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Variability in the Properties of Wakes Generated by High-Speed Ferries

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ABSTRACT

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The largest impact on the coast of waves generated by high-speed ferries is usually caused by the highest and longest components of transcritical wakes. Building reliable statistics of these parts of vessel-generated waves is usually nontrivial because of the high variability in the properties of wakes and their infrequent occurrence. Tallinn Bay is one of the few places where high-speed ferries frequently operate at transcritical speeds close to the shoreline. We report the results of measurements performed in 2008 at the entrance of Tallinn Bay. The time series of water surface elevations were collected in 2.5–3 m water depth, ~100 m offshore from an almost non-reflecting beach, ~2700 m from the sailing line. The data from 418 wakes on 15 days allows the construction of distribution functions of different wake properties (maximum height, wake energy, and energy flux) with an acceptable accuracy. The periods of the highest waves vary insignificantly and are closely related to the cruise speed of the vessels. An appropriate measure of the properties and variability of wakes is the maximum wave height. Wakes from 'classic' high-speed ships are very variable. Wakes from large, basically conventional, but strongly powered ferries show quite limited variability, thus, both the average and extreme wake properties of such ships can be more easily adjusted by changing their sailing regime.

ADITIONAL INDEX WORDS: *coastal zone management, wave measurements, ship wakes*

INTRODUCTION

The properties of approaching surface waves provide key information necessary for solving many coastal engineering problems. Vessel wake waves add energy to coastal systems wherever they occur. Their contribution is obviously negligible on high-energy coasts that are open to large ocean waves. Although many medium- and high-energy shorelines have been affected by vessel wakes for many years, the effects have either been negligible or accepted as reasonable. However, following the introduction of high-speed passenger ferries in the 1980s, and large and fast high-speed craft (HSC) capable of carrying passengers and vehicles, with service speeds ~50 knots, new and significant adverse effects were observed in numerous locations (PARNELL and KOFOED-HANSEN, 2001; SOOMERE, 2007).

High-speed (fast) ferries are interpreted here as the vessels, the regular sailing regime of which, contains extensive sections in which the depth Froude number (the ratio of the ship's speed and the maximum phase speed of linear water waves for the given depth) exceeds 0.6. Their wakes can be a major contributor of energy to sections of coasts that are exposed to significant natural hydrodynamic loads (SOOMERE, 2005). The actual effect depends upon the features of the coastal environment and the existing hydrodynamic loads. In this context, specific types of disturbances, such as high leading waves, monochromatic packets of relatively short waves (BROWN *et al*., 1989), solitary and cnoidal wave trains ahead of the ship (NEUMAN *et al*., 2001) and associated depression areas (GAREL *et al*., 2008), all qualitatively different from the usual wind waves or constituents of the linear Kelvin wake, are extremely important.

Vessel wakes may also seriously damage the coastal environment (PARNELL and KOFOED-HANSEN, 2001; SOOMERE, 2007; PARNELL *et al*., 2007). For example, in the low-energy environment of the Marlborough Sounds, New Zealand, the sudden change in the wave regime caused by introduction of HSC caused initial rapid and significant accretion, which continued in many places for the duration of HSC operation (PARNELL and KOFOED-HANSEN, 2001). The changes have been irreversible: there has not been a return to pre-HSC beach morphology following their slowing in late 2000 (PARNELL *et al*., 2007). The reason is that natural energy levels are not sufficient to move gravel sized sediment in supra-tidal berms. These features are now essentially relict (and quite stable), and will take a long time, or increased energy, to become active again.

The major source of the problems associated with ship-induced hydrodynamic activity is that solitonic wake waves may create extremely strong impulse loads (SCHOELLHAMER, 1996). For example, the annual mass of sediment resuspended by these waves in Hillsborough Bay is greater than the annual mass of sediment resuspended by wind waves by one order of magnitude. A secondary impact of the impulse loads is that sediments that are disturbed are more susceptible to resuspension by natural currents than undisturbed bottom sediments.

The basic method of management to prevent undesired impact from vessel wakes consists of setting limits to certain properties of the wake. A number of criteria are used in different parts of the world. The Wash Rule employed in Denmark since 1997 and a modified version of it employed in New Zealand limits the maximum height of wake components at the depth of 3 m (PARNELL and KOFOED-HANSEN, 2001). Washington State Ferries compares wave height and energy in deep water at a distance of 300 m from the ship track (see. e.g., BEGOVIC *et al*., 2006).

The rules are based on assuming that the wave effects caused by conventional ships are generally acceptable and tolerated by the public. In medium-energy environments a similar tolerable level should be established for each coastal section from the properties of natural waves. From the coastal engineering viewpoint, the primary properties are wave height, period, propagation direction, energy, and energy flux. Many of the common practices of wind wave analysis, however, are difficult to apply as wake waves vary in their basic parameters not only over the course of a single wake event but also show extremely high spatial variability (TORSVIK and SOOMERE, 2008). It is clear that many factors, both environmental (tidal currents, wind speed etc.) and operational (loading, trim etc.) affect wake characteristics. The HSC wakes generated at near-critical speeds (depth Froude number ~0.9) are usually the most sensitive with respect to small changes in the sailing regime. Small changes in the way the vessel is operated, such as loading and trim, can have major consequences for wake height (STUMBO *et al*., 1999). Thus it is not surprising that a common feature of wake wave measurement programmes is the significant variability in the data records for the same vessel at different times at the same location, and at different locations (PARNELL and KOFOED-HANSEN, 2001, PARNELL *et al*., 2007).

On the one hand, this feature considerably complicates the coastal management issues and creates the need for a substantial safety factor in the planning of local coastal engineering structures. On the other hand, it suggests that mitigation of the related problems can be achieved by small changes in the sailing regime, at least, in some places and for certain classes of vessels.

This paper aims to quantify the variability of the primary parameters (such as the maximum height, energy, and energy flux) of high-speed vessel wakes. The study is based on high-resolution records of >400 wakes from different types of ships near the Island of Aegna at the entrance to Tallinn Bay (Figure 1).

STUDY SITE AND MEASUREMENTS

The sea area between Tallinn (Estonia) and Helsinki (Finland, Figure 1) is one of the most intense HSC traffic regions in the world. The annual mean energy of ship-generated waves was at least 6–8% of the total wave energy and the ship wave power may have been as high as 34% of the total wave power on coasts adjacent to the ship lane in Tallinn Bay (SOOMERE, 2005). While in many countries there is a speed limit for vessels sailing near the coast, Tallinn Bay is one of the few places in the world where HSC continue to operate at service speeds close to the shoreline. There have been significant changes in the types of vessels, similar to changes elsewhere in the world. The vessels that produced very dangerous waves have been taken out of service. The biggest change is that a new generation of high-powered conventional ferries with service speeds 25–30 knots has replaced the older ferries that sailed at 15–20 knots.

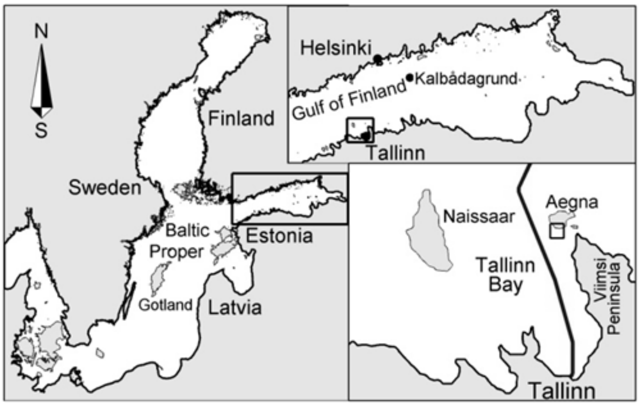

Figure 1. The Baltic Sea, Tallinn Bay, the study site on the SW coast of Aegna (right lower panel), and approximate sailing line of ferries from Tallinn to Helsinki.

The HSC fleet now consists of a range of vessel types (Table 1). There are two sister monohulls (both called *SuperSeaCat*), and two twin hull sister vessels (*Nordic Jet* and *Baltic Jet*) which have been used on the route for several years. Small monohull hydrofoils have been replaced by a twin-hull vessel *Merilin*. The fleet of high-powered conventional ferries consists of sister ships *Star* and *Superstar*, *Superfast*, and *Viking XPRS*. The total number of departures of HSC ships from Tallinn to Helsinki was 22–25 per day in summer 2008 (PARNELL *et al*., 2008). As sailing lines have remained largely unchanged and no limitations have been imposed on the speed, the new ships may operate at near-critical speeds in areas where older ships were clearly subcritical. With these changes, the number of departures of large vessels that are able to travel at near-critical speeds has almost doubled in Tallinn Bay since about the year 2000 (PARNELL *et al*., 2008).

Modeling of the properties of ship wakes (TORSVIK and SOOMERE, 2008) indicates that there is significant spatial variability of the wake loads on the shorelines of Tallinn Bay. The

Table 1: High speed ships operating in Tallinn Bay in summer 2008 (PARNELL *et al*., 2008) and properties of wakes on days with comparatively low wind wave background (28–30 June, 1–9, 12, 13 and 20 July 2008). Wake energy and power have been integrated over the duration of the wakes. Unidentified wakes (UW) belong to smaller or slower ships, or to ships sailing to Tallinn.

Vessel	**Type**	**Constr-uction**	**Cruise speed, knots**	**Length / Width / Draught, m**	**Dis-place-ment, t**	**# of wakes**	**Maximum wave height, cm**		**Energy, 10^4 J·s/m^2**		**Power, 10^4 W·s/m**	
							avr	**std**	**avr**	**std**	**avr**	**std**
SuperSeaCat	High-speed craft	Monohull	35	100.3/17.1/2.6	900	55	85	18	5.4	1.3	27.4	7.2
Nordic Jet **Baltic Jet**		Catamaran	36	60/16.5/2.22	515	70	59	16	2.8	0.9	13.6	4.8
Star	High-powered conventional ships	Monohull	27.5	186.1/27.7/6.75	13 316	25	89	26	5.0	1.8	24.0	9.5
SuperStar		Monohull	27.5	176.9/27.6/7.1	14 073	28	98	11	6.6	1.2	30.7	6.4
Viking XPRS		Monohull	25	185/27.7/6.55	14 165	27	58	23	2.0	1.0	8.9	4.7
Superfast		Monohull	25.5	203.3/25/6.5	10 703	14	70	14	3.3	0.9	14.8	4.4
UW						157	32	12	0.7	0.5	3.0	2.0
Double wakes						42	101	19	9.1	2.5	46.0	12.7

faster vessels enter the transcritical regime close to the port for vessels arriving in Tallinn, and in the vicinity of Aegna Island for vessels leaving Tallinn. The SW coast of Aegna is fully open to the wakes of ships sailing from Tallinn to Helsinki but somewhat sheltered from waves produced by ships sailing to Tallinn. The isobaths in the vicinity of this coast are predominantly oriented perpendicular to the ship wave rays. The nearshore contains a belt of boulders and is almost non-reflective (Parnell *et al.*, 2008). This coast is therefore a suitable place for measurements of vessel wave parameters and has also been the subject of several previous studies (Soomere and Rannat, 2003; Erm and Soomere, 2006).

The properties of waves were established from a high resolution (5 Hz, ±1 mm) time series of water surface elevations collected almost continuously over the period from 21 June to 20 July using an ultrasonic echosounder (General Acoustics LOG_aLevel®) mounted on a heavy tripod in about 2.7 m water depth, ~100 m offshore from the shore. The site was about 2700 m from the sailing line of outgoing vessels, at the closest point (Parnell *et al.*, 2008). The total record contains more that 650 wake events from fast ferries sailing from Tallinn to Helsinki.

DATA PROCESSING

The raw data from the water level gauge (the distance from the echosounder to the water surface) were first quality-checked, re-formatted and time-synchronised. The record contained only one unreliable section with a duration of 5 minutes and <10 unrealistic negative spikes with a duration of a few seconds, which were excluded from the analysis. The record also contained several positive spikes, most of which corresponded to real wave motions and were identified as examples of natural ‘freak’ waves. These were also excluded from the analysis.

A major challenge in the analysis was separation of wakes from single vessels not only because of the presence of wind wave background and operational changes to the ferry timetable and therefore the actual arrival time of wakes at the study site, but also because of large variations in the duration of the wakes and partial overlapping of wakes from different ships (Figure 2). This operation was performed manually based on different kinds of visualization of the water level data. It was straightforward on relatively calm days when both the leading group of high and long vessel waves and the final, short group of almost monochromatic waves (Soomere, 2007) were easily identifiable from the record. On days with substantial wind-wave activity, spectral filters with different properties (elliptical filters in the Matlab environment) were applied to the raw record sections in order to suppress wind waves, to locate the components of vessel wakes, and to adequately define the start and end of the wake event. The shorter components of wakes were sometimes completely masked by wind waves. As a result, wake records from 15 days were selected for the further analysis of their properties and variability.

The total number of clearly identified wakes (418) contained 21 “double” wakes of ships that arrived almost simultaneously at the study site and were indistinguishable from each other, and 157 wakes of unidentified origin (UW). Among the latter were wakes from the hydrofoil *Merilin*, conventional passenger and cargo ferries, and wakes from ships sailing to Tallinn.

An attempt was made to specify a section of the record of pure background wind waves with a duration of 10–20 min, preferably just before the start of the each single wake. The properties of this background were used to quantify the mean water level during the wake and the spectral composition of the wind-wave field. As ship traffic was very intense, frequently we had to use one background interval for a few wakes.

Data from each wake event were then adjusted to a mean of 0 with the use of the closest section of the background and, if necessary, the water level trend was removed. Then, a Matlab low-pass elliptic filter of 9th order with at most 0.1 dB passband ripple, 60 dB stopband attenuation, and a 2.5 s cutoff frequency was used to remove most of the wind wave components from the recorded signal. As the proportion of wave components from fast ferries with periods <2.5 s is very small (Soomere and Rannat, 2003), such a filtering almost exactly conserves the energy of the wake. The majority of wind wave components on relatively calm days, with periods <2 s, are effectively removed from the signal.

While the unfiltered signal correctly reflects the short-term changes of the position of the water surface and related characteristics (such as the wave shape or asymmetry), the filtered signal frequently gives much better information about the role of long wave components in a particular wake in terms of both their local height and duration of presence, and in many cases allows more exact determination of the end of the wake.

Further analysis of each wake event was performed in parallel on the original data and on the filtered signals. Single waves and their properties in each wake were extracted with the use of both zero-upcrossing and zero-downcrossing methods. The maximum vessel wave height was defined as the maximum of wave heights obtained by these two methods. On days with strong wind wave background, this estimate was replaced by the maximum variation of the water surface within a 30 s interval (Parnell *et al.*, 2008).

The wave energy density of each wake was calculated from the power spectrum of the water elevation record within the duration of the wake using the standard procedures of spectral analysis. An estimate of the energy density of ship waves was found by means of subtraction of the energy density of the wind wave background from the total energy density. The total energy of a wake was then found as a product of the vessel wave energy density and the duration of the wake.

Finally, the energy flux (wave power, equal to the product of wave energy and group velocity) was calculated for each wake by means of summing the energy flux carried by each wave for the given water depth and during the period of each wave.

RESULTS

Maximum wave height of single wakes varies significantly within each day (Figure 2), and frequently is substantially different for different departures of the same ship. The daily

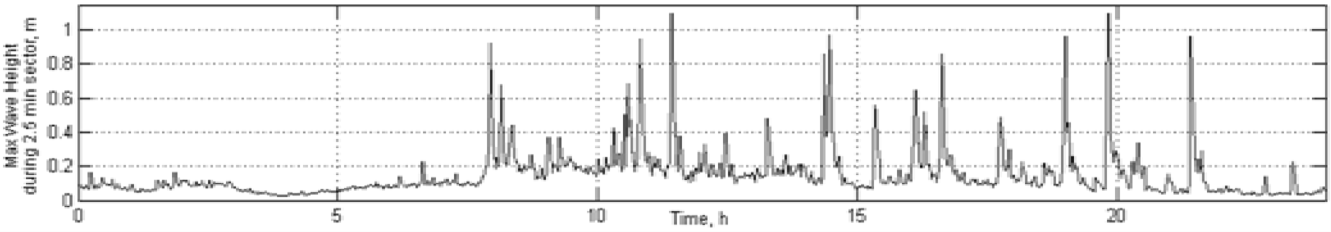

Figure 2. Maximum wave height within 5-minute sections on 08 July 2008. Almost all spikes higher than 20 cm correspond to ship wakes.

maxima of ship wave heights occurred exclusively for the longest waves in the wakes, with periods >10 s. They all exceeded 1 m and were typically approximately 1.2 m (Figure 3). The largest ship wave heights in more or less calm conditions were 1.5 m. The combined ship and wind wave heights reached 1.7 m on a few days, with the significant height of the background about 0.3–0.4 m. The low height of the echosounder above the water surface may have caused some erroneously low values for the maximum elevations before 7 July (PARNELL *et al*., 2008).

The double wakes were typically the highest. On average, the highest waves of single ship were generated by *Superstar* with the overall mean of the highest waves being 98 cm (Table 1). Her sister ship, *Star* produced waves of comparable height. The average of maximum wave heights from the *SuperSeaCats* was 85 cm. The typical values of the highest waves from other ships were clearly smaller, about 60 cm. The typical total energy and energy flux of wakes from different ships had a similar pattern. Unlike the maximum wave height of double wakes (which only slightly exceeded the wave heights of *SuperStar*), energy contained in double wakes was about twice as large as energy in the single wakes. The energy in wakes of unidentified origin was only a small fraction (a few per cent) of energy in wakes from fast vessels sailing to the North.

Based on the above discussion of sensitivity of wake parameters to ship operation details at near-critical speeds, one could expect that the wakes of ships that produce larger average values of the maximum wave height would have also larger variability. Remarkably, variation in the maximum wave heights of different ships was small (indicated by the standard deviation) and was almost uncorrelated with the typical wave height from these ships (Table 1). It was very small for *Superstar* indicating that waves from this ship were always of almost the same height. The large variation for double wakes is not unexpected, because such wakes contained waves from different ships. The standard deviation of maximum wave height was relatively large for *Star*, *SuperSeaCat* and *Viking XPRS*.

The ratio of the standard deviation of wake energy and the average wake energy (also the ratio of the standard deviation of wake energy flux and the average wake energy flux) for different ships was very similar to the ratio of the standard deviation of maximum wave heights and the average of maximum wave heights. As the typical variation coefficients were the largest for the wave heights, the maximum wave height is an appropriate parameter to characterize the ship wakes and their variability.

The histograms of the frequency of occurrence of different maximum wave heights (Figure 4) also show some interesting features. The maximum height of wakes from *Superstar* lies in quite a narrow range, from 81 to 117 cm. The range for *Superfast* is somewhat wider, but still concentrated between 41 and 97 cm. Both distributions are almost symmetric and contain no outliers. The distribution for unidentified wakes (UW) is somewhat wider and skewed, but it also contains no clear outliers.

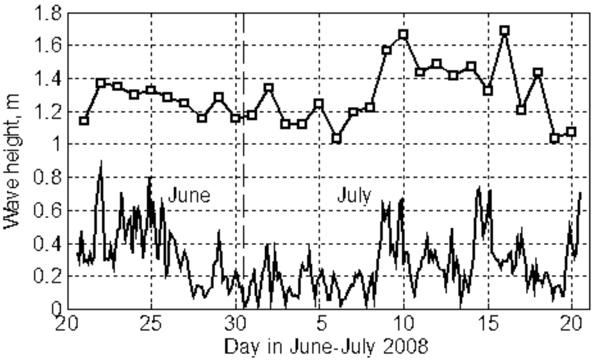

Figure 3. Daily maximum ship wave heights extracted from non-filtered data (squares) and modelled significant wind wave height at the measurement site (KELPŠAITE et al., 2009).

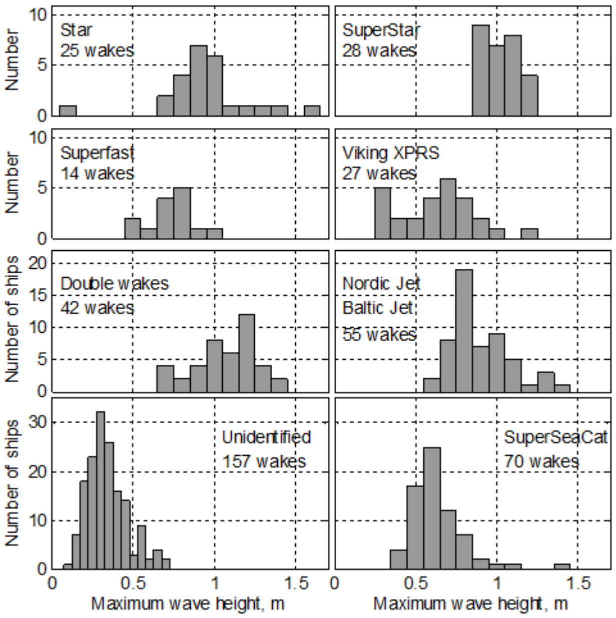

Figure 4. Frequency of occurrence of maximum wave heights in wakes from different ships.

The distinguishing feature of the distributions for other ships is the presence of a number of outliers – very high wakes. Their number is relatively small for *Nordic Jet* and *Baltic Jet*, yet these ships may produce >130 cm high waves. The waves from *Viking XPRS* were usually reasonable (20–80 cm), but at times reached 120 cm. Accompanying runup studies (DIDENKULOVA *et al*., 2009) indicated that waves from this ship had the largest variability usually being fairly small, but at times being dangerously high, damaging equipment and causing safety concerns for the shore-based field personnel (PARNELL *et al*., 2008). The largest number of outliers was recorded for *Star* and the *SuperSeaCats*. While the distribution of maximum wave heights is almost symmetric for *Star*, it is substantially skewed towards large values for *SuperSeaCat*. On the contrary, the distribution for double wakes is skewed towards smaller values, apparently because the synchronous arrival of the largest waves from two ships is improbable.

The overall mean vessel-wake energy density was ~15 J/m^2 (PARNELL *et al*., 2008) and varied between 10 and 23 J/m^2 on different days. The weekly average of wake energy density differed only a few per cent from its overall average during the entire experiment. The relatively high values of energy density on 10–11 July may reflect problems with separating the vessel wakes from the background. The lowest daily energy densities occurred on weekends, with somewhat less intense ship traffic than on weekdays.

As found in previous experiments in this area (SOOMERE and RANNAT 2003; SOOMERE, 2005), the major component (about 70%) of ship wave energy is concentrated in the frequency range of 0.06–0.2 Hz (periods T=5–16 s). The energy spectrum within this range contains four peaks (Figure 5). The highest peak is located at 9.2 s, a peak of comparable height at 12.3 s and two minor peaks at 7.6 s and 6.6 s. The location and relative magnitude of these peaks is almost constant on all days for which separation of ship waves from the background was possible.

The two peaks for longer waves reflect the typical properties of the leading waves of ship wakes whereas the two peaks around 7 s represent wave components from the second group of HSC wakes that usually have periods of 6–8 s (SOOMERE and RANNAT, 2003). The presence of two clearly separated peaks for both long waves and for periods around 7 s shows that the high-speed fleet in Tallinn Bay represents two families, the members of which produce leading waves with similar properties (and which apparently travel at more or less equal speeds).

Comparison of the cruise speeds of different ships (Table 1) suggests that the *SuperSeaCats*, *Nordic Jet* and *Baltic Jet*, and possibly the twin hull hydrofoil *Merilin* belong to one (faster) group, the wakes of which mostly form the peak at 12.3 s. Ships sailing at 25–30 knots (~45–55 km/h) are probably responsible for the other, slightly higher, peak.

CONCLUSIONS AND DISCUSSION

The results suggest that the periods of the highest ship waves vary insignificantly and are closely related to the cruise speed of the vessels. An appropriate measure of variability of wakes from high-speed vessels is the maximum wave height of their wakes remote from the sailing line. Although the variability of the total energy or its flux do not necessarily correspond directly to the wave height, energy and energy flux provide the essential information necessary for the planning of coastal engineering structures and for coastal zone management in general.

The variability of properties of single wakes from particular ships is relatively large. The largest variability is in the properties of wakes from ‘classic’ high-speed ships having relatively small tonnage (~1,000 tons) and using very high cruise speeds (35–40 knots). The frequent occurrence of very high waves suggests that management of threats associated with their wakes poses a serious problem and substantial changes or limitations to the sailing regime may be required to ensure an acceptable level of wake intensity. On the other hand, the properties of wakes from most of large, basically conventional, but strongly powered ferries show quite limited variability. Although they may create relatively high waves under present sailing conditions, it is natural to expect that both the average and extreme wake properties can be more easily adjusted by changing either their speed or sailing line.

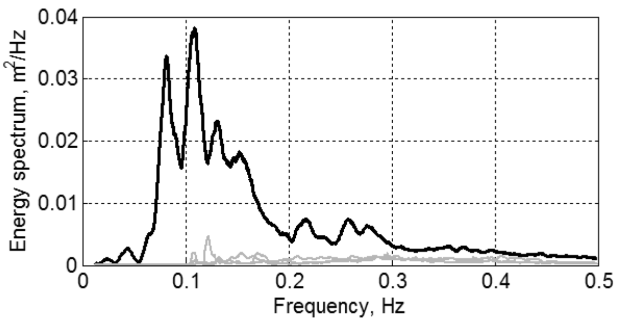

Figure 5. Total wave energy density on 4–6 July (solid line) and the energy density of wind waves at 00:30–07:30 on the same days (grey lines).

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