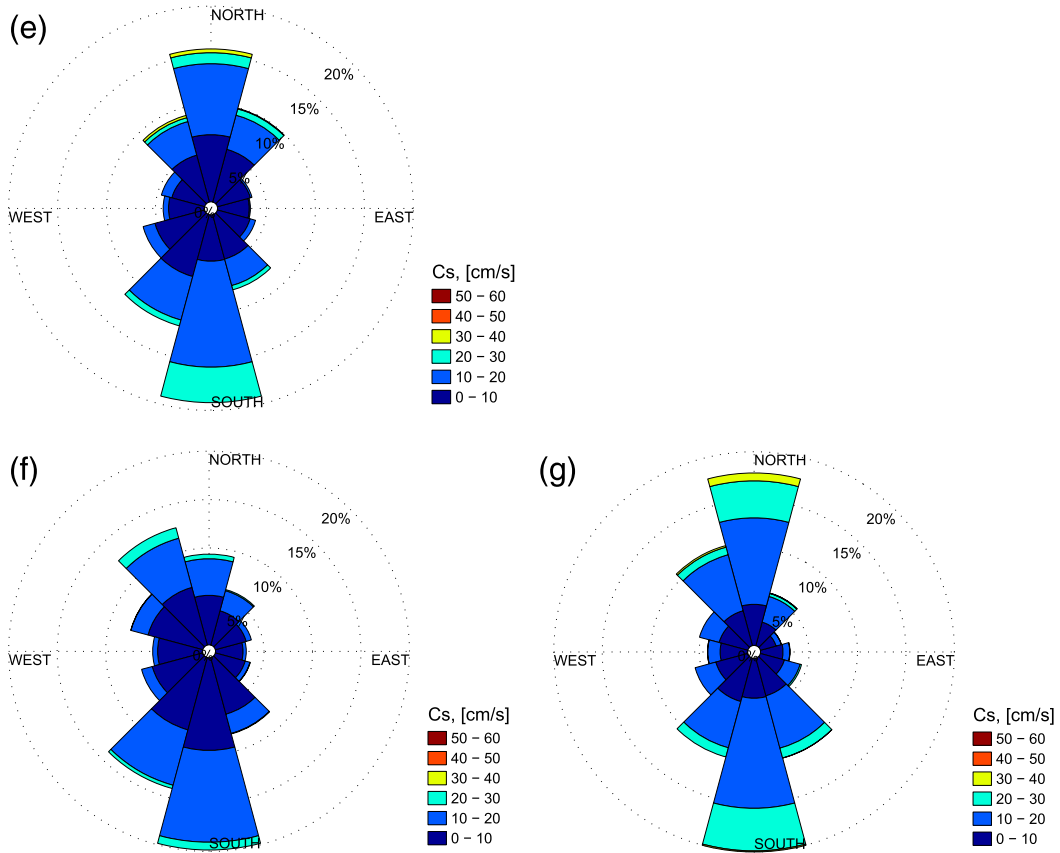
- the RMS error

FIG. 10. (*Continued*)

$$\mathrm{RMS}_{\mathrm{error}} = \sqrt{\frac{1}{N} \sum_N [(X_N - Y_N)^2]}, \qquad (3)$$

where X and Y are the different measured current data compared and N is the total number of simultaneously measured current data available for comparison

- the scatter index

$$\mathrm{SI} = \frac{\mathrm{RMS}_{\mathrm{error}}}{\overline{X}} \times 100\%, \qquad (4)$$

where $\overline{X}$ is the mean of the measured current speed taken as a reference for comparison, that is, RCM7 and CM04.

These measures of scattering are summarized in Table 4.

The difference$_{\mathrm{means}}$ for the measured current data available through all phases of CurVeS range from −6.01 to 1.87 cm s^{-1}. The largest difference$_{\mathrm{means}}$ are −5.17 and −6.01 cm s^{-1}, found when the RCM7 at 30-m water depth was compared with AQD and QM ADCP (CurVeS I), and the smallest are 0.56 and 0.63 cm s^{-1}, found when the RCM7 and LR ADCP (CurVeS I) and CM04 and AQD (CurVeS II), respectively, near the seabed were compared. These values of difference$_{\mathrm{means}}$ are in general larger than reported in previous work—see the last column of Table 1.

For the measured current data available through all phases of CurVeS, the estimated r range from 0.70 to

TABLE 2. Summary statistics of the different current measurements.

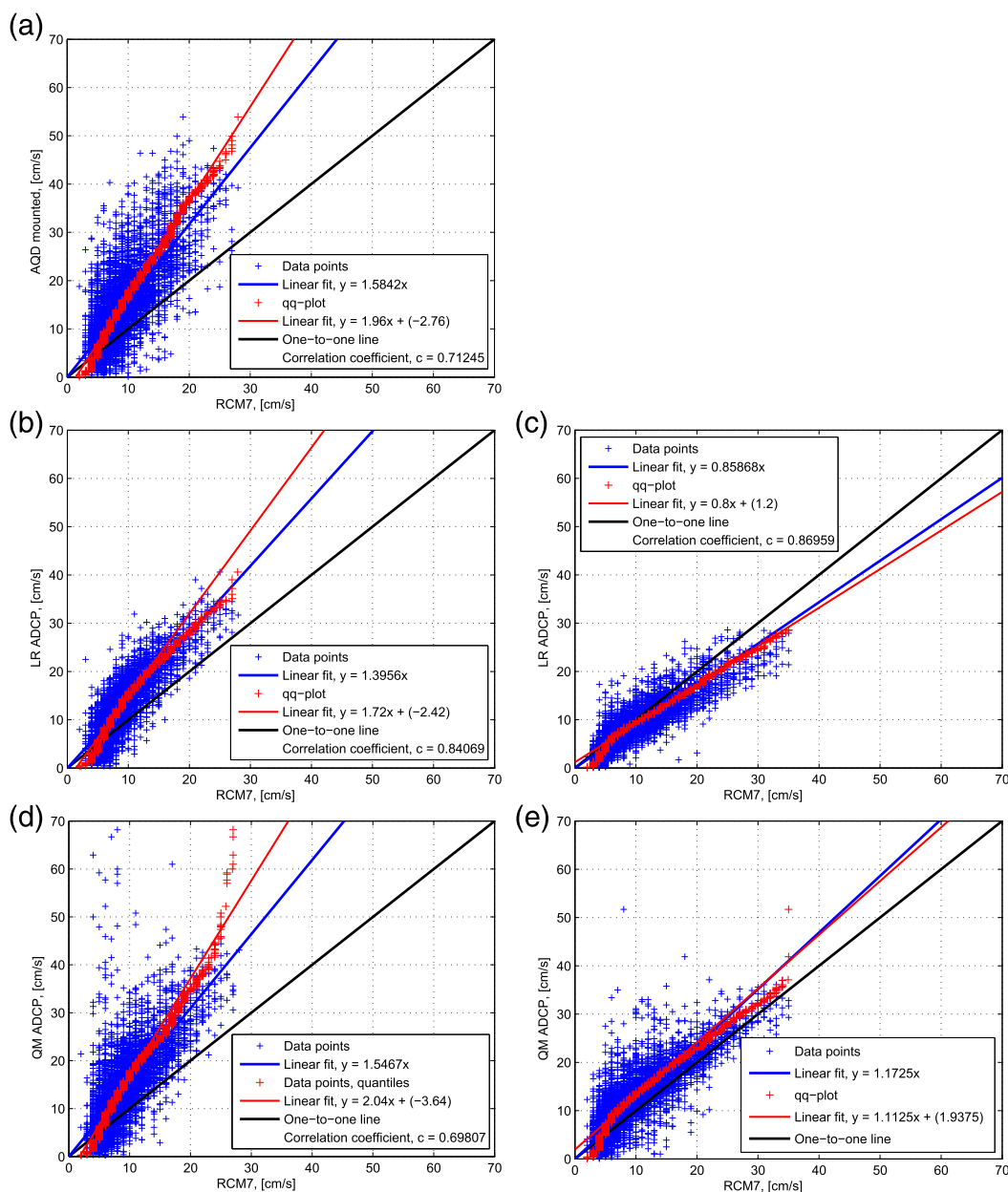| Water depth	Current speed (cm s^{-1})	RCM7	AQD mounted	LR ADCP	QM ADCP	QM ADCP 70-min mean
30 m	Mean	8.26	13.43	11.46	13.08	14.27
	Max	28.00	53.90	40.60	181.40	40.00
	Std dev	3.82	7.82	6.36	7.98	6.67
100 m	Mean	8.56	—	8.00	10.77	12.46
	Max	35.00	—	28.60	51.70	35.00
	Std dev	5.64	—	4.87	6.50	6.07

FIG. 11. Scatter and q-q-plots for the current measurements in CurVeS I: (a) RCM7 vs. AQD mounted - 30 m, (b) RCM7 vs. LR ADCP - 30 m, (c) RCM7 vs. QM ADCP - 30 m, (d) RCM7 vs LR ADCP - 100 m, (e) RCM7 vs. QM ADCP - 100 m.

0.92 and the corresponding r^2 range from 0.49 to 0.85. These values for r and r^2 are much lower than the corresponding values from previous work—see the last column of Table 1—which range from 0.95 to 0.99 and 0.97 to 0.99, respectively. As for difference in means, the smallest correlations were found when RCM7s are compared with AQD and QM ADCP at 30-m water depth (CurVeS I), respectively, and the largest correlations were found when RCM7 and LR ADCP at 100-m

water depth (CurVeS I), CM04 and AQD 3 m above the seabed (CurVeS II), and CM04 and AM ADCP (CurVeS III) were compared.

The RMS_{error} estimated for the measured current data, ranging from 2.97 to 8.10 cm s^{-1}, are in general quite comparable to the RMS_{error} reported for other current measurements—see last column of Table 1.

The SI is a measure of spreading when two different datasets are compared. The SI is usually estimated and
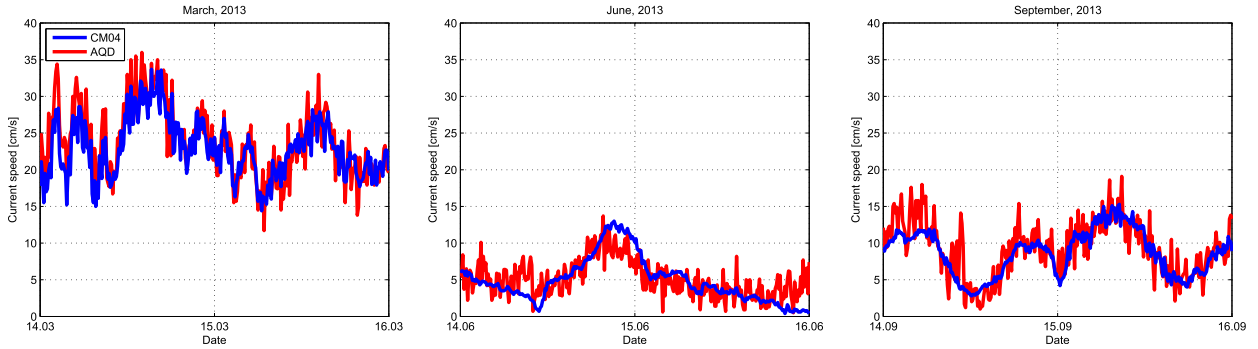
FIG. 12. Time histories of the available current measurements in CurVes II for two selected days each season.

used when the skill of hindcast data is compared to measured data. For comparison of measured and hindcast wave and wind data, an estimated SI between 10% and 15% indicates a good correspondence between data and an SI less than 25% indicates an acceptable correspondence (Cox and Swail 2001; Swail and Cox 2000). These criteria may also be used for comparison of other types of data.

The SI was estimated for the measured current data presented and compared here, although the SI has not been estimated in any of the previous published work concerning comparisons of current measurements. The values of SI range from 23.8% to 89.5%. Again, the smallest SI values of 29.8% and 23.8% were found for RCM7 and LR ADCP (CurVeS I) and CM04 and AQD (CurVeS II) near the seabed, respectively. The largest SI values of 87.8% and 89.5% were found for RCM7 compared with AQD and QM ADCP (CurVeS I) at 30-m water depth, respectively. The estimated SI values suggest that most of the compared current measurements do not compare well.

In general, the current conditions studied in previous work are benign or moderate, and thus it is reasonable to

assume that the mean current speeds (if those were estimated) are lower than the mean current speeds estimated in CurVeS—see Tables 2 and 3. The RMS$_{error}$ estimated for the CurVeS and previous data are found to be quite comparable. Based on the definition of SI, this implies that if the SI were estimated for the measured current data presented in previous work, then the SI would be larger than the SI estimated and given in Table 4. This reasoning is supported by the large estimated SI for the measured current data studied by Mayer et al. (2007), where both RMS$_{error}$ and the mean of the measured current speed were given. Thus, the SI could prove to be a good and complementary measure to the difference in means, correlation coefficient, and RMS$_{error}$ of how good measured current data at the same location and water depth compare.

5. Concluding remarks

Motivated by the potential in simultaneous met–ocean data for design and in order to be able to establish joint distributions for waves and currents, a met–ocean measurement program of waves and current profiles at
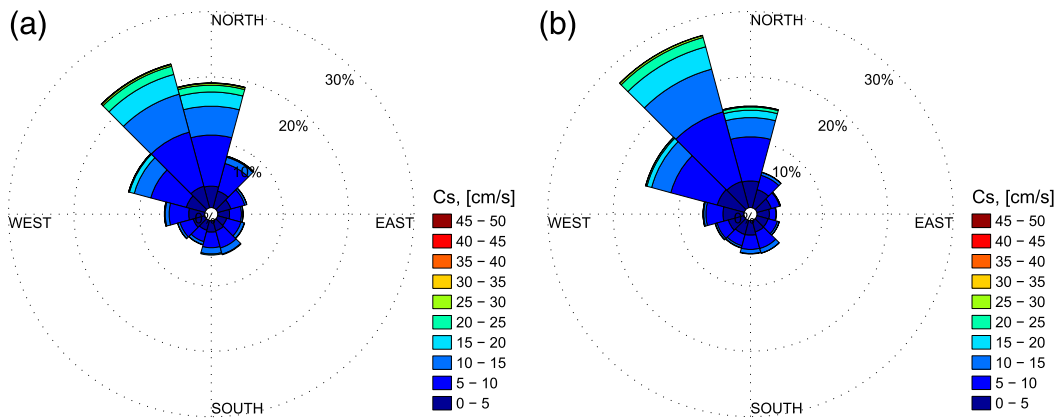

FIG. 13. Current roses for the available current measurements in CurVeS II: (a) AQD: 3 m above seabed and (b) CM04: 3 m above seabed.

TABLE 3. Summary statistics of the different current measurements.

Water depth	Current speed (cm s^{-1})	CM04	AQD
3 m above seabed	Mean	7.59	8.22
	Max	33.70	36.30
	Std dev	4.94	4.85

five locations in the northern North Sea was initiated in early 2011 and completed in late 2015. Despite quality control of the measured current data, these measured current speeds were found to contain more noise than expected, resulting in spikes in the data. Discrepancies between overlapping measured current speeds were also observed. Possible explanations for both the observed noise and discrepancies in the measured current speeds were discussed, but none of these are considered for explaining the amount of noise or the large discrepancies as observed. The main motivation of this article is to further investigate the noise and discrepancies seen in the quality-controlled time series of measured current speeds being used to establish design criteria for offshore structures, that is, from an engineering point of view. We also attempt to improve the knowledge of different methods and current meters for performing current measurements for the design of offshore structures.

A detailed overview of comparable previous comparisons of overlapping measured current data was given. These studies were performed with a variety of different acoustic and mechanical current meters deployed in different moorings types; at different locations all over the world's oceans; at different water depths, ranging from very shallow to very deep; in different wave and current conditions, such as very benign to severe; and through all four seasons of the year. In general, all comparisons of overlapping measured current data reach the same general conclusion: different current meters measuring the current speed at the same location and water depth compare well.

Three phases of the Current Verification Study (CurVeS) were described. The aim of these studies was
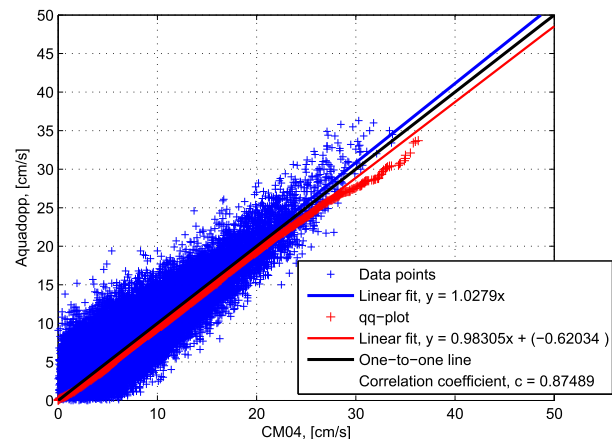

FIG. 14. Scatter and q–q plots for the available current measurements in CurVes II.

to give guidance on (i) how current measurements should be conducted in order to obtain high-quality current data for the design of offshore structures and (ii) how the uncertainties of the measured current data can be addressed and accounted for.

Through CurVeS I additional current measurements at one of the five measurement locations (location 4) was performed. The overall aim of this phase of CurVeS was to compare current speed and direction 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, at that time, ongoing met–ocean measurement program and to try to quantify the uncertainties prior to further analyses of these data. Current roses, summary statistics, time series, scatter, and q–q plots of current speeds at the same location and water depths were given. The differences in measured current speeds between the different current meters at the same location and water depths were much larger than the specified accuracies of the instruments and thus much larger than expected. Possible reasons for these differences in measured current speeds, such as surface waves,
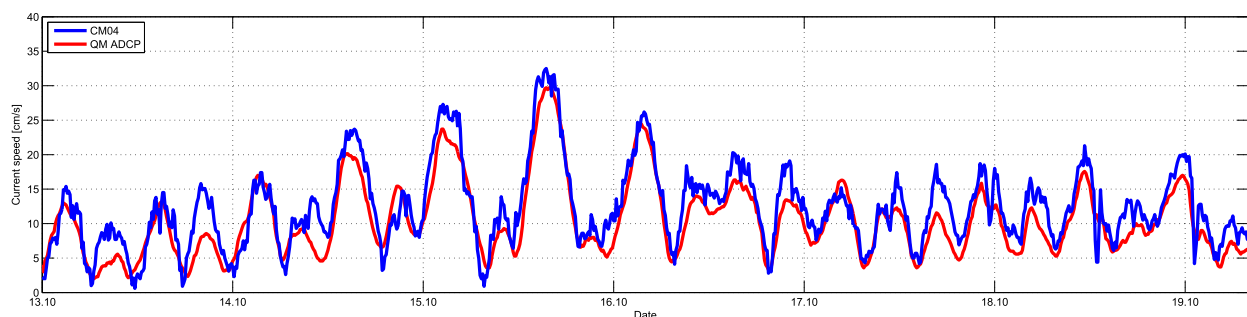

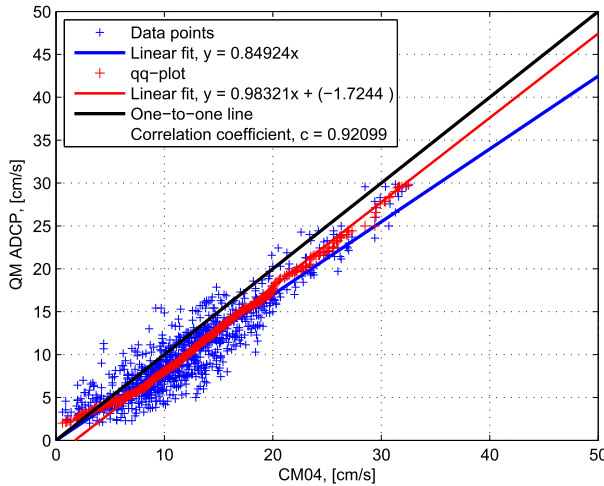FIG. 15. Time histories of the current measurements in CurVes III.

FIG. 16. Scatter and q–q plots of the current measurements in CurVes III.

temperature gradients, and local topography, were discussed. However, it is not clear that any of these could influence the current measurements to this extent and explain the very substantial differences as observed. The current speeds measured by the acoustic profiler suspended from the surface buoy (suspended AQD) were concluded to be of poor quality, due to the extensive influence of surface waves. Consequently, this mooring configuration is not recommended. The current speed measurements by the acoustic profiler mounted in the hull of the surface buoy (mounted AQD) were also somewhat influenced by surface waves and such current measurements are recommended to be treated with caution. It was not possible to draw any clear conclusions on how the uncertainties in measured current speed data should be considered in the design of offshore structures. Even though the uncertainties still need to be more formally considered, just to be aware of the uncertainties related to measured current data is an important finding.

Based on the lack of conclusive results from CurVeS I, a second phase of CurVeS was carried out, where existing measured current data collected by different acoustic and mechanical instruments at the same time, location, and water depth were analyzed and compared. This desk study is confidential with only the executive summary released for reference. As for CurVeS I, the main finding of CurVeS II is that "differences in observed current speed is much larger than the specified accuracy of the instruments, suggesting that the accuracy achieved in the field is less than the user might expect" (RPS MetOcean 2015, p. i). Two current meters of the same type (CM04) at the same location and water depth showed good agreement. This suggests that this type of current meter could be very appropriate to use as a reference current meter for future comparisons. However, it is necessary to determine whether these results hold for other water depths, flow, and wave regimes. Similar comparisons done by other current types are not available, so this conclusion could prove to hold for other types of current meters as well.

The third and so far last phase of CurVeS also consisted of additional current measurements at location 4. A new mooring with the same design and instruments as the now completed met–ocean measurement program was deployed. In addition, two CM04s, one each at 50- and 90-m water depths, were deployed for reference. The CM04 at 50 m did not work at all during the entire measurement period and no comparison of overlapping current speed could be made. The CM04 at 90 m worked, but the acoustic current meter to compare with QM ADCP worked for only 6 days, which is not sufficient for a proper comparison. Thus, no additional knowledge was gained through CurVeS III.

The previous studies of overlapping current measurements performed with different current meters at the same location and water depths are in contrast with the results of CurVeS. Both the difference$_{means}$ and r and r^2 are found to be larger for the measured current data available in CurVeS than for the previous work, but the estimated RMS$_{error}$ are quite comparable and have the same range. In general, the SI estimated for the

TABLE 4. Different measures of scattering in the measured current data.

CurVeS phase	Instrument depth (m)	Instruments	Difference in means (cm s^{-1})	Correlation		rms (cm s^{-1})	SI
				r	r^2		
I	30	RCM7, AQD	−5.17	0.71	0.51	7.97	0.878
		RCM7, LR ADCP	−3.20	0.84	0.71	5.18	0.573
		RCM7, QM ADCP	−6.01	0.70	0.49	8.10	0.895
	100	RCM7, LR ADCP	0.56	0.87	0.76	2.97	0.298
		RCM7, QM ADCP	−3.90	0.84	0.70	4.37	0.439
II	3 m above seabed	CM04, AQD	0.63	0.87	0.77	2.53	0.301
III	90	CM04, QM ADCP	1.87	0.92	0.85	2.93	0.238

measured current data available in CurVeS are large and suggest that the overlapping measured data do not compare well. Based on the general benign to moderate current conditions in the previous work and thus expected low to moderate mean values of current speeds, if the SIs were to be estimated for the measured current data compared in the previous work, then these are expected to be large as well. It is clear that when comparing different measured current datasets, several complementary measures of scattering between the data should be used in order to obtain unbiased and as complete information as possible about how well the data actually compare.

The three phases of CurVeS did not succeed in providing any clear guidance on how current measurements best could be conducted in order to obtain high-quality current data for the design of offshore structures and how the uncertainties of the measured current data best can be addressed and accounted for. The current measurements from phases I and III indicate that current measurements from instruments attached to a surface buoy will suffer from the influence from surface waves. Although several possible explanations for the uncertainties observed in the measured current data were discussed, these are not believed to fully explain the observed differences in measured current speeds. However, as current measurements are considered to be state of the art and superior to current modeling, a very important finding of CurVeS is that the accuracy of current measurements is not as good as specified for current meters and thus not as good as the user expects. Uncertainties like these are important to consider in the design of offshore structures, but how such uncertainties could best be implemented in the analysis of current speed data remains to be determined. Furthermore, the investigation of noise in measured current speeds and discrepancies found between measured current data at the same location and water depth raises two other fundamental questions: (i) how can the true current speed be found and (ii) how much is physically possible for the current speed to vary from one 10-min measurement interval to the next? Further work considering these two questions could lead to answers on the questions from which CurVeS originated.

To utilize that the occurrence of extreme wind, waves, and currents are not fully correlated in the design of offshore structures, Norwegian design regulations presently recommend at least 5 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 were primarily used and no available current hindcast for the Norwegian continental shelf (NCS) is considered to be of high enough quality. However, Bruserud and Haver (2016) compared measured and hindcast current data in the northern North Sea and found good correspondence. For instance, at 40-m water depth at location 4, the scatterplot of current speeds measured by the QM ADCP compared to model current speeds shows that the linear fit to data follows the one-to-one line closely and deviates only around 4%. Compared to Fig. 5a, this is significantly better than the linear fit to AQD and QM ADCP data, which deviate around 15% from the one-to-one line. Further work is required to determine whether these results hold when a larger database of both overlapping measured current data and measured-versus-modeled current data are examined. 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 that it must be used with caution. Nevertheless, this constitutes a very promising starting point for further development of an even better current hindcast for the northern North Sea.

Considering the quality of measured current data presented and discussed in this article, rather than to measure currents simultaneously with wind and waves for a long period, it might be more prosperous and appropriate to focus on the development of a high-quality current hindcast, validated with a shorter period of current measurements. 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.

APPENDIX

Current Meter Technical Specifications

This appendix summarizes how the basic principles of how the current sensors work and comments on other important characteristics of the sensors. The range, resolution, and accuracy of the different sensors are given in Table A1.

TABLE A1. Comparison of sensor specifications. Details of the vector-averaging and measuring current meters are not available.

Instrument	Variable	Range	Accuracy	Resolution
Aanderaa SG	Current speed	0–3 m s^{-1}	±1% of measured value or ±0.015 m s^{-1}	0.001 m s^{-1}
	Compass	0°–360°	±2°	0.1°
Aanderaa RCM9 and RCM11	Current speed	0–3 m s^{-1}	±1% of measured value or ±0.015 m s^{-1}	0.003 m s^{-1}
	Compass	0°–360°	±5° (0°–15° tilt), ±7.5° (15°–35° tilt),	0.35°
Nortek AQD	Current speed	±10 m s^{-1}	±1% of measured value or ±0.005 m s^{-1}	0.001 m s^{-1}
	Compass	0°–360°	±2°	0.1°
RDI QM ADCP	Current speed	±5 m s^{-1}	±1% of measured value or ±0.005 m s^{-1}	0.001 m s^{-1}
	Compass	0°–360°	±2°	0.01°
RDI WH ADCP	Current speed	±5 m s^{-1}	±0.3% of measured value or ±0.003 m s^{-1}	0.001 m s^{-1}
	Compass	0°–360°	±2°	0.01°
Aanderaa RCM7 and RCM8	Current speed	0.02–2.95 m s^{-1}	±4% of measured value or ±0.01 m s^{-1}	0.001 m s^{-1}
	Compass	0°–360°	±5° for measured values 0.05–1.0 m s^{-1}, ±7.5° for other values	0.35°
RDI DVS	Current speed	±5 m s^{-1}	±0.3% of measured value or ±0.003 m s^{-1}	0.001 m s^{-1}
	Compass	0°–360°	±2°	0.01°
RPS MetOcean CM04	Current speed	0–4 m s^{-1}	±1% of measured value or ± 0.01 m s^{-1}	0.001 m s^{-1}
	Compass	0–360°	±1°	1°

a. Acoustic current meters

The acoustic current meters discussed in this paper are both acoustic Doppler current profilers ADCPs and different types of single-point acoustic current meters ACMs. The Aanderaa Recording Current Meter RCM9 and RCM11, and Seaguard SG are examples of an ACM, and the Teledyne RD Instruments RDI 150-kHz Quartermaster ADCP QM ADCP, RDI 75-kHz Long Ranger ADCP LR ADCP, 400-kHz Nortek AquadoppAQD, and RDI Doppler Volume Sampler DVS are examples of ADCPs.

To measure current velocity, all the different acoustic current sensors use acoustic Doppler effects that depend on the speed of sound at the instrument head. The instrument head of the AQD consists of three transducers tilted at 25° relative to the centerline of the instrument, while the RCM9 and RCM11 and the SG, QM, WH, and LR ADCPs have four transducers tilted at 20°. The DVS has four transducers tilted at 45°. Each transducer independently transmits acoustic pulses into the water column. Portions of this energy are reflected by particles or air bubbles. The transducers detect the backscattered energy and calculate the change in frequency—that is, the Doppler frequency shift—in the signal. Based on this Doppler frequency shift, the current speed component along each of the transducer axes is calculated for each acoustic beam. Then, the measured current speed components are converted from the current sensor to an Earth-referenced current velocity using pitch, roll, and heading data obtained from the sensors inside the current sensor. By this, it is implicitly assumed that the flows in the four beams are the same. Current sensors that utilize the Doppler frequency shift to measure current velocity require a number of variables—all of which are related to the resolution of the measurements—to be configured, including the bin size, ensemble interval, number of pings per ensemble, and operating mode. All these variables affect the battery life and standard deviation of the current measurements. Thus, considerations of battery life weighted against the required resolution must be made.

The principal advantage of current sensors based on the Doppler frequency shift is that a single instrument can measure the current profile remotely from the instrument. The most important drawback is that calibration is performed only by the manufacturer and that is neither recommended nor practical to carry out on a regular basis. The assumption made when current speed components are transformed to Earth coordinates—that is, flow in the four beams is the same—can be poor due to wave orbital velocities.

b. Mechanical current meters

The mechanical current sensors discussed in this paper are vector-averaging current meter VACMs, vector measuring current meter VMCMs, and Aandreaa Recording Current Meter RCM7 and RCM8. Please note that the VACM and VMCM are no longer commercially available.

The VACM is a polar-sampling instrument and consists of a rotor to measure the current speed and a vane, a magnetic vane follower, and a magnetic compass to compute the direction relative to magnetic north. Time-averaged east and north displacements and velocities—that is, horizontal currents—are then computed. A disadvantage of this instrument is that damping of current might occur in the vane follower and compass.

The VMCM is developed to measure small horizontal mean currents in the presence of large, especially vertical,

current oscillations. It is an electromechanical sensor consisting of two pairs of orthogonal propeller sensors mounted approximately 38 cm apart in the vertical. The east and north components measured by both propeller pairs are combined during the recording interval to produce the net time-averaged east and north. The VMCM has a threshold flow rate of about $1\,\mathrm{cm\,s^{-1}}$. The direction is determined with a fluxgate compass to allow rotation of the components into geographical coordinates. A drawback of this sensor is that a relatively large sampling volume can be perturbed to an extent by the sensor itself, which results in erroneous measurements.

To measure current velocity, the RCM7 and RCM8 consist of a mechanical propeller to detect the water velocity and a vane to determine the direction of the flow. The difference between the two sensors is that the RCM8 is just a high pressure model for measurements down to 6000-m water depth.

The main advantage of a mechanical instrument is that they can be tested and calibrated in a laboratory. Some general disadvantages are apparent: small velocities are difficult to measure because of the need to overcome friction for the rotor and inertia of the vane, and biofouling can interfere with the current rotor and vane performance. In addition, the wave orbital velocities are often not well averaged out.

c. Other current meters

The most recently developed current sensor is the RPS MetOcean's CM04. This is a vector-averaging current meter that operates on an acoustic phase shift principle between transmitting and receiving transducers. The instrument head consists of four transducers, an acoustic mirror, and a fluxgate compass unit. Sound is transmitted through a small volume of approximately 10 cm and measures the Doppler shift caused by the current flow. The acoustic path is from transmitter to mirror to the receiver, so it is not dependent on the water's properties. The velocity components are internally rotated to a north–south, east–west coordinate system, using the orientation information from an internal compass. The resultant velocity components are then averaged over a specified period. The principal advantage of the CM04 is that the instrument can be calibrated in a towing tank or a constant flow flume. Very low power consumption coupled with a large battery and memory capacity allow CM04 measurements of long durations.

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