Ocean Dynamics

SIMULATED WIND-GENERATED INERTIAL OSCILLATIONS COMPARED TO CURRENT MEASUREMENTS IN THE NORTHERN NORTH SEA

--Manuscript Draft--

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Abstract:	Measured current speed data show that episodes of wind-generated inertial oscillations dominate the current conditions in parts of the northern North Sea. In order to acquire current data of sufficient duration for robust estimation of joint metocean design conditions, such as wind, waves and currents, a simple model for episodes of wind-generated inertial oscillations is adapted for the northern North Sea. The model is validated with and compared against measured current data at one location in the northern North Sea and found to reproduce the measured maximum current speed in each episode with considerably accuracy. The comparison is further improved when a small general background current is added to the simulated maximum current speeds. Extreme values of measured and simulated current speed are estimated and found to compare well. To assess the robustness of the model and also the sensitivity of current conditions from location to location, the validated model is applied at three other locations in the northern North Sea. In general, the simulated maximum current speeds are smaller than the measured, suggesting that wind-generated inertial oscillations are not as prominent at these locations and that other current conditions may be governing. Further analysis of the simulated current speed and joint distribution of wind, waves and currents for design of offshore structures will be presented in a separate paper.

Manuscript Number ODYN-D-17-00019: Simulated wind-generated inertial oscillations compared to current measurements in the northern North Sea

Authors' comments to review

Please note that the comments from both reviewers have been arranged by section of the paper for a better overview.

Comment	**Authors response**
Reviewer 1	
The changes made by the Authors in the manuscript and the response to the comments are satisfactory for me.	No response required.
Reviewer 2	
The review does not cover properly all of the questions that were raised previously.	Implemented to possible extent.
1. I still think this is an oversimplified model approach especially for the task that it tries to accomplish.	1. The main motivation of the presented work is <u>not</u> to model the general current conditions as good/correct as possible, but the aim of this work is to generate current data of <u>sufficient</u> quality and duration to perform joint modelling of waves and currents for design of offshore structures. As the reviewer points out, more extensive modelling efforts are required for that and this has also been done in a separate work, but for shorter period of 5 years. This work is described and referred in the Introduction and a comparison of the simulated current data to this more advanced modelling of current data has been included in Section 5. This comparison confirms that the simple model has the required skill, since the results compare very well.
2. If it is true that the simplified model is capable of estimating the extreme current values, it seems to fail in the estimates of the timing of when these events occur, which is a problem if the current-to-wave interaction needs to be accounted for (https://doi.org/10.1175/JPO-D-12-043.1).	2. For a robust joint consideration of waves and currents for design of offshore structures waves and currents are considered independently, wave-current interactions are not considered and only the maximum current speed in an episode of wind-generated inertial oscillations are of relevance and interest. Consequently, the timing of the simulated maximum current speed has not been focused much on and is considered outside the scope of this work. This has been further emphazised in the text and some figures removed as these seem only to be confusing and not contribute to main purpose of the present work.
3. Some physics should be better parametrised and a numerical model simulation could be run (even on a standard laptop) which would provide way more useful results than the ones presented here.	3. A more refined and advanced model, covering a shorter period of five years has been run. It requires quite substantial efforts to run such a model for a period of >50 years, which is the reason why the authors found it worth pursuing a much simpler current model with potential of giving current data of sufficient quality for the intended use. Running a more advanced current model may very well be done in the future and is considered outside the scope of this work, but the purpose of this work presented here has been to show that it is possible to acquire adequate current data by quite simple means.
4. Inertial currents depend on vertical stratification (see for instance Davies A.M. https://doi.org/10.1016/0079-6611(85)90032-1; and relevant bibliography). Inertial currents are baroclinic in nature and show phase / amplitude propagation along the water column often showing a node at mid-depth (https://doi.org/10.1175/1520-0485(1976)006<0879:AAOIOO>2.0.CO;2). the wind-to-current response is usually delayed with depth.	4. Stratification is discussed in Section 5 and argued not to be very explicit in this area (northern North Sea) within the mixed layer which the simple model is applied in.
5. No indication of the actual period of the inertial currents is given in the text, which is quite surprising in my opinion.	5. For a robust joint consideration of waves and currents for design of offshore structures, only the maximum current speed in an episode of wind-generated inertial oscillations are of relevance and interest. Consequently, the periods of the wind-generated inertial oscillations are not of interest or relevance in this context and considered outside the scope of this work. If operations conditions, rather than design

	conditions, for marine structures were of interest, then the period of the inertial oscillations would be highly relevant.
Editor	
1. I tend to agree with the concerns expressed by Reviewer #2 on the timing of the modeled events; I wish you could address them with some more analysis and better discuss them providing some plausible explanations in the next round of revision. 2. In addition to that, a brief recall to wave-current interactions could probably be added, in order to better set the scene. There is enough literature around on this, DOI: 10.1016/j.ocemod.2016.03.007 or http://dx.doi.org/10.1016/j.pocean.2014.08.015, and references therein cited.	Implemented to possible extent. In general, Review #2's main concern about the simple model beeing too simple has been address by including a description and reference to such a work (which actually has been done) as well as a comparison of these current data. 1. See comment 2 above. 2. See comment 2 above. In addition, in the storm conditions relevant for design of offshore structures (which typically have dimensions of 80 x 80 m), the sea and upper part of water column will be very chaotic, so any wave-current interactions is not considered to be relevant or contribute on such a scale or in such weather conditions. This is discussed briefly.

TITLE

SIMULATED WIND-GENERATED INERTIAL OSCILLATIONS COMPARED TO CURRENT MEASUREMENTS IN THE NORTHERN NORTH SEA

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ABSTRACT

Measured current speed data show that episodes of wind-generated inertial oscillations dominate the current conditions in parts of the northern North Sea. In order to acquire current data of sufficient duration for robust estimation of joint metocean design conditions, such as wind, waves and currents, a simple model for episodes of wind-generated inertial oscillations is adapted for the northern North Sea. The model is validated with and compared against measured current data at one location in the northern North Sea and found to reproduce the measured maximum current speed in each episode with considerably accuracy. The comparison is further improved when a small general background current is added to the simulated maximum current speeds. Extreme values of measured and simulated current speed are estimated and found to compare well. To assess the robustness of the model and the sensitivity of current conditions from location to location, the validated model is applied at three other locations in the northern North Sea. In general, the simulated maximum current speeds are smaller than the measured, suggesting that wind-generated inertial oscillations are not as prominent at these locations and that other current conditions may be governing. Further analysis of the simulated current speed and joint distribution of wind, waves and currents for design of offshore structures will be presented in a separate paper.

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KEYWORDS

Currents, wind-generated inertial oscillations, measurements, simulations, northern North Sea

ABBREVIATIONS

c	empirical damping coefficient
C_D	drag coefficient
Cs	current speed
Cs_{back}	background current speed
Cs_{max}	maximum current speed during an episode of wind-generated inertial oscillations
$CsDir$	current direction, degrees clockwise from north towards which the current is flowing
D_0	mixed layer depth, [m]
F	wind stress force, x component
f	Coriolis parameter, $2\Omega sin\varphi$
G	wind stress force, y component
Hs	significant wave height
NCS	Norwegian Continental Shelf
φ	latitude, °N
Ω	rotation of the Earth, $7.29 \cdot 10^{-5}$ s^{-1}
ρ_a	air density
ρ_w	water density
q	annual probability of exceedance
$\boldsymbol{\tau}$	wind stress, vector
τ_x	wind stress, x component
τ_y	wind stress, y component
θ	wind direction, degrees clockwise from north towards which the wind is blowing
u	wind-stress induced current, x component
v	wind-stress induced current, y component
$\boldsymbol{W}$	wind velocity
Ws	wind speed
Ws_{max}	maximum wind speed during an episode of wind-generated inertial oscillations
$WsDir$	wind direction, degrees clockwise from north from which the wind is blowing

1. INTRODUCTION

Design and operation of marine structures, such as offshore oil- and gas-producing facilities, wind power plants and pipelines, require knowledge of the extreme meteorological and oceanographic (metocean) conditions and loading. Design codes stipulate that offshore structures should be designed to exceed specific levels of reliability. To define extreme environmental loading, extreme metocean design criteria, primarily wind, waves and currents, must be specified. Accurate estimates of metocean design conditions, based on measured and/or hindcast data, are of fundamental importance for the reliability and thus safety of marine structures over time.

For the Norwegian Continental Shelf (NCS), Norwegian design standard, NORSOK N-003 (NORSOK 2017), define the extreme metocean loads and load effects in terms of their annual probability of exceedance, q. The requirements for ultimate limit state and accidental limit state (ULS and ALS) for metocean actions on an offshore structure are $q \leq 10^{-2}$ and $q \leq 10^{-4}$, respectively. These requirements refer to the resulting metocean load obtained by accounting for the joint occurrence of environmental parameters such as wind, waves and current. The parameters are not fully correlated and to utilize this for design, joint data of good quality covering several years are required.

In lack of sufficient joint data, the Norwegian design standard, NORSOK N-003 (NORSOK 2017), recommends 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, NORSOK N-003 (NORSOK 2017) recommends at least three years of joint wind, wave and current data to base estimation of joint design criteria.

For wind and waves at NCS, both measured and hindcast data of sufficient quality and duration are available. During the last decades, wind and wave models have been improved and consequently also the quality of available wind and wave hindcast data. Validated hindcast data, i.e., hindcast data found to compare well with corresponding measurements, are often preferred when establishing metocean design criteria, due to the long periods of continuous data. For the Norwegian waters, the Norwegian Reanalysis Archive (NORA10) hindcast (Reistad et al. 2011) and the NEXTRA hindcast (Francis 1987; Oceanweather Inc. 2014; Peters et al. 1993) hold high quality and are widely used.

For currents, measured data are considered state of the art. Some current hindcast data are available, but they are not considered to be of sufficient quality for design purposes. Thus, only measured current data are considered to hold the required quality for a joint consideration of metocean parameters. A challenge is that current measurements are rarely performed for more than one year, so the duration of measured current data is not sufficient. Consequently, the limiting factor for estimation of joint metocean conditions for design of marine structures at NCS is the duration of available current data.

A metocean measurement programme has been performed at five locations in the northern North Sea for nearly five years, initiated early 2011 and completed late 2015 (Bruserud and Haver 2017a; Bruserud and Haver 2017j). However, challenges related to the quality of measured current data have been reported lately and it has been suggested that the accuracy of measured current data might not be as good as the user initially anticipated (Bruserud and Haver 2017g).

Recently, a new current hindcast, the Northern North Sea Current Hindcast Study (NoNoCur) has been developed (Danish Hydraulic Institute 2012), covering a continuous period of five years from January 2008 to December 2012. This current hindcast incorporates the latest advancements in both model physics and computational efforts and as such represents the state-of-the-art when compared to alternative current hindcast databases. Compared to available measured current data in the northern North Sea, the new current hindcast shows a good correspondence (Bruserud and Haver 2016). The quality of the current hindcast is not as good as the quality of available wind and wave hindcast for the northern North Sea/NCS and must be used with some caution. In addition. considering the large inter-annual variations in current conditions in the northern North Sea (Bruserud and Haver 2017j) the period covered by this hindcast is considered too short for reliable consideration of joint metocean models. Nevertheless, this hindcast constitutes a very promising starting point for further development of an improved current hindcast for the northern North Sea.

In summary, neither the recent measured nor hindcast current data succeed completely in providing the current data required to establish joint distributions of metocean parameters in the northern North Sea. Considering the quality of measured current data, long periods of simultaneous metocean measurements of wind, wave and currents could still be insufficient for estimation of joint metocean conditions. It could prove more adequate and prosperous to further develop available modelled current data, to obtain sufficient current data for estimation of joint metocean conditions.

The measured current data showed that currents from wind-generated inertial oscillations dominate the current conditions in the northern North Sea and also generate the largest observed current speeds (Bruserud and Haver 2017a). Following this, a simple mathematical model for wind-generated inertial oscillations can be applied to simulate current conditions of a longer duration for the northern North Sea. Tuned with appropriate site-specific parameters for the northern North Sea and validated against available measured current data, such a simple model has the potential to generate current data sufficiently accurate to represent the maximum current speed in a storm event with large current speeds. The motivation of such a current modelling would not be to model all aspects of the current conditions as correct as possible during a long period, but to model the current conditions of relevance, i.e. current speed, for performing joint modelling of waves and currents for design of offshore structures. Since such a simple approach may be found sufficient considering how the modelled current data are intended to be used, it is worth first pursuing such a simple modelling of current conditions to acquire the current data of a long duration, rather than applying a more refined and costly modelling of current conditions, such as used for NoNoCur.

The main purpose of this work is to acquire current data covering several years, by as simple as possible means, but still with the quality considering necessary for the intended use of these data to perform joint modelling of waves and currents for design of offshore structures. The focus of this paper is on description, application and validation of a simple model for wind-generated inertial oscillations at one location in the northern North Sea. First, this paper provides a concise overview of the general current conditions in the northern North Sea and arguments for why wind-driven currents dominate the current conditions in the northern North Sea, before current measurements of wind-generated inertial oscillations in the northern North Sea are discussed. Next, the simple model for wind-generated inertial oscillations is described, before application and validation of the model at one selected location in the northern North Sea are discussed. Several other locations in the northern North Sea are briefly considered. At last, a summary is made.

2. GENERAL CURRENT CONDITIONS IN THE NORTHERN NORTH SEA

Current velocity can be considered divided into different components, e.g. Jonsson (1990), Faltinsen (1990), classified according to forces that act on the water masses; tidal currents, large-scale ocean currents, wave-induced currents and wind-driven currents. In addition, local density-driven currents and currents due to set-up phenomena and storm surge can contribute to the currents in the upper part of the water column.

In deep water past the shelf break, tidal currents are generally weak and in the central northern North Sea, between 59 to 61ºN and 1 to 3 ºE with water depths ranging from typical 75 to 200 m, tidal variations of water level are of the order decimeters. Thus, the tidal currents are very small and often not considered separately.

Large-scale ocean currents depend on geographical location. The main circulation in the Norwegian waters was first described by Helland-Hansen and Nansen (1909), with more detailed description of the current systems at and close to the NCS given by Sætre and Gjøen (1971) and in the northern North Sea by Dooley (1974). As the oil and gas industry developed and expanded from the southern North Sea into the northern North Sea during the 1970ties and 80ties, extensive mapping and investigations of current conditions followed (Førland 1985; Sætre 1983; Sætre 2007). In general, no large-scale ocean currents are found to influence directly the central northern North Sea east of Scotland.

Wave-induced currents are generated by both surface and internal waves. In deep water, Stokes drift dominates the surface wave-induced currents, but when the mean current velocity at a fixed point is considered as here, Stokes drift will not contribute to the current speed, see for instance Kundu et al. (2016). At the NCS, internal waves have only been observed and reported at the Ormen Lange location in the Norwegian Sea, where the water depth is 850 m and the water masses have a distinct density-stratification (Alendal et al. 2005; Grue and Sveen 2010). Thus, there are no indications that internal waves are present in the central northern North Sea.

Wind-driven currents are often approximated by 1 to 3 % of the 1-hour wind speed at 10 m above sea level. The direct response of the ocean to the wind stress, is called Ekman transport. Away from boundaries, a change of wind, either speed and/or direction, can cause oscillations in the existing Ekman transport, which is referred to as wind-generated inertial oscillations. According to Dooley (1974), the currents between Shetland and the Norwegian Trench are principally wind-driven.

Based on the different current velocity components discussed for the northern North Sea, it is reasonable to assume that the general current conditions are dominated by wind-driven currents. However, some additional contributions to the total current conditions will always be present and is here considered to be a general background current.

3. MEASUREMENTS OF INERTIAL OSCILLATIONS

3.1. Current measurements

A metocean measurement programme of simultaneous waves and current profiles at five locations in the northern North Sea was initiated early 2011, see Fig. 1. A brief summary of the measurement campaign is given here and more details can be found in Bruserud and Haver (2017a).

First, a pilot phase was performed at Location 1 from January to May 2011, before the 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. At the other locations, the measurements were completed in October 2015, i.e. a total duration of about 4.5 years. An overview of the water depths and data return rates 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. The surface mooring consisted of a Wavescan buoy to measure surface waves, with a Nortek 600 kHz Aquadopp (AQD) attached in the hull to measure near-surface current speed (*Cs*) and direction (*CsDir*). The seabed mooring consisted of a RDI 150 kHz Quartermaster (QM) ADCP and a RDI 1200 kHz Workhorse (WH) ADCP to measure the *Cs* and *CsDir* throughout the entire water column and near seabed, respectively. Sea temperature and salinity measurements were also done near seabed.

The wave measurements were done with a sampling interval of 30 minutes. All current profilers were set to record samples at 10-minutes intervals. The ping interval was originally set to 10 seconds, but from October 2013 shortened to 2.5 seconds. The ping interval was changed in an attempt to reduce the noise observed in the measured current data. Following this change, in ping interval, the measured *Cs* did not present the same amount of noise as seen before and were somewhat improved. All measured data were transferred in real-time by satellite.

Although extensive quality control of the measured current data have been done, the accuracy of the measured current data were found to be less than the specified accuracies of the instruments, see Bruserud and Haver (2017g). Large fluctuations in the subsequent measured 10-minutes *Cs* are seen in the upper levels of the current data measured by the upward looking current profiler placed in the seabed mooring. This is resulting in large spikes in the measured current data, which are too large to be real variations in *Cs*. Discrepancies were observed between overlapping current data, i.e. the *Cs* measured at the same water depth by two different current profilers (the downward looking current profilers placed in the hull of the surface buoy and the upward looking current profilers placed in the seabed moorings) differ significantly. The bottom topography near all the measurement locations were analyzed, but no local bottom topographic forms which would cause local disturbances which again would affect the current field were identified. Extensive efforts have been made to resolve these quality issues with measured current data, see Bruserud and Haver (2017g), but have so far not succeeded. As a preliminary, preemptive measure until more insight is acquired, the *Cs* and *CsDir* from the surface and down to 40 m water depth are not considered to have sufficient quality to be included in further analysis. Consequently, neither current data measured by the ADQ are nor from the QM ADCP down to 40 m water depth have been analyzed further. In this work, measured current data from the QM ADCP has been utilized. In addition, a 70-minutes running mean is applied to the measured *Cs* at all other water depths.

3.2. Inertial oscillations

The extensive measured wave and current data set from the northern North Sea has been analyzed to describe and give new insight about both the general and inter-annual current conditions at three selected water depths (40 m, 80 m and 3 m above seabed) at the four locations; see Bruserud and Haver (2017a); Bruserud and Haver (2017j) for further details.

One of the main findings in that paper is the observation and description of wind-generated inertial oscillations resulting in regular oscillations with large peak *Cs* through the entire water column. Inertial oscillations with smaller *Cs* are also observed. These wind-generated inertial oscillations resulting in large *Cs* are clearly the dominating and governing current conditions at Location 2, 4 and 5. In addition, another small contribution to the current conditions, taken as a general background current or noise, is apparent in the measured current data in the upper part of the water column.

An example of a typical episode of wind-generated inertial oscillation during August 2014 at Location 4 and 5 is shown in Fig. 2. Time series of *Cs* at 40 m, 80 m and 3 m above seabed are given and regular oscillations in *Cs* with large peak values of *Cs* are seen. It is noticed that the values of *Cs* decrease with increasing water depth. The oscillations in *Cs* are seen to gradually decrease with time until they are not apparent in the measured current data, after around 3 to 4 days. The inertial oscillations disappear because they are either dampened completely or disturbed by other counteractive weather phenomena such as changing dominating wind conditions. The general background current at 40 m is seen to be varying between 2.5 to 10 cm/s. Just before the inertial oscillations start, relatively large wind speeds (*Ws*) in the range 15 m/s to 20 m/s, with a peak value of around 20 m/s, are observed. The magnitude of the inertial oscillations *Cs* is primarily controlled by strength of the wind, but the depth of the mixed layer also affects the generated *Cs*. During summer when the mixed layer is relatively thin, currents associated with inertial oscillations can be reasonably large. Thus, there is no typical seasonality in episodes of inertial oscillations generating large *Cs* values. Due to this, the seasonal maximum *Cs* values during summer are actually larger than during the spring and autumn at Location 4 and 5. As seen in Fig. 2, at 40 m water depth at Location 4 and 5, the maximum *Cs* is reached in August 2014 with *Cs* around 60 cm/s and 80 cm/s, respectively,

Bruserud and Haver (2017a) found that the current conditions at Location 1 differ from the three other locations. As Location 1 is located further north in the northern North Sea in an area with steeper bottom topography and larger water depths, than the other 3 locations, other phenomena than wind-generated inertial oscillations such as large-scale current contribute to the current conditions here.

4. MODEL FOR WIND-GENERATED INTERTIAL OSCILLATIONS

Near-inertial oscillations are an intermittent phenomenon, commonly observed in the oceans from subtropical to polar latitudes. Increased use of current meters through the 1960ties provided several examples of the occurrence of inertial oscillations. Webster (1968) gave a complete overview of these observations of inertial oscillations; discussed their properties and summarized the theories put forward to explain them. Based on a model for the ocean response forced by wind stress, Pollard (1970) concluded that "most of the properties of inertial oscillations observed near the ocean surface could be explained under the hypothesis that they were generated by winds". This model was simplified, i.e. inertial current oscillations were computed based on measured surface winds only, and compared with measured current data by Pollard and Millard (1970). In support of the previous conclusion that inertial oscillations are predominantly locally generated by surface winds, the results showed a surprisingly good resemblance between simulated and measured currents. The model is still widely used to simulate near-inertial currents forced by wind; in comparison with measured current data, e.g. Chaigneau et al. (2008); D'Asaro (1985); DiMarco et al. (2000); Firing et al. (1997); Knight et al. (2002); Kundu (1976); Paduan et al. (1989); Pollard (1980), Kim and Kosro (2013) and in ocean modeling, e.g. Alford (2001); Ridgway and Condie (2004); Watanabe and Hibiya (2002). While useful for many different types of investigations, such a simple model has limitations and would obviously not describe phenomena related to e.g. wave-current interactions or stratification such as mixing due to passing storms, coupling between mixed layers and lower layers, production of internal waves and the effect of bottom friction in shallow water. However, with this motivation here of modelling current data of an adequate quality covering several years for a very specific use in estimating joint wave and current conditions for design of offshore structures, the benefit of such a simple model is considered more important than the limitations of the model.

Pollard and Millard (1970) presented the following simple model for the mixed surface layer to generate wind-stress induced currents

$$\frac{\partial u}{\partial t} - fv = F - cu \qquad (1)$$

$$\frac{\partial v}{\partial t} + fu = G - cv \qquad (2)$$

Where *u* and *v* [m/s] are the horizontal *x* and *y* current components of the wind-stress induced currents, *f* [s^{-1}] is the Coriolis parameter or inertial frequency defined as $2\Omega sin\varphi$ where Ω is the rotation of the Earth equal to 7.29 · 10^{-5} s^{-1} and φ is the latitude [°N] of the location considered, *F* and *G* [m/s^2] are the horizontal *x* and *y* force components from the wind stress and c [s^{-1}] is an empirical damping coefficient, sometimes called a "Rayleigh friction" parameter, introduced to allow for losses of energy from the wind generated surface currents. The model is according to the coordinate system used by convention in oceanography with the x-axis positive eastwards and the y-axis positive northwards.

Since the model is unstratified, the inertial frequency f will only be the natural frequency of the water layer. The force components from the wind stress can be expressed by

$$F = \frac{\tau_x}{\rho_w D_0} \quad (3)$$

$$G = \frac{\tau_y}{\rho_w D_0} \quad (4)$$

where τ_x and τ_y [kg/ms^2] are the wind stress x and y components, ρ_w [kg/m^3] is the water density and D_0 [m] the mixed layer depth through which the wind stress is distributed as a body force. The wind stress can be computed from

$$\boldsymbol{\tau} = \rho_a C_D |\boldsymbol{W}|\boldsymbol{W} \quad (5)$$

i.e.

$$\tau_x = \rho_a C_D Ws^2 sin\theta \quad (6)$$

$$\tau_y = \rho_a C_D Ws^2 cos\theta \quad (7)$$

where ρ_a [kg/m^3] is the air density, C_D the dimensionless drag coefficient and $\boldsymbol{W}$ [m/s] the wind velocity with $Wssin\theta$ and $Wscos\theta$ [m/s] denoting the x and y components of wind speed. To allow for losses of energy from the wind-generated surface currents, a decay factor of the form e^{-ct} is introduced where c^{-1} (unit s) is the e-folding decay time. Further description and details of the model can be found in (Kundu 1976) and Kim et al. (2014).

5. APPLICATION AND VALIDATION OF THE MODEL AT LOCATION 4

5.1. Application

To apply the Pollard-Millard model to simulate time series of wind-generated current components *u* and *v*, time series of wind velocity, ***W***, and the numerical values of the parameters ρ_w, ρ_a, C_D and D_0 are needed to estimate the force components, *F* and *G*, from the wind stress, $\boldsymbol{\tau}$. An estimate for the damping coefficient, *c*, must also be given.

At the NCS, the Norwegian Reanalysis Archive (NORA10) hindcast comprise high-quality wind and wave data (Bruserud and Haver 2016). The NORA10 hindcast is a regional hindcast for the northeast Atlantic, including the North Sea, the Norwegian Sea and the Barents Sea, developed by the Norwegian Meteorological Institute (Aarnes et al. 2012; Reistad et al. 2011). The period of NORA10 data available for this study is September 1957 to January 2015. However, the NORA10 is extended continuously and updated with a delay of approximately 2 months. The data are assumed to be homogenous through this entire period, although the data quality has probably improved somewhat with time as more measured meteorological data have become available. The time step of the hindcast data is 3 hours. In principle, this time step gives the conditions at that exact point of time, i.e. not any sort of 3 hours averaging, but in practice the NORA10 hindcast data are assumed to represent a 1-hour mean value. Such a time step is considered to be adequate for the northern North Sea, where tropical cyclones are the dominating storm conditions.

For the North Sea, reasonable approximate values for the sea water and air densities ρ_w and ρ_a are 1.0 g/cm^3 (1.0· 10^3 kg/m^3) and 1.22 · 10^{-3} g/cm^3 (1.22 kg/m^3) respectively (United Kingdom Hydrographic Office 2011; United Kingdom Hydrographic Office 2012) .

Values of the drag coefficient, C_D, are found by measurements, but as measurements over the ocean are more difficult to perform than over land, less is known about how C_D varies over the ocean, particularly at high wind speeds. Several different empirical relations for C_D, based on measurements, have been proposed and are in use, e.g. Smith (1980), Yelland and Taylor (1996), and a typical value for C_D is 1.3 · 10^{-3}. For storm conditions C_D is in the range 2.75 – 3.0 · 10^{-3}, which also seems to be an upper limit for the measured C_D. Since episodes with strong wind, where the peak *Ws* exceeds 25 m/s, are of interest here, a large value of C_D is considered appropriate. Setting C_D equal to 3.0 · 10^{-3} yields values of simulated *Cs* comparable to the measured *Cs* and this value of C_D is selected to use in the simulations. This is also in accordance with Young (1999) Fig. 5.2.

The mixed layer depth, D_0, can be estimated from measurements of sea temperature or salinity profiles. Such measurements are not available for any of the measurement locations, but measured profiles for the entire northern North Sea area can be found in the World Ocean Database (Johnson et al. 2006). In the northern North Sea, the mixed layer depth is seen to have a very distinct seasonal variation; in the summer and early autumn the mixed layer is relatively thin and around 50 m deep, while the mixed layer the rest of the year goes nearly through the entire water column down to 70 – 80 m water depth. From Eqn.(1) and (7), it is seen that D_0 also contributes to the magnitude of the simulated *Cs*. Thus, the magnitude of D_0 was varied between 50 and 90 m and also tested with different defined seasonality in the simulations. Based on these sensitivities D_0 is set to 50 m in the summer months, i.e. June, July and August, and to 80 m for the rest of the year. In additions, this confirms that there is not much vertical stratification in this part of the northern North Sea and thus the adequacy of an unstratified model such as the Pollard-Millard model.

Reasonable estimates of the damping coefficient, *c*, can be made from the measured current data. When time series of the inertial oscillations generating the largest current speeds are inspected, the inertial oscillations are either dampened completely or disturbed by other weather phenomena after 3 to 4 days. Accordingly, *c* (unit s^{-1}) was varied in the range 2 to 5 days and also set to 20 days in the simulations. The larger *c*, the longer duration of the simulated inertial oscillations. Following the measured data and the sensitivity studies, *c* is set to 5 days to ensure that the entire episodes of inertial oscillations are included in the simulations.

With this, Eqn. (1) and (2) were integrated forward using a Runge-Kutta scheme, see Dormand and Prince (1980) or any elementary textbook on differential equations and boundary value problems such as Boyce and DiPrima (2012), to obtain time series for the wind-generated inertial current components, *u* and *v*. The simulations were done with an input time step of 3 hours, corresponding to the time step of NORA10 wind data, but simulated wind-generated inertial currents can be extracted for any required point of time during the simulations. Since current measurements at the NCS are normally performed with a 10-minute time step, simulated wind-generated inertial currents were extracted for every 10-minutes interval.

5.2. Validation

The model has been validated at Location 4. For validation of the model, measured current data by the QM ADCP at 40 m water depth, described in Section 3, has been used. Since the model is validated against “real”, measured current data, the effect of any wave-current interactions on the current conditions would be implicitly accounted for since the current speed is measured when waves are present. Further considerations of the effect of wave-current interactions are not relevant within the context of this paper, but may be subject to further work.

The period of current measurements is called the validation period. The validated model was then used to perform simulations at Location 2 and 5 and at Location 1, although other current conditions than wind-driven currents are believed to be governing at the latter location. Thus, the robustness of the validated model can be assessed by comparing the results for Location 1, 2 and 5 with measured data at the respective locations. However, some site-specific adjustment of the model will probably be required at the other locations to obtain optimal results.

As this work is motivated by the need for a long time series of simultaneous wind, wave and current data of good quality to establish reliable extreme response values for design of offshore structures, the largest values of *Ws*, significant wave height (*Hs)* and *Cs* are of interest. Consequently, it is reasonable to perform the simulations of wind-generated inertial currents for episodes of strong winds, i.e. typically wind speeds exceeding 15 m/s. To ensure that the appropriate strong wind episodes generating the largest *Cs* are selected, all episodes of the largest measured *Cs*, i.e. *Cs* exceeding 40 cm/s, were identified. The time between the episodes of large *Cs*, a so-called decorrelation time, was required to be 36 hours. A total of 25 episodes with maximum *Cs* (Cs_{max}) larger than or equal to 40 cm/s were identified within the validation period. Out of these 25 episodes, 18 episodes are clearly seen to be inertial oscillations and 7 episodes more undefined. A typical inertial oscillation is shown in Fig. 3 (a) where oscillations in *Cs* are very evident with several peaks of large *Cs* close to 50 cm/s. The corresponding wind conditions are also shown and *Ws* is seen to exceed 20 m/s for more than 2 days, coming from a nearly constant southeasterly direction of 120°. An example of a large *Cs* episode not explained by an inertial oscillation is shown in Fig. 3 (b) where only one large *Cs* peak of around 50 cm/s is seen and no oscillations of *Cs* values around this peak.

The corresponding wind conditions before, under and after the 18 episodes of large currents generated by inertial oscillations were then scrutinized. The maximum *Ws* (Ws_{max}), the spread in wind direction (Δ *WsDir*) and the duration of *Ws* exceeding certain levels were considered. Based on this investigation, different wind conditions selection criteria were defined to select the wind episodes generating the largest *Cs* from the NORA10 data to be used in the simulations. To ensure selection of the right wind episodes for simulation of wind-generated currents, enough episodes of strong winds during the validation period must be included to be able to do a proper validation of the model. First, quite strict selection criteria were applied with little Δ *WsDir*, starting at 30°, long duration of *Ws*, starting at 24 hours, exceeding a relatively high threshold, starting at 25 m/s. These criteria were gradually loosened until all the typical inertial oscillation episodes generating large *Cs* exceeding 40 cm/s were included in the selection and also a sufficient number of strong wind episodes during the validation period. The final wind criteria for selection of strong wind episodes as input in the simulations are *Ws* > 12 m/s for at least 15 hours and Δ *WsDir* < 100°. The different tested selection criteria and the resulting number of wind episodes during both the entire NORA10 and the validation period are summarized in Table 2. In total, 223 episodes of strong winds have been selected during the validation period. Due to some gaps in the measured current data, measured current data corresponding to 23 of the 223 selected strong wind episodes were not available. Thus, 200 episodes of measured and simulated *Cs* and *CsDir* were available for comparison during the validation period.

The simulations are initiated at the time step when *Ws* exceeds 12 m/s and performed for 5 days after the last time step with *Ws* > 12 m/s. As mentioned previously, a typical inertial oscillation is seen to last for around 3 to 4 days. Thus, 5 days is a longer duration than any inertial oscillation in the northern North Sea is anticipated to last, but nevertheless the duration is set this way to ensure that the entire inertial oscillation is included in the simulation.

Different initial conditions were tested for all the 200 episodes, but these had a minimal effect seen to vanish completely after around one day or less. Thus, for simplicity, zero initial conditions are assumed for all simulations. This is in accordance with Kundu (1976).

The selected 200 episodes of strong wind conditions were used as input for simulation of 200 episodes of inertial current components *u* and *v*, generated by inertial oscillations. The tidal contribution to the measured current conditions was calculated (Francis 1992) and removed. To obtain a general, over-all impression of how the simulated *Cs* compares to the corresponding measured *Cs*, visual inspections of the time series of measured and simulated *Cs*, *CsDir* and *x*- and *y*-components were done for each of the 200 episodes. The tidal contribution to the measured current conditions has been calculated (Francis 1992) and removed. In most the episodes, both the levels of simulated *Cs* compared well to the measured *Cs*, while the timing compared satisfactory enough, considering the final use of the simulated current data. Further improvement of the timing and periods of the simulated wind-generated inertial oscillations is considered outside the scope of work of this study since this is not relevant for how the simulated current data is intended to be used further. Since the maximum values of *Cs* (Cs_{max}) in each episode will be selected and used to establish extreme value distributions and estimate extreme values (based on a peak-over-threshold approach), the focus of comparison is on the maximum values in each episode. In general, the measured and simulated Cs_{max} in each episode are found to correspond good.

The scatter and q-q plot of the measured and simulated Cs_{max} excluding tides are shown in Fig. 4. The scatter plot shows a spread between the measured and simulated Cs_{max}. However, since the Cs_{max} values in each episode are of most interest and will be used to establish an extreme value distribution, it is more appropriate to emphasize the q-q plot, which the extreme value distribution will be based directly on. The comparison of measured and simulated Cs_{max} is quite good in most of the episodes and especially for the largest Cs_{max}. However, a quite systematic deviation is evident, especially for simulated Cs_{max} less than around 35 cm/s; the measured Cs_{max} are often slightly larger than the simulated *Cs*, very explicitly seen when the Cs_{max} are compared. This deviation between the simulated and measured Cs_{max} is around 2.5 cm/s for simulated Cs_{max} in the range 25 cm/s to 35 cm/s and somewhat larger around 5 cm/s for simulated Cs_{max} in the range 10 cm/s to 25 cm/s. A reasonable, physically rooted approach, in accordance with the simplicity of the current model, would be to consider this deviation as a more general background current, which would comprise several different effects such as any small contributions from other current components other than the wind-generated inertial oscillations, wave-current interaction, noise in the current measurements. Following this, a general background current must be added to the simulated *Cs* to make the comparison with the measured *Cs* more consistent.

5.2.1. Background current

Several different approaches to account for a general background current speed, Cs_{back}, have been considered. Empirical (case a-1 and a-2), wind-based (case b-1 and b-2) and stochastic (case c-1 and c-2) approaches to estimate Cs_{back} were tested and the details of these approaches are summarized in Table 3.

Both the empirical approaches to estimate Cs_{back} gave good results, significantly better than the wind-based and stochastic approaches. The model for wind-generated inertial currents is simple and it can be argued that the simplest empirical approach to estimate Cs_{back}, (case a-1) is best in accordance with the model. Following this, the empirical approach based on constant Cs_{back} for different classes of simulated Cs_{max} is selected to use. The corresponding scatter and q-q plots for case a-1 of the simulated Cs_{max} including Cs_{back} versus the measured Cs_{max} are given in **Error! Reference source not found.**. The q-q plot follows the one-to-one line very closely nd compared to Fig. 4, a clear improvement of the q-q plot is evident.

5.2.2. Comparison to NoNoCur hindcast

Since the validation period for simulated Cs_{max} is overlapping with the period of the NoNoCur hindcast, the simulated Cs_{max} from the simple model for wind-generated inertial oscillations can be compared to the corresponding Cs_{max} from this more refined current model. The overlapping period is from May 2011 to December 2012, during which 93 episodes of wind-generated inertial oscillations are identified.

The scatter and q-q plot of the NoNoCur and simulated Cs_{max} including both tidal and background currents at 40 m water depth are shown in Fig. 5. Please note that both tidal and background currents must be added to the simulated Cs_{max} for the most suitable comparison to NoNoCur Cs_{max}. As for measured and simulated Cs_{max}, the scatter plot shows a spread between the NoNoCur and simulated Cs_{max}, but a very good agreement is seen for the q-q plot with only some slight deviations between the q-q plot and one-to-one line evident. However, it is still reasonable to conclude that this simple model for wind-generated inertial oscillations has just as good skill as the more refined current model for simulation of current data for joint considerations of waves and currents for design of offshore structures.

6. EXTREME VALUES

Extreme values of both measured and simulated Cs_{max} (including Cs_{back}) at Location 4 has been estimated and compared. Since the Cs_{max} are the maximum or peaks of *Cs*, during an episode of inertial oscillations selected by specific criteria on the wind conditions, i.e. thresholds of wind (see Table 2), these estimated extreme values of Cs_{max} are based on a peak-over-threshold (pot) approach. The long-term distribution of Cs_{max} have been modelled by the following two distributions; 3-parameter Weibull distribution for Cs_{max} and 2-parameter Weibull distribution for Cs_{max} exceeding a threshold set equal to the smallest Cs_{max} value, both based on the method of moments. For further details on the estimation of extreme values, see for instance Bruserud and Haver (2015).

The different empirical and fitted Weibull distributions of Cs_{max} and three levels of different annual probability of exceedance, 0.63, 10^{-1} and 10^{-2}, marked with thin horizontal lines, are shown in Fig. 6. The corresponding Weibull parameters and extreme values are given in Table 4. Please note that these extreme values are not suitable as specific design values.

As expected from the q-q plot in **Error! Reference source not found.**, the main parts of the empirical istributions of measured and simulated Cs_{max} correspond very good. According to Fig. 6 (a), the fitted Weibull 3-parameter distributions to the measured and simulated Cs_{max} correspond well to the empirical distributions and follow each other closely up to around 45 cm/s. Some deviations in the upper parts of the empirical distributions are evident and the simulation is seen to overestimate the two largest measured Cs_{max}, For Cs_{max} larger than 45 cm/s, the distribution fitted to the simulated Cs_{max} is somewhat more conservative than the distribution fitted to the measured $Cs_{max,}$ resulting in larger estimated extreme values of simulated Cs_{max}. This is seen to be well within the uncertainty band of the statistical model applied, based on typical Monte-Carlo simulations, and concluded to compare well. The difference in estimated extreme values based on measured and simulated Cs_{max} increases with decreasing probability of annual exceedance; for annual probability of exceedance 0.63 the difference is only 3 cm/s, i.e. around 5 %, while for 10^{-2} the difference is 11 cm/s, i.e. 15 %.

The distributions shown in Fig. 6 (b) are Weibull 2-parameters distributions, but fitted to the measured and simulated Cs_{max} exceeding a threshold set equal to the smallest corresponding Cs_{max} value. The minimum Cs_{max} can be considered as a pre-set location parameter. The fitted distributions are comparable and follow the empirical distributions up to around 50 cm/s. The distribution fitted to the simulated Cs_{max} is more conservative than the distribution fitted to the measured Cs_{max} for values larger than 50 cm/s, as seen for the Weibull 3-parameter distributions shown in Fig. 6 (a).

Both the fitted Weibull 3-parameter and Weibull 2-parameter distribution are appropriate models for the current data and yield reasonable extreme values. The difference between these two fitted Weibull models to measured and simulated Cs_{max} indicates the range of statistical uncertainty. However, the Weibull 3-parameter distributions seem to follow the empirical distributions slightly better, especially for the largest values of Cs_{max}, and this long-term distribution is recommended to use for estimation of extreme values of Cs_{max}. In addition, since no threshold is applied directly to select episodes of current data, it will be more correct to allow the statistical model select the most appropriate location parameter, as for the Weibull 3-parameter distribution, rather than to require the location parameter to be equal to the minimum Cs_{max}.

7. OTHER LOCATIONS

To assess the robustness of the model for wind-generated inertial oscillations validated at Location 4, the model has been applied at Location 1, 2 and 5 and compared to measured current data at these locations during the validation period. With this, the variability of current conditions at the different locations in the northern North Sea has also been investigated.

Fig. 7 shows the scatter and q-q plots of the measured and simulated Cs_{max} at Location 1, 2 and 5. In the left panels, the comparisons of measured and simulated Cs_{max} are shown, while comparisons of the measured and simulated Cs_{max} including an optimized Cs_{back} are shown in the right panels.

At Location 1, large-scale eddies, i.e. one type of large-scale currents, are known to contribute to the current conditions, see for instance Sætre (1983) and Førland (1985). Consequently, a larger addition to the simulated inertial current (Cs_{back}) is expected to be necessary for the q-q plot of measured and simulated Cs_{max} to compare well with the one-to-one line.

As seen in Fig. 7 (a-1), the q-q plot of measured and simulated Cs_{max} forms a nearly straight line well below the one-to-one line at Location 1. This is as anticipated and suggests that due to more contributions from large-scale currents to the current conditions, a larger Cs_{back} is required at Location 1 than at Location 4. Several constant Cs_{back} in the range between 5 cm/s to 20 cm/s have been added to the simulated Cs_{max}. A Cs_{back} of 15 cm/s is found to give the best results in terms of the q-q plot. The q-q plot of measured and simulated Cs_{max} including Cs_{back} of 15 cm/s is shown in Fig. 7 (a-2). The q-q plot is seen to follow the one-to-one line closely.

At Location 2, the water depth is significantly smaller; around 90 m rather than 120 m as at Location 4. To achieve a good comparison between the measured and simulated current data at Location 2, it is expected to be more appropriate that the mixed layer depth in the simulations is scaled accordingly.

Fig. 7 (b-1) shows that the simulated Cs_{max} underestimate the measured Cs_{max}, except for the two largest Cs_{max} exceeding 60 cm/s. Since the total water depth is more shallow than at Location 4, around 75 % smaller, a mixed layer depth, D_0, scaled accordingly is expected to improve the simulated Cs_{max}. Based on this, the D_0 during summer is set to 37.5 m rather than 50 m and during the rest of the year to 60 m rather than 80 m. Optimized results based on a smaller D_0 are shown in Fig. 7 (b-2). The same Cs_{back} as at Location 4 has been added to the simulated Cs_{max}. The q-q plot is seen to improve for Cs_{max} up to around 50 cm/s, but for Cs_{max} exceeding 50 cm/s the simulations overestimate Cs_{max}.

Although Location 5 is quite close to Location 4, some differences in the current conditions are also expected when the model validated for Location 4 is applied at Location 5. As Location 5 is further south and more exposed to the Faroe-Shetland channel, more large-scale currents, i.e. the Dooley current (see Section 2), may contribute to the current conditions. Consequently, a slightly larger Cs_{back} is expected to contribute to the current conditions also at Location 5.

At Location 5 the model is again underestimating the simulated Cs_{max}, see Fig. 7 (c-1). For simulated Cs_{max} less than 45 cm/s, this underestimation seems to be quite constant around 10 cm/s. For measured Cs_{max} larger than around 50 cm/s, the model underestimates Cs_{max} even more and the underestimation is up to around 25 cm/s. Addition of a constant Cs_{back} of 10 cm/s improves the q-q plot for simulated Cs_{max} less than 50 cm/s, see Fig. 7 (c-2), but the largest measured Cs_{max} exceeding 50 cm/s are still underestimated.

Application of the model validated at Location 4 at Location 1, 2 and 5 do not yield as good results as when applied at Location 4. Slightly different optimization of just one parameter; Cs_{back} at Location 1 and 5 and D_0 at Location 2, improves the q-q plots significantly. However, at Location 2 and 5 the largest measured Cs_{max} are still not simulated well and the largest measured Cs_{max} are over- and underestimated, respectively, by the simulations. Further investigations are required to explain these differences. These results highlight the sensitivity of current conditions to location and also stress the importance of site-specific assessments of current conditions in the northern North Sea.

7.1. Extreme values

Based on the optimized simulations at Location 1, 2 and 5, the long-term distributions of measured and simulated Cs_{max} have been modelled by a 3-parameter Weibull distribution, as recommended in Section 6 for Location 4. The empirical and fitted 3-parameter Weibull distributions of measured and simulated Cs_{max} and three levels of different annual probability of exceedance, 0.63, 10^{-1} and 10^{-2}, marked with thin horizontal lines, are shown in Fig. 8. The corresponding Weibull parameters and extreme values are given in Table 5. Please note that these extreme values are not suitable as specific design values.

As expected from the optimized q-q plots shown in Fig. 7, the empirical and fitted long-term distributions at Location 1 follow each other closely. There are only very minor differences in the estimated extreme values, which for all practical purposed will not have any effect.

Due to the deviations between the largest measured and simulated Cs_{max}, at Location 2 and 5, the fitted distributions to measured and simulated Cs_{max} differ. At Location 2, the fitted distribution to simulated Cs_{max} is much more conservative than the distribution fitted to the measured Cs_{max}. Correspondingly, large differences are observed in the estimated extreme values. For annual probability of exceedance 0.63, 10^{-1} and 10^{-2} the estimated extreme values based on simulated Cs_{max} are around 30 %, 50 % and 75 % larger, respectively.

Contrary to Location 2, at Location 5 the fitted distribution to simulated Cs_{max} is less conservative than the distribution fitted to the measured Cs_{max}. The differences in estimated extreme values with annual probability of exceedance 0.63, 10^{-1} and 10^{-2} are 7 %, 12 % and 17 %, respectively. At Location 2 and 5, these deviations in long-term distributions fitted to the measured and simulated Cs_{max} and the corresponding extreme values, emphasize the need for further investigations of the largest observed Cs_{max} before the simulated Cs_{max} at these two locations can be used for further analysis.

8. SUMMARY AND CONCLUDING REMARKS

In order to acquire simultaneous metocean data of sufficient quality and duration for robust design of offshore structures, simulations of the current conditions in the northern North Sea has been performed. Measured current data have showed that currents from wind-generated inertial oscillations dominate the current conditions in the northern North Sea (Bruserud and Haver 2017a) and a simple model for wind-generated inertial oscillations has been adapted for the northern North Sea. Further validation of the model and comparison with both measured current data and modelled current data from a more advanced current model, focused on episodes of large currents, has been done for one location, Location 4. To assess the robustness of the model and also the sensitivity of current conditions from one location to another location, the validated model has been applied at the other three locations as well.

This simple model for wind-generated inertial oscillations is found to reproduce the maximum measured current speed in each episode of large currents, Cs_{max}, surprisingly well and with considerable accuracy at Location 4. The comparison between the simulated and measured Cs_{max} is further improved when a small addition, considered to be a general background current, Cs_{back}, is made to the simulated currents. Moreover, this suggests that wind-generated inertial oscillations indeed are the governing current conditions at Location 4.

Extreme values of measured and simulated Cs_{max} including Cs_{back} have been estimated based on two different long-term distributions. The Weibull 3-parameter distribution is recommended to use. The estimated extreme values for simulated Cs_{max} are slightly larger than the corresponding values for measured Cs_{max}. Nevertheless, this is expected to be well within the uncertainty band of the statistical model and both fitted distributions and the estimated extreme values for measured and simulated Cs_{max} compare well.

Based on simple considerations of the current conditions at three other locations in the northern North Sea, the validated model is not expected to perform as well as at Location 4. When the model is applied at these other locations, the simulated Cs_{max} is in general considerable smaller than the measured Cs_{max}. This indicates that wind-generated inertial oscillations are not as prominent at these locations as at Location 4 and that other current conditions may be governing. A slightly different optimization of just one parameter; background current at Location 1 and 5 and mixed-layer depth at Location 2, improves the results. At Location 1, all the measured and simulated Cs_{max} compare well and so the estimated extreme values. The comparison between the largest measured and simulated Cs_{max} at Location 2 and 5 is not improved by optimization. At Location 2, the deviation between the largest measured and simulated Cs_{max} influences the estimated extreme values strongly. At Location 5, deviations in the estimated extreme values based on measured and simulated Cs_{max} are also observed. The cause of the deviations between the largest measured and simulated Cs_{max} including Cs_{back} is yet to be determined, but these deviations suggest that other current conditions than wind-generated inertial oscillations are governing the largest currents at Location 2 and 5.

Based on the good correspondence between the simulated and both the measured and modelled Cs_{max} in each episode of large currents and between the estimated values of extreme currents speed at Location 4, the simulated Cs_{max} is considered to form an appropriate data base of current speed data for estimation of joint distributions of wind, waves and currents at this specific location in the northern North Sea. Simulation of current data for the entire period of available wind data and analysis of joint wind, wave and current data for design of offshore structures will be subject to further work.

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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 A summary of the different wind criteria for selection of strong wind episodes as input for the simulations. The number of episodes of strong wind corresponding to each set of criteria is also given.

Wind criteria			**No. of episodes**	
Δ *WsDir* [°]	**Duration [hrs]**	***Ws* > [m/s]**	**NORA10 period**	**Validation period**
30	24	25	0	0
		22.5	10	3
		20	54	12
		17.5	146	16
		15	281	27
		12	572	37
30	18	25	3	0
		22.5	32	11
		20	93	18
		17.5	246	23
		15	516	40
		12	954	64
90	18	25	3	0
		22.5	36	11
		20	117	19
		17.5	368	32
		15	914	74
		12	2205	174
100	15	25	6	0
		22.5	50	10
		20	163	20
		17.5	521	38
		15	1228	90
		12	2800	223

Table 3 Summary of the different approaches to account for background current, Cs_{back}, in the simulations.

Case			Criteria for Cs_{back}
Type	**No.**		
Empirical	**a1**	**1**	When simulated Cs_{max} is < 20 cm/s; Cs_{back} is set to 5 cm/s 20 cm/s - 35 cm/s; Cs_{back} is set to 2.5 cm/s > 35 cm/s; Cs_{back} is set to 0 cm/s, i.e. no background current
		2	$Cs_{back} = p_1 \cdot Cs_{max}^{\,2} + p_2 \cdot Cs_{max} + p_3$ where p_1 = - 0.0049, p_2 = 0.044 and p_3 = 5.8
Wind-based	**b**	**1**	The Cs_{max} is 5 cm/s when one of the following criteria is fulfilled Ws > 15 m/s in ≥ 3days during the simulation Ws > 15 m/s in ≥ 30 hours during the simulation and Ws_{max} ≥ 20 m/s The Cs_{back} is 10 cm/s when both the following is fulfilled Ws > 15 m/s between 1 and 3 days during the simulation $\Delta\ WsDir \leq 30°$ The Cs_{back} is 1 % of the Ws_{max} when both the following is fulfilled Ws > 15 m/s between 1 and 2 days during the simulation $\Delta\ WsDir \leq 30°$ The Cs_{back} is set to 0 cm/s when one of the following is fulfilled Ws_{max} ≥ 30 m/s In May, June, July and August
		2	The Cs_{max} is 5 cm/s when all the following criteria is fulfilled Ws > 15 m/s in ≥ 18 hours during the simulation Ws_{max} ≥ 18 m/s $\Delta\ WsDir \leq 95°$
Stochastic	**c**	**1**	The Cs_{max} is set based on random numbers drawn from a normal distribution with μ = -0.13 and σ = 12.
		2	The Cs_{max} is set based on random numbers drawn from a normal distribution with μ = -0.13 and σ = 12. Cs_{max} is negative, this is set to 0 cm/s.

Table 4 Weibull parameters and corresponding extreme values for Cs_{max}, [cm/s], at Location 4. Total number of episodes is 200. Please note that the given extreme values are not suitable to use as specific design values.

Distribution	**Data**	**Weibull parameters**			**Annual probability of exceedance**		
		γ	β	α	**0.63**	10^{-1}	10^{-2}
3-parameter Weibull for Cs_{max}	Measurements	1.294	10.37	18.83	51	61	73
	Simulations	1.087	9.20	18.90	54	67	84
2-parameter Weibull for Cs_{max} – min(Cs_{max})	Measurements	1.837	15.24	14.85	48	55	63
	Simulations	1.419	16.47	12.54	51	61	73

Table 5 Weibull parameters and corresponding extreme values based on a 3-parameter Weibull distribution for Cs_{max}, [cm/s], at Location 1, 2 and 5. Please note that the given extreme values are not suitable to use as specific design values.

Location	**No.**	**Data**	**Weibull parameters**			**Annual probability of exceedance**		
			γ	β	α	**0.63**	10^{-1}	10^{-2}
1	170	Measurements	1.586	21.67	22.69	77	91	107
		Simulations	1.271	15.92	26.32	75	91	110
2	165	Measurements	2.202	14.08	23.4	58	66	75
		Simulations	0.984	22.53	12.73	75	100	131
5	190	Measurements	0.977	23.69	10.35	69	89	115
		Simulations	1.220	23.27	12.59	64	78	95

FIGURES

Graphics program used to create figures

Fig.1 has been made with ArcGis, Fig.2 with Microsoft Visio and Fig.3 to 11 have been made with Matlab.

Figure caption list

Fig. 1 Measurement locations in the northern North Sea.

Fig. 2 Example of current speed (*Cs*) and wind speed (*Ws*) during a typical episode of wind-generated inertial oscillation in August 2014 at Location 4 and 5.

Fig. 3 Example of large current speed (*Cs)* episodes at Location 4; (a) generated by inertial oscillations and (b) not explained by inertial oscillations.

Fig. 4 Scatter and q-q plots of the measured maximum current speed (Cs_{max}) and simulated Cs_{max} at Location 4, (1) without and (2) with background current (Cs_{back}).

Fig. 5 Scatter and q-q plots of the NoNoCur Cs_{max} at 40 m water depth and simulated Cs_{max} including tidal and background current at Location 4.

Fig. 6 Empirical distribution of maximum measured (squares) and simulated (triangles) current speed (Cs_{max}) and the fitted distributions to the measured data (solid line) and simulated data (dashed line) based on (a) 3-parameter Weibull distribution of Cs_{max} and (b) 2-parameter Weibull distribution of Cs_{max} exceeding the smallest corresponding Cs_{max}. Please note that the given extreme values are not suitable to use as specific design values.

Fig. 7 Scatter and q-q plots of the maximum measured current speed (Cs_{max}) and simulated Cs_{max} and the maximum measured current speed (Cs_{max}) and simulated Cs_{max} including optimized background current speed (Cs_{back}) at (a) Location 1, (b) Location 2 and (c) Location 5.

Fig. 8 Empirical distribution of maximum measured (squares) and simulated (triangles) current speed (Cs_{max}) and the fitted distributions to the measured data (solid line) and simulated data (dashed line) based on 3-parameter Weibull distribution of Cs_{max} at (a) Location 1, (b) Location 2 and (c) Location 5. Please note that the given extreme values are not suitable to use as specific design values.

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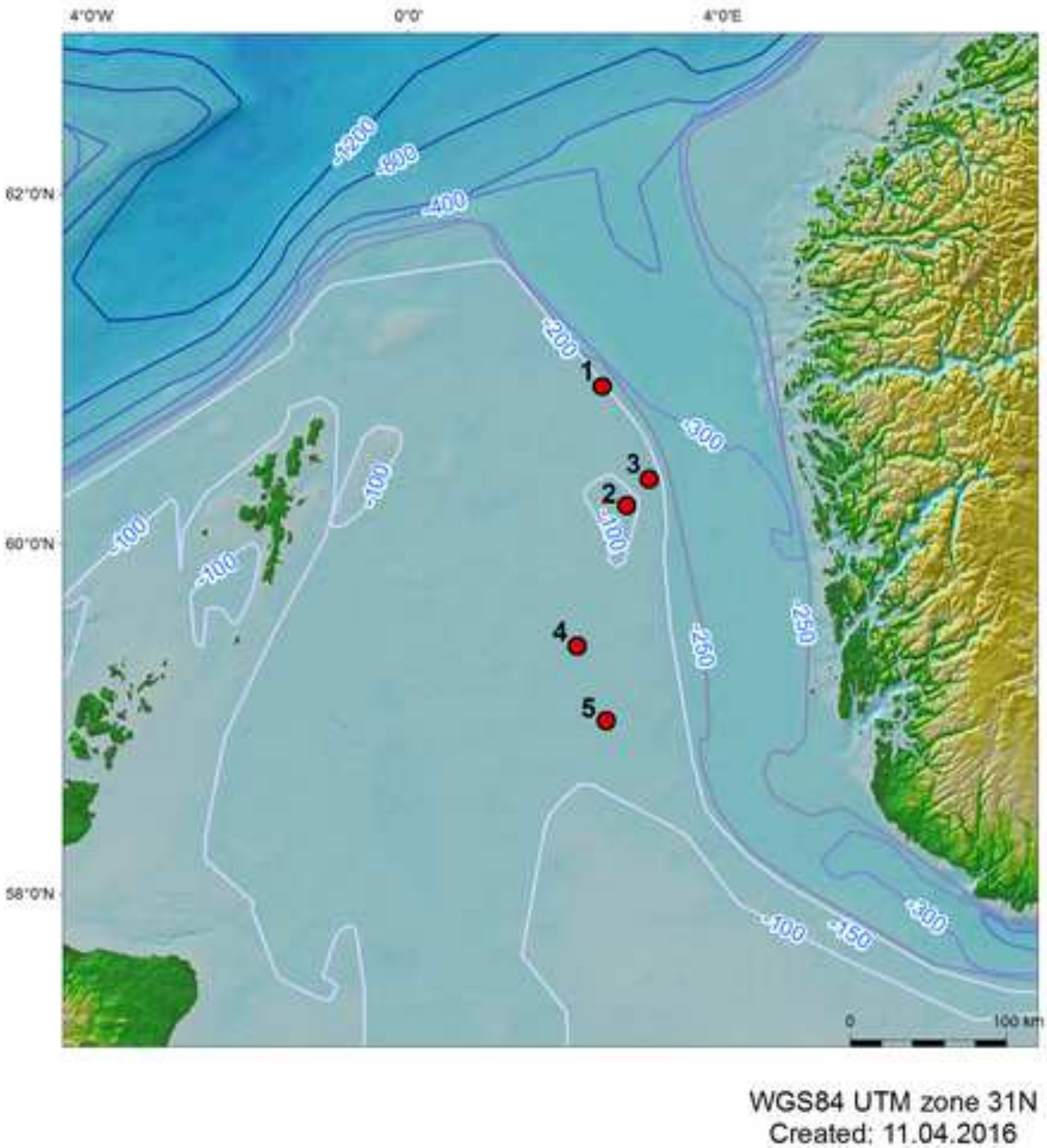

4°0'W
0°0'
4°0'E
62°0'N
60°0'N
58°0'N
-1200
-800
-400
-200
-300
-100
-250
-150
1
2
3
4
5
0
100 km
WGS84 UTM zone 31N
Created: 11.04.2016

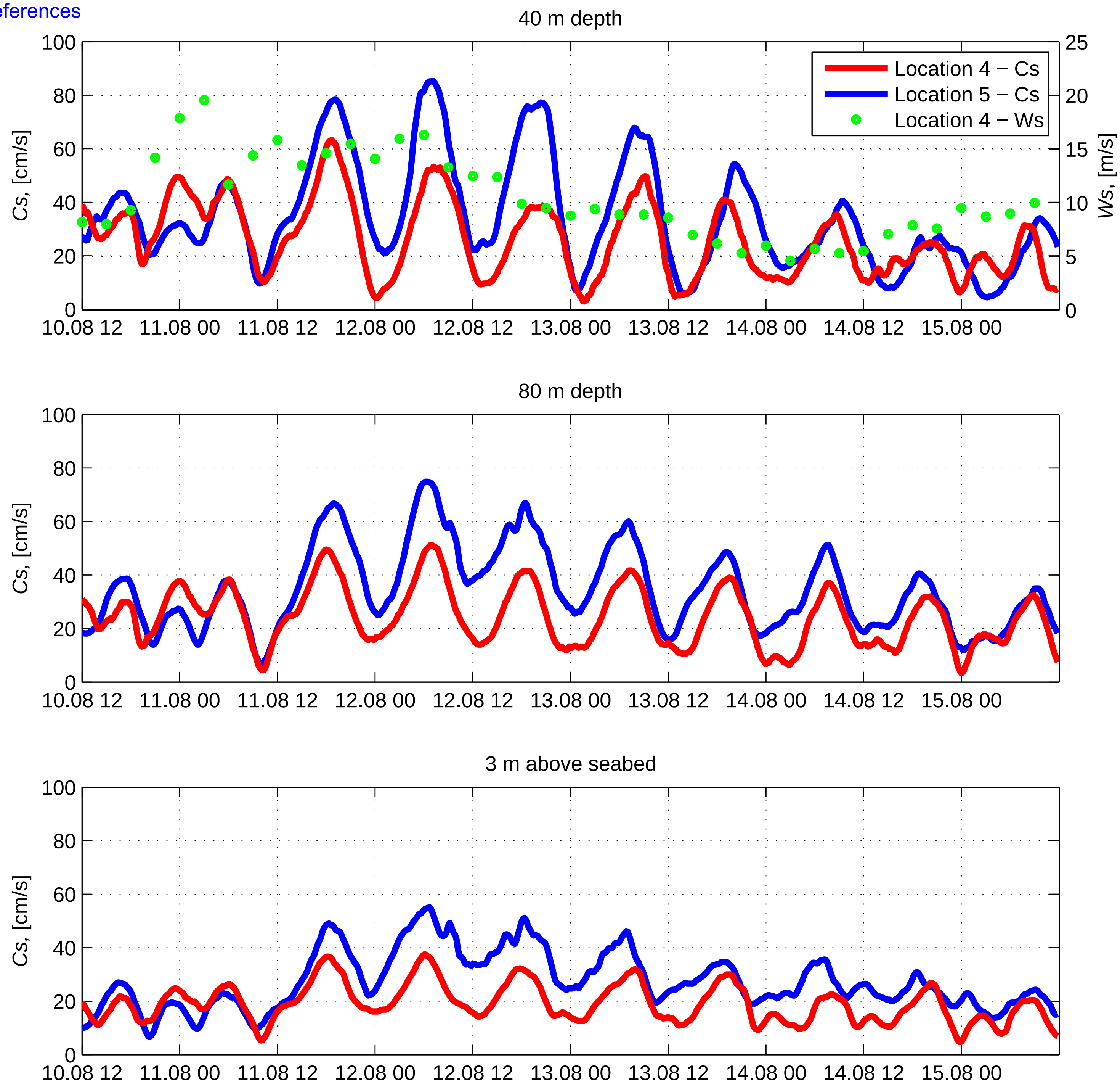

40 m depth
Location 4 − Cs
Location 5 − Cs
Location 4 − Ws
Cs, [cm/s]
Ws, [m/s]
100
80
60
40
20
0
25
20
15
10
5
0
10.08 12
11.08 00
11.08 12
12.08 00
12.08 12
13.08 00
13.08 12
14.08 00
14.08 12
15.08 00
80 m depth
Cs, [cm/s]
3 m above seabed
Cs, [cm/s]

Figure 3a

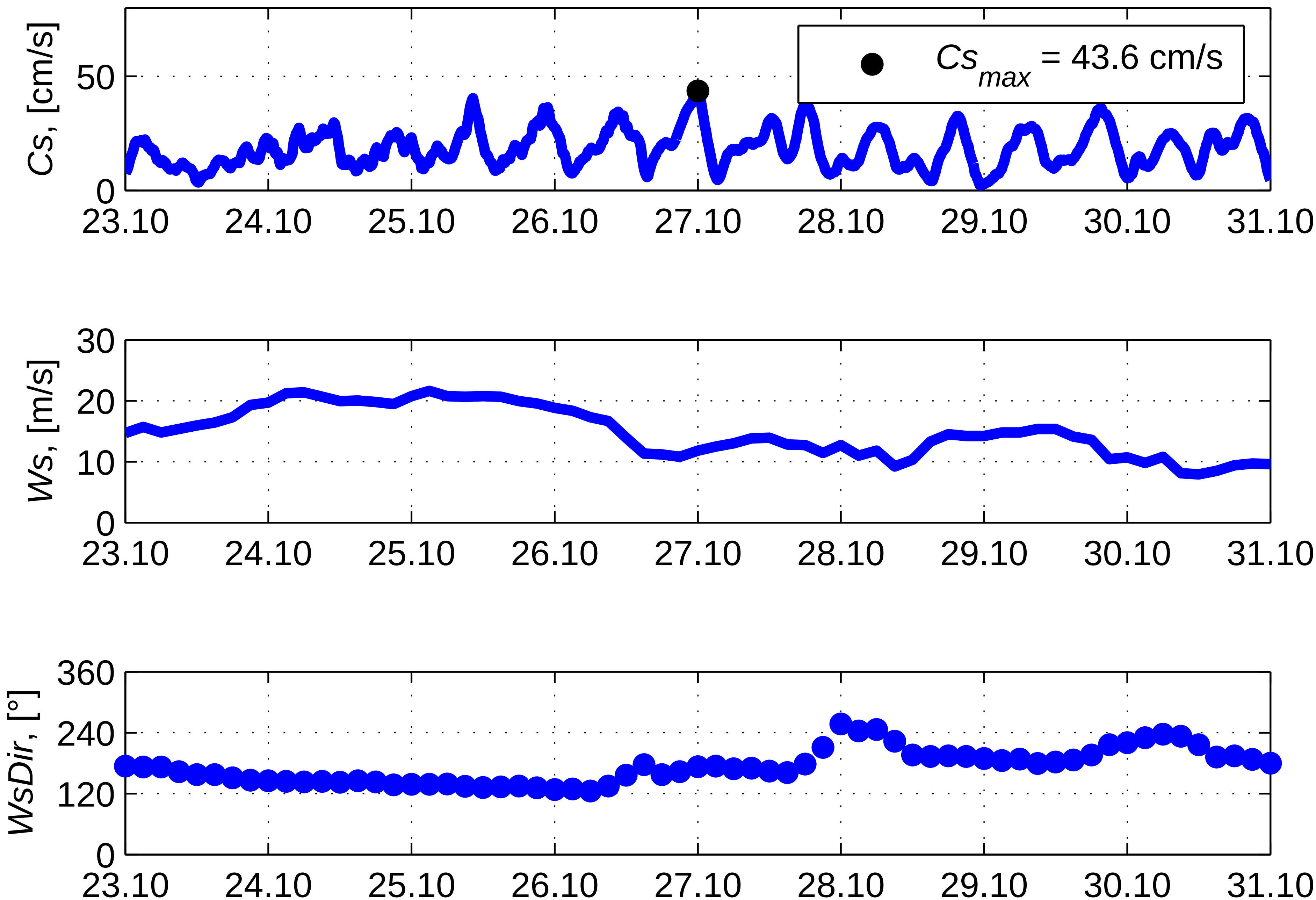
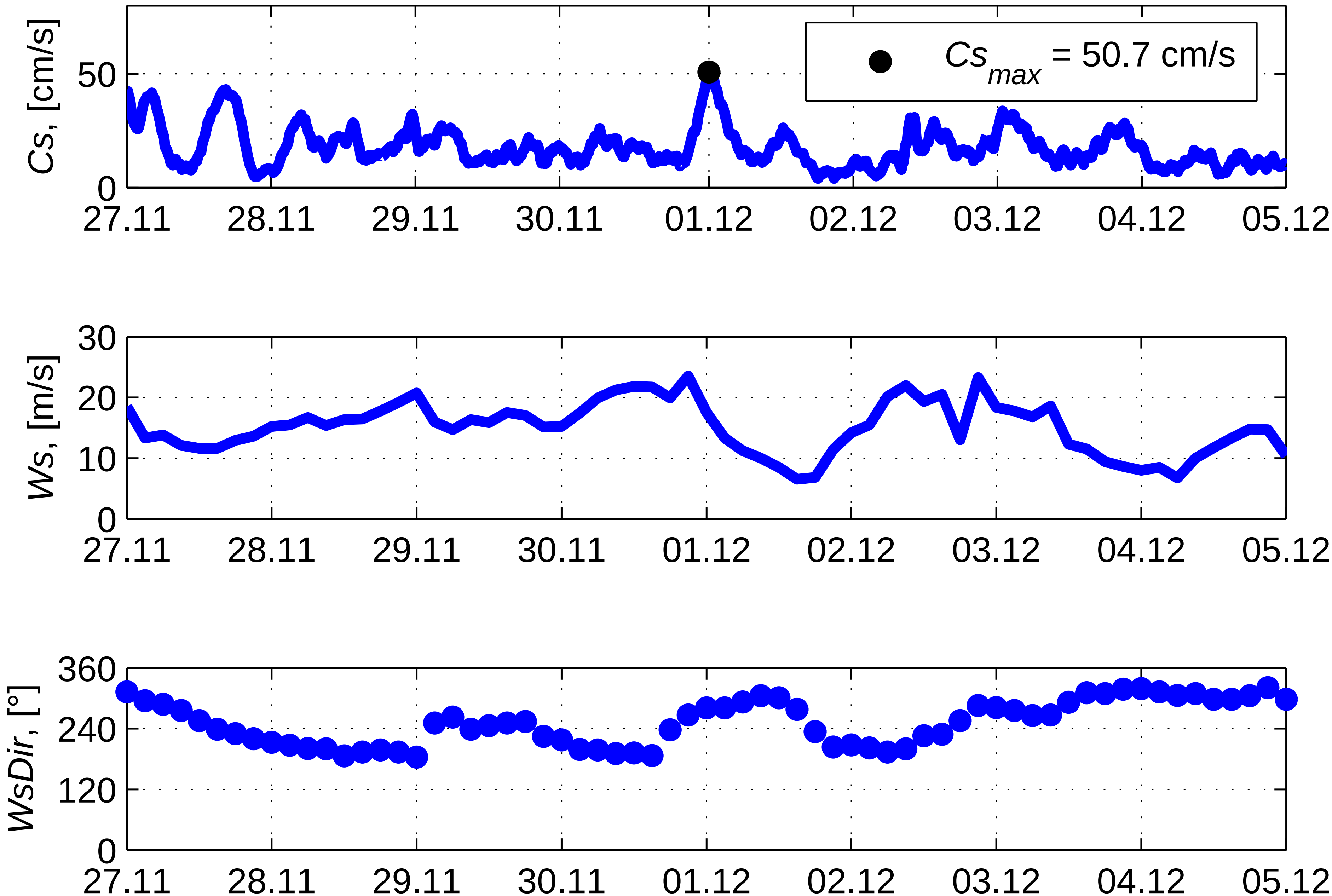
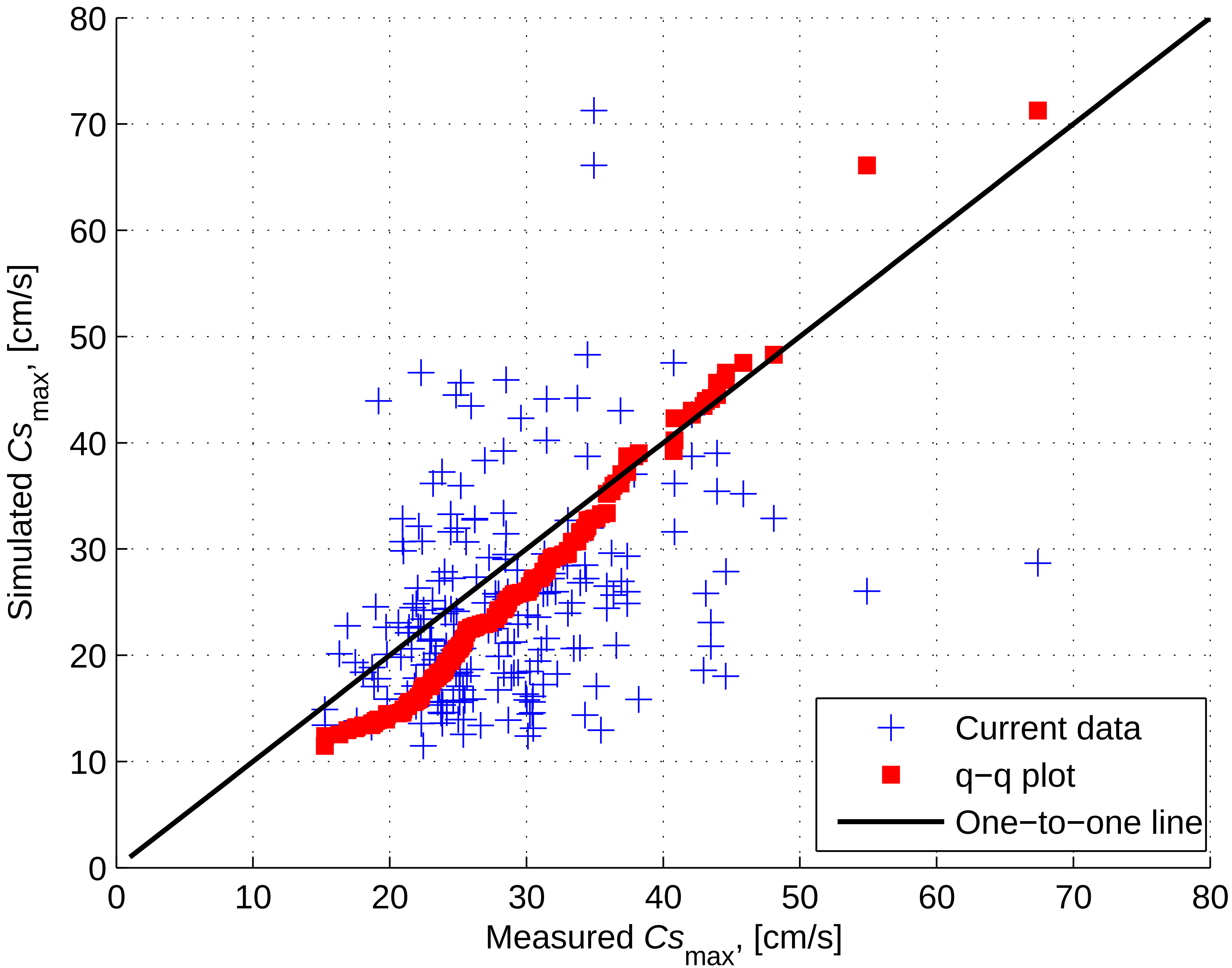

Cs_{max} = 43.6 cm/s
Cs, [cm/s]
0
50
Ws, [m/s]
0
10
20
30
WsDir, [°]
0
120
240
360
23.10
24.10
25.10
26.10
27.10
28.10
29.10
30.10
31.10

Figure 3b



Cs, [cm/s]
50
0
Cs_{max} = 50.7 cm/s
27.11
28.11
29.11
30.11
01.12
02.12
03.12
04.12
05.12
Ws, [m/s]
30
20
10
0
27.11
28.11
29.11
30.11
01.12
02.12
03.12
04.12
05.12
WsDir, [°]
360
240
120
0
27.11
28.11
29.11
30.11
01.12
02.12
03.12
04.12
05.12



0
10
20
30
40
50
60
70
80
Simulated Cs_{max}', [cm/s]
Measured Cs_{max}', [cm/s]
Current data
q−q plot
One−to−one line

Figure 4b

Click here to download Manuscript Fig8-a1.eps

Click here to view linked References

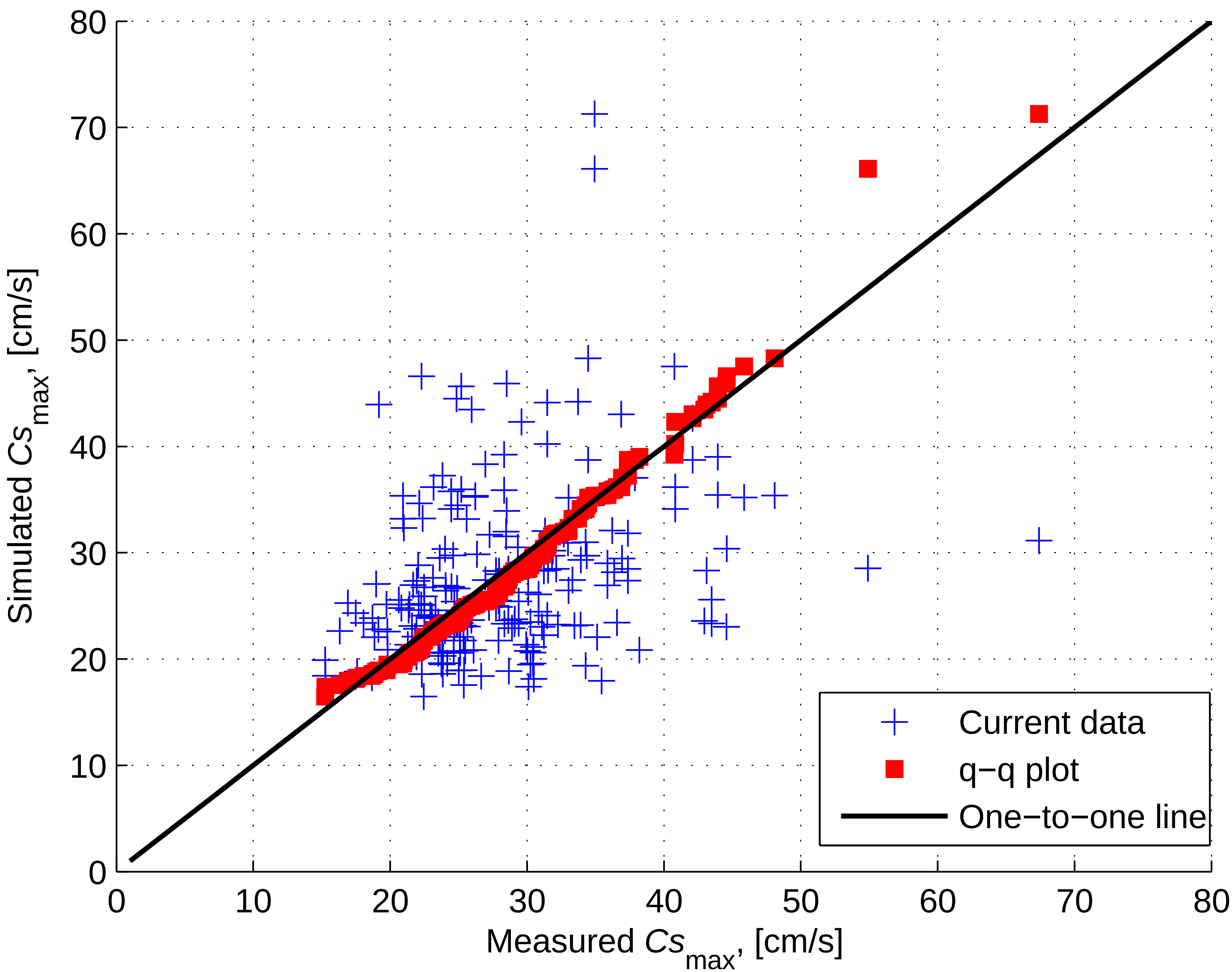
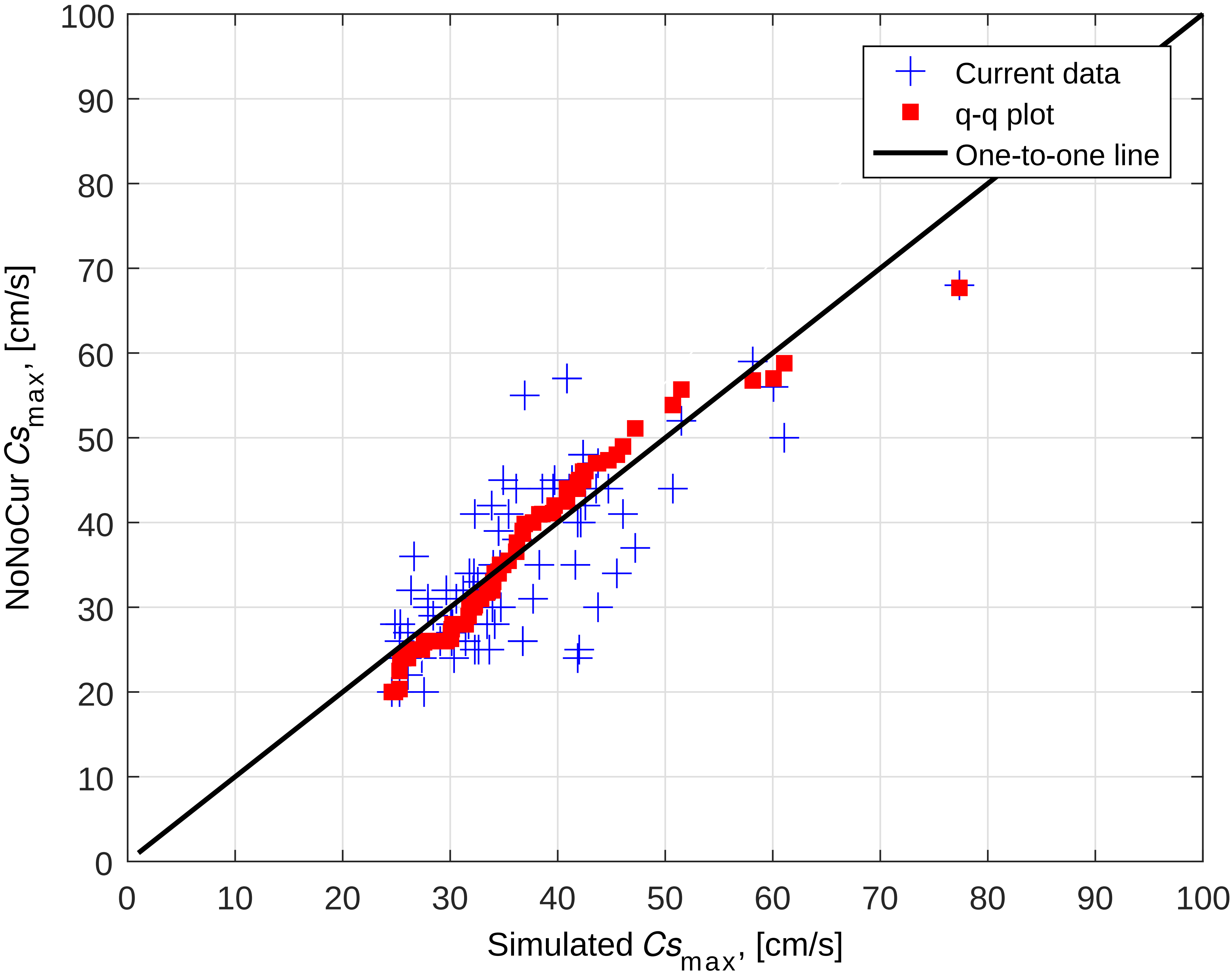


Figure 5

Click here to download Manuscript Figure_CsScatter.eps

Click here to view linked References



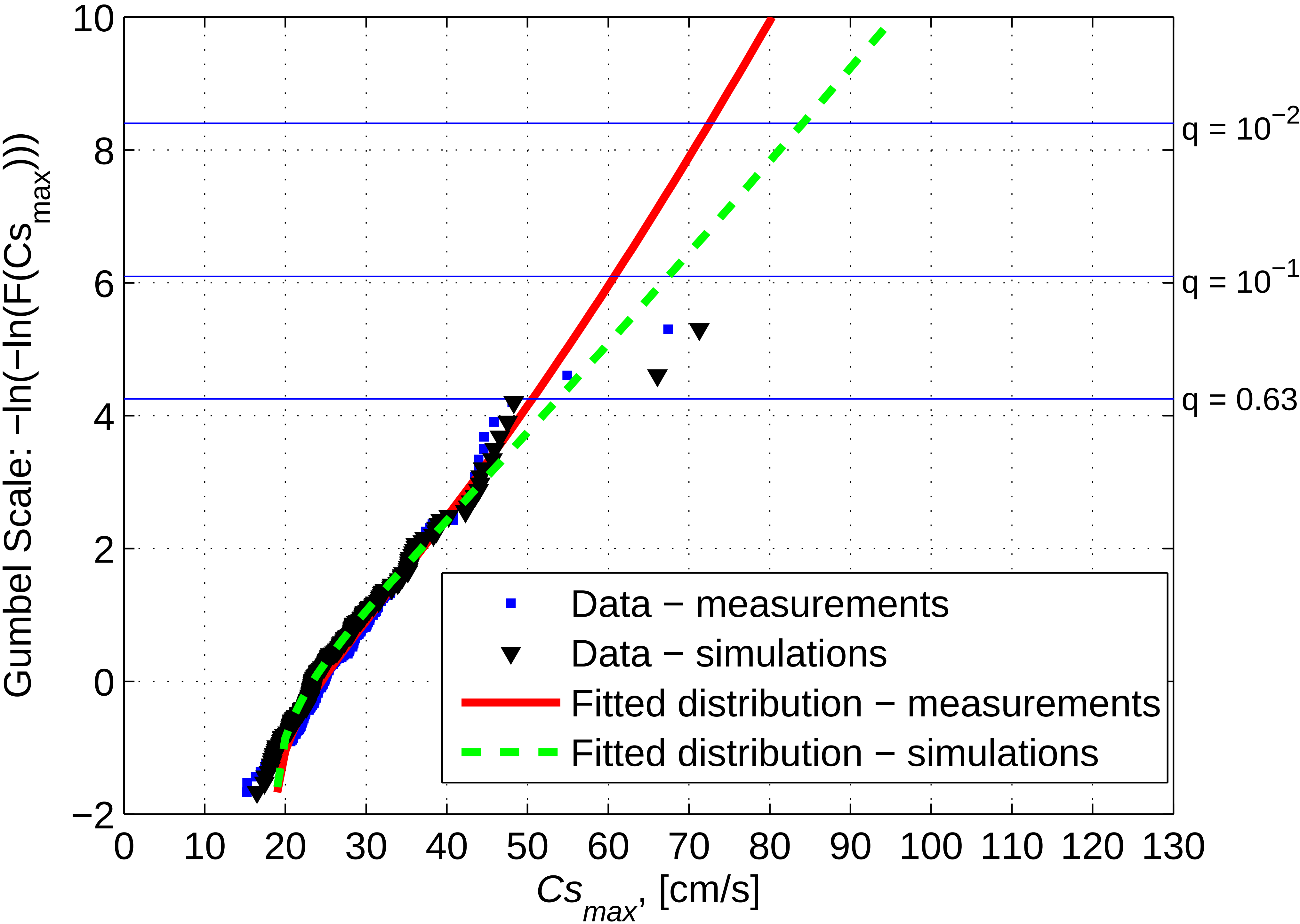

Gumbel Scale: −ln(−ln(F(Cs_max)))
10
8
6
4
2
0
−2
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Cs_max, [cm/s]
q = 10^−2
q = 10^−1
q = 0.63
Data − measurements
Data − simulations
Fitted distribution − measurements
Fitted distribution − simulations

Figure 6b

Click here to download Manuscript Fig11-b.eps

Click here to view linked References

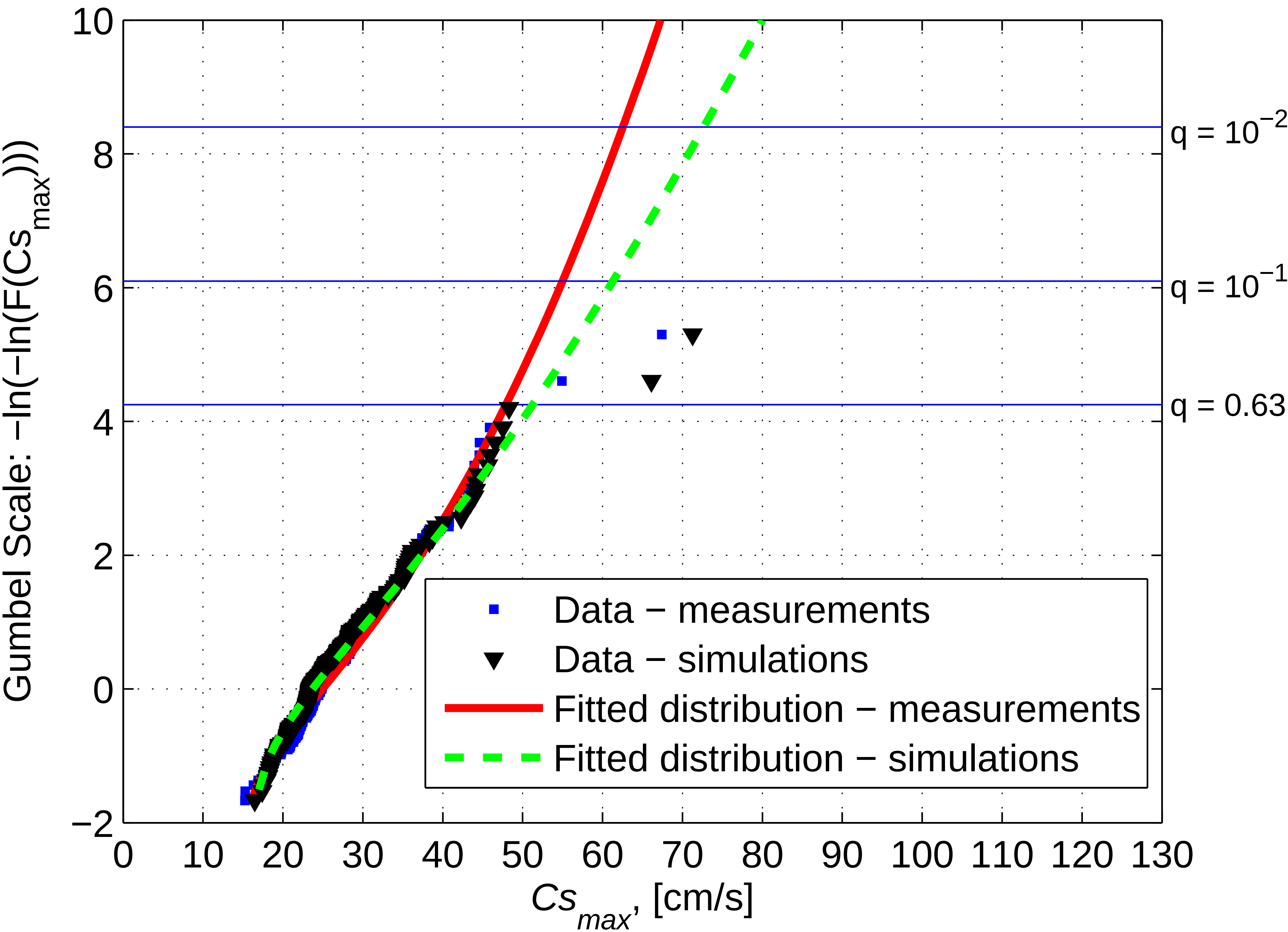


Figure 7a2

Click here to download Manuscript Fig12-a1.eps

Click here to view linked References

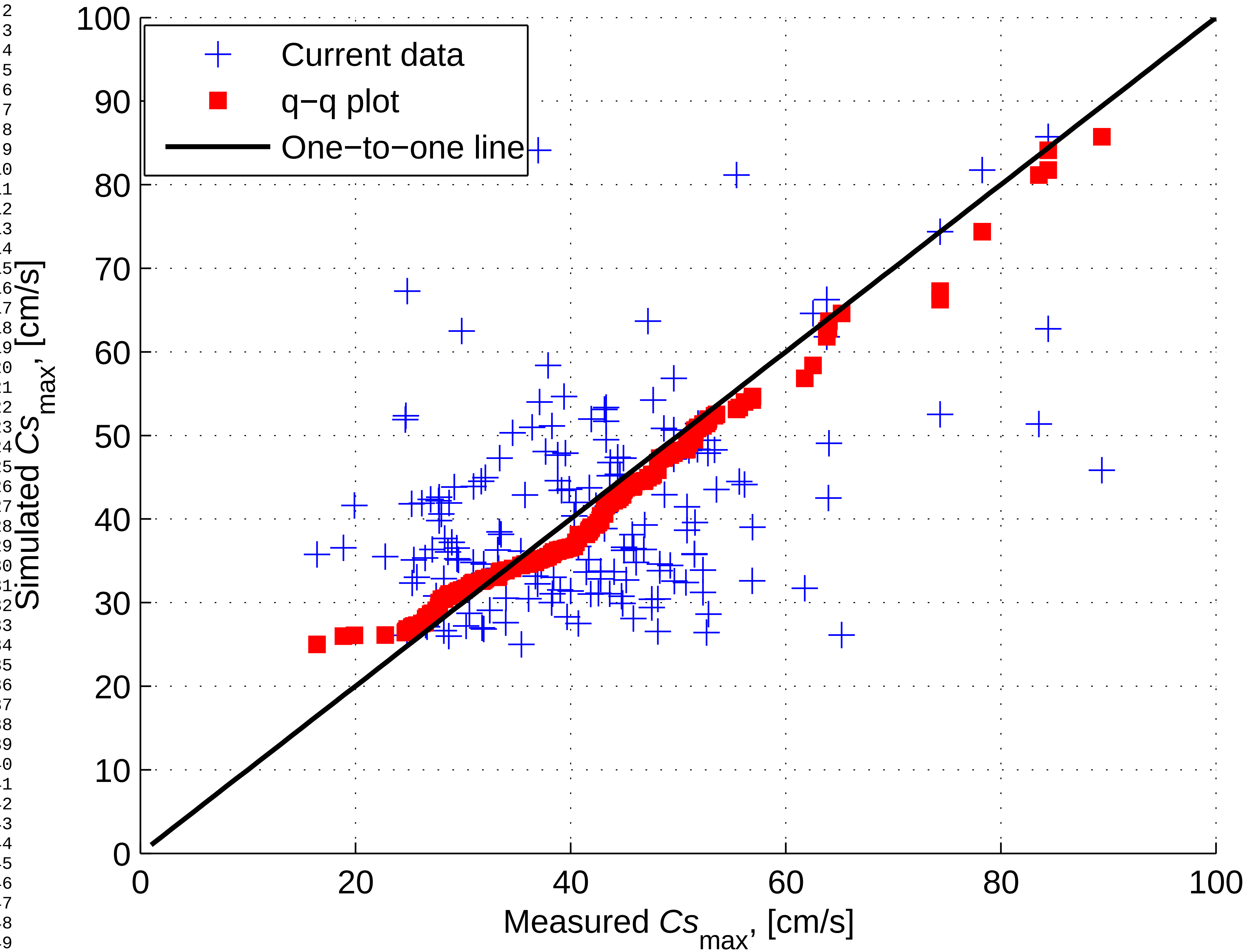


Figure 7a1

Click here to download Manuscript Fig12-a2.eps

Click here to view linked References

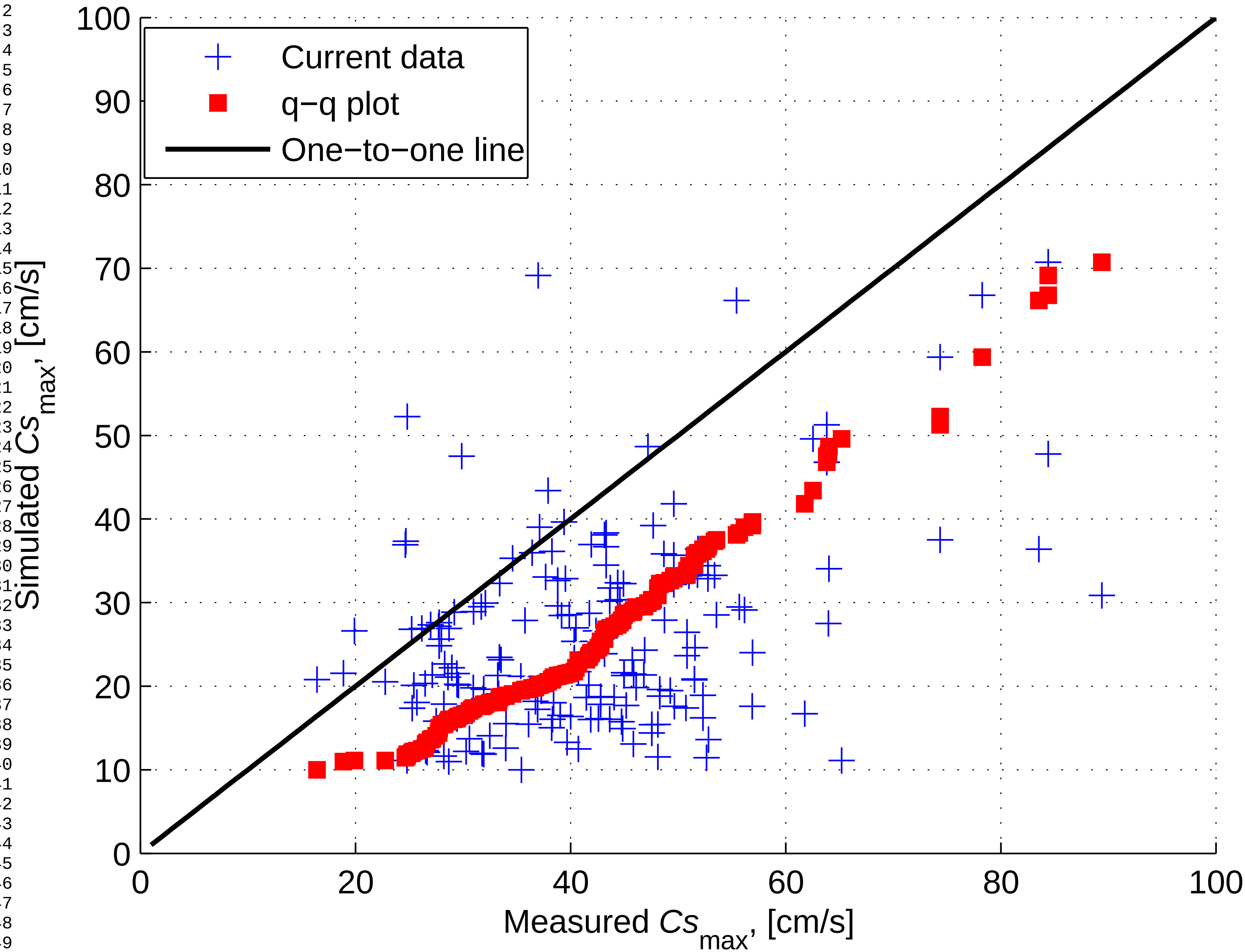
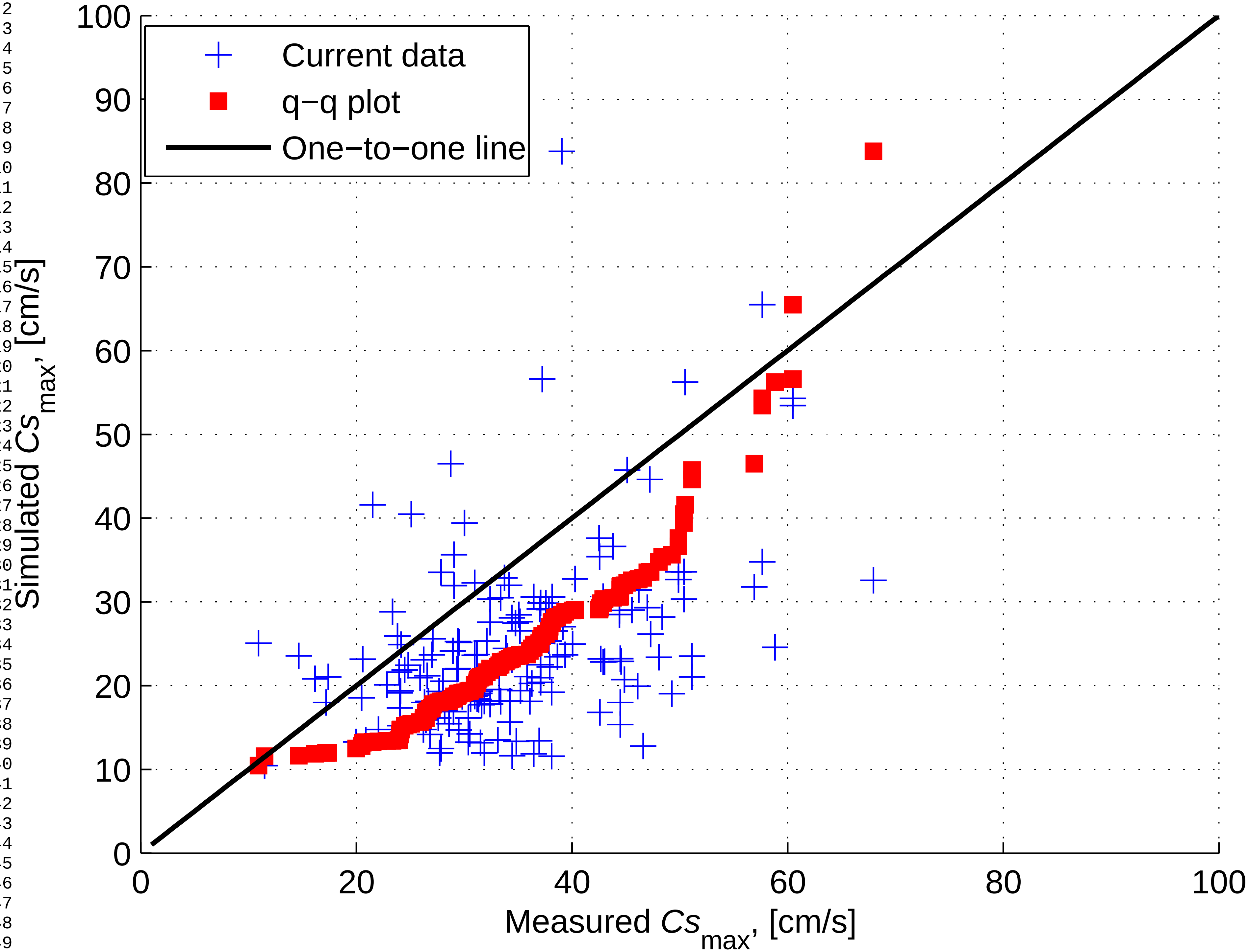


Figure 7b1

Click here to download Manuscript Fig12-b1.eps

Click here to view linked References



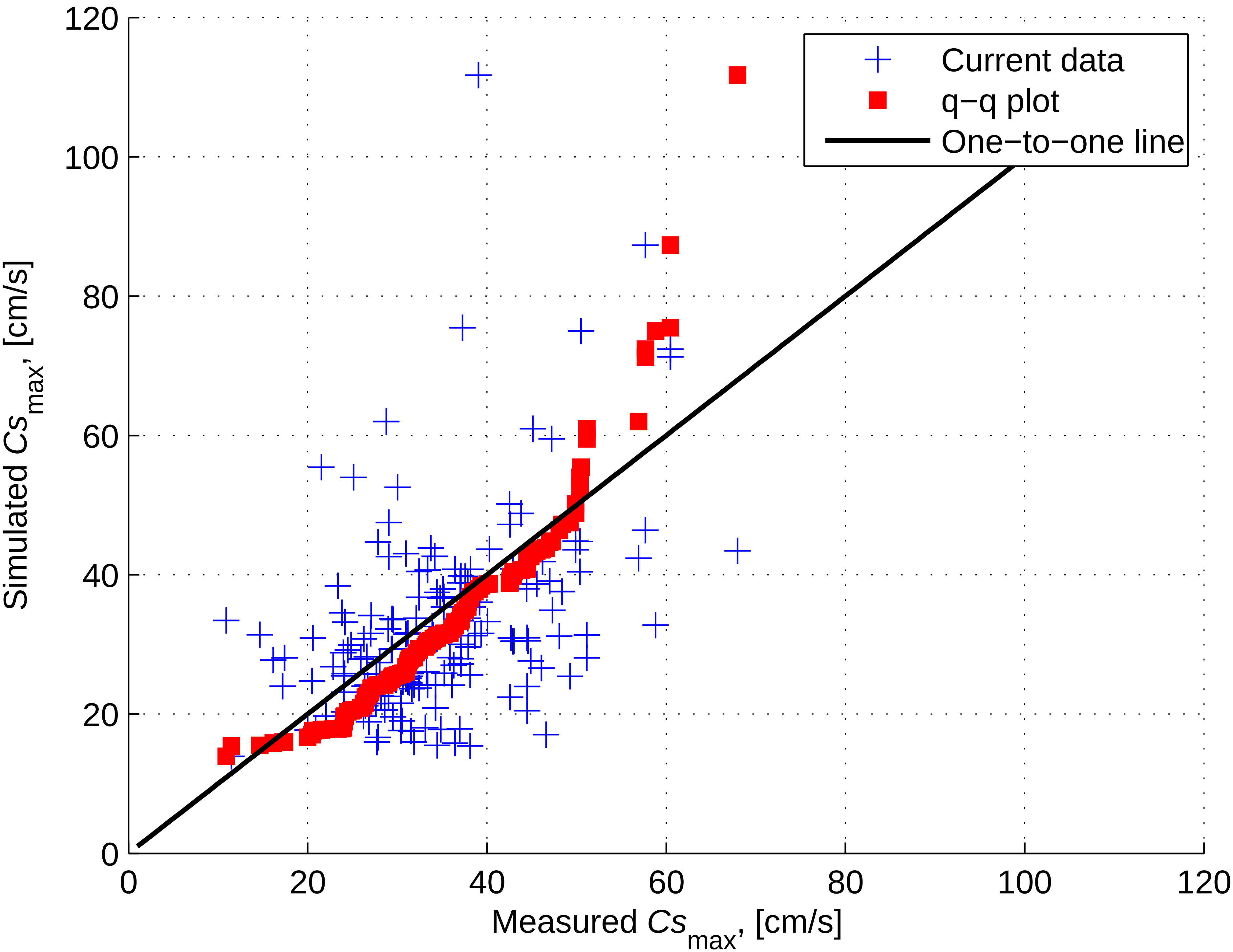

Current data
q−q plot
One−to−one line
Simulated Cs_{max}' [cm/s]
Measured Cs_{max}' [cm/s]
0
20
40
60
80
100
120

Figure 7c1 Click here to download Manuscript Fig12-c1.eps

Click here to view linked References

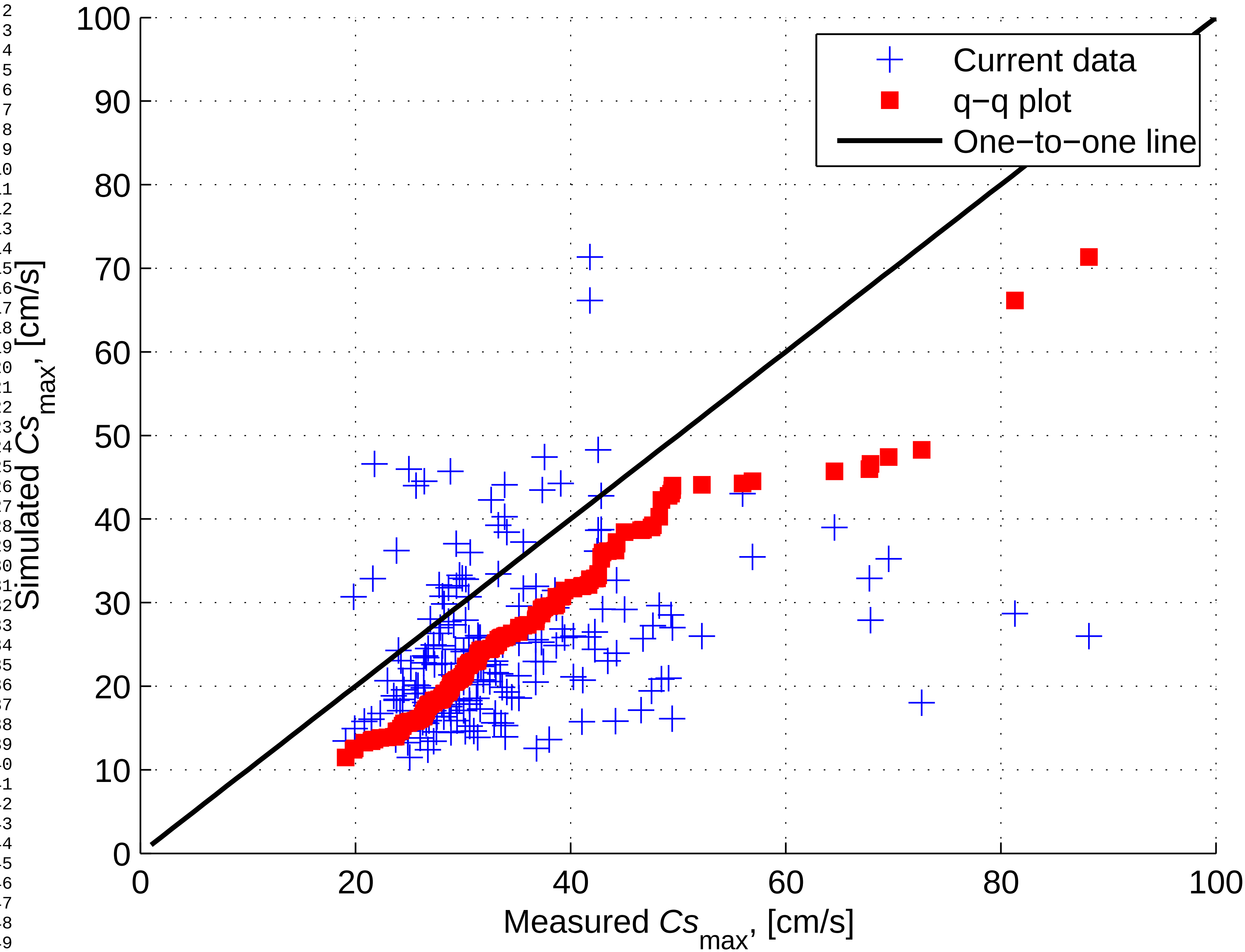


Figure 7c2

Click here to download Manuscript Fig12-c2.eps

Click here to view linked References

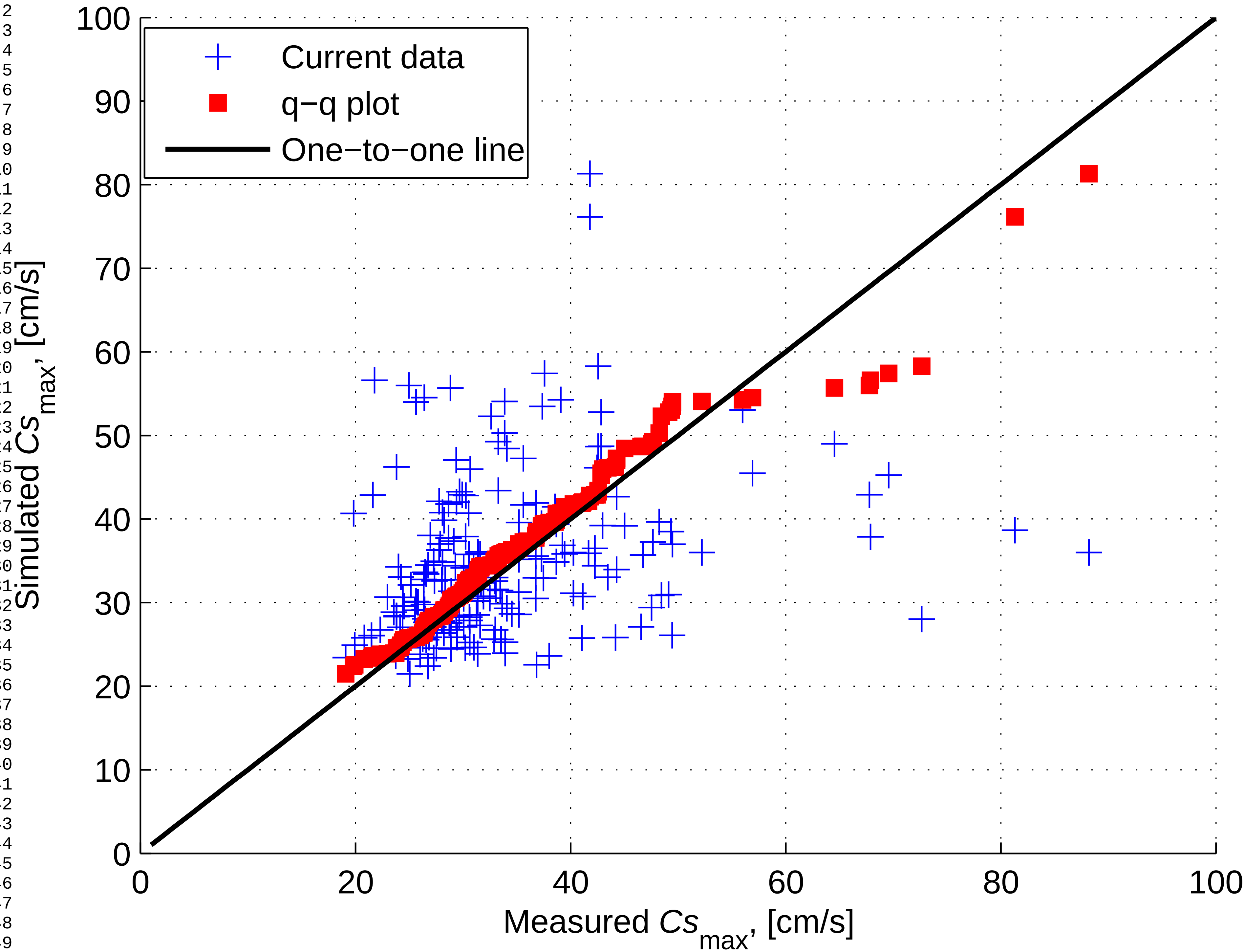


Figure 8a

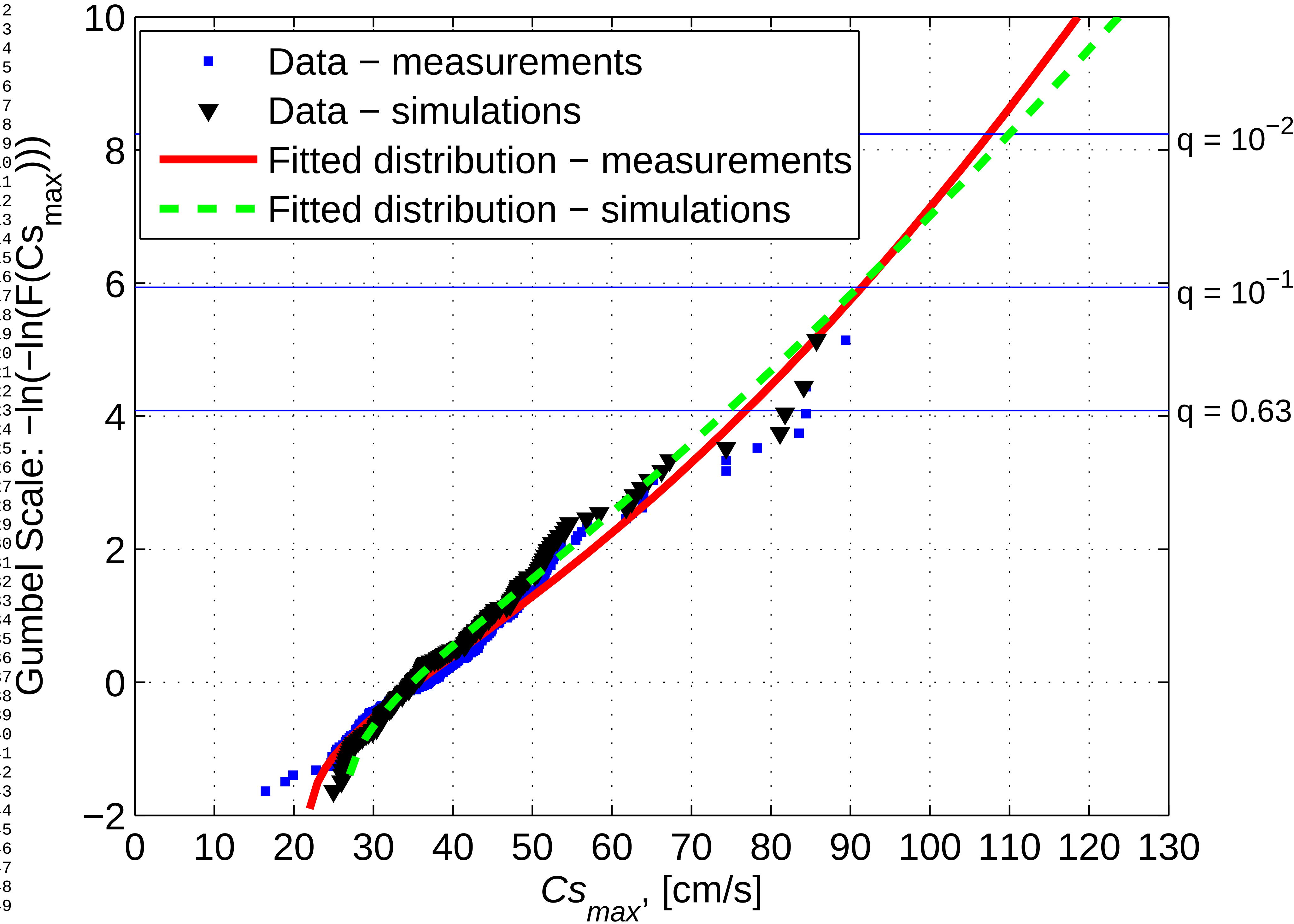

Data − measurements
Data − simulations
Fitted distribution − measurements
Fitted distribution − simulations
q = 10^−2
q = 10^−1
q = 0.63
Gumbel Scale: −ln(−ln(F(Cs_max)))
Cs_max, [cm/s]
10
8
6
4
2
0
−2
0 10 20 30 40 50 60 70 80 90 100 110 120 130

Figure 8b

Click here to download Manuscript Fig13-b.eps

Click here to view linked References

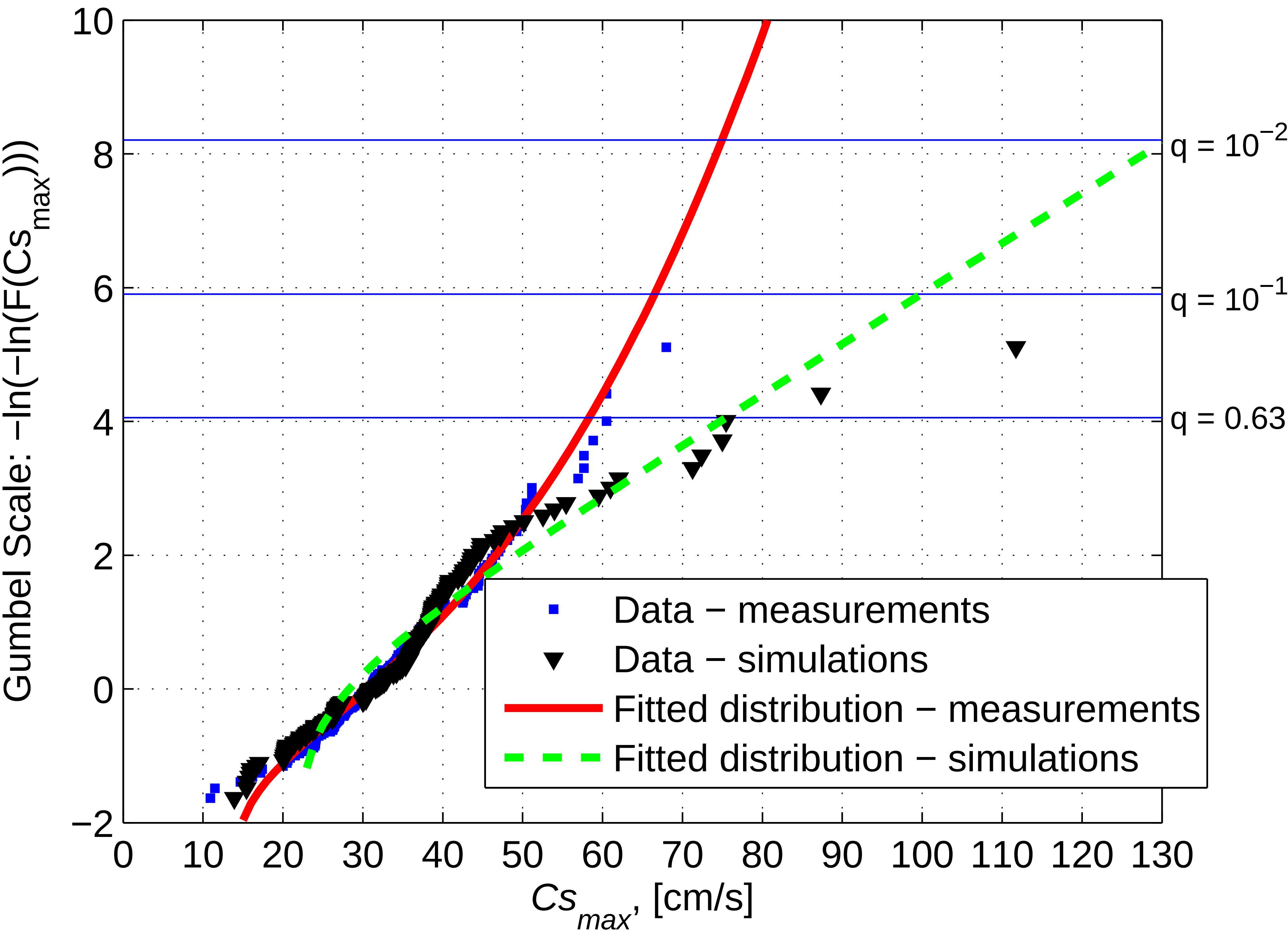
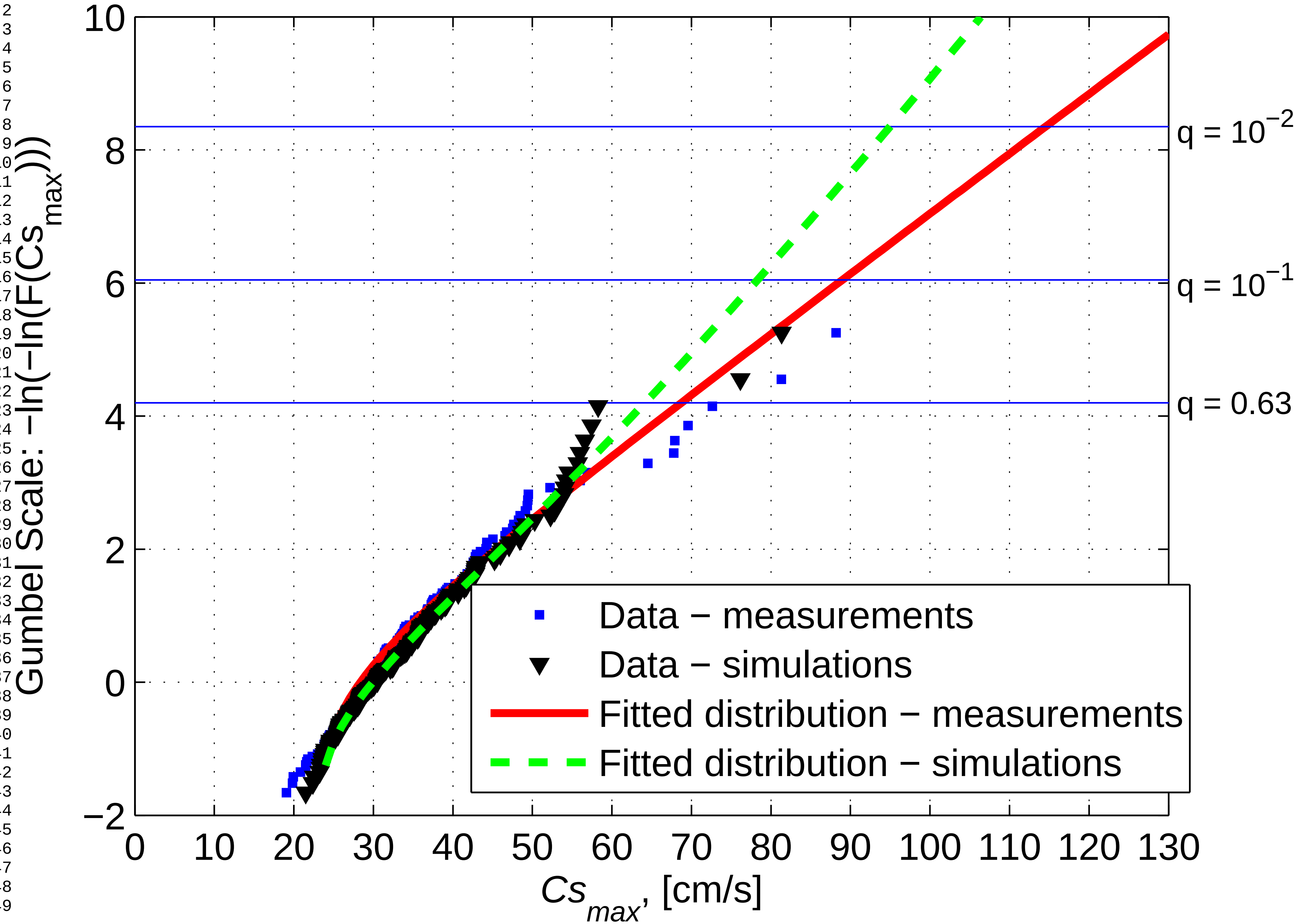


Figure 8c


10
8
6
4
2
0
−2
Gumbel Scale: −ln(−ln(F(Cs_max)))
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Cs_max, [cm/s]
q = 10^−2
q = 10^−1
q = 0.63
Data − measurements
Data − simulations
Fitted distribution − measurements
Fitted distribution − simulations

Manuscript Number ODYN-D-17-00019: Simulated wind-generated inertial oscillations compared to current measurements in the northern North Sea

Authors' comments to review

Please note that the comments from both reviewers have been arranged by section of the paper for a better overview.

No.	Reviewer	Comment	Authors response
General			
C1	1	The subject is of scientific interest, and of strong practical interest. The title and summary are informative and relevant.	No response required.
C2	1	The tables are relevant in their present form.	No response required.
C3	1	The interpretations and conclusions are sound and justified.	No response required.
C4	1	The text is clear and well written, however, not free of misprints. The narration is detailed. In my opinion, it is good for electronic version of publication, except for such phrases as "every 10 minutes interval, i.e. 600 seconds".	Implemented - the written text has been reviewed thoroughly; misprints have been checked for misprints and obvious extra explanations, as illustrated by the reviewer, removed.
C5	2	The manuscript has good potentialities but a major revision is needed before it can be accepted for publication. the aim of the work is clearly stated through the paper, however the general feeling is that the proposed approach (an oversimplified model of wind-induced inertial currents) is way far to simplistic for the task that it tries to accomplish. it is not clear why a 2-ways fully-coupled ocean-wave model is used instead (say, a fully-coupled SWAN+ROMS for instance; or, any other model).	Implemented - the motivation and aim of the work is further detailed and specified in the introduction and it is also pointed out why a simple approach to model the current conditions at this specific location in the northern North Sea has been chosen over a more sophisticated approach. The main motivation of the presented work is <u>not</u> to model the general current conditions as good/correct as possible. As the reviewer points out, more extensive modelling efforts are required for that. However, the aim of this work is to generate current data of <u>sufficient</u> quality and duration to perform joint modelling of waves and currents for design of offshore structures, i.e. to generate current data is more of a mean to meet the over-all aim of this work; namely to establish joint distributions of waves and currents. For this location, that can be achieved by a simple model and there would be little value added by using more extensive (and more expensive) modelling here – it is not necessary here with such extensive modelling to obtain a sufficient description of the current conditions. In addition, it is important and a very valid point to show that for some specific current conditions, these can be modelled by very simple means and that advanced current models are not always necessary to use to obtain good descriptions of the current conditions.
C6	2	Sometimes I feel that the Authors already assume that only inertial currents are important in the region.	Implemented – the text has been rewritten to stress that in accordance with previous published work, wind-generated inertial oscillations are of most importance. This is correct; inertial current has been documented to dominate the current conditions relevant for design of offshore structures in this part of the northern North Sea and specifically at the location in focus. Separate papers have been published and are referred (Section 1) and in addition, a brief extract/overview of this previous work is also included (Section 3). This does

			not mean other current conditions cannot be of importance for other applications, but as wind-generated inertial currents have been found to generate the largest observed current speeds, these will be of most importance when it comes to design of offshore structures in this part of the northern North Sea. This is already pointed out very clearly in both Section 1 and 3.
C7	2	Sometimes I feel that 1, the available dataset is not properly exploited in its full potential. It may already been detailed in the cited literature review but, for instance: - what is the vertical structure of currents from the moorings? - how is the current variance distributed over frequency? I was expecting at least a variance spectra for the currents at surface - intermediate depth – bottom. - a more detailed analysis on wind-to-currents relation (a coherence - phase spectral analysis); or, a more simple but robust wind-to-current correlation analysis to check for the wind-to-current lags. A simple Hoevmoeller-type diagram would most likely provide a major insight on the points mentioned before.	Implemented – see comment C5 and C6. The aim of this work is not to analyze measured current data and give a description of the general current conditions in the northern North Sea, since this has already been done in a separate paper which is also referred to. Unfortunately, this paper is still under review and not published. However, some of this work is published and references are made in the text already. The main purpose of this work is to use the available measured current data to validate a simple model for the governing current conditions, i.e. wind-generated inertial oscillations, to generate current data of sufficient quality and duration to obtain joint wave and current conditions to be used in design of offshore structures.
1. Introduction			
C8	1	Section 1 p.4, l.42 (and further) plural "data" is used as singular (datum). Nowadays it can be often found, however, in the same manuscript, e.g. p.4, l.42 data is plural - I suppose, it would be better to use one version in the entire text.	Implemented - the text has been thoroughly reviewed and updated for consistency about this.
2. General current conditions			
C9	1	For the paper publication the text should be much shortened. For example, Section 2 includes too much textbook information.	Implemented – the text has been shortened significantly. However, general information about and references for the general current conditions in the northern North Sea relevant for design are not easily available. This section serves as an argument for the proposed simplified methodology and is thus considered to be an important part of this manuscript. Thus, this section has been shortened, but not completely removed.
C10	2	Section 2 for instance suggests that inertial currents appear when storms or fronts pass over the moorings. How about the seasonal effects of diurnal sea-breezes? how about the effects of the seasonal stratification in T-S?	Not implemented – see comment C5, C6 and C7. A general, high-level overview of the main components which constitute the all-year current conditions in the northern North Sea is given. In general, seasonal variations in current conditions have not been investigated and are considered to be outside the scope of the presented work. However, neither diurnal sea-breezes nor stratification in temperature/salinity are known to affect the wind-generated inertial oscillations. Diurnal sea-breezes are observed near shore and not expected to influence a location far offshore as considered in this work. Seasonal stratification in temperature/salinity have been discussed in Section 5.2, but density-driven currents are very local and not considered to contribute much to the current conditions relevant for design of offshore structures (which typically have dimensions of 80 x 80 m).

3. Measurements of inertial oscillations			
3.1. Current measurements			
C11	1	Instead of giving illustration with different ADCP devices, it would be enough to name the device, which data were used in the study. The illustrations are clear and well presented except Fig. 2, which can result in misunderstanding.	Implemented - Figure 2 has been removed from the manuscript and the text rewritten to give a written description of the mooring configurations and the different ADCP devices.
C12	1	Re: p. 8, lines 10 and 34 - Fig. 1, Fig. 2: change of order	Implemented – Figure 2 has been removed.
C13	1	Re: last paragraph of 3.1: It is not clear what device was used to determine current data used in the paper. Only the Table 1 caption suggests that the data were obtained from the QuarterMaster ADCP. In my opinion, intensive turbulence during strong winds can significantly affect results of measurements, also at larger depths. ADCPs of different frequencies measure currents in different volumes and have different resolutions, the measured volume depends also of direction. The higher frequency, the more intensive the noise. Probably 150 kHz QuarterMaster would give better results for higher water column than the other devices.	Implemented – specified in the text; as the reviewer correctly assumes, Quartermaster ADCP data have been used in this work.
C14	1	I suppose that the bottom topography in the vicinity of the all measurement locations was analysed and no local disturbances due to local bottom topographic forms affect the current field. If so, it would be useful to mention it.	Implemented - mentioned in the text.
5. Application and validation of the model at Location 4			
5.1. Application			
C15		Discussion of the drag coefficient could be shorten.	Implemented - discussion shortened.
C16	2	Simulations are run with wind reanalyses. I believe this is quite a limiting factor given that -if I read correctly- they are provided at 3-h time steps. how accurate are them in replicating the "true", observed small-scale wind variability in the region? I remember for instance major biases from ECMWF or BoM wind fields when compared to observations? was this taken into account in the simulation results?	Implemented - the concerns raised by the reviewer has been mentioned in Section 5.1. Moreover, see comment C5, C6 and C7. At the Norwegian Continental Shelf, it is considered state-of-the-art to use the NORA10 wind and wave hindcast with a time step 3-hours to estimate design conditions. Several thorough validations of this hindcast have been published and referred – both the hindcast wind and wave data are found to compare very well with available measurements. For design of offshore structures, variations in wind conditions on a temporal scale of less than 3-hours are normally not considered, since tropical cyclones are dominating the storm climate. The ECMWF and BoM wind fields are not used here and consequently not appropriate to consider in the simulation results.
5.2 Validation			
C17	1	Re: 5.2. p.13, l.62-63: Section 3, not 2	Implemented – changed.
C18	1	Re: p. 15, l. 16-26: No information on the initial "background current speed of 5 cm/s" direction. On the other side, this paragraph could be much shortened, as zero speed was finally taken.	Implemented – paragraph generalized and significantly shortened. Consequently, information about the direction of the initial background current of 5 cm/s will be to detailed and is not included.
C19	1	Re: p.15, l.38: sentence repeats that of l. 32	Implemented – the first sentence removed.
C20	2	Authors suggest that Figure 6 is an example of simulations - observations. Authors seem to suggest that they match quite well in magnitude and timing; if it is reasonably true in magnitude, simulations and observations seem to be	Implemented – this section has been rewritten to emphasize that in the presented work focused on joint design criteria of waves and currents, only

		out-of-phase most of the times. I understand that focus is given on current speed, however the timing should match as well.	the magnitude of current speed is of interest and not the timing. Moreover, see comment C5, C6 and C7.
5.3 Background current			
C21	1	Re: 5.3. pp.16-17: Discussion of different approaches can be considerably shortened (especially figures), as empirical approach was selected to use.	Implemented – this discussion has been significantly shortened and only figures from the selected approach are included.
6. Extreme values			
C22	1	p.18 l.22 marked instead of rmarked	Implemented - typo corrected.
7. Other locations			
C23	1	Re: Fig. 12 (a1) and (a2): change of order	Implemented - order changed.
C24	1	p.20 l.46 except instead of expect	Implemented - typo corrected.
C25	1	Re: p.21, l.3-4: probably Dooley current, not Doodley	Implemented - typo corrected.
C26	1	Re: (Figs. 13): The model tuned for the Location 4 did not work so well at other locations. Empirical distribution of maximum measured and simulated current speed show better agreement at the deepest Location 1 than at Locations 2 or 5. May be, it is because that at Location 1, turbulence can be weaker and thus better determination of current speed from ADCP records.	Implemented - mentioned and discussed in text.
8. Summary and concluding remarks			
C27	1	Despite of good results for Location 4, the Authors rightly conclude that the problem of robust estimation of extreme currents for design of offshore structures is still open. It has to be stressed that, according to Authors (Section 1), sea current hindcast gives no satisfactory results yet.	Implemented - this has been further discussed in the summary.