Modelling the sea aerosol emission in the coastal zone

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Abstract

A model of aerosol emission from the coastal zone is presented. Based on the equation describing wind-wave energy dissipation in the coastal zone of the sea, it enables the aerosol emission from any coastal zone to be calculated provided the parameters of wave motion in a deep sea and the bathymetry are known.

The aerosol emissions for a real bottom profile (the coastal station at Lubiatowo, southern Baltic Sea) are given.

The effect of the sea bottom profile on aerosol emission is discussed on the basis of numerous implementations of the model. The logarithmic relationship between the total aerosol emission flux from the coastal zone and the tangent of the bottom slope is demonstrated, and the total aerosol emission from a coastal zone with a smooth sea-bed is compared with that from a coastal zone with a rough bed. The aerosol emission flux is independent of wave size in deep water at short distances from the shore.

1. Introduction

The physical parametrisation of the sea aerosol emission and the design of models describing its flux as influenced by its dynamic interaction with the atmosphere has been extensively researched.

A number of models describing aerosol emission from open sea areas have been developed. However, as far as the coastal zone, the most energoactive area, is concerned, no models taking into account the complex conditions characteristic of only this zone have yet been constructed. So far, the following parameters have been used to describe aerosol emission flux from the coastal zone: a sea surface covered by whitecaps (Monahan, 1971; Monahan and MacNiocall, 1986), Reynolds roughness (Garbalewski, 1974), and the transfer of humidity and latent heat (Ling and Lao, 1976). These examples do not allow for the effect of the sea bottom, which is particularly important as regards emission in coastal zones. In the present paper, the effect of the dissipation of wind-wave energy on mass emission and the model of aerosol emission within the coastal zone are discussed. The model is based on a wave-energy equation that takes bathymetry into consideration.

2. Model

Data obtained in the southern Baltic Sea during the international BAEX–I experiment (Baltic Aerosol Experiment) were used in the development of the model (Petelski and Chomka, 1996).

Interesting results were obtained, *e.g.* by comparing the mass sea-salt concentration of the open sea and the beach. Figs. 1a and 1b show that

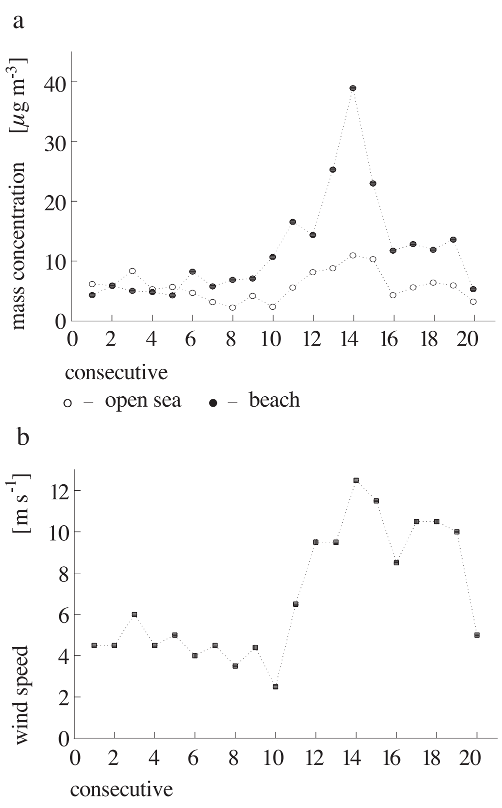


Fig. 1 Comparison of the mass sea-salt concentration of the open sea and the beach (a), the wind speed (b) for consecutive measurements

the aerosol concentration above the beach is considerably higher than that over the open sea; however, the difference in concentration is small when the wind is weak, though significant when this reaches a velocity of 7.0 m s^{-1}. It should be stressed that the trend was reversed at points 10, 19 – the concentration increased despite the decrease in wind speed. This is the result of continuous wave motion within the coastal zone. At sea, the aerosol concentration responds more quickly to changes in the wind velocity.

The findings presented in Figs. 1a and 1b were a prerequisite for stating that the aerosol emission within the coastal zone should be related to the wave motion parameters rather than to the changes in wind velocity. The aerosol fluxes were calculated and correlated with various dynamic quantities in order to check whether or not it was worth searching for such a parametrisation. The maximum correlation coefficient of 0.87 was obtained for an energy loss to the power 3/4, which verified the idea of the wind-wave energy being the key factor in the parametrisation of the aerosol emission flux within the coastal zone. This concept was therefore applied in the design of the model.

2.1. Assumptions of the model

Coastal areas are especially active in terms of air-sea mass exchange. Along with aerosol emission, the most important effect of breaking waves is the dissipation of their energy. Since wave energy and its dissipation are easily detectable, the aerosol flux has been parametrised by means of these two factors. To simplify the approach, stationary conditions and horizontal homogeneity of the coastal area described have been assumed. Additionally, the following coordinates are employed:
x – horizontal axis perpendicular to the shoreline,
y – horizontal axis parallel to the shoreline,
z – vertical axis (upwards).

2.2. Parametrisation of the emission flux

The emission flux of the marine aerosol can be calculated from gas bubble fluxes in the water column. Since the bursting of bubbles at the sea surface is the principle mechanism of particle and droplet emission, the other mechanisms of aerosol generation can be neglected. The emission flux is calculated from the equation (Wu, 1992)

$$F_E = \int_0^\infty \frac{1}{\tau(r)} \varphi(r) \left[n_j(r) + n_f(r) \right] dr, \qquad (1)$$

where
$\tau(r)$ – suspension time [s] of a bubble of radius r,
$n_j(r)$ – the number of jet droplets produced by a bubble of radius r,

r – bubble radius [μm],
$\varphi(r)$ – distribution function of the bubble size per sea surface unit [m^{-2}],
$n_f(r)$ – number of film droplets produced by a bubble of radius r.

The number of bubbles per sea surface unit is described by the integral

$$L_p = \int_0^\infty \varphi(r)dr. \tag{2}$$

Because the determination of functions $\varphi(r)$, $\tau(r)$ and $N(r)$ – the number of sea-salt particles in one cubic metre of air – in the coastal zone is problematic, the use of eq. (1) to calculate the emission flux is difficult in practice. The functions describing the number of droplets $n_j(r)$ and $n_f(r)$ are well known and are given in the literature. Wu (1992) gives the following formulae to describe them:

$$n_j(D) = 7\exp\left(\frac{-D}{3}\right), \qquad n_f(D) = 0.65D^{2.15}, \tag{3}$$

where
$D = 2r$ – bubble diameter [μm].

Slightly different factors for these functions can be found in Blanchard and Syzdek (1988) and in Resch *et al.* (1986). However, both works make it clear that the number of droplets emitted is always proportional to the number of bursting bubbles. In the emission model, the problem is simplified by setting all bubble radii equal to the mean radius r_s, defined as

$$r_s = \frac{\int_0^\infty r\varphi(r)dr}{\int_0^\infty \varphi(r)dr}. \tag{4}$$

This leads to the conclusion that the emission flux F_E is proportional to the number of bursting bubbles per sea surface unit

$$F_E = A\,L_p, \tag{5}$$

where
A – a constant, describing the rate of bubble bursting and the number of droplets formed from single bubble [s^{-1}]:

$$A = \frac{\int_0^\infty \frac{1}{\tau(r)}\varphi(r)\left[n_j(r) + n_f(r)\right]dr}{\int_0^\infty \varphi(r)dr}. \tag{6}$$

It was assumed that the number of bubbles participating in aerosol emission is related to the sea surface covered by foam from breaking waves and to the mean bubble size. If the volume of foam produced during wave breaking is proportional to the water volume discharged due to this breaking, we obtain

$$L_p \cong C_1\,\frac{U_l}{\frac{4}{3}\pi\,r_s^3}, \tag{7}$$

where
U_l – volume of water discharged by a single breaking wave [μm^3],
r_s – mean bubble radius [μm],
C_1 – dimensionless coefficient of proportionality.

Taking into account the theory of wave geometry, the water volume U_l can be assumed proportional to the third power of the wave height increment:

$$U_l = C_2\,(\Delta H)^3, \tag{8}$$

where
ΔH – wave height increment [m],
C_2 – dimensionless coefficient of proportionality.

The difference in potential energy of the waves due to wave energy dissipation is

$$\Delta E = \rho_w\, g\, U_l\, \Delta H. \tag{9}$$

Eqs. (7), (8) and (9) yield

$$L_p = \frac{3}{4}\,\frac{C_1\, C_2^{-0.5}\left(\frac{\Delta E}{\rho_w\, g}\right)^{\frac{3}{4}}}{\pi\, r_s^3}, \tag{10}$$

where
ρ_w – water density = 10^3 kg m^{-3},
g – acceleration due to gravity [m s^{-2}],
ΔE – dissipation of wave energy [J].

Finally, the emission flux can be parametrised by the wave energy dissipation per sea surface unit using the following equation:

$$F_E = A\,\frac{3}{4}\,\frac{C_1\, C_2^{-0.5}\left(\frac{\Delta E}{\rho_w\, g}\right)^{\frac{3}{4}}}{\pi\, r_s^3}. \tag{11}$$

If the quotient of the constants in eq. (11) is replaced by a single constant A_p, we then obtain eq. (12):

$$F_E = A_p\,(<dE>)^{\frac{3}{4}}, \tag{12}$$

where
A_p – a constant representing the bubble sizes and the rate of bursting.

The key to the emission flux parametrisation described earlier is the energy of wind waves. There are two types of models describing wave motion in coastal areas. The earlier one (Battjes, 1972; Kuo and Kuo, 1974; Goda, 1975) takes only local depth into consideration, whereas the second type (Battjes and Janssen, 1978; Thornton and Guza, 1983; Szmytkiewicz and Skaja, 1993) is based on the wave energy flux balance. The latter type provide an accurate description of wave energy dissipation even when sea bottoms have complicated profiles. It was therefore the second type that was employed as part of the aerosol emission model. The key formula of the model is that describing the wave energy flux balance.

The wave energy losses per sea surface unit (dE) were calculated from the wave energy flux balance equation (Massel, 1987)

$$\frac{\partial F}{\partial x} = <dE> + <dE_t>, \tag{13}$$

where
$F = E\,C_{gx}$,
$<dE_t>$ – mean energy loss due to friction against the bottom,
C_{gx} – group wave velocity component,
E – wave energy,

$$E = \frac{1}{8}\rho_w\, g\, H^2_{\mathrm{rms}} = \frac{1}{8}\rho_w\, g \int_0^\infty H^2\, p(H) dH, \tag{14}$$

where
H_{rms} – quadratic mean wave height,
H – wave height,

$$C_{gx} = \frac{C}{2}\left(1 + \frac{2hk}{\sinh 2kh}\right)\cos\Theta, \tag{15}$$

where
C – phase velocity of the wave,
k – wave factor,
h – depth,
Θ – the angle between the wave radius and a line perpendicular to the shoreline.

$< dE >$, *i.e.* the mean wave energy dissipation across unit area has been determined as the interpolation of single monochromatic waves according to the formula

$$<dE> = \int_0^\infty dE(H)\, p(H) dH, \tag{16}$$

where
$p(H)$ – the probability of occurrence of waves height H.

In every model of this type, it is assumed that the probability distribution of the occurrence of waves of height H is described by the Rayleigh distribution (Massel, 1987)

$$p(H) = \frac{2H}{H^2_{\mathrm{rms}}}\exp\left[-\left(\frac{H}{H_{\mathrm{rms}}}\right)^2\right]. \tag{17}$$

Using their own field measurements, Thornton and Guza (1982) concluded that a subset of breaking waves has a height distribution such that it can be described as a tapering function in the Rayleigh distribution for all waves:

$$p_b(H) = W(H)\, p(H). \tag{18}$$

The tapering function W(H) is given by

$$W(H) = \left(\frac{H_{\text{rms}}}{\gamma_f\, h}\right)^4, \tag{19}$$

where

γ_f – a parameter representing the slope of the sea bottom and the wave curvature.

Formula (19) for the coastal zone and the inner part of the surf zone reads as follows:

$$W(H) = \left(\frac{H_{\text{rms}}}{\gamma_f\, h}\right)^4 \left[1 - \exp\left(\frac{H}{\gamma_f\, h}\right)^2\right] \leq 1. \tag{20}$$

The energy dissipation flux dE of a single wave can be determined by assuming that waves breaking in shallow waters can be described as bore waves (Stoker, 1957).

Combining eqs. (17)–(19) with eq. (16) yields the following formula:

$$<dE>= \frac{3\sqrt{\pi}}{16}\, \rho_w\, g\, B^3\, f\, \frac{H^5_{\text{rms}}}{\gamma_f\, h^3} \left[1 - \frac{1}{\left[1 + \left(\frac{H_{\text{rms}}}{\gamma_f\, h}\right)^2\right]^{\frac{5}{2}}}\right], \tag{21}$$

where

B – index of wave breaking,

f – wave frequency.

According to Massel (1987), the component $< dE_t >$, *i.e.* the energy portion lost due to friction against the bottom, is considerably smaller than $< dE >$, and is for this reason neglected in the model. Eq. (13) is resolved using the models by Battjes and Janssen (1978), Thornton and Guza (1982). The full equation system in the model takes the form

$$\begin{aligned}
F_E &= A_p\, (<dE>)^{\frac{3}{4}}, \\
\frac{\partial E\, C_{gx}}{\partial x} &= <dE>, \\
C_{gx} &= \frac{C}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right)\cos\Theta, \\
E &= \frac{1}{8}\, \rho_w\, g\, H^2_{\text{rms}}, \\
<dE> &= \frac{3\sqrt{\pi}}{16}\, \rho_w\, g\, B^3\, f\, \frac{H^5_{\text{rms}}}{\gamma_f\, h^3} \left[1 - \frac{1}{\left[1 + \left(\frac{H_{\text{rms}}}{\gamma_f\, h}\right)^2\right]^{\frac{5}{2}}}\right].
\end{aligned} \tag{22}$$

2.3. Constants in the model

The constants B, γ_f and A_p in the model have to be determined in order to calculate the aerosol emission fluxes. The dimensionless parameter γ_f represents the sea bottom slope and the magnitude of wave curvature. The construction of the tapering function underpinned by a simple condition, which can be written for a monochromatic wave and shallow water:

$$H = \gamma_f \, h, \tag{23}$$

where
H – wave height,
h – depth,
is the basis for constructing the tapering function.

Thornton and Guza (1983) proved that the coefficient $\gamma_f = 0.42$ is the most suitable one for this model. In the Battjes and Janssen (1978) model, however, the parameter γ_f appears in the maximum wave height criterion at a given depth

$$H_b = \frac{0.88}{k} \, \mathrm{tgh} \left(\frac{\gamma_f}{0.88} \right) k \, h, \tag{24}$$

were
H_b – maximum wave height.
This equation can be reduced to formula (23).

Stive (1982) analysed the parameter γ_f using the Battjes and Janssen (1978) model and sought values of γ_f for which the model would best describe the experimental data. That analysis confirmed the relation between γ_f and the wave curvature. The values of γ_f calculated by various authors are given in Tab. 1.

Thornton and Guza (1983) obtained the value of coefficient B by comparing the findings of numerous applications of the model to a number of surveys (Tab. 2). As Tab. 2 shows, parameter B is equal to 0.8 only for laboratory data, while for surveys done on a real beach it ranges from 1.3 to 1.7. We can take the value of $B = 1.54$, which is the mean of all the results, as optimum. To sum up, the above solutions regarding constants γ_f and B enable us to state that an accurate and definitive determination of their values is not possible.

In this model parameters B and γ_f regarding wave breaking and the wave slope were adapted from the Szmytkiewicz and Skaja (1993) model when $B = 0.88$ and $\gamma_f = 0.41$. If there is not enough experimental data on wave motion, it is possible, according to the Thornton model, to assume that $B = 1.54, \gamma_f = 042$.

Table 1. Parameter γ_f as a function of H_{rms} – quadratic mean wave height

References	h [m]	H_{rms} [m]	f [Hz]	s	γ_f
Battjes and Janssen, 1978	0.705	0.144	0.511	0.026	0.73
	0.697	0.220	0.383	0.012	0.60
	0.701	0.143	0.453	0.018	0.70
Battjes and Janssen, 1979	0.703	0.137	0.450	0.019	0.72
	0.645	0.121	0.443	0.016	0.69
	0.763	0.104	0.467	0.016	0.70
	0.732	0.118	0.481	0.019	0.70
	0.616	0.143	0.498	0.024	0.72
Stive, 1984	0.700	0.138	0.341	0.010	0.62
	0.700	0.136	0.633	0.038	0.81
	4.190	1.000	0.185	0.023	0.82
Derks and Stive, 1984	10.80	1.29	0.157	0.022	0.67
	15.65	2.78	0.115	0.026	0.73
Dingemans (after Battjes and Janssen, 1979)	16.40	0.94	0.143	0.013	0.70
	11.10	2.43	0.128	0.028	0.82

h – depth, f – wave frequency, s – wave curvature

Table 2. The value of parameter B (Battjes and Janssen, 1978)

Type of measurements	B	Error [%]	Number of measurements
in situ	1.5	7.3	16
in situ	1.7	5.3	12
in situ	1.3	7.0	8
in situ	1.5	7.9	14
in situ	1.5	9.3	12
laboratorium	0.8	6.1	9

In this model the determination of the parameter A_p, connecting aerosol emission and wave energy dissipation, is crucial. The average emission flux calculated from the aerosol emission flux balance over the coastal zone (Petelski and Chomka, 1996) and the dissipation of wave energy for the whole coastal zone were used to calculate A_p. The average wave energy per sea surface unit was calculated on the assumption that energy is lost evenly along the entire breaker zone:

$$< dE >= \frac{E_p}{D_p}, \tag{25}$$

where
E_p – total wave energy loss within the breaker zone,
D_p – width of the breaker zone.

The values of E_p and D_p were obtained using the Thornton model, where the sum of all values of E_p was taken to be E_p, and the maximum distance where wave energy dissipation was >0.001 (*i.e.* $dE > 0.001$) was taken to be D_p.

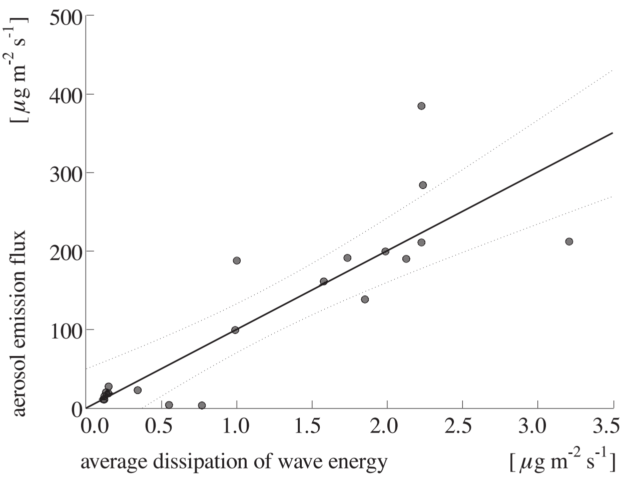


Fig. 2. The emission aerosol flux as a function of wave energy dissipation to the power 3/4

Fig. 2 shows the relation between the aerosol emission flux and the average wave energy dissipation to the power 3/4. The regression line in this figure is described by the equation $F_E = 99.4 < dE > +3.5$. For these values the correlation coefficient is 0.86. The dashed lines on either side of the straight line represent the 95% confidence interval. Consequently, A_p can be taken to be 99.4.

2.4. Calculations of the model

This model enables the aerosol emission along a profile perpendicular to the shoreline to be calculated, provided the following quantities are known:

- quadratic mean wave height,
- direction of wave propagation,
- bathymetry,
- frequency.

Calculations should be carried out from deep water towards the shore through a grid with a 0.5 m step, and are based on eq. (22) written in the form of finite differences and solved numerically.

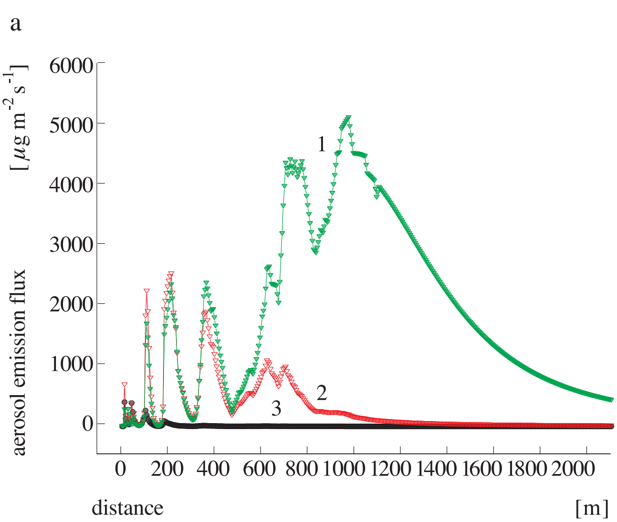
On the basis of further equations the average loss of energy, the component (along the x-axis) of the waves' group velocity for each point and the quadratic mean wave height at each point were calculated, which made it possible to determine the aerosol emission flux according to the formula.

The calculations were done on the basis of the model in accordance with the following procedure:

- establishment of the grid and initial parameters,
- calculations of dE according to the equation at the first point of the grid,
- calculations of energy flux according to the equation at the first point on the grid,
- calculations of energy flux according to the equation at the next point on the grid,
- calculations of H_{rms} according to the equation,
- passing on to the next point on the grid,
- repetition of this procedure until the whole grid has been covered,
- calculating dE for all points of the grid and calculating F_E according to the formula afterwards.

3. Results and discussion

The aerosol emission fluxes at Lubiatowo (the sea bottom profile Fig. 3b) were obtained numerically from the model. The aerosol emission fluxes shown in Fig. 3a were calculated from the model for three variants of the boundary conditions characteristic of that area, *i.e.* slight, moderate and gale-force winds. The green line shows the values calculated on the assumption that the wave coming into the modelled zone has an average height of $H_{\mathrm{rms}} = 3.6$ m and a period $T = 8$ s; the respective values for the red line are $H_{\mathrm{rms}} = 1.6$ m and $T = 5.5$ s and for the black line $H_{\mathrm{rms}} = 0.4$ m and $T = 1.5$ s. It is clear from Fig. 3 that, for both a real bottom and one of constant slope, emission is independent of wave height in deep water, so long as the offshore distance is small. The maximum aerosol emission occurs where shallows are accompanied by a steeply sloping bottom. The steeper the local slope of the bottom, at limited depths, the larger the maximum emission flux. This conclusion is valid not only for local maxima but also for the sloping bottom throughout the coastal zone.



$1 - H_{rms} = 3.6$ m, $T = 8$ s, $2 - H_{rms} = 1.6$ m, $T = 5.5$ s,
$3 - H_{rms} = 0.4$ m, $T = 1.5$ s

b

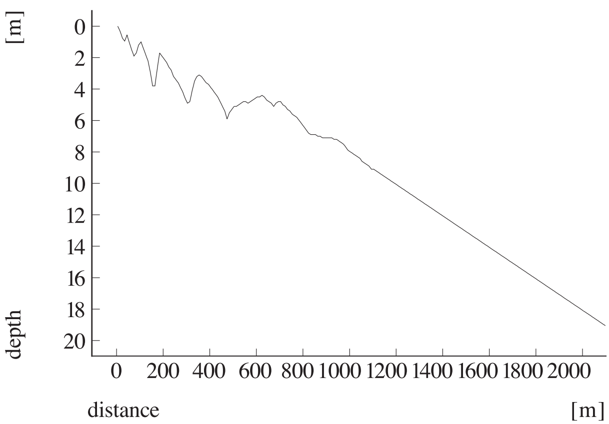


Fig. 3. Aerosol emission flux for a sea bottom profile under different wind conditions (a), a sea bottom profile at Lubiatowo (b)

The aerosol emission flux obtained from the numerical model for two cases of constant sea bottom slope is shown in Figs. 4a and 4b, the former when the tangent of the angle of the sea bottom slope $\tan\alpha = 0.026$, the latter when $\tan\alpha = 0.065$. The plots show that the emission flux is greater for a steep bottom. The maximum value in Fig. 4b is twice as high as in Fig. 4a. The average emission flux for $\tan\alpha = 0.026$ is 30.4 μg m^{-2} s^{-1}, but when $\tan\alpha = 0.065$ it is 40.8 μg m^{-2} s^{-1}. Hence, the steeper the sea bottom slope, the higher the maximum emission flux; at the same time, however, the overall emission from the entire coastal zone is lower.

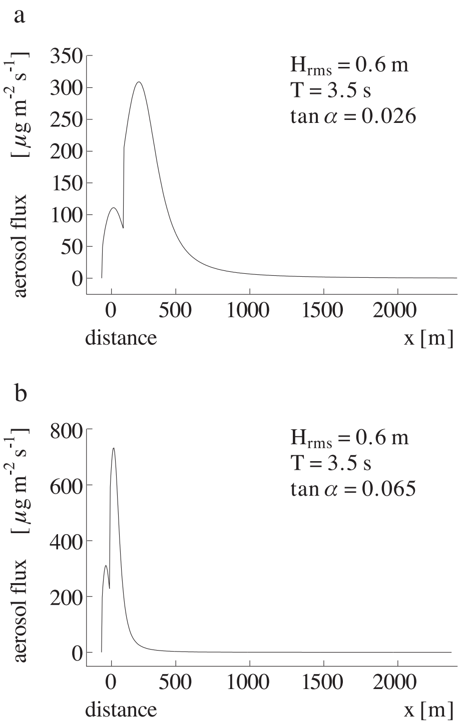


Fig. 4. Aerosol emission flux for a constant sea bottom slope ($\tan\alpha = 0.026$) (a), ($\tan\alpha = 0.065$) (b)

4. Conclusions

This model enables the horizontal profile of the emission flux within the coastal zone to be obtained if the wave motion beyond this zone and the bottom profile are known.

To sum up, some interesting conclusions can be drawn from the numerical experiments run using this model:

- the sea bottom slope within the coastal zone has a decisive effect on the aerosol emission; the steeper this slope, the smaller the emission from the coastal zone;
- the total emission from the coastal zone is higher from over a smooth bottom than from over a rough one. The larger the amplitude of the sea bottom, the smaller the total emission and the average emission from the coastal zone;
- local aerosol emission fluxes are inversely proportional to the total emission: maximum emission fluxes occur over very shallow water. The steeper the local sea bottom slope, the higher the maximum emission fluxes;

- the emission flux is independent of the deep-water boundary condition and is determined entirely by the depth in the shallower, active part of the zone;
- for each wave size outside the coastal zone there is an area within the zone from which emission will not increase, despite the general increase in the wave motion. This implies that the width of the breaker zone is a parameter that accurately describes the quantity of aerosol emission from the coastal zone.

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