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# Agenda voor de Toekomst
# Waves in the estuary

Analysis of wave measurements at Appels (Dendermonde)

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# Agenda voor de Toekomst – Waves in the Scheldt estuary

## Analysis of wave measurements at Appels (Dendermonde)

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# Abstract

One of the questions within the “Agenda voor de Toekomst” research is the importance of waves in the estuary. Waves are important as they can have an influence on the hydraulic load on river banks (and dikes). These hydrodynamic forcing can have morphological effects (erosion) on intertidal areas and therefore influence the ecological role of tidal flats and marshes. To estimate this, field measurements are necessary. Within project 14_082 : “Waves in the estuary”, several measurement campaigns are foreseen, both in the Western Scheldt (Saeftinghe, Hooge Platen) as in the Sea Scheldt (Appels, Notelaer). This report describes the measurements performed at the location of Appels, near Dendermonde, in combination with the recorded ship traffic during the same period.

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# 1 Introduction

In the period 2014-2017 the four-year research program "Agenda for the Future" of the Scheldt estuary will be executed. This Agenda for the Future was created as part of the first evaluation of the Treaty Common Policy and Management. The Flemish-Dutch Scheldt Commission (VNSC) has approved this agenda at the autumn meeting of 2013. Following this, an action plan was defined (Beirinckx et al., 2014), which served as the guide for the study from 2014 to 2017. The present report is part of the research that aims to improve the knowledge of wave loading on intertidal areas. In this report, within project "14_082: Waves in the estuary", measurements at Appels (Dendermonde) will be discussed.

Waves can be caused by meteorological conditions (wind waves) as by sailing ships (ship waves). In this report the importance of wind- and ship waves is investigated in the central part of the Upper Sea-Scheldt (approx. 125 km upstream of Vlissingen). The relation between wind speed and direction on wave heights is determined. Also a link between the ship characteristics (length, width, speed, distance from the mud flat) and the wave height characteristics is investigated.

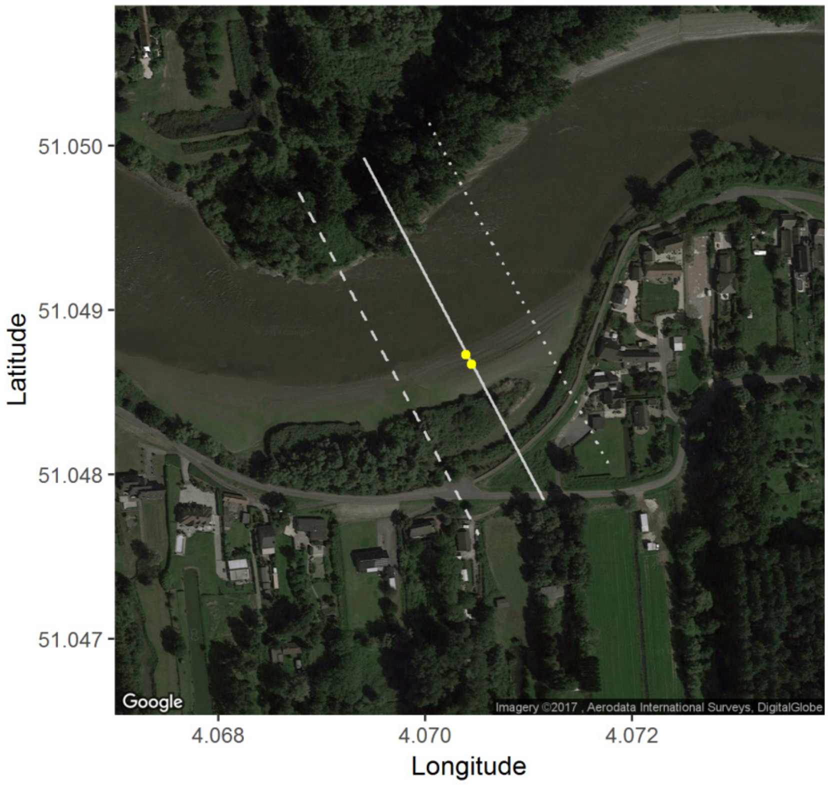
In Chapter 3, the study area, the devices used in the intensive measuring campaign and the main measurement settings, are presented. Wave and wind data that were recorded during the measuring campaign are included in Chapter 4. Particular attention is paid in the analysis of the wave data measured by high-frequency pressure sensors, which are used in the ship and wind wave analysis. In Chapter 5, information about the shipping traffic during the measuring campaign in the investigated area, is analyzed. The processed information, which included static (type, length, beam, etc.) and dynamic (speed, heading, draught, etc.) data about the total amount of ships, was retrieved by the database of the AIS (Automatic Identification System) tracking system. Then, in Chapter 6, the coupling of the wave measurements with the ship passages, is presented. Chapter 7 includes the implementation of a similar methodology for the coupling of the measured wind data with the wave measurements. Finally, in Chapter 8, the conclusions resulting from the ship- and wind-wave analysis are presented.

# 2 Field description and measurement settings

## 2.1 Study area

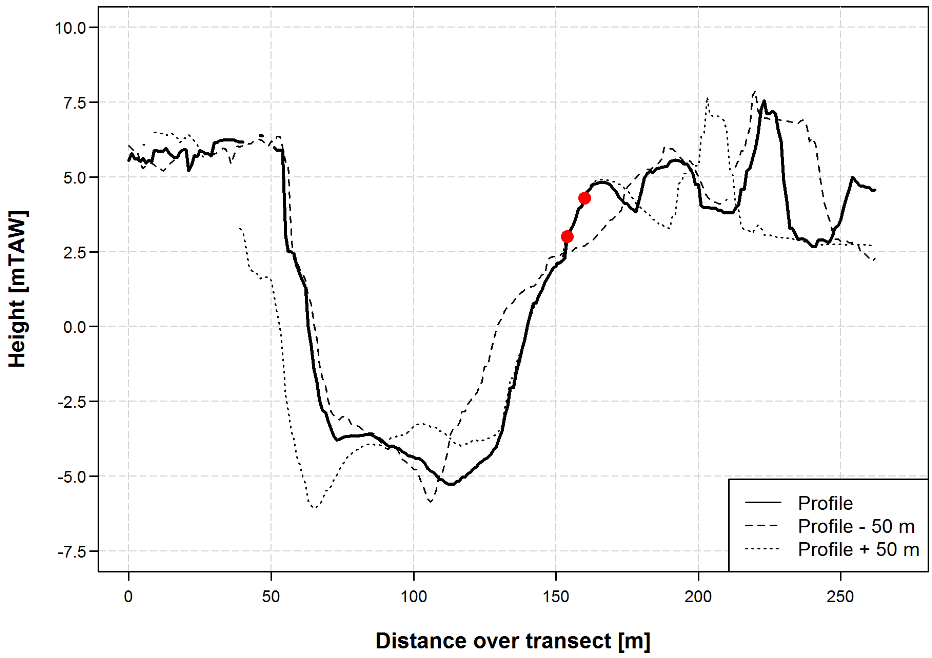
The measurements are performed at the intertidal areas of Appels, near Dendermonde, in the Upper Sea Scheldt 125 km upstream from Vlissingen. An overview of the location is given in Figure 1. The measurement locations are indicated with yellow dots. The measurements are located on the right bank of the river, just behind the river bend. Three cross-section are defined, through the measurements and cross-sections 50 m up-estuarine- and down-estuarine, which are shown in Figure 1.

Figure 1 – Overview of the measuring location (indicated with yellow dots) together with the position of the cross-sections, depicted in Figure 2.




In Figure 2 the cross-section through the measurement points, and the sections 50 up- and downstream are shown. The measurements are indicated with red dots. The maximum depth on the cross-sections is around -7.5 m TAW. The tidal flat at the measurement location and 50 m down-estuarine have the same slope, 50 m upstream, the slope of the tidal flat is clearly more gentle. A small tidal channel can be observed between the marsh and the dike, for the 2 most up-estuarine profiles.

Figure 2 – Overview of the cross-sections through the measurements points, together with a cross-sections 50 m up- and downstream. The measurement points are indicated with a red dot.




## 2.2 Measurement settings

Both pressure sensors and Aquadopp© insturements are deployed during the measurement campaign, which lasted from 10th of May till 8th of June 2017. A pair of instruments (pressure sensor and Aquadopp©) was located at the low tidal flat (around + 2.7 m TAW), the other pair of instruments was located at the high tidal flat (around + 4.1m TAW). The vertical position is measured using an RTK gps. An overview of the measurement locations is given in Table 1, with the geographic coordinates in WGS84 (EPSG code 4326). The pressure sensor on the low tidal flat is recording data at 20 Hz, the pressure sensor on the high tidal flat was unintentionally measuring at 2 Hz. The Aquadopp© insturements are recording a vertical profile of velocities every 5 minutes. The vertical resolution of the measurement is 10 cm.

Table 1 – Overview of the measurement locations of the different instruments.

| | Instrument | Long (E) | Lat (N) | Vertical position [m TAW] |
|---|---|---|---|---|
| **Low** | Pressure sensor | 4.070414 | 51.048735 | 2.690 |
| | Aquadopp© | 4.070394 | 51.04873 | 2.739 |
| **High** | Pressure sensor | 4.07046 | 51.048674 | 4.099 |
| | Aquadopp© | 4.070448 | 51.048671 | 4.101 |

The ship traffic is recorded using AIS, as explained in Chapter 4. Because not all ships are recorded in this database, additionally photos are taken using a Reconyx Hyperfire PC800, to detect other ships. This camera is fixed on a tree, and photos are recorded every 3 s.

Figure 3 – Photo of the passing ship, view from the fixed camera position.


As both the battery and the memory card are not lasting for a long time, photos are only for a limited number of days. In Table 2 an overview is given of the days and times for which photos are available. An algorithm was written in R, to automatically select ship passages using the pictures.

Table 2 – Overview of the days and time slots for which photos are available

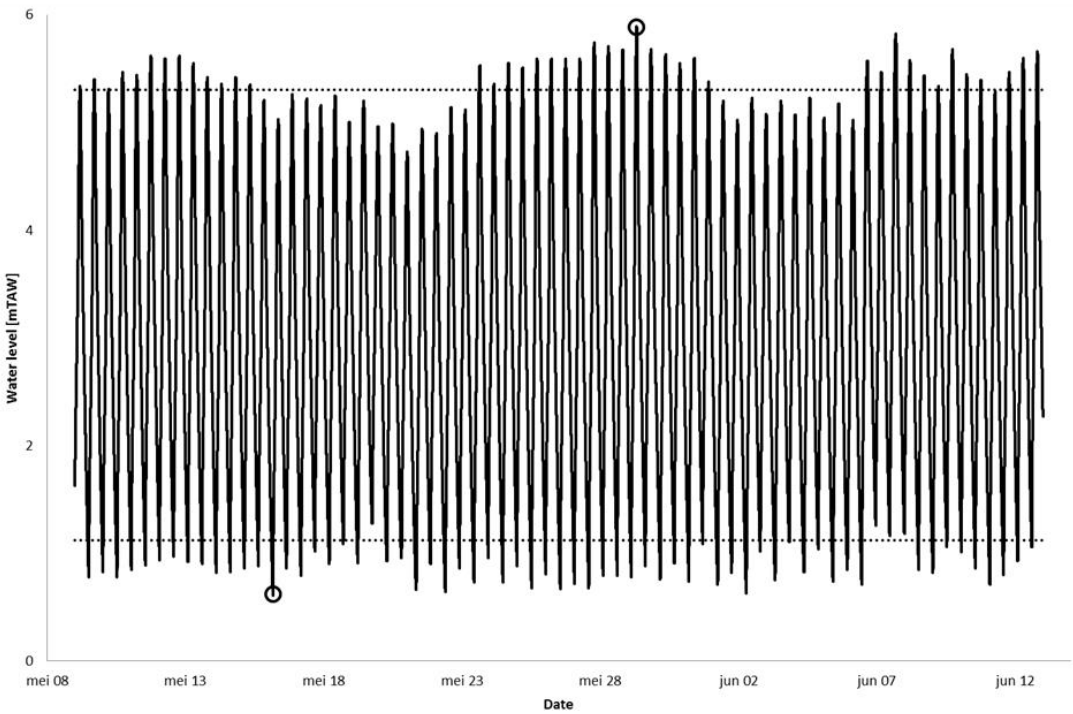
| Day | Hours |
|---|---|
| 10 / 05 / 2017 | 16 - 21 |
| 11 / 05 / 2017 | 8 – 9:10 |
| 23 / 05 / 2017 | 9:34 – 11 & 14 - 20 |
| 24 / 05 / 2017 | 9 – 11 & 14 - 20 |
| 25 / 05 / 2017 | 9 – 11 & 14 – 16:15 |

# 3 Measurements

## 3.1 Tidal measurements

The closest tidal gauge in the neighbourhood of the measurements is Dendermonde, situated approximately 3.5 km downstream of the measurement location. The average high water during the measurement campaign is 5.34 m TAW, the average low water 0.86 m TAW. This leads to an average tidal range of 4.48 m. Compared with the average tidal range of 4.17 m during the period 2001- 2010 (Vanlierde et al., 2016), the tidal factor during the concerned period is 1.07. The maximum high water during the measurement period is 5.89 m TAW, the minimum low water 0.61 m TAW. Both points are also indicated in Figure 4.

Figure 4 – Overview of the tidal variations during the measurement campaign.
The maximum and minimum value is indicated with a circle.

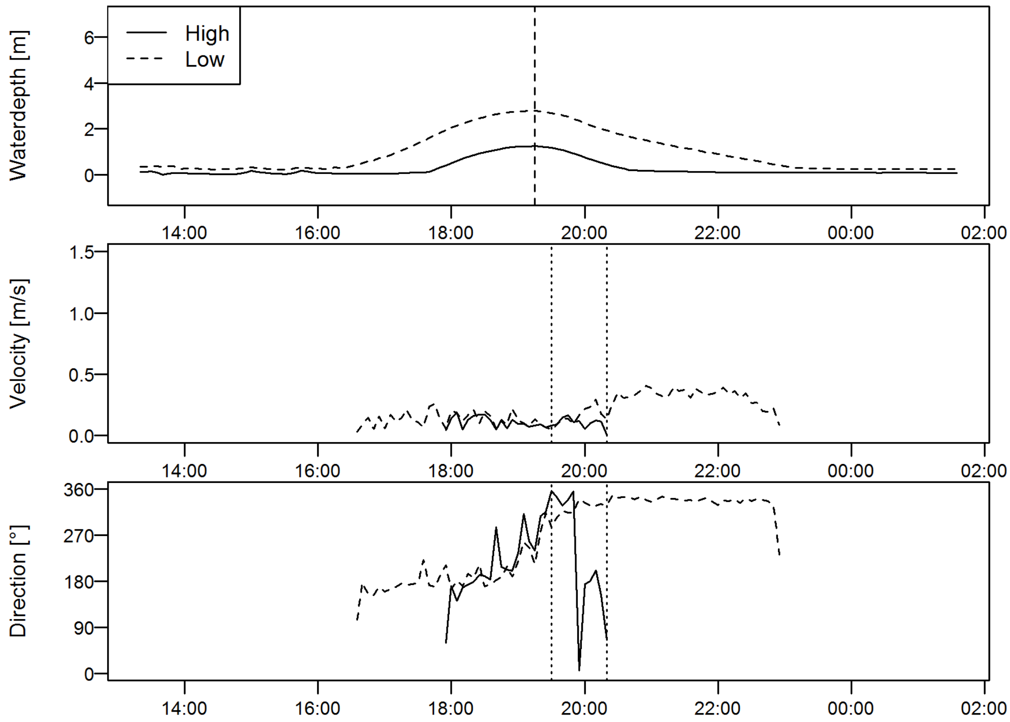



## 3.2 Velocity measurements

Velocity profile measurements are performed Acoustic Doppler Profile (ADP) technology. The Aquadopps© are placed into the tidal flat, up-looking, with the head of the instrument approx. 0.20 m above the bed. A blanking distance of 0.20 m is present, as such the first measurement location is about 0.40 m above the bed. Measurement records are available every 5 minutes. In this section the depth-averaged values are presented.

As can be seen in Figure 5, which shows the evolution of the depth-averaged velocities for a specific tide, the flow velocities on the tidal flat are very low.

Figure 5 – Overview of the waterdepth (upper plot) above the two sensors,
de depth-averaged velocities (m/s) in the middle plot and velocity directions (lower subplot).




The relation between the tidal range and the maximal velocity during respectively the flood and ebb phase is plotted and shown in Figure 6 and Figure 7. The maximal flood velocities are low, maxima around 0.4 m/s and 0.3 m/s are found for the low and high tidal flat respectively. The relation at both location between tidal range and maximal velocities is similar, with a slope of ca. 0.11 to 0.12. For the ebb phase, the velocities are clearly higher for the low tidal flat position, with maxima around 0.5 m/s. For this period of the tide, no clear relation with the tidal range could be observed (very low slope values are calculated and the $R^2$ values are very low also).

Figure 6 – Overview of the relation between the tidal range and the maximum peak velocities during the flood phase,
for the low tidal flat (left) and the high tidal flat (right)

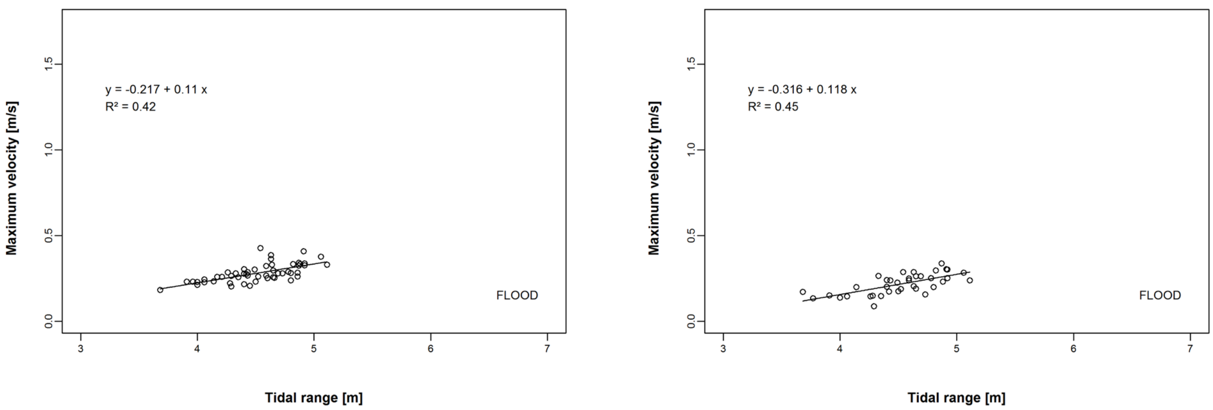
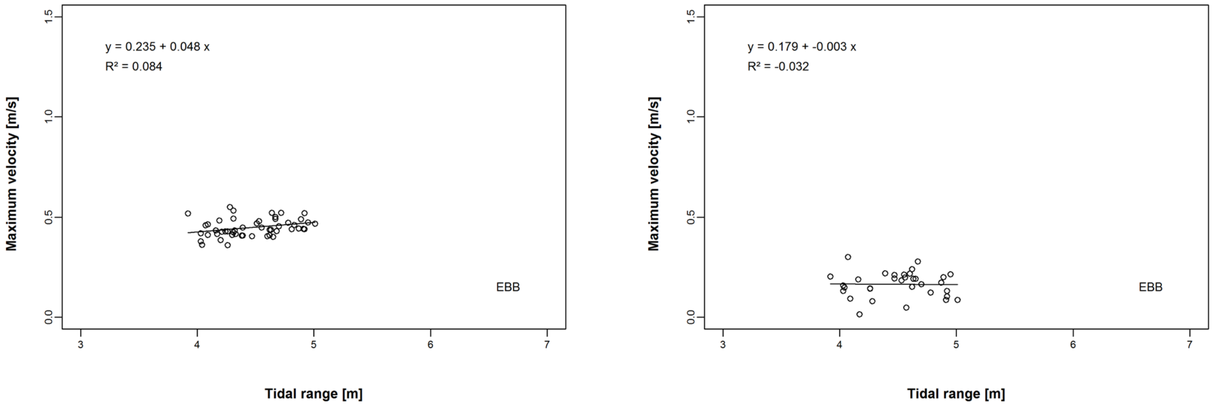


Figure 7 – Overview of the relation between the tidal range and the maximum peak velocities during the ebb phase, for the low tidal flat (left) and the high tidal flat (right)



## 3.3 Wind measurements

The VMM (Flanders Environment Agency) measures wind speeds and directions at Melsele, at a height of 10 m above the ground level. The measurement period ranges from 08/05/2017 to 12/06/2017. The variation of instantaneous wind speed and direction during the measurement period are shown in Figure 8 and Figure 9.

Figure 8 – Variation of instantaneous wind speed during the measuring campaign (08/05-12/06/2017).

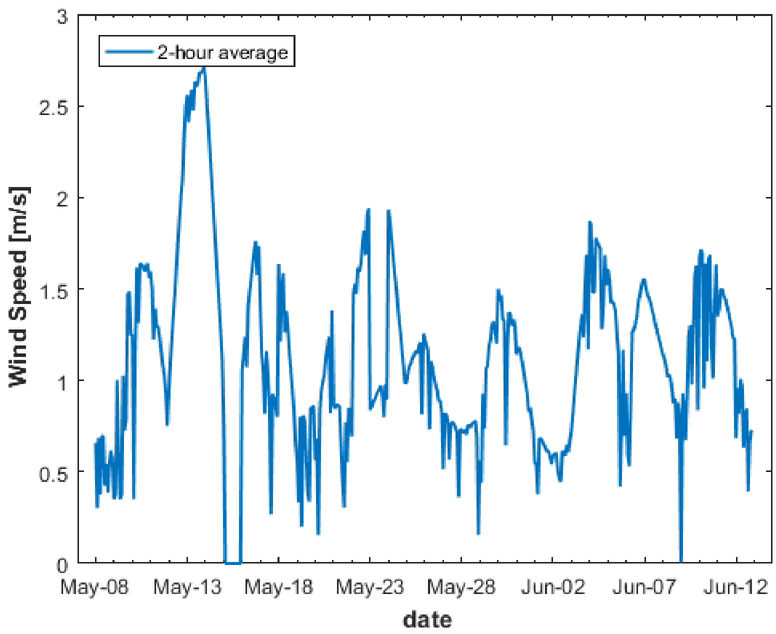
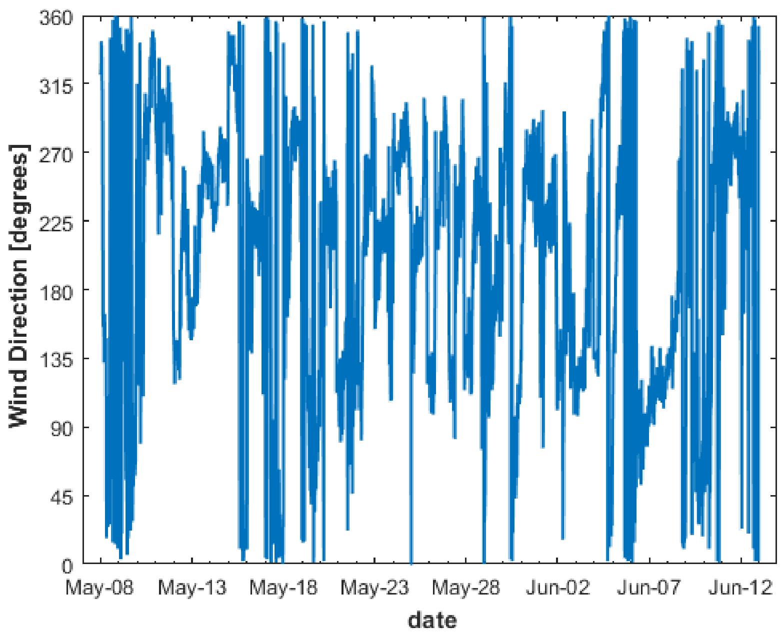



Figure 9 – Variation of instantaneous wind direction during the measuring campaign (08/05-12/06/2017). Wind direction follows nautical convention (North = 0°, East = 90°)



In Figure 10, the average daily wind direction and the direction of the maximum daily wind speed are shown. In both figures the campaign averages are depicted as well (green lines). The campaign average of wind speed and direction equals to 0.4 m/s and 266 (west-southwest direction), respectively. The maximum wind speed, approximately 5.68 m/s, is observed during the 6th day of the campaign (13/05/2017) and corresponds to an southwest (196°) wind direction.

The maximal maximum daily wind speed, ~5.6 m/s, appears on 14/05/2017 and corresponds to a west-southwest wind direction (240°). The minimum daily average is observed on the 23rd day (30/05/2017), i.e. 0.27 m/s.

Figure 10 – Daily-averaged wind speed (blue line), daily maximum wind speed (red line) and campaign average (green line).

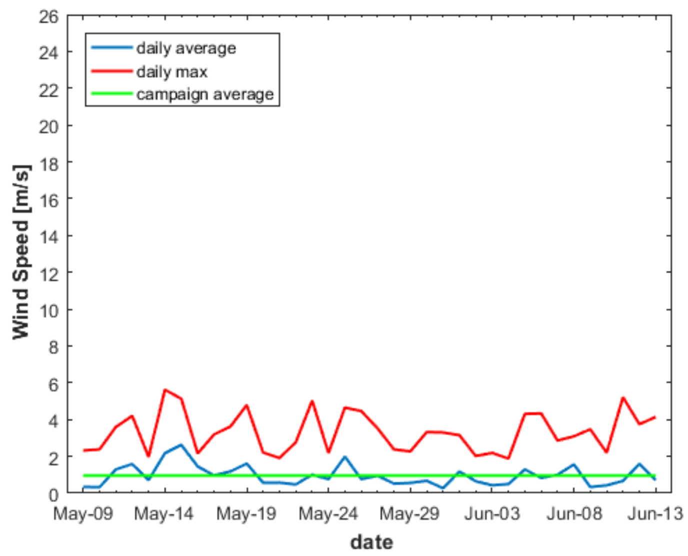
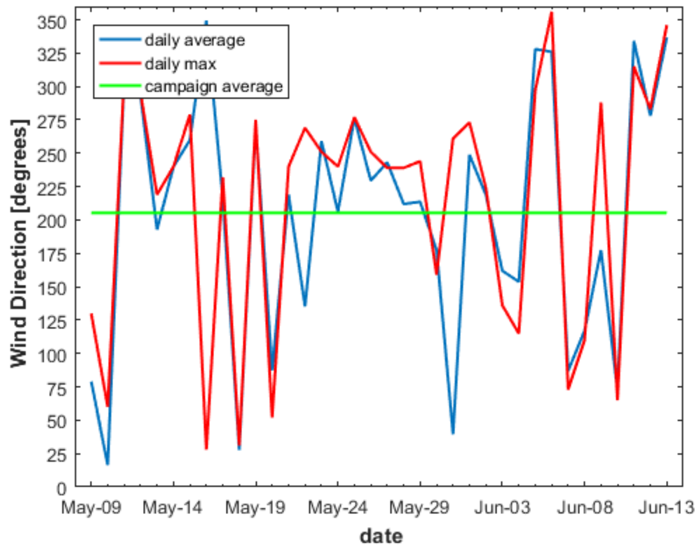
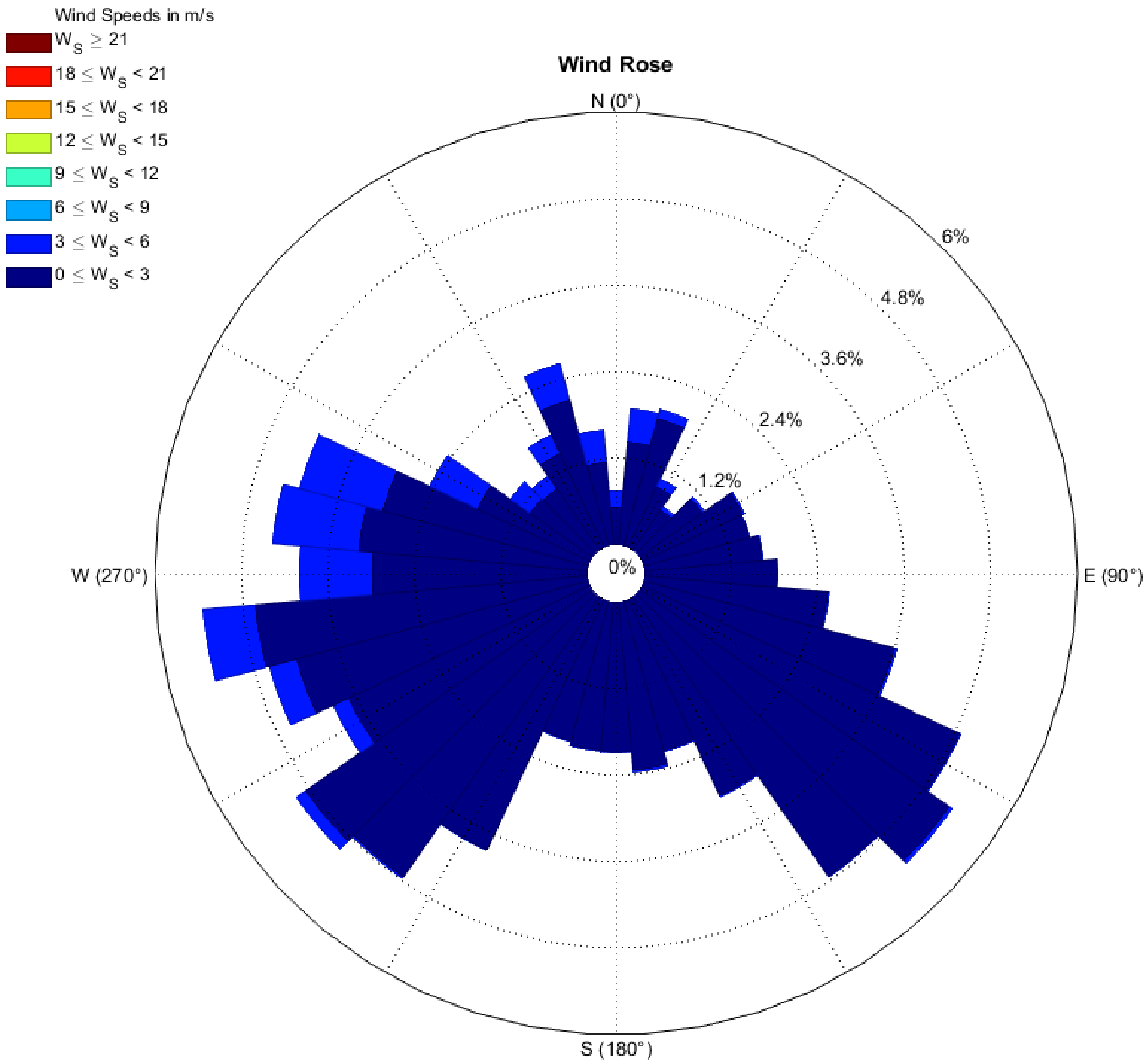



Figure 11 – Daily-averaged wind direction (blue line), direction that corresponds to maximum wind speed (red line) and campaign average (green line).



For a deeper insight into the wind measurements during the campaign, a wind rose is presented in Figure 12. In this graph the frequency of winds blowing from particular directions (directional bin amplitude = 5º), along with several wind speed ranges, are shown. Dominant wind directions range from west-northwest to southeast directions. Note that around 75% of the wind directions belong to the Southern semicircle. Furthermore, as indicated by the coloured bars, the strongest winds are coming from the west north-west. About 75%, generally lower wind speeds, belong to the southern quadrants (circular sectors each equal to one quarter of a circle).

Figure 12 – Wind rose with directional bins of 5°, for the measurement period.



## 3.4 Wave measurements

The wave measurements are based on the data recorded continuously by two pressure sensors (wave gauges) during the intensive measuring campaign. The vertical coordinates of the pressure sensors in respect with the TAW reference level are measured with RTK gps and given in Table 1. The sampling frequency of the sensor placed on the low tidal flat is 20 Hz, the sensor at the high tidal flat is measuring, unintentionally, at a lower sampling frequency of 2 Hz. The sensor is still used in the analysis, although some of the results should be treated with more care.

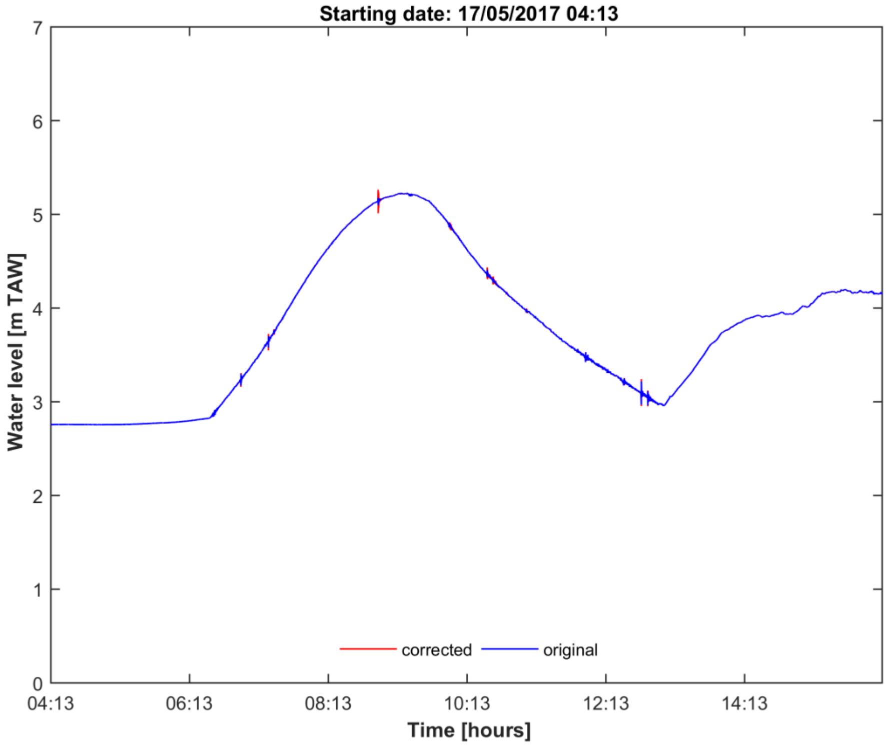
### 3.4.1 Methodology for data processing

In order to acquire information about wave characteristics in the area of interest, the raw data recorded by the aforementioned pressure sensor were processed by means of MATLAB (version 2016a) scripts. These scripts were developed within another project concerning the analysis of wind and ship waves (described in Kolokythas et al., 2016). An overview of the procedure that was followed includes the following steps:

1. compensation of raw data due to atmospheric pressure and conversion to water levels, using TAW as the reference level
2. division of water level time-series per tidal cycle
3. correction of resulting water level time series due to pressure attenuation with depth
4. low-pass filtering of the data for the separation of the tide from the water fluctuations (waves)
5. calculation of individual wave characteristics per tidal cycle, from the resulting water fluctuations time series

As the pressure sensors used in this campaign are calibrated to read zero at standard atmospheric pressure, 1.01325 bar, the compensation was accomplished by subtracting the fluctuations around the standard atmospheric pressure from the raw pressure data, i.e. $P_{comp} = P_{raw} - (P_{atm} - 1.01325)$. For the compensation due to atmospheric pressure, corresponding barometric measurements at Melsele, were utilized. Then, the conversion of compensated pressure to water level in m TAW takes place, in which pressure is multiplied by a factor equal to 10.1972 (conversion from bars to mH2O) and the vertical position of the gauge. A typical daily water level time-series in respect with TAW reference level after atmospheric pressure compensation, is represented in Figure 13. It is clear that the tidal variation is well measured, but the sensor sometimes produces weird results when the sensor is not flooded. These periods are detected visually and are eliminated with care.

Figure 13 – Overview of the measurement recorded with the pressure sensor, for one tidal cycle.




### 3.4.2 Wave statistics

In Table 3 an overview of the main wave statistics during the measurement campaign is shown. A significant and maximum wave height is calculated over each tide, the values shown in Table 3 are the statistics on these wave values per tide. The average significant wave height per tide is around 0.04 m, both for the low and high tidal flat. This significant wave height is maximal 0.06 to 0.07 m over one tide during the measurements and a minimum value around 0.015 m is found for both locations. The maximal $H_{max}$ values during the measurement campaign are respectively around 0.43 m and 0.40 m for the low and high tidal flat. On average, the maximum wave height is slightly larger on the low tidal flat (0.19 m) compared to the high tidal flat (0.15 m). An overview of the evolution of $H_{max}$ and $H_{1/3}$ is shown in Figure 14 and Figure 15 respectively.

Table 3 – Main statistics of the significant ($H_{1/3}$) and maximum ($H_{max}$) wave height during the measurement campaign.

| | **Low tidal flat** | | High tidal flat | |
|---|---|---|---|---|
| | **$H_{1/3}$ [m]** | **$H_{max}$ [m]** | **$H_{1/3}$ [m]** | **$H_{max}$ [m]** |
| *Min* | 0.015 | 0.020 | 0.014 | 0.019 |
| *mean* | 0.044 ± 0.012 | 0.181± 0.11 | 0.038 ± 0.009 | 0.149 ± 0.095 |
| *Max* | 0.071 | 0.435 | 0.058 | 0.398 |

Figure 14 – Overview of the significant ($H_{1/3}$) and maximum ($H_{max}$) wave height per tide, during the measurement campaign for the low tidal flat position

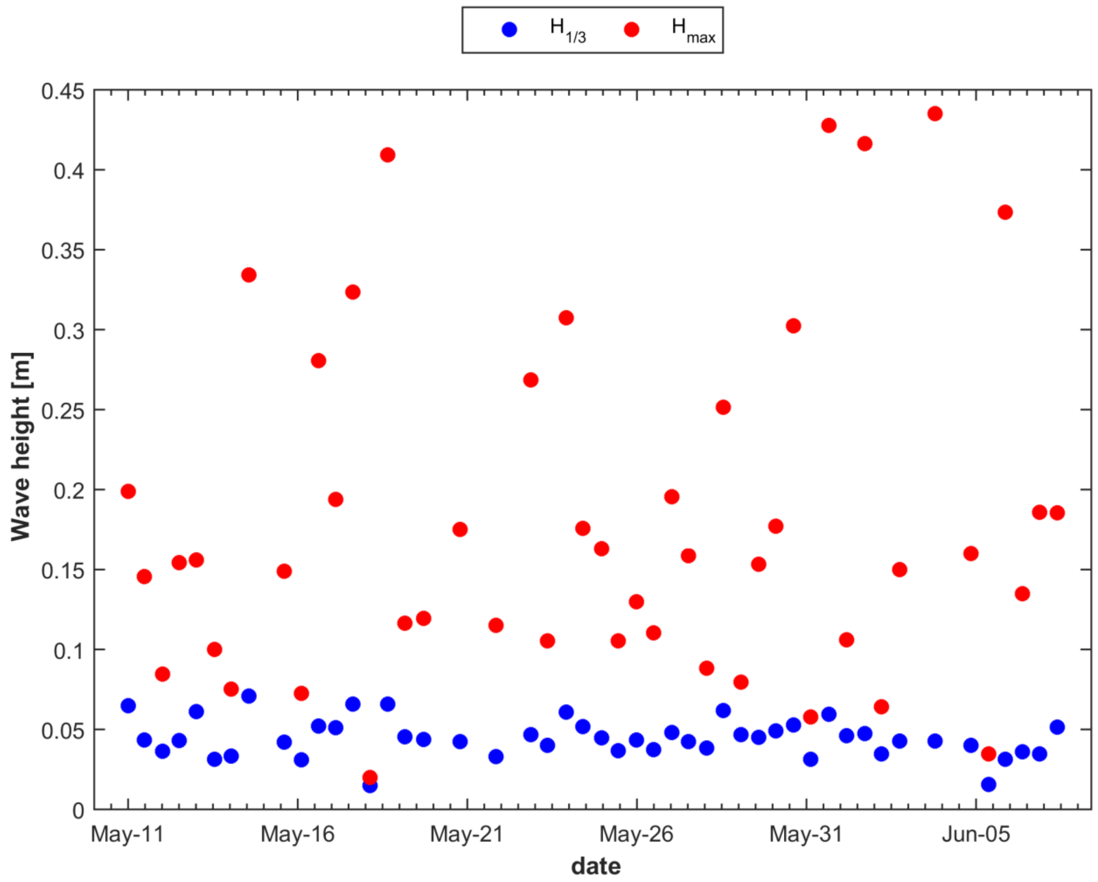
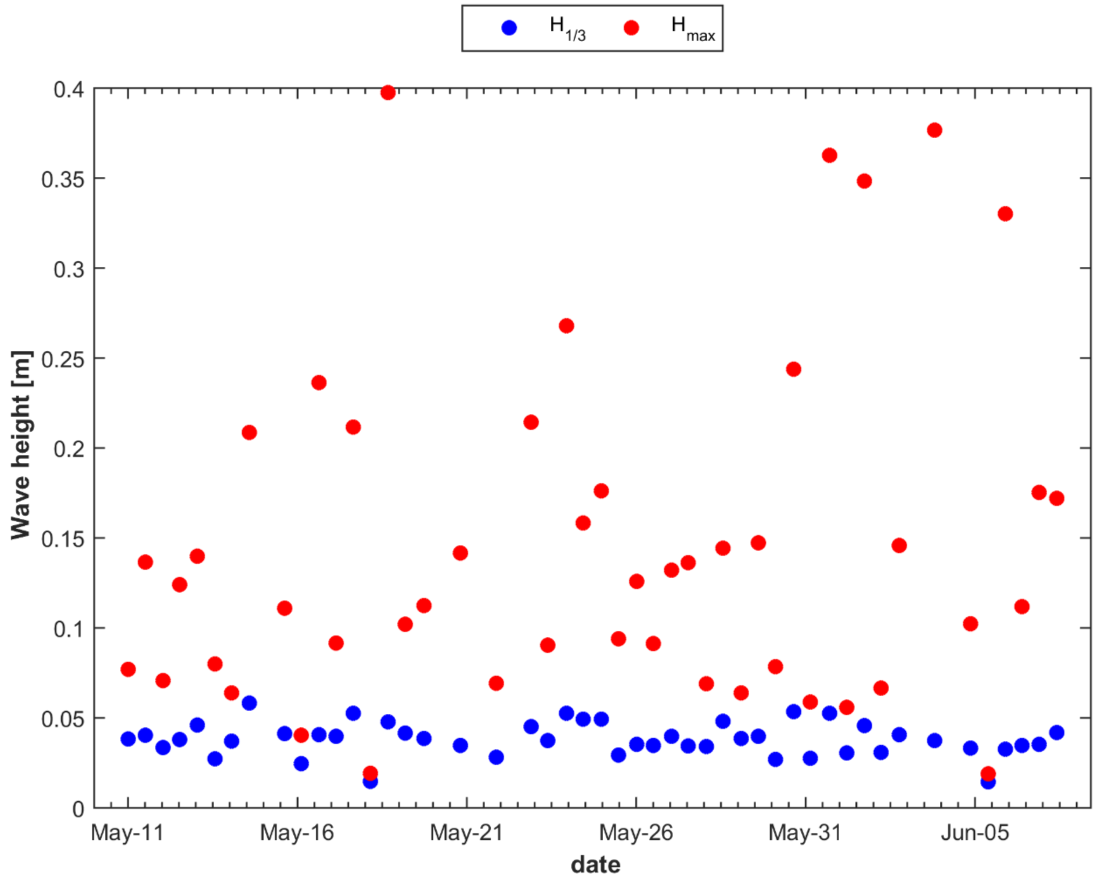


Figure 15 – Overview of the significant ($H_{1/3}$) and maximum ($H_{max}$) wave height per tide, during the measurement campaign for the high tidal flat position



# 4 Ship data(AIS)

## 4.1 General information about AIS data

The Automatic Identification System (AIS) is a tracking system used by Vessel Traffic Services (VTS) for identifying and locating ships. Each ship exchanges data with other ships or base stations containing information on its position, course and navigation speed. On the Western Scheldt and the North Sea AIS data are received by more than 10 base stations, which are logged in a central server operated by the Scheldt Radar Chain and each day approximately 0.5 GB of data are logged (Knowledge Centre Manoeuvring in Shallow and Confined Water, 2015). For more information, the reader is referred to (Kolokythas, G. et al, 2017).

A tool, developed by FHR for processing the AIS data, was utilized in this study considering as entry lines the transect where the measurement devices were installed. This transect is extended in order to connect the right and the left bank of Scheldt estuary (see dashed line in Figure 1). The resulting data files (one for each entry line) contain the following static and dynamic information about crossing ships: (a) time of passage, (b) Maritime Mobile Service Identity (mmsi) number, (c) name of ship, (d) type, (e) length, (f) beam, (g) draught, (h) speed (over ground) and (i) course. The distance to the measurement devices is an extra parameter added in the AIS information.

## 4.2 General information about CEMT data

West-Europe's inland navigation is structured following the CEMT (Conférence Européenne des Ministres des Transports) classification established politically in 1992 to harmonize channels and rivers' dimensions (ECMT-CEMT, 1992). Each class defines which waterways may be borrowed by any given ship. National classifications such as the Dutch Rijkswaterstaat exist (Dr. Ir. Brolsma & Ir. Roelse, 2011). In that latter example, each class is named after the largest ship capable of borrowing the waterways falling under the related class.

Classes definitions may also vary depending on the source. For example the limits presented by (Expertise- en innovatieCentrum Binnenvaart (EICB) - Vaarwegklassen (CEMT), s.d.) vary slightly from those of the original classification. The original classification has been used as reference for this project. Some classes were defined by ranges, sometimes overlapping each other. In such cases, ranges' maxima were retained as upper classes limits.

For the results here discussed, the following values are used for the classification of the ships into ECMT classes:

Table 4 – Definition used to determine ship class

| Class | Length |
|---|---|
| ECMT 0 | ≤ 35 m |
| ECMT I | 35 m < L ≤ 48 m |
| ECMT II | 48m < L ≤ 60 m |
| ECMT III | 60m < L ≤ 80 m |
| ECMT IV | 80m < L ≤ 90 m |
| ECMT Va | 90m < L ≤ 105 m |

## 4.3 AIS data analysis

In Figure 16, an overview is given of the passage of ships, from different ECMT classes, as described in section 4.2. In total, 530 ship passages were recorded by the AIS system during the measurement campaign, between 10th May and 8th June. Approximately 40 % of the ships passing are of ECMT class I, another 40% are class II and class III ships. In Figure 17 an overview is given of the length and beam of the ships, together with the associated ECMT class, defined according to the definitions as mentioned in section 4.2.

Figure 16 – Overview of passages per ship type during the measuring period

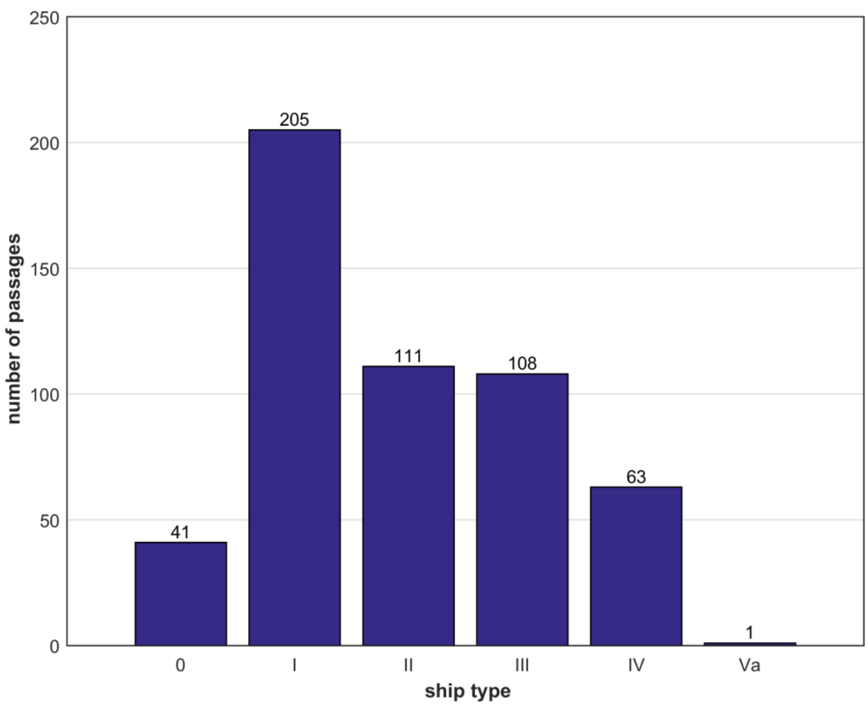
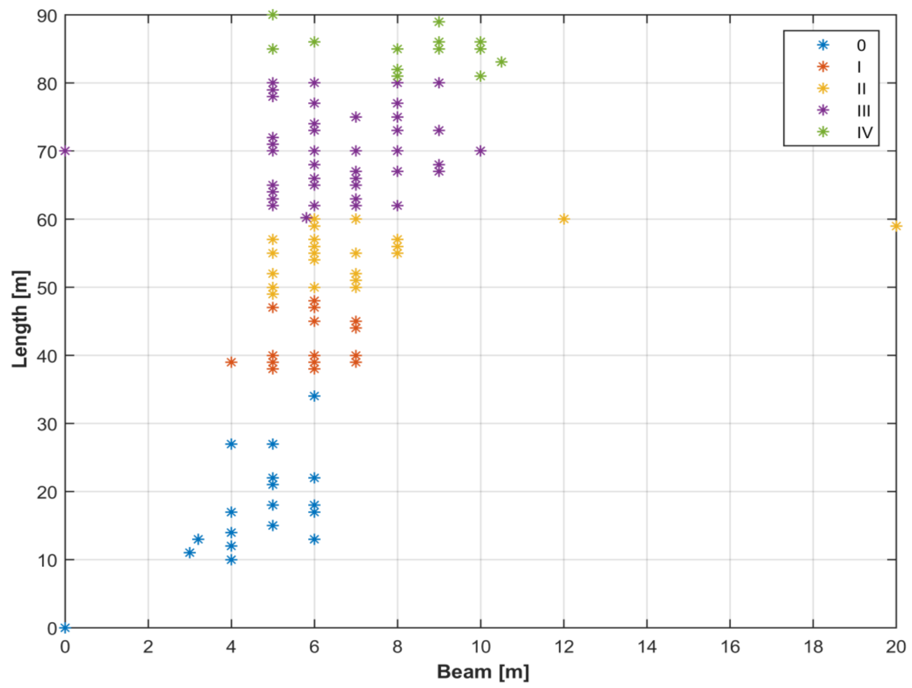


Figure 17 – Distribution of length and width for the ships, showed per ECMT category




If we look to the time the ships are passing the measurement location, it can be clearly seen in Figure 18 that the number of ship passages is clearly higher on days during the week (on average 21.5 ships/day), compared to days in the weekend or holidays (both Ascension Day and Pentecost lie within the measuring period), where only 12 ships per day are passing.

Concerning the passing of ships during the day, in Figure 19 an overview is given of all the ships passing the measurement location and their associated time of passing. It's clear that the ships mainly pass during daytime, with 87 % of the ships passing between 8 AM and 8 PM.

Figure 18 – Average number of ship passages in weekdays, weekends and on holidays.

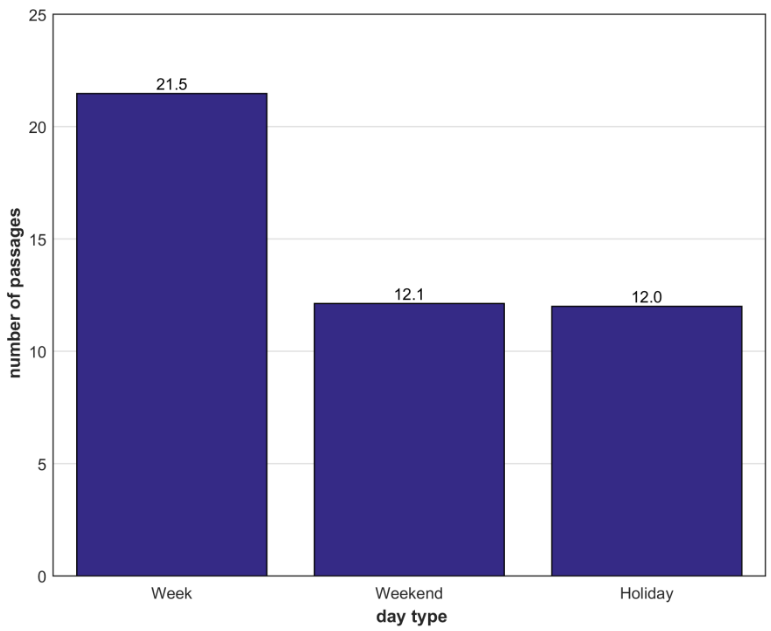
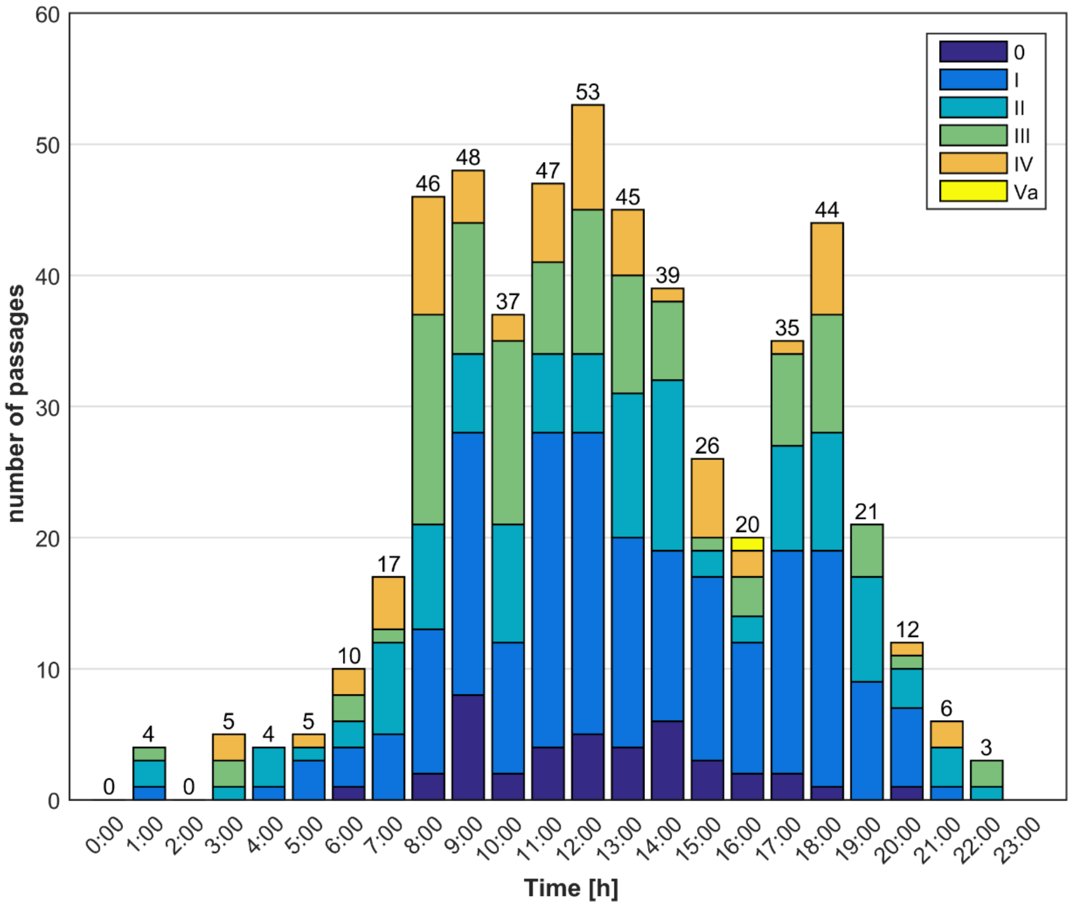


Figure 19 – Distribution of ship passages over a day, integrated over all measuring days



# 5 Ship wave analysis

In this chapter, the coupling of the wave measurements (presented in section § 3.4) with the passages of the vessels from the investigated entry line (chapter 5), is presented. The results of this coupling are graphically visualized, illustrating the distribution of wave statistic parameters ($H_{max}$) with respect to selected static and dynamic information of the ships (AIS data), in order to acquire deeper knowledge about ship-induced waves in the Scheldt waterway around the area of Appels. The methodology followed for the coupling of data is similar to the one presented in detail in Kolokythas et al. (2016). However, small modifications applied in the methodology will be highlighted.

## 5.1 Ship – wave analysis in function of time and tidal cycle

In Figure 20 the wave fluctuations for a certain tide are shown (tide 15). As there are no red dots, which indicate the passage of a ship, visible on the figure, no passages of ships are observed. If we look to the time interval of the tide, these falls mainly during night hours.  The wave fluctuations during the tide are very small, with maximum values around 2 cm recorded. In Figure 21, a similar plot is shown, but for a tide mainly during daylight hours. It is clear from the figure that both the wave fluctuations are clearly higher (> 30 cm) and also the the passage of ships are recorded.

Figure 20 – Wave fluctuations during one tide (tidal cycle 15), with associated ship passages recorded with AIS (red dots)

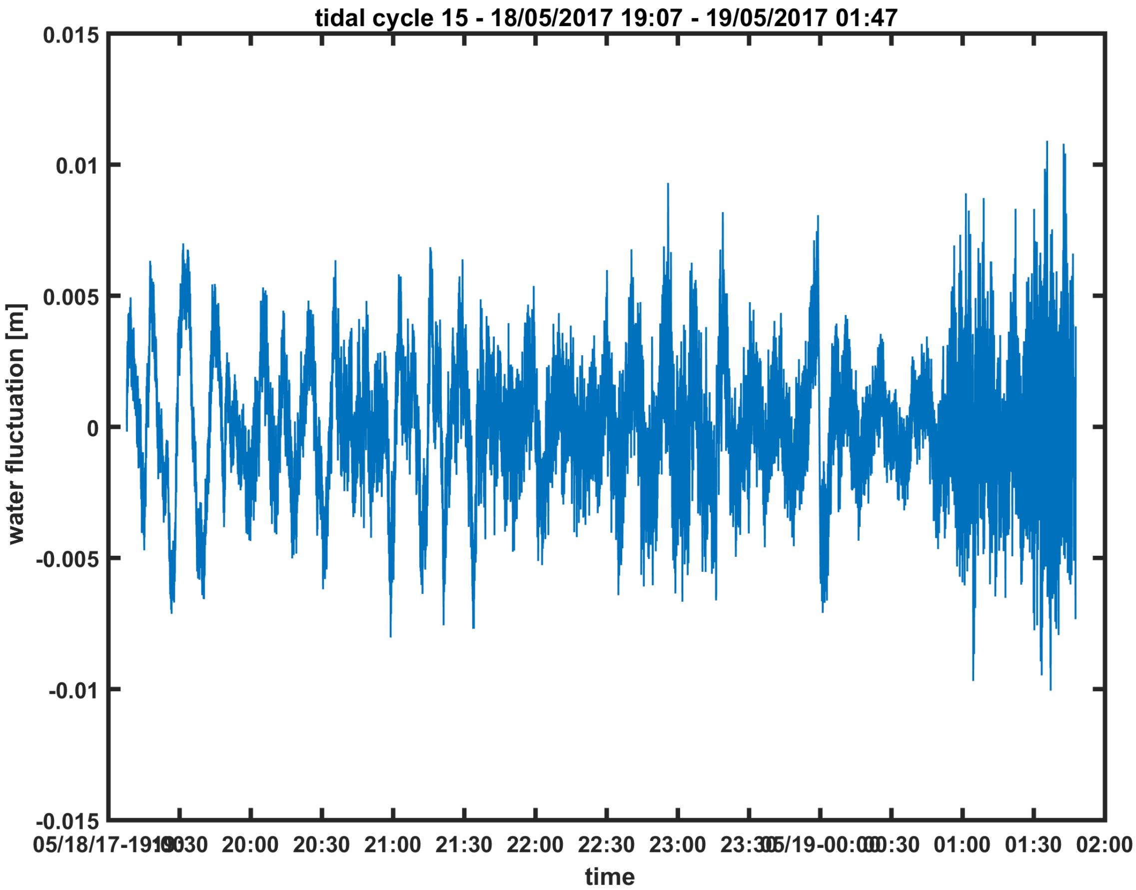
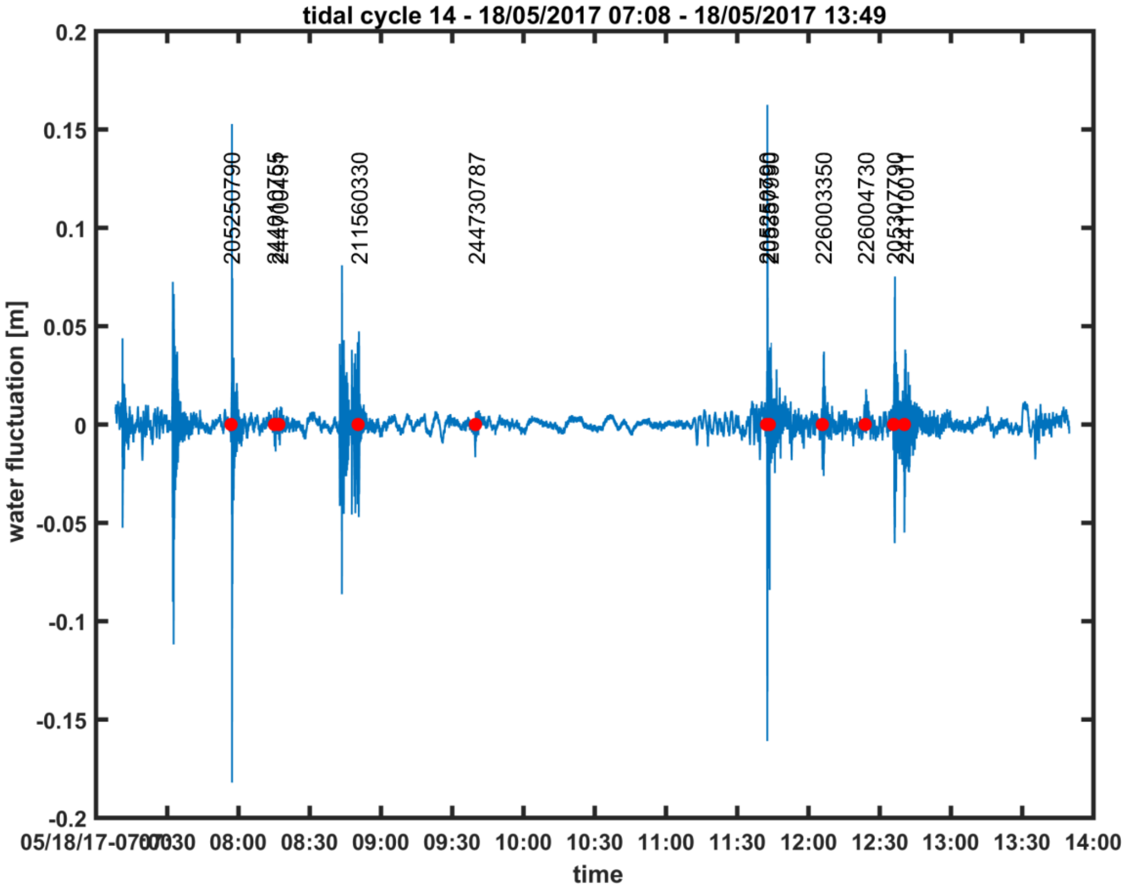


Figure 21 – Wave fluctuations during one tide (tidal cycle 14), with associated ship passages recorded with AIS (red dots)




For the (AIS) recorded ships in Figure 21, mostly a clear wave signal can be observed. Still there are some wave signals for which no (AIS) recorded ship passage is found. Figure 22 shows the result of an analysis, where we do not zoom on a single tide, but count the number of wave events over all tidal cycles, and group them per hour. The minimum treshold for a wave, according to the algorithm who is used, is a wave height of 1 cm. It is clear from Figure 22 that most waves, detected by the algorithm, are occuring during daytime and the curve shows a very similar pattern, compared to the occurrences of ships, recorded with AIS (Figure 17). In Figure 23, the significant and maximum wave height is calculated based on all wave recordings, grouped per hour, as is shown in Figure 22. For the significant wave height, no pattern can be observed in relation to the time of the day. The maximum wave height is clearly higher during daytime, but the picture is less clear compared to the number of waves, as shown in Figure 22.

Figure 22 – Total number of waves, over all measured tidal cycles, detected by the algorithm, presented per hour

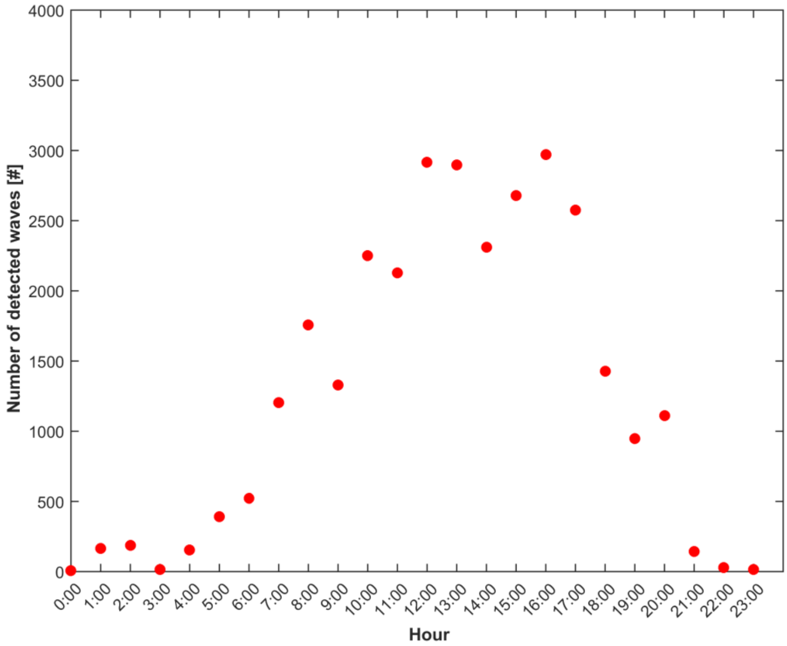
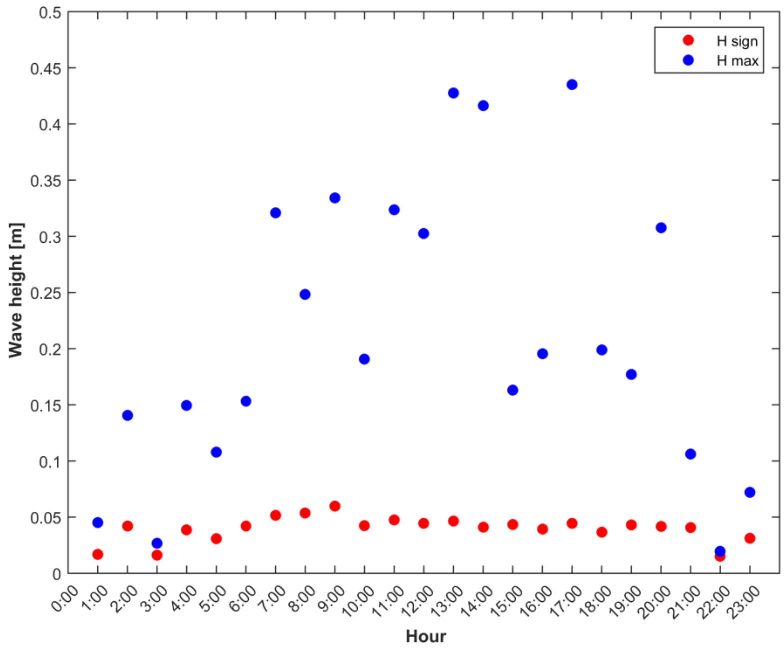
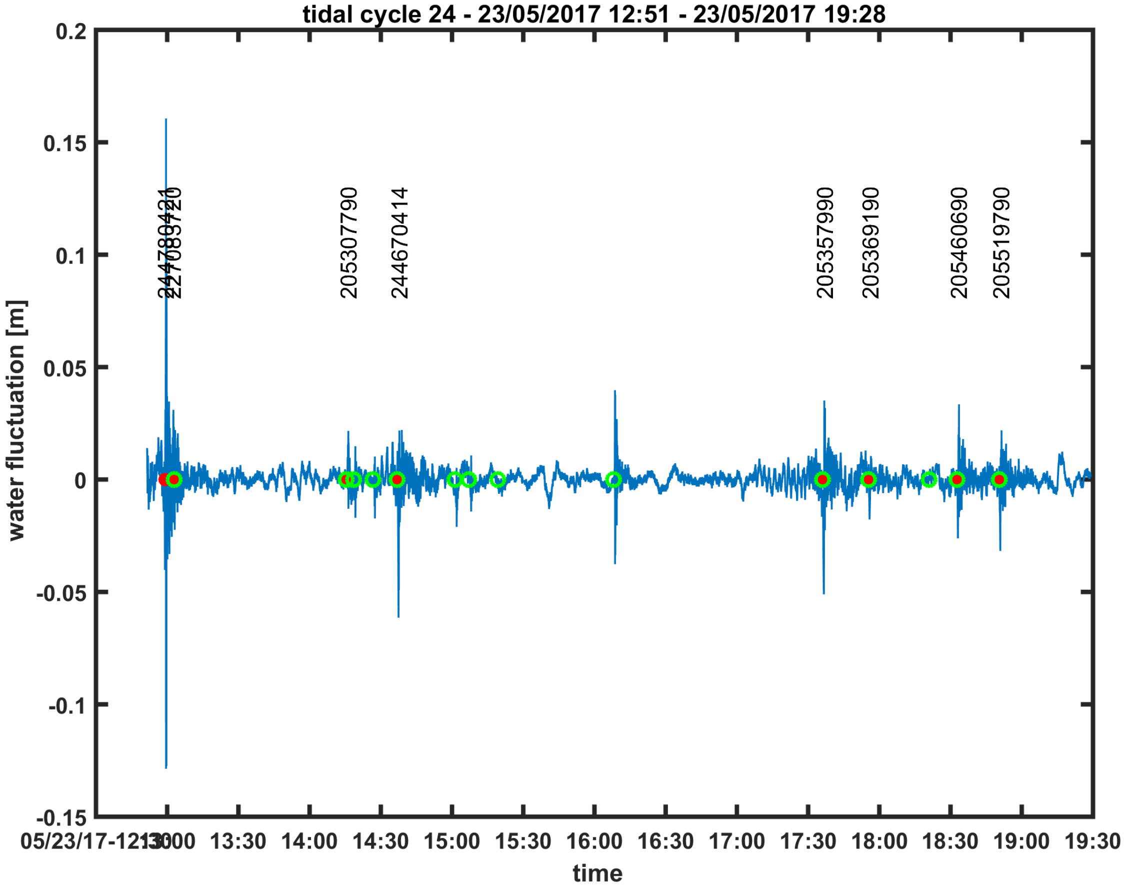



Figure 23 – Significant and maximum wave height of all measured tides, calculated per hour of the day



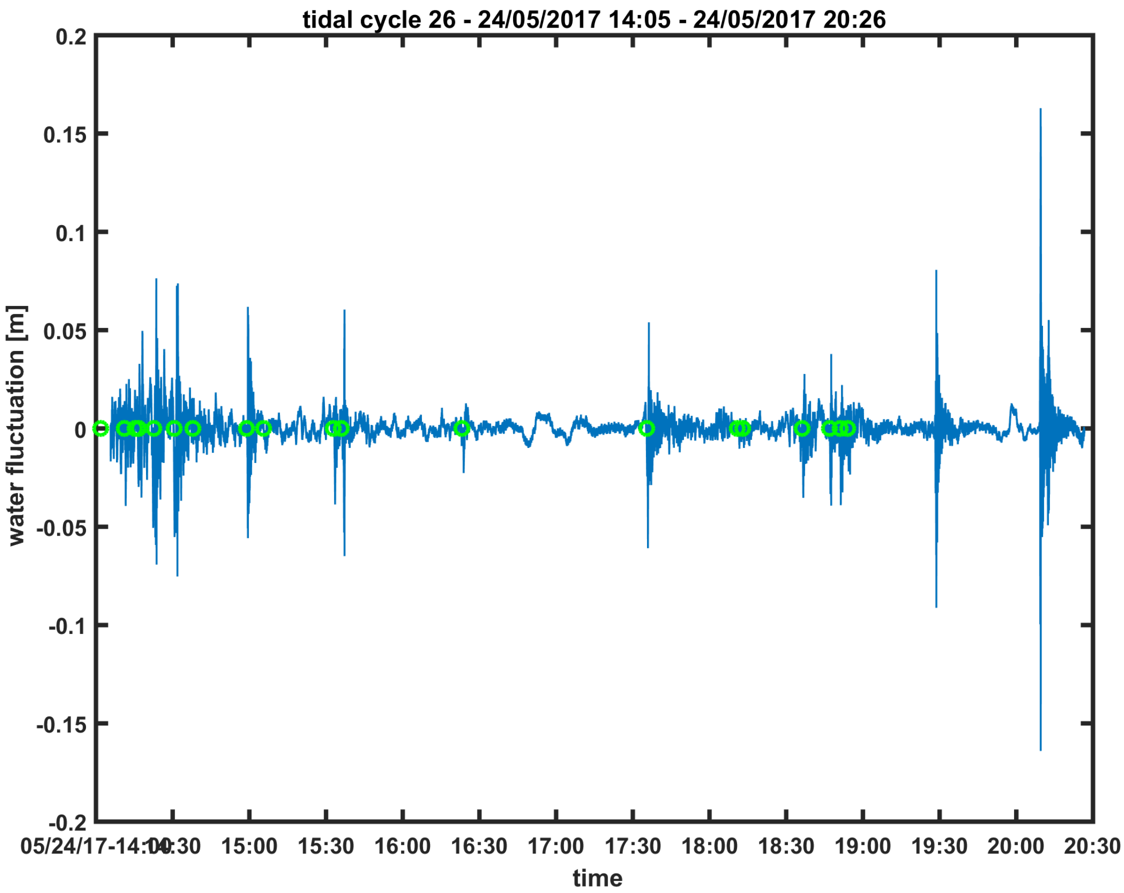

If we consider also the information of ships which was gathered through pictures, additional information can be gathered. In Figure 24 the information for tidal cycle is given. In red dots, the passage of ships is shown which are recorded by the AIS data (cfr. Figure 21). The green circles indicate also ship passages, but recorded with the camera. For this tidal cycle, only 7 out of 15 passages are recorded by the AIS system (the first AIS passage is not recorded by the camera, as the camera is only working from 1 PM).

Figure 24 – Wave fluctuations during one tide (tidal cycle 24),
with associated ship passages recorded with AIS (red dots) and recorded with a camera (green circles).



Considering another tidal cycle, as shown in Figure 25, no AIS passages are observed. The considered day is the day before Ascension Day. However, using a camera, 19 passages can be observed (until 8 PM, when the camera stops recording). Associated wave patterns can be observed clearly, with wave heights larger than 10 cm. For the large wave (> 30 cm) at the end of the tidal cycle, it can be supposed that these is also created by a passing ships, probably pleasure craft.

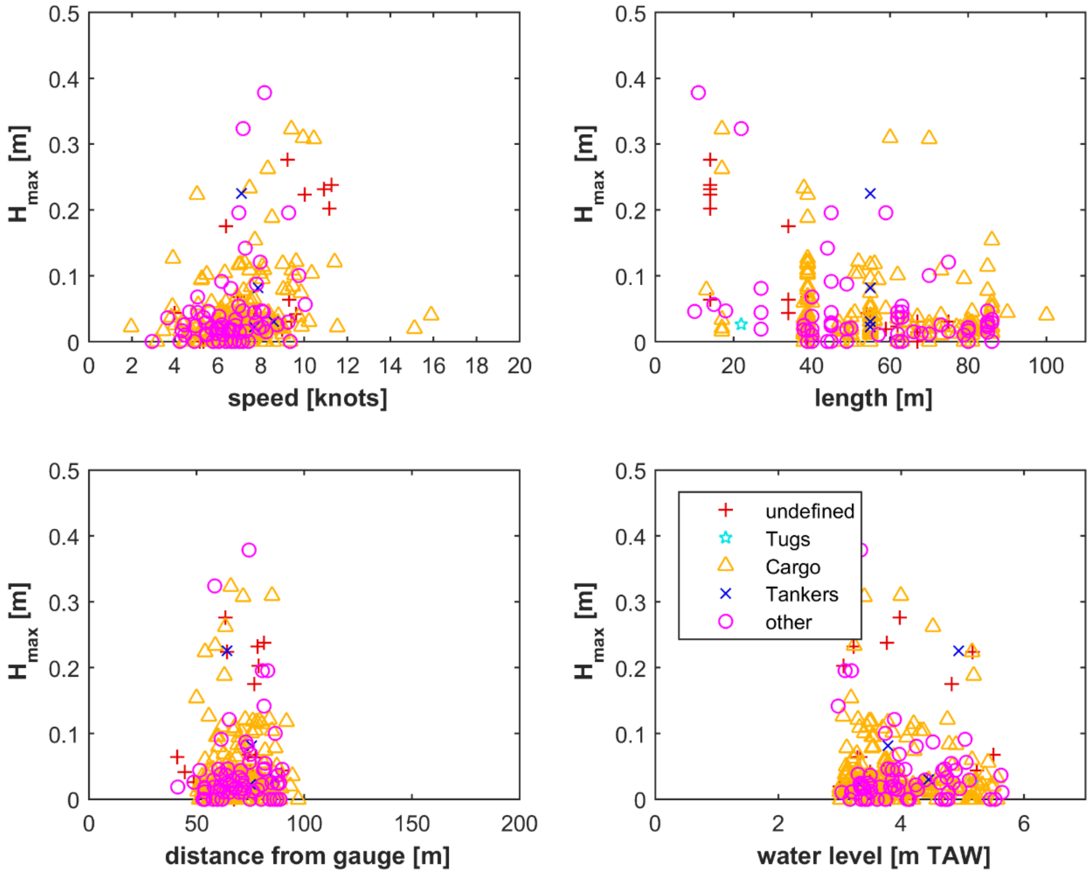
Figure 25 – Wave fluctuations during one tide (tidal cycle 26),
with associated ship passages recorded with AIS (red dots) and recorded with a camera (green circles).



## 5.2 Ship wave analysis in function of ship

In Figure 26 an overview is given from the relation of the maximum secondary wave height, with some of ship characteristics (speed over ground and ship length) and a selection of environmental parameters (water level and distance of the ship to the gauge). If we consider ship length, it seems that the smaller the ships the higher the waves it produces. Although it is not very clear from the plot, most (but not all) high waves are recorded for the small ships. If we consider the ships' speed, a slight positive relation (visual) with the wave height could be distinguished.

Figure 26 – Relation between the maximum secondary wave height and the speed of the ship, the length of the ship, the distance from the gauge and the water level.



# 6 Wind wave analysis

In this chapter the coupling of the measured wind data during the measuring campaign (presented in §0) with the wave measurements at the pressure gauge position (presented in §3.4), is discussed.

As mentioned in section 0, the daily average and daily maximum wind speeds during the measurement campaign are low, respectively lower than 3 and 6 m/s. The main wind directions during the campaign are western to south-western winds and south-eastern winds, as shown on the wind rose in Figure 12. From this measurement, no relations with wind speed and directions could be found.  It’s not clear if this is due to the measurement location itself or the very low wind speeds during the campaign.

# 7 Conclusions

In this report the wave measurements at Dendermonde are discussed. The measurements are performed at Appels, a tidal flat and marsh in a bend of the Scheldt a few kilometers upstream of Dendermonde. The measurement campaign lasted for approximately 4 weeks, from 10$^{th}$ May till 8$^{th}$ of June 2017.

A significant wave height of ca. 5 cm was observed for all tides, maximum wave heights of 0.45 m were recorded. These values are clearly lower compared to the values recorded at e.g. Saeftinghe, where maximum values of > 1.0 m were observed (Meire et al., 2019).

Considering the ship passages, approximately 22 ships per day are passing on normal weekdays (recorded by AIS). For holidays and weekends, this value reduces to 12. It is also shown that the ships mainly pass during daylight, 75% of the passages is between 7 AM and 8 PM. If we compare the AIS data with the photo recordings, it is clear that a lot of passages of (particularly) pleasure craft, are missed in the AIS database.

It is clear from the figures that the ship passages increase the wave loading on the tidal flat. However, no clear relation between the ship characteristics and the induced waves could be observed. If an estimation of the wave loading on tidal flats is based only on AIS data, this may lead to an underestimation because not all vessels are recorded.

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