The impact of fast ferry traffic on underwater optics and sediment resuspension*

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Abstract

Wake waves produced by fast ferries bring about significant changes in the optical parameters of sea water in the c. 1 m thick near-bottom layer of the coastal areas of Tallinn Bay. The greatest of these changes occur at relatively small depths, but the duration of the influence increases with increasing depth. Rough quantitative estimates suggest that the overall influence of fast ferry traffic in Tallinn Bay may result in an annual loss of the order of several hundred litres of fine sediments from each metre of the coastline.

1. Introduction

In recent years, growing concern has been expressed in many countries about the waves produced by fast ferries in the vicinity of shipping lanes (Kofoed-Hansen & Mikkelsen 1997, Kirk McClure Morton 1998, Parnell & Kofoed-Hansen 2001, Guidelines 2003, Soomere et al. 2003). Since all waves, no matter whether wind- or ship-generated, have a similar impact on the marine environment, it is generally believed that the effect of ship wakes is negligible in coastal areas that are open seawards (see, for example,

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Lindholm et al. 2001). This assumption is correct with regard to coasts exposed to high tidal waves or dominant winds. However, in semi-enclosed non-tidal seas, such as the Baltic, the impact of ship wakes may be decisive along certain parts of the coastline (Soomere 2005a). This feature partially originates from a specific property of wakes from fast ferries, namely, that their energy may propagate in the form of a compact wave packet and may adversely affect the marine ecosystem a long distance from the shipping lane (Stumbo et al. 1999, Soomere 2005a).

Tallinn Bay is an example of a semi-open sea region (c. 10×20 km) in the central part of the Gulf of Finland, Baltic Sea. Since 2000, it has hosted extremely heavy fast ferry traffic. During the high season, a variety of high-speed vessels cross the gulf nearly 70 times daily. The heights of ship waves in the coastal area are moderate compared with the highest wind waves reaching this area each year (Soomere & Rannat 2003, Soomere 2005b). But the role of ship waves is the most impressive in terms of wave energy flux (wave power): ship waves make up 18–35% of the annual mean wind wave power along the shores of Tallinn Bay. The anthropogenic waves may even dominate during part of the high shipping season (April–June), when biological productivity is at its seasonal maximum (Soomere et al. 2003, Soomere 2005a).

The highest ship waves – about 1 m in height – usually have a period of over 10 s (Soomere & Rannat 2003). Such waves very seldom exist in the Tallinn Bay area under natural conditions; the ferry traffic has therefore added a qualitatively new key forcing factor to the local marine ecosystem (Soomere 2005a). In terms of near-bottom velocities, the impact of a typical ship wake on bottom sediments and aquatic wildlife at depths of 5–30 m frequently exceeds the impact of wind waves whipped up during the most violent storms (Soomere & Kask 2003).

The primary reaction of the seabed to such increased hydrodynamic activity involves an intensive (re)suspension of the benthic layer and bottom sediments. Since most of the fast ferry sailings take place in the biologically active season and, moreover, during the daytime, an overall deterioration in the underwater light conditions due to this traffic is likely. The extent of the accompanying sediment transport is a crucial question in assessments of the impact of fast ferries (Guidelines 2003, Soomere & Kask 2003). This reaction can be identified and roughly estimated with the use of optical measurements (Bauer et al. 2002, Erm & Soomere 2004), which are much more flexible and much less expensive than geological studies of underwater sediment transport processes. The 'optical' approach also allows quantification of the indirect influence of the increased wave activity on primary production (which is limited by the amount of light in the deeper nearshore waters, e.g. Paalme 1997). The relevant results will be analysed elsewhere.

Optical methods have been successfully used in studies of the properties and condition of Estonian and Finnish lakes (Arst et al. 1999, 2000, Arst 2003, Erm et al. 1999, 2001, 2002, Reinart et al. 2001, 2003) and have recently been applied in studies of coastal sea areas. Equipment similar to that used in the current study allowed the under-ice light conditions to be surveyed and the concentrations of optically active substances in the ice cover to be estimated (Leppäranta et al. 2003, Erm & Reinart 2003).

The present paper describes wave-induced changes of the optical properties of the sea water and the underwater light regime in the coastal area of Tallinn Bay at various depths and under various wind wave conditions. The preliminary results have already been described by Erm & Soomere (2004). The main aim of the present work is to quantify the wave-induced changes in the light regime and to establish a relationship between the concentration of suspended matter and the optical properties of sea water. By doing this, the amount of material resuspended by a single ship wake as well as the annual bulk sediment transport due to fast ferry traffic can be estimated.

The experimental set-up and basic optical parameters are described in section 2. The changes in the optical properties of the sea water in different parts of the water column are described in section 3. The amount of material resuspended by a single ship wake and the bulk sediment transport due to the fast ferry traffic is estimated in section 4, in accordance with the per-ship-passage approach by Bauer et al. (2002). An integral measure for quantifying the impact of a single wake is constructed in section 5. Basic conclusions are formulated and discussed in the final section.

2. Methods

Combined hydrodynamic and optical field measurements were carried out in Tallinn Bay in 2003–04 (Fig. 1). The SW coast of Aegna, located about 2 km from the Tallinn–Helsinki shipping lane, was chosen as the measurement site for two reasons: (i) both the properties of ship-generated waves and the features of the sea bottom have been thoroughly studied in this area (Soomere & Rannat 2003, Kask et al. 2003); (ii) pilot experiments targeted towards establishing the actual shape of leading ship waves have also been performed in this area (Soomere et al. 2005).

Earlier studies clearly demonstrated that only large, fast, car-carrying ferries excite waves, the effect of which could be significant, whereas wakes from other ships sailing in the Tallinn Bay area are practically indistinguishable from the natural wave background at the measurement sites (Soomere & Rannat 2003). Below we shall refer to these ships simply

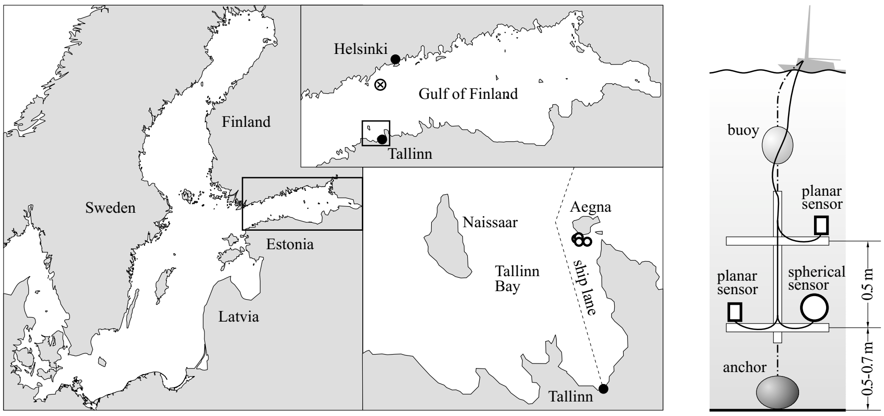

Fig. 1. Scheme of Tallinn Bay and measurement sites (left) and assembly scheme of the optical sensors (right)

as 'fast ferries'. During the study period, six such ships were in regular service in Tallinn Bay: two monohull ferries of the displacement type run by the Silja Line (the 'SuperSeaCat 3' and 'SuperSeaCat 4'), two medium-size catamarans operated by the Nordic Jet Line (the practically identical vessels 'Nordic Jet' and 'Baltic Jet'), and two larger catamarans belonging to Tallink (the 'Autoexpress' and 'Autoexpress 2', with little difference in their dead weights). Since the pairs of ships have mostly similar properties, there is no need to distinguish the sister ships from each other: in the following, they will be referred to simply as *SeaCat*, *NordicJet* and *AutoExpress*.

Measurements of the optical properties of sea water were accompanied by wave measurements. Water samples were taken early in the morning, before the ships began sailing, and again immediately after the leading ship waves had passed. Laboratory analysis of the samples permitted quantification of the volume of sediments resuspended by ship-generated waves, as well as other potential changes in the optically active substances (suspended matter, chlorophyll *a* and yellow substance).

Concentrated on the photosynthetically active region (PAR) of light (400–700 nm), the optical measurements were performed simultaneously near the sea bottom and above the sea surface. A frame with three optical sensors was anchored to the sea bottom (Fig. 1). Two Li192SA plane sensors (Li-Cor Corporation) for measuring downwelling plane irradiance $E_d(z)$ and an Li193SA spherical sensor for measuring scalar irradiance $E_0(z)$ were fixed rigidly to the frame. The spherical sensor and the lower plane sensor were located at a distance of 0.5–0.7 m from the bottom. The upper plane sensor was installed 0.5 m above the lower sensors (Fig. 1). A third Li192SA plane sensor, placed in the boat, registered incident irradiance $E(+0)$ from the sky. The Li1400 Datalogger was used for logging the optical data.

The theoretical basis of the light measurements is thoroughly discussed by Jerlov (1976), Dera (1992) and Zaneveld et al. (1992), and has recently been expanded by Arst (2003) to include multicomponental waters such as lake water and brackish water in coastal areas. For this reason we only very briefly describe certain points relevant to the current study.

The diffuse attenuation coefficient (Dera 1992)

$$K_d(z) = \frac{d}{dz} \ln E_d(z) = \frac{1}{E_d(z)} \frac{dE_d(z)}{dz}, \tag{1}$$

characterises the attenuation rate of the downwelling irradiance at a certain depth z. The larger this coefficient, the less light that penetrates to the deeper layers. It was calculated from the field data as

$$K_d\left(\frac{z_l + z_u}{2}\right) = \frac{1}{z_l - z_u} \ln \frac{E_d(z_u)}{E_d(z_l)}, \tag{2}$$

where z_l and z_u stand for the depths of the lower and upper underwater sensors, respectively.

Water samples were taken with cylindrical batometers (c. 0.4 m in length) from the water layer between the plane sensors. The batometers were usually affixed vertically; this position was also used in the 2003 experiments. Since long surface waves excite mostly horizontal water motion in the near-bottom region, the batometers were installed horizontally in 2004 in order to obtain better samples of water from the layer of interest. The amount of suspended matter C_S in the samples was determined by its dry weight after the water had been passed through HAWG047S1 Millipore membrane filters. Details of the procedure can be found in Erm & Soomere (2004).

3. Results

The measuring points were chosen in different sections of the coastal area with a depth from 2.1 to 13.5 m. The properties of seawater at these sites were typical of Baltic Sea conditions. The Secchi depth was 2.6–5 m, $C_S = 0.3$–5 g m^{-3}, $C_{chl} = 2.0$–2.5 mg m^{-3}, and the concentration of yellow substance $C_{ye} = 1.9$–3.2 g m^{-3}. The diffuse attenuation coefficient K_d, calculated from $E_d(z_u)$ and $E_d(z_l)$ by eq. (2), was 0.2–0.6 m^{-1} before ship wakes arrived, and exceeded 2 m^{-1} during the passage of the fast ferries' wakes. The biggest ship-generated waves were about 50–80 cm in height, i.e. much lower than the highest examples reported by Soomere & Rannat (2003).

The typical patterns of changes in the underwater light regime and optical properties of water at a depth of about 1 m from the bottom due to ship wakes were established in the experiments in 2003–04. The directly measurable optical quantities $E_d(z)$ and $E_0(z)$ mostly follow the incident irradiance $E(+0)$. Apart from changing cloudiness, the surface waves also greatly affect the instantaneous values of E_d: firstly, they cause the height of the water column above the anchored underwater sensors to vary; secondly, they bring about a practically stochastic variation in the scattering properties of the sea surface, thereby creating high-frequency noise in the measured optical signal. The ship-wave-induced changes in $E_d(z_l)$ and $E_d(z_u)$ are often completely masked by the changes in incident irradiance $E(+0)$ and other variations. The role of ship waves in these changes is substantial only when the sky is bright and the sea very calm. For the above reasons, the measured values of $E_d(z)$ and $E_0(z)$ are normalised with the use of $E(+0)$. However, the diffuse attenuation coefficient $K_d(z)$ characterises the optical properties of the water column between the two sensors and is thus mostly independent of these factors.

A typical record of the reaction of the optical properties of sea water to ship wakes in relatively shallow waters (2.1 m deep) is shown in Fig. 2. The cloudiness was 1 Ci, the wind speed c. 2 m s^{-1} and the significant height of the natural wave background c. 20 cm on the fine morning of 17 July 2003. The increasing trend in the values of $E(+0)$, $E_d(z_l)$ and $E_d(z_u)$ followed the change in the Sun's position. A certain scatter in their values was apparently caused by irregular changes in the position of the sensor, which was located in a small boat. The wakes induced by the *Autoexpress* and *SuperSeaCat* at 10:22 and 10:46, respectively, did not significantly affect the light field at the upper plane sensor but did cause changes at the lower one. The maximum increase in $K_d(t)$ was about threefold (from 0.5 to 1.5 m^{-1}) but the wake-induced changes of $E_d(z_l)$ only insignificantly exceeded the typical level of the noise in its time series.

The effect of ship wakes is more impressive in somewhat deeper areas. Fig. 3 represents the reaction of optical parameters to three wakes in an area with a depth of 4.8 m on 20 July 2003. The wakes from the *AutoExpress* (14:55), *NordicJet* (15:04) and *SeaCat* (15:14 and 15:17) caused a substantial decrease in the downwelling irradiance $E_d(z_l)$ at a height of about 0.7 m above the sea bottom. The decrease was up to 60–70% from its typical value, which was considerably larger than its natural variability. The coefficient K_d reacted dramatically to ship waves, increasing by nearly one order of magnitude. Apart from the greater cloudiness (5 Cu), the other important background parameters were nearly the same as in the case described above: the wind speed was about 4 m s^{-1} and the background wave height was about 30 cm. Thus, the described effects were definitely caused by ship wave packets.

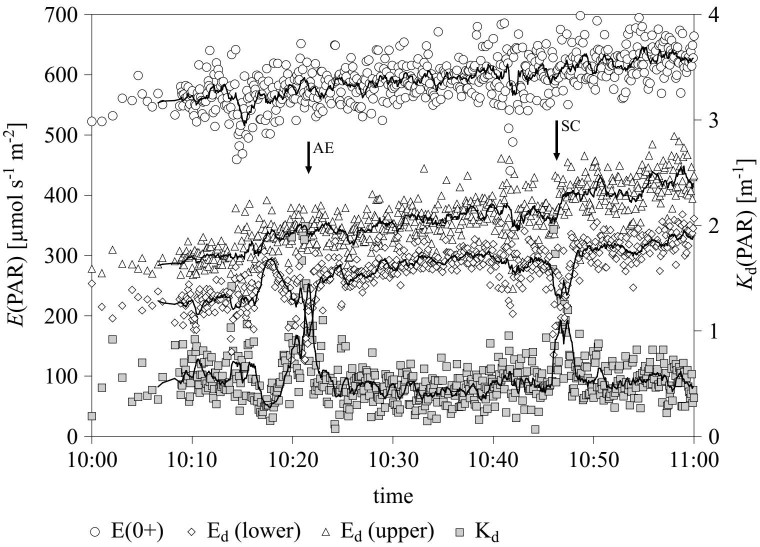

Fig. 2. Incident and underwater light field on 17 July 2003 in a sea area with a depth of 2.1 m. $E_d(+0)$ is the incident irradiance measured on the boat, E_d (upper) and E_d (lower) are the irradiances at depths 1.0 m and 0.5 m from the bottom, respectively, and K_d is the diffuse attenuation coefficient of the water layer between the upper and lower sensors. Shown are the instantaneous values of the measured parameters (averaged over 5 s) and a moving average over 10 subsequent measurements. From Erm & Soomere (2004)

There were no substantial changes in the optical signal of the upper plane sensor at either measurement site; neither did the scalar irradiance react to the ship wakes to any considerable extent. This suggests that (i) a single ship wake only affects the optical properties of the c. 1 m thick near-bottom layer and (ii) that the decrease in the downwelling irradiance may be compensated for by an increase in light scattered in turbid water or from the bottom. The first conclusion apparently reflects the fact that water motion in very long water waves is mostly horizontal. The second feature is evidently only true in the case of relatively small depths and optically clear waters (see Erm & Soomere 2004).

Soomere et al. (2003) suggest that the long, leading waves of ship wakes excite unusually large near-bottom velocities in waters as deep as 20–30 m in the study area. The reaction of the optical properties of the near-bottom water layer may therefore be even more extensive in deeper sections of the coastal slope, where ever finer sediments dominate and the natural hydrodynamic activity is relatively weak. This is partially confirmed by the analysis of the overall changes in the optical density of water. These changes were hardly identifiable at a depth of about 2 m. The beam attenuation

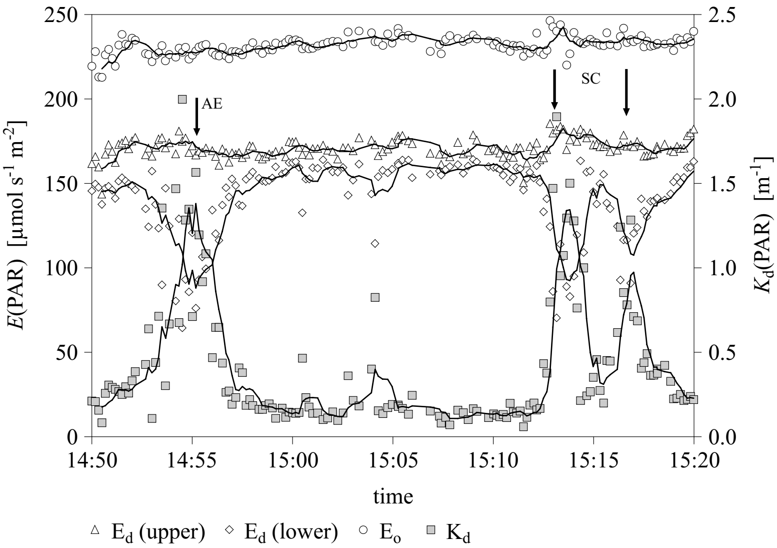

Fig. 3. The surface and underwater light field and the diffuse attenuation coefficient on 20 July 2003 in a sea area with a depth of 4.8 m. Shown are the instantaneous values of the measured parameters (averaged over 5 s) and a moving average over 5 subsequent measurements. E_0 is the scalar irradiance measured by the spherical sensor. In contrast to Fig. 2, the plots of E_0, $E_d(z_u)$ and $E_d(z_l)$ are normalised with the use of the values of the downwelling irradiance $E_d(+0)$ measured by the plane sensor on the boat. From Erm & Soomere (2004)

coefficients, however, more than double in value, owing to the bulk influence of wakes from nine fast ferries at a depth of about 5 m (Erm & Soomere 2004). In 2004, the field measurements were carried out in much deeper regions of the sea (6.5–14 m) than in 2003 (2.1–6 m). The above-described features became evident in nearly all the measurements at greater depths. The influence of ship wakes on the optical properties of near-bottom water, and therefore also on bottom sediments, is clearly expressed down to depths of about 14 m. Yet the influence of ship waves does not appear to extend deeper than 20 m, where the maximum ship-wave-induced near-bottom velocities are comparable with the velocities of coastal currents.

An interesting type of behaviour of the optical properties of water was observed in stronger wind conditions in relatively deep areas. The results of one such experiment, performed in waters c. 7 m deep on 15 June 2004, are depicted in Fig. 4. On this day, a fairly strong wind with a mean speed of 8–10 m s^{-1} excited a wave field with a significant wave height close to 1 m. The highest waves exceeded 1.5 m and their periods were 3–4 s.

All the measured parameters exhibited quite a strong scatter. This can be explained by the influence of relatively large waves. A feature qualita-

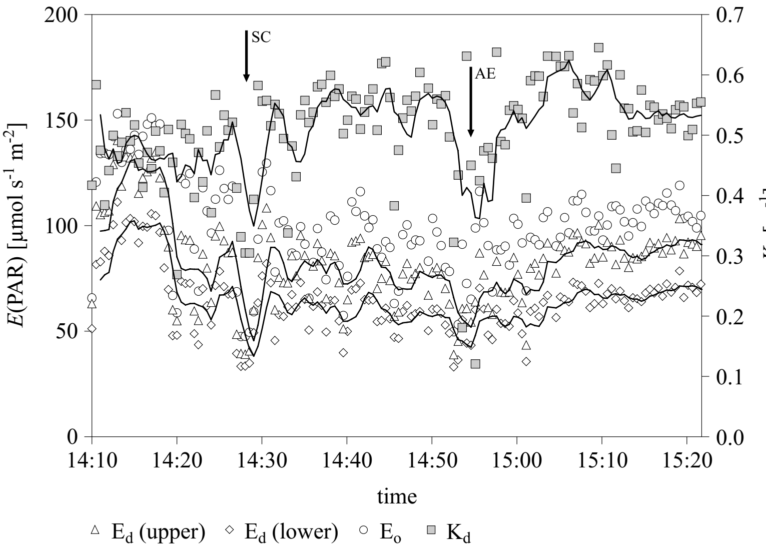

Fig. 4. The surface and underwater light field and the diffuse attenuation coefficient on 15 June 2004 in a sea area with a depth of about 7 m. Shown are the instantaneous values of the measured parameters (averaged over 5 s) and a moving average over 5 subsequent measurements. Symbols as in Figs 2, 3

tively different from the above cases is that not only the plane downwelling irradiance near the bottom but also all the measured parameters of the light field $E_d(z_l)$, $E_d(z_u)$ and $E_0(z)$ decrease substantially when the ship wake arrives. The decrease is of the order of a few dozen %, and in extreme cases can be as much as about 60–70%. This can be explained, as above, by the transport of near-bottom turbid water a relatively large distance away from the bottom.

A surprising outcome is that the diffuse attenuation coefficient K_d shows a deep minimum after the passage of ship wakes in such cases. In other words, the water in the layer between the two plane sensors becomes more transparent for a while. The analysis by Erm & Soomere (2004) shows that the concentration of yellow substance is more or less constant in the study area. This means that the changes in K_d occur as a result of the decrease in the concentration of suspended matter. A possible explanation for this may be given on the assumption that the amount of resuspendable sediments is limited. Then, wind waves in relatively rough seas can raise the whole of the potentially detachable fine sediment fraction from the sea bottom into the water column. Ship wakes may further bring them above all our optical sensors and cause some clear water to descend into the near-bottom layer. Such 'ventilation' may lower the optical density in the near-bottom layer. Effects of this type are more probable in the case of solitonic or strongly cnoidal ship waves (see Soomere et al. 2005), water motion in which has a much stronger vertical component compared to that in classical sine waves.

4. Reaction of bottom sediments

During the experiments in 2003, a number of water samples were taken from the layer between the plane sensors 1–3 min after the leading waves had arrived. The batometers (cylinders c. 0.4 m in length) were oriented vertically. Since long ship waves excite mostly horizontal water motions, several samples probably contained a portion of clear water from the upper layers. For that reason, the analysis in Erm & Soomere (2004) was mostly qualitative and in essence showed the lower limit of wave-induced changes in water properties.

In the 2004 field experiments, the batometers were oriented horizontally. The samples apparently represent more exactly the properties of sea water in the relevant layer. Even so, the sampling procedure is not perfect. Owing to the fast reaction of the sea water to ship waves, it was virtually impossible to take samples exactly at the instant of the maximum effect of the wake *in situ*. Although we did our best to ensure that the samples represent elevated values of $K_d(t)$, we probably did not exactly catch the peaks of $K_d(t)$ in the water samples. Therefore, the estimates below should be interpreted as the lower limits of the relevant quantities.

Despite the limitations of the sampling procedure, significant changes in the suspended matter concentration C_S due to ship wakes were registered in the water samples (Fig. 5). Although the concentrations varied moderately, the changes in the suspended matter concentration qualitatively followed the temporal behaviour of the directly measured diffuse attenuation coefficient $K_d(t)$. The changes in C_S were about 0.4–1.8 g m^{-3}, a range of values quite close to the resolution limit of the procedure (which is about 0.5 g m^{-3}).

The variation in C_S during the wake of the *SuperSeaCat* at about 14:24 on 5 September 2005 is impressive and unambiguous. The concentration of suspended matter increased from 1.5 g m^{-3} to 3.3 g m^{-3} , thereafter dropping back to 1.4 g m^{-3}. The change in C_S was 1.8 g m^{-3} (Table 1), which is well above the resolution of the procedure. These data were supported by the values of c^*, characterizing the optical density of samples (Fig. 5). Note that in earlier studies the systematic increase in the concentration of suspended matter due to ship waves was estimated as probable but not finally confirmed, because the maximum change in concentrations established from water samples was only 0.8 g m^{-3} (Erm & Soomere 2004).

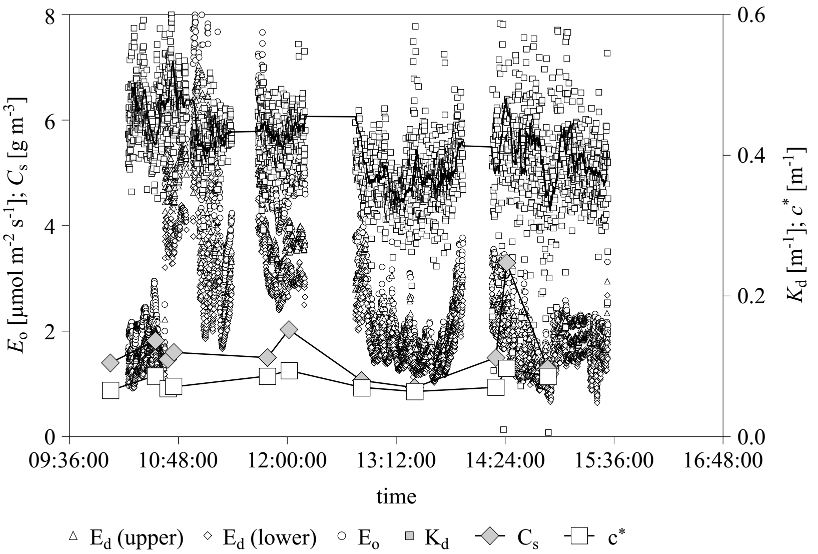

Fig. 5. The surface and underwater light field, diffuse attenuation coefficient, beam attenuation coefficient c^* and C_S on 5 September 2004 in a sea area with a depth of about 10.3 and 13.5 m. Shown are the instantaneous values of the measured parameters (averaged over 5 s) and a moving average line of $K_d(t)$ over 5 subsequent measurements. The meanings of the other optical parameters are as in Figs 3 and 4

Erm & Soomere (2004) drew some conclusions on the basis of measurements of optical properties and the concentration of optically active substances in sea water in the vicinity of the island of Prangli (Muuga Bay, adjacent to Tallinn Bay). The conditions for water sampling and optical measurements were favourable near Prangli because the optically dense water was mostly homogeneous. Based on this data, the dependence of $K_d(t)$ on C_S was expressed as a linear approximation with a slope of 0.0498. The theoretical basis for calculating K_d from C_S is given by Kirk (1984). An analogous relationship (based on data from many Estonian and Finnish lakes) between K_d and c^* is given by Arst et al. (1996). A method for estimating K_d from c^* spectra is applied by Arst et al. (2002).

Adding the data collected in 2003–04 during the measurements of ship waves, the dependence of $K_d(t)$ on C_S is virtually the same, with the correlation coefficient increasing from 0.89 to 0.90:

$$K_d = 0.0494\ C_S + 0.36 = K'_S C_S + 0.36. \tag{3}$$

Here $K'_S = 0.0494\ \text{m}^2\ \text{g}^{-1}$ has the meaning of a specific attenuation coefficient similar to the specific absorption coefficient of suspended matter a'_S described, for example, by Arst (2003, p. 9).

Table 1. Parameters of ship wakes. The following symbols are used: z_{sea} is the water depth at a particular measurement site, z_l is the height of the lower sensor from the seabed, t_{tr} is the time when the ship was on the traverse ΔK_d – maximum change in K_d from its initial value before the arrival of a wake, ΔC_S (meas) – change in C_S determined from water samples after the passing of a wake, fixed from water samples, $\Delta C_{S,\max}$ (calc) – change in C_S calculated from eq. (4), m_F – the amount of excess sediment transport induced by a single wake calculated by eq. (6), $\overline{C_S} = M/(t_2 - t_1)$. As the value of $m_F = 459$ is unusual for the *AutoExpress* sailing from Helsinki to Tallinn, it was not taken into account in estimates of the mean values

Date	z_{sea}	z_l	Ferry	t_{trav}	ΔK_d	$(t_2 - t_1)$	m_F	Δ_S (meas)	ΔC_S (calc)	$\overline{C_S}$ (calc)
	[m]				[m^{-1}]	[min]	[g s^{-1}]	[g m^{-3}]		
Tallinn – Helsinki										
17 July 03	2.4	0.5	*AutoExpress*	10:12	1.31	13	317		26.2	4.1
17 July 03	3.2	0.5	*AutoExpress*	08:16	0.41	4.2	84	0.35	8.2	3.3
20 July 03	4.8	0.7	*AutoExpress*	10:10	0.7	12.1	44	0.8	14.0	0.6
20 July 03	6.0	0.7	*AutoExpress*	13:17	0.11	16.3	96		2.2	1.0
20 July 03	6.0	0.7	*AutoExpress*	14:47	1.2	7.8	352		24.0	7.5
14 July 03	6.0	0.5	*AutoExpress*	11:25	0.16	12.3	116		3.2	1.6
16 July 03	6.0	0.5	*AutoExpress*	10:15	0.37	26.2	586		7.4	3.7
15 June 04	7.0	0.5	*AutoExpress*	14:46	0.27	21	153		5.4	1.2
5 Sept. 04	10.3	0.5	*AutoExpress*	10:11	0.27	23.5	82		5.4	0.6
5 Sept. 04	13.5	1.0	*AutoExpress*	14:47	0.44	15.5	100	0.6	8.8	1.1
			average		**0.5**	**15.2**	**193**		**10**	**2.5**
17 July 03	2.1	0.5	*SeaCat*	10:38	0.76	3.4	113		15.2	5.6
20 July 03	6.0	0.7	*SeaCat*	15:09	1.07	6.5	287	0.8	21.4	7.4
16 July 03	6.0	0.5	*SeaCat*	11:05	0.42	5.3	91		8.4	2.9
15 June 04	7.0	0.5	*SeaCat*	14:22	0.22	13	102		4.4	1.3
5 Sept. 04	10.3	0.5	*SeaCat*	10:37	0.19	5.7	58	0.1	3.8	1.7
5 Sept. 04	13.5	1.0	*SeaCat*	14:10	0.4	15.1	121	1.8	8.0	1.3
			average		**0.5**	**8.2**	**129**		**10**	**3.3**
Helsinki – Tallinn										
16 July 03	6.0	0.5	*AutoExpress*	09:14	0.11	8.5	39		2.2	0.8
17 July 03	2.4	0.5	*AutoExpress*	09:04	0.96	11.6	459		19.2	6.6
5 Sept. 04	13.5	1.0	*AutoExpress*	13:19	0.15	3.7	19		3.0	0.9
			average		**0.41**	**7.9**	**29**		**8**	**2.7**
7 Oct. 04	7.5	0.5	*SeaCat*	12:24	0.11	8.5	33		2.2	0.6
14 July 03	6.0	0.5	*SeaCat*	12:10	0.14	16.5	11		2.8	0.1
			average		**0.13**	**12.5**	**22**		**2.5**	**0.4**

The inverse regression from eq. (3) is

$$C_S = \frac{1}{K'_S} K_d - 7.3 = 20 K_d - 7.3. \tag{4}$$

Eq. (4) was used for estimating the maximum increase of suspended matter concentration ΔC_S (Table 1).

5. The impact of a wake

The reaction of the optical properties of sea water to ship wakes becomes evident in many different ways. Apart from the magnitude of changes in K_d, the duration and nature of its changes also depend on the particular ship and the water depth. Some wakes give rise to one well-defined maximum (Fig. 4), others to two or more maxima (Figs 3, 4). Sometimes there is one minimum of K_d, but cases of two or more minima, and even changes involving both maxima and minima, also occur (Fig. 5).

There apparently exists no single simple measurable parameter (such as the maximum variation in K_d or the duration of the measurable reaction) of the reaction of the properties of the water column to ship wakes. Both the *in situ* measured parameters – irradiance and wave-induced pressure – can be interpreted in terms of total loss of light or wake energy. However, comparison of such measures is questionable, because, for example, the underwater light field depends on the season and time of day, weather conditions and water depth. Also, they provide little information about the potential intensification of sediment transport.

Thus, a more complex measure of the impact of different ships must be sought. An acceptable measure of the 'total impact' can be formulated as an integral combining different aspects of the impact. A convenient measure to start with is the diffuse attenuation coefficient, because it characterises the rate of increase in the concentration of suspended matter, which can be used to estimate the total amount of (re)suspended sediments.

The impact of a wake in terms of bulk changes of the diffuse attenuation coefficient K_d from its background value K_{d0} can be obtained by integrating the absolute value of the deviation $K_d(t) - K_{d0}$ over any time interval containing the wake. Doing so corresponds to the reasonable assumption that $K_d(t)$ minima correspond to the lifting of suspended matter above both the sensors by the wake in a process that also contributes to the potential intensification of sediment transport in the area in question. Dividing this integral by K'_S we obtain:

$$M = \frac{1}{K'_S} \int_{t_1}^{t_2} |K_d(t) - K_{d0}| dt \qquad [\text{g m}^{-3}\ \text{s}]. \tag{5}$$

The quantity M can be interpreted as the 'total impact' of a wake, which describes both the rate and duration of the excess and drought of the suspended matter concentration compared to its background level.

The right-hand side of expression (5) does not depend on the particular choice of t_1 and t_2, provided there are no secular changes in K_d and the interval $[t_1, t_2]$ contains all the waves of the wake in question. Since wakes may induce long-term and cumulative changes in the properties of near-bottom water (Erm & Soomere 2004), t_1 and t_2 should be identified with the beginning and end of the particular wake, and K_{d0} with the average value of K_d immediately before the wake.

From Figs 3–5 it follows that the mean value of $K_d(t)$ is usually restored after a short time. It is natural to assume that during the increase (decrease) of a peak (minimum) there is a more or less continuous supply (seepage) of suspended matter to (from) the water layer between the plane sensors and that an equal amount of suspended matter moves in the opposite direction when the mean value of $K_d(t)$ is restored after the peak (minimum). Since the amount of suspended matter brought into the upper layers is eventually compensated for by (re)suspension from the bottom, the above 'total impact' of a wake M thus characterises the bulk quantity of (re)suspended sediments.

Generally, M must be found by means of numerical integration. As the simplest approximation, the summation $\sum |K_{d0} - K_d(t_i)|\Delta t_i$ replaces the integration in (5) over all time instants when $K_d(t)$ was influenced by a wake, and Δt_i is the time interval between the sequential values.

Let us roughly estimate the additional sediment transport caused by the joint influence of ship wakes and longshore currents with a typical velocity v. The water volume flowing through the cross-section of the current in the measurement area during time interval $[t_i, t_2]$ is $V = vhL(t_2 - t_1)$, where L is the width of the current and h is the thickness of the water layer affected by the ship wakes. If the suspended matter is distributed uniformly in this layer, then the total amount of suspended matter transported along the shoreline through the cross-section is $m_S = VC_S = vhLC_S(t_2 - t_1)$.

If we further assume that in some part of the water column the average excess of sediments resulting from this wake is equal to $\overline{C_S} = M/(t_2 - t_1)$, then the excess transport of sediments during the duration of this wake is $m_{excess} = vhLM$. From the analysis above, it follows that the excess of sediments occurs in the c. 1 m deep near-bottom water layer. The characteristic coastal current speed in Tallinn Bay is about 0.1 m s^{-1} (Orlenko 1984). Hence, the amount of excess sediment transported in unit time is

$$m_F = vhL\overline{C_S} \qquad [\text{g s}^{-1}]. \tag{6}$$

where L stands for the width of the coastal area affected by ship wakes from the very shallow water to deep areas with a depth of about 20 m. This width is typically of the order of 1 km in Tallinn Bay conditions. The mean values of $\overline{C_S}$ are around 3 g m^{-3} (Table 1). An average wake therefore causes a sediment transport of about 300 g s^{-1} through any cross-section of the coastal slope. The typical duration of a wake is about 10 minutes; the sediments are thus transported a distance of about 60 m.

The mean excess concentration of 3 g m^{-3} created by a wake in a water column 1 m in height means that, on average, 3 g m^{-2} or about 3000 g of sediments per metre of coastline is set in motion by the wake in the whole coastal area and for the duration of the wake. These estimates potentially apply to the whole shoreline of Tallinn Bay, the east coast of which is about 10 km long. Therefore, one wake, on average, brings a total of about 30 000 kg of sediments into the water column, and the coastal currents eventually move this bulk through a distance of about 60 m.

A major part of this sediment transport occurs between different coastal areas of the same depth. A certain amount, however, appears to be transported beyond the area affected by ship waves, either beyond the bay, as far as the bayhead, or to deeper areas. This part can be regarded as the bulk loss of sediments due to ship waves. Erm & Soomere (2004) suggest that the loss is of the order of 10% of the total amount set in motion.

Note that many assumptions have been made in the derivation of eq. (6) and in the above estimates; the results should therefore be interpreted as estimates of the order of magnitude of the sediment transport.

Some significant measured and calculated parameters of clearly identified ship wakes are given in Table 1. An overall feature of the measurements is the large scatter of the results. This is not surprising, because the properties of ship wakes may in fact depend on small changes of route, loading or speed (Parnell & Kofoed-Hansen 2001). There may be some additional causes of scatter: the weather conditions may affect the data, there may be a cumulative influence of interactions of different factors, and, last but not least, the seabed may have greatly different properties even at slightly separated measurement points (Kask et al. 2003). For example, the somewhat unusual data from 16 July 2003 (water depth 6 m, t_{tr} is 10:15) can be explained either by the slightly quicker speed of the ferry or by some differences in the properties of the seabed.

We were unable to track the changes in the influence of a single wake as it approaches the coast. However, some tendencies can be followed from the regression analysis of different wakes measured at sites of different depths (Table 2).

The duration of the detectable influence of a single wake is larger for greater depths. This is apparently caused by the bigger quantity of finer sediments at greater depths, which are moved more easily and which remain in the water column for a longer time. Yet the amount of resuspended sediments decreases very rapidly when the depth increases. This feature evidently reflects the larger near-bottom velocities at smaller depths and

Table 2. Regression coefficients k and correlation coefficients R of properties of wakes at different depths. The notation is the same as for Table 1. The data concerning ferries sailing from Helsinki to Tallinn have not been taken into account

	ΔK_d		$(t_2 - t_1)$		m_S		$\overline{C_S}$	
Ferry	k	R	k	R	k	R	k	R
AutoExpress	**–0.049**	0.4	**0.91**	0.4	**–12.3**	0.2	**–0.27**	0.4
SeaCat	**–0.045**	0.5	**0.83**	0.7	**–4.2**	0.2	**–0.42**	0.7

perhaps also the increasing influence of non-linearity on the wave shape in shallow areas. The impact of the wakes of all the ferries in Table 2 show a similar dependence on the water depth.

6. Conclusions

Field measurements in 2003–04 covered a major part of the eastern coastal slope of the Tallinn Bay area with depths of 6.5–14 m. The basic outcome of these studies is that the clearly detectable influence of ship wakes on the optical properties of sea water and on the bottom sediments extends to a depth of at least 15 m.

The influence of a wake, identifiable with the optical methods in use, usually lasts about 6–15 minutes. This means that the actual influence of wakes on the seabed is mostly limited to the first wave group (see Soomere & Rannat 2003) and sometimes to the leading waves of the second group. The largest changes in the optical properties of water masses, expressed in terms of the diffuse attenuation coefficient K_d, occur at relatively small depths – 2.1–4.8 m. This feature evidently reflects the fact that the highest near-bottom orbital velocities occur in shallow water. This may also reflect the highly non-linear nature and unusually large vertical velocities of the longest waves of wakes in shallow areas (Soomere et al. 2005).

There is some difference in the influence of wakes from different ships, although the maximum change of K_d varies only insignificantly. The difference becomes evident in integral measures and reflects a longer duration of the wakes from certain vessels (e.g. the *AutoExpress*). The time series of $K_d(t)$ corresponding to wakes with a longer duration usually have two well-defined maxima, which probably correspond to the first and the second wave group.

There were 6 crossings of Tallinn Bay by the *AutoExpress*, 5 crossings by the *SeaCat* and 5 crossings by the *NordicJet* each day along the Tallinn–Helsinki route from March/April to December 2004. During that time, the *AutoExpress* made a total of about 1600 crossings, and the *SeaCat* and *NordicJet* 1350 crossings each. The wakes of the vessels of the Nordic Jet Line have not been described here. Although they are somewhat smaller and their influence is apparently not decisive, they may still make an appreciable contribution to the total ship wave activity (Soomere & Rannat 2003). From the above it follows that the wakes from these 4300 crossings bring into motion, on average, some 10 000 kg of sediments per metre of coastline. If only c. 10% of that amount is transported away from the coasts, the total loss of sediments would be several hundred litres per metre of coastline.

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