Papers

Sea salt emission from the coastal zone

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Tomasz Petelski
Maria Chomka
Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, PL–81–712 Sopot, Poland;
petelski@iopan.gda.pl

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Abstract

The paper presents the findings of experiments to determine marine aerosol emission from the coastal zone. A relation between aerosol flux and wave energy dissipation was found. The emission fluxes calculated for the distribution of aerosol concentration are proportional to the dissipation of wave energy to the power of 3/4. The calculations were carried out using the experimental data obtained during the TABEX and BAEX experiments.

1. Introduction

Aerosol emission from the sea surface is one of the most interesting phenomena characterising the marine boundary layer. The marine aerosol affects nearly every physical process taking place in that layer (Garbalewski 1999). Aerosol fluxes participate in the transfer of mass and heat between the sea and the atmosphere (Andreas *et al.* 1995), and they can affect turbulent fluxes considerably greater than themselves (Petelski 1996). The aerosol as a factor determining climate through its influence on the optical properties of the atmosphere has recently been attracting increasing attention (Wright 2000). The development of satellite detection methods has generated greater interest in the marine aerosol. Several aerosol models (Gonng *et al.* 1997) are now used in the optics of the atmosphere. However, the problem of the parameterisation of aerosol emission from the sea surface is still far from solved. Monahan & Van Patten (1989) determined aerosol emission fluxes using the findings of whitecap simulation in the open sea. There are no papers describing emission on the basis of direct field measurements owing to difficulties in making such measurements: most of the references cited deal with the mean macro scale emission fluxes calculated on the basis of marigenic aerosol concentrations in the atmosphere. Petelski & Chomka (1996a) presented a method of calculating mean emission fluxes from the coastal zone based on the balance of the aerosol over that zone: these fluxes were calculated according to the method used during the BAEX experiment. Equations of aerosol emission from the coastal zone were formulated from these results (Chomka & Petelski 1997). The model used in that paper related the aerosol emission flux to wave energy dissipation, and showed that aerosol emission was proportional to the dissipation of wave energy to the power of 3/4. However, as the quantity of data was rather small, it became necessary to demonstrate the relation for data from other experiments. The aim of the present work was therefore to show that the relation between the aerosol emission flux and energy dissipation to the power of 3/4 is universal, *i.e.* applicable not only to the conditions during the BAEX experiment. The sea salt gradients in the TABEX experiments (TABEX ′97, TABEX ′98, TABEX ′99) are given and the aerosol emission fluxes have been calculated using those data. The fluxes have been correlated with the wave energy dissipation within the coastal zone.

2. Measurements

The aerosol measurements described here were carried out during the BAEX (Baltic Aerosol Experiment) and TABEX (Tracer Aerosol Baltic Experiment) experiments and are shown in Fig. 1.

The data were collected in the coastal zone from on board s/y 'Oceania' and from the land station at Preila (Lithuania) during TABEX in October 1997, October 1998 and September 1999. Aerosol formation was measured with six-stage impactors working simultaneously and located at different heights above sea level. At the Preila station the lowest impactor was situated 2, 3, 4 and 5 metres above sea level in 1997, and 2 and 5 metres above the water level during the 1999 experiment. During

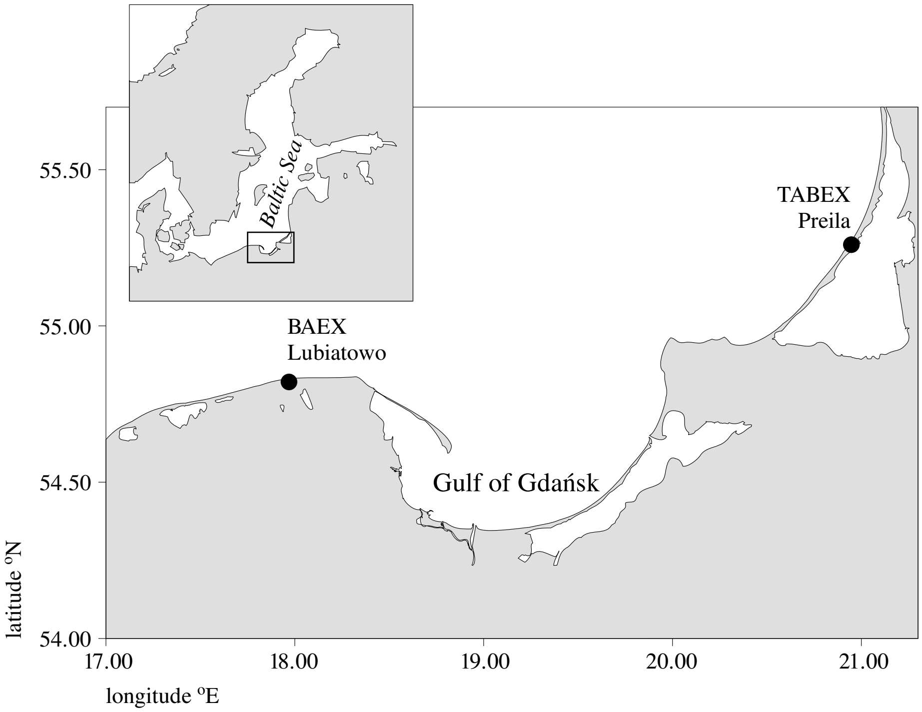

Fig. 1. Location of measurement sites: land stations at Lubiatowo – BAEX and Preila – TABEX

TABEX ′98 the horizontal aerosol concentration gradient was measured, the impactors being situated 2 metres above the ground at distances of 0, 22, 32, 52, 82 metres from the shore, while on board ship they were placed 2 and 5 m above the water level.

The average wind velocity, temperature and humidity were measured at the land station and also on board the ship anchored about 2 miles off shore, facing the wind. The number of sea salt particles and size distribution were analysed under a microscope.

3. Sea salt concentration over the coastal zone

The concentrations of sea salt in the air 2 m above the sea are shown in Fig. 2 (1997), Fig. 3 (1998) and Fig. 4 (1999). The vertical axis is scaled in micrograms per cubic metre, whereas the horizontal one shows consecutive measurement numbers.

Apart from the values obtained at sea and on the beach, the data from the horizontal inland profile are shown in Fig. 3.

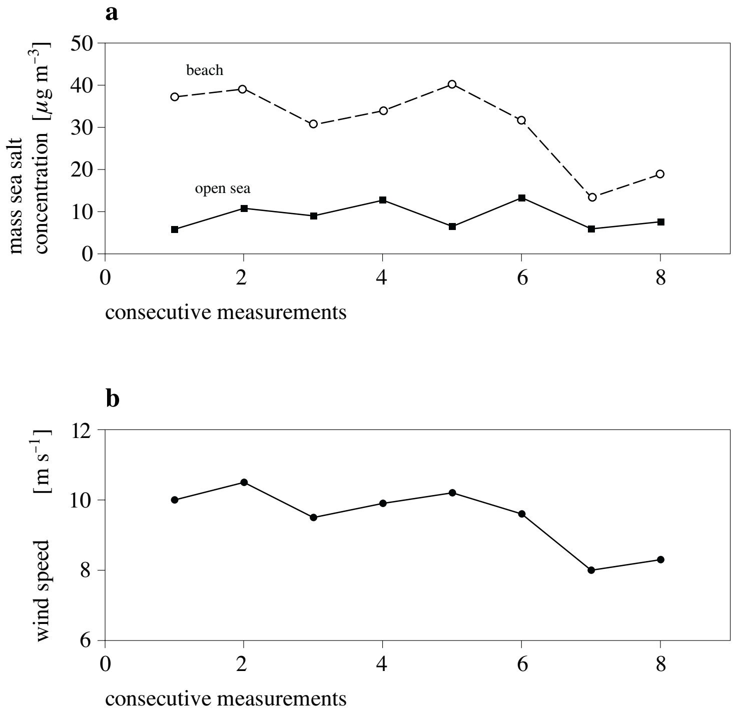

Fig. 2. Comparison of the mass sea salt concentration of the open sea and the beach (a), the wind speed – TABEX ′97 (b)

It can be seen in Figs. 2, 3 and 4 that the concentration of the salt at sea is lower than on the beach; this demonstrates that aerosol emission within the breaker zone is intense. The wind velocities at which the measurements were taken are shown below the concentration curves. Analysis of the data combining concentration with wind velocity indicates that the difference between the concentration on the beach and that at sea does not depend directly on the wind. For instance, in Fig. 2 the greatest difference between the beach and sea concentrations lies in measurement 5, when one of the lowest wind velocities during that series was recorded. This confirms the conclusions, drawn from the analysis of the BAEX experiment (Petelski & Chomka 1996b), that emission from the coastal zone depends mainly on wave energy dissipation in the coastal zone.

Fig. 5 shows the horizontal profiles of sea salt concentration in the line perpendicular to the seashore obtained during the TABEX ′98 experiment.

In both Figs. 5 and 3 it can be seen that the salt concentration falls quickly with increasing distance from the shoreline, and at a distance of 82 m is several times smaller than on the beach. The dynamics of the

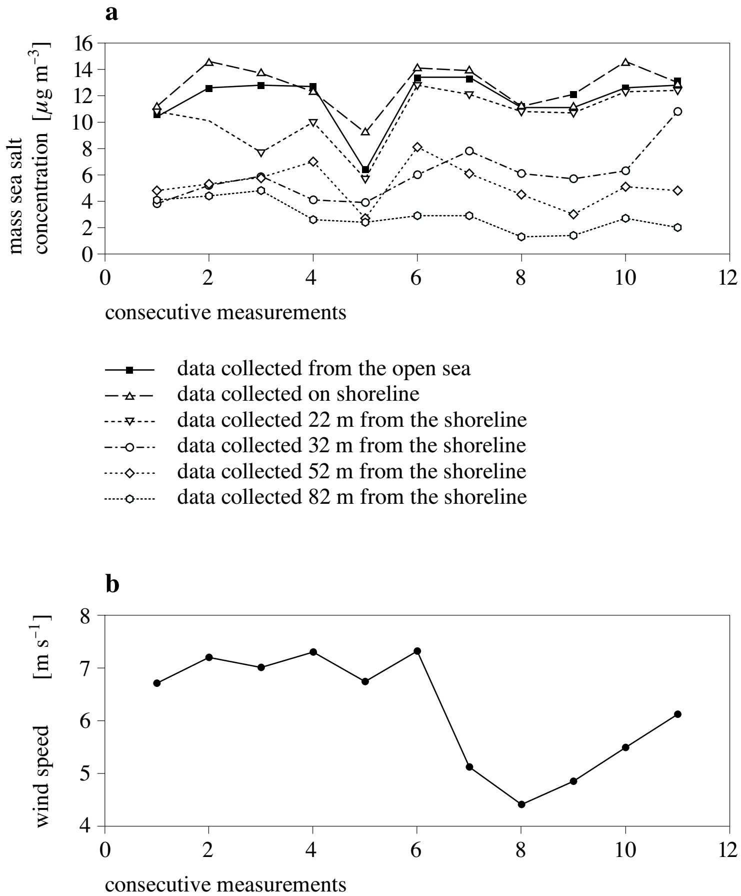

Fig. 3. Comparison of the mass sea salt concentration of the open sea and the beach (a), the wind speed – TABEX ′98 (b)

concentration changes also decreases: concentrations on the beach range from 6 to 40 μg m^{-3}, but 82 m inland, the concentration range is from 1.5 to 4 μg m^{-3} (Fig. 3). This is so because, with increasing distance from the shore, large sea salt particles quickly drop out of the atmosphere. The change in size distribution in relation to distance from the sea is shown in Fig. 6.

Fig. 6a shows the number concentration (number of sea salt particles per cubic metre) as a function of diameter of sea salt particles $N(r)$, in accordance with the open sea measurements, while Figs. 6b, c, d, e and f show the same relationships derived from the beach data at various distances from the shoreline: 0 m, 22 m, 32 m, 52 m and 82 m. The further from the seashore, the steeper the slope of the $N(r)$ function. No salt particles greater than 10 m were found further than 82 m from the shore.

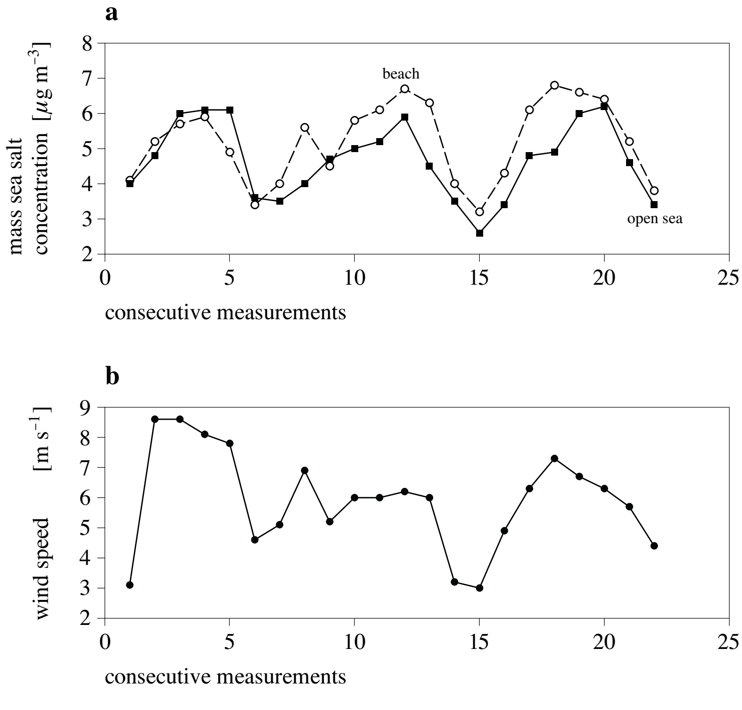

Fig. 4. Comparison of the mass sea salt concentration of the open sea and the beach (a), the wind speed – TABEX ′99 (b)

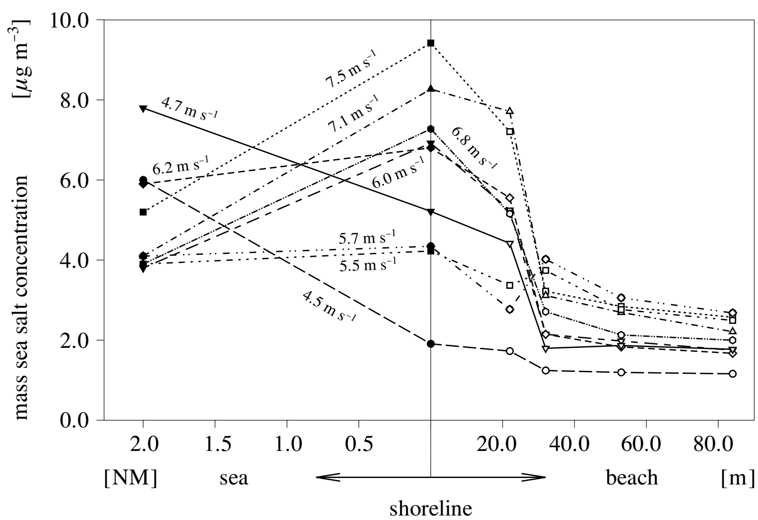

Fig. 5. Comparison of the mass sea salt concentration of the beach for different distances from the shoreline (0.0 m, 22.0 m, 32.0 m, 52.0 m and 82.0 m) and from the sea (2.0 NM)

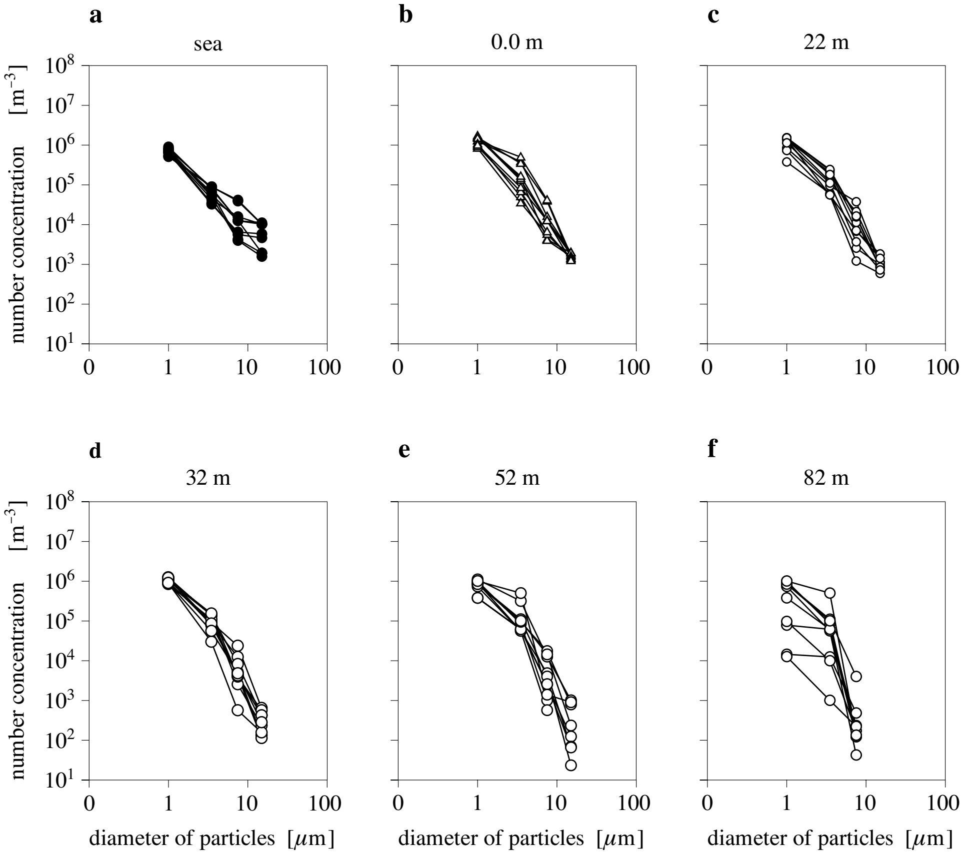

Fig. 6. The relation between number concentration and diameter of sea salt particles for different measurement sites: open sea (a), on shoreline (b), 22 m (c), 32 m (d), 52 m (e), 82 m (f)

4. Sea salt fluxes

Emission fluxes were calculated using marine aerosol concentrations in the coastal zone. The fluxes were calculated according to the equation of aerosol balance over the coastal zone (Petelski & Chomka 1996b)

$$F_{u_s} + F_E - F_{I_1} + F_{I_2} - F_T - F_{u_b} = 0, \tag{1}$$

where

F_{u_s}, F_{u_b} – advective fluxes through the side walls of the cuboid,
F_{I_1}, F_{I_2} – respective imission fluxes at the top and bottom walls,
F_T – turbulent diffusion flux through the top,
F_E – aerosol emission flux from the bottom of the cuboid.

The same boundary conditions as in Petelski & Chomka (1996a) were assumed, *i.e.* horizontal quasihomogenity and stationarity. Turbulent fluxes of heat and humidity momentum were not directly measured during the TABEX experiments. Therefore the so-called *Bulk formulas* were applied (Panin & Krivitski 1992)

$$\begin{aligned} H &= c_{h10}\ u_{10}\ (t_p - t_w), \\ Q &= c_{q10}\ u_{10}\ (q_{10} - q_0), \\ \tau &= c_{10}\ u_{10}^2, \end{aligned} \tag{2}$$

where
H – sensible heat flux,
Q – humidity flux,
τ – shearing stress,
c_{10} – drag coefficient,
u_{10} – wind speed,
t_p – air temperature,
t_w – water temperature,
c_{h10} – heat transport coefficient,
c_{q10} – humidity transport coefficient,
q_0 – humidity at sea level,
q_{10} – humidity at the level of 10 m above the sea.

Vertical emission fluxes were calculated on the basis of concentration using the following formula:

$$F_I = N\ V_D, \tag{3}$$

where
N – particle concentration,
V_D – deposition velocity.

Deposition velocity was calculated from the following equation (Carruthers & Choularton 1986):

$$V_D = \frac{V_T}{1 - \exp[-V_T/c_{10}\ u_{10}]}, \tag{4}$$

where
$c_{10} = 1.14 \times 10^{-3}$ for $u_{10} < 10\ \mathrm{m\ s^{-1}}$,
$c_{10} = (0.49 + 0.065\ \mathrm{u}_{10}) \times 10^{-3}$ for $u_{10} > 10\ \mathrm{m\ s^{-1}}$,
V_T – Stokes' speed.

Vertical turbulent sea salt fluxes were calculated using the formula from Petelski & Chomka (1996a)

$$F_T = M_*\ u_*, \tag{5}$$

where
u_* – friction velocity.

The M_* is a scale determined using the vertical gradient of concentration at the shoreline. For the TABEX '98 data, where there are no vertical gradients at the shoreline, turbulent fluxes were calculated using the horizontal gradients.

$$\frac{\partial M_s(r,z)}{\partial z} = \frac{U_2}{V_D(r)} \frac{\partial M_{2B}(r,x)}{\partial x}, \tag{6}$$

where
$M_s(r,z)$ – concentration of sea salt particles of radius r at a height of 2 m above the sea,
$M_{2B}(r,x)$ – concentration of sea salt particles of radius r at a height of 2 m above the ground at a distance x from the shoreline,
U_2 – wind velocity 2 m above the water level,
$V_D(r)$ – deposition velocity of particles of radius r.

Advection fluxes were calculated using the following formulas:

$$F_{u_s} = \int_0^{Z_1} M_1(z)\ u_1(z)dz, \qquad F_{u_b} = \int_0^{Z_2} M_2(z)\ u_2(z)dz, \tag{7}$$

where
u_s – wind speed over the sea,
u_b – wind speed over the beach.

Using formulas (3), (4), (5) and (7) the components of the sea salt balance over the coastal zone were calculated, after which the emission fluxes were calculated using the balance eq. (1). The obtained emission fluxes were correlated with the mean values of wave energy dissipation. The wave energy dissipations were calculated from the numerical model based on the equation of wave energy transport within the coastal zone (Thornton & Guza 1983, Chomka & Petelski 1997). The model enables the magnitude of wave energy dissipation in the profile perpendicular to the shore to be calculated in relation to the depth. The wave parameters obtained from empirical equations (Paszkiewicz 1989) and based on the meteorological data measured on board the ship were used as initial conditions for the calculations. The real bathymetry of the sea bottom at Preila was used in the model.

The average wave energy per sea surface unit was calculated on the assumption that energy is lost evenly throughout the breaker zone

$$\langle dE \rangle = \frac{E_P}{D_P}, \tag{8}$$

where
E_P – total wave energy loss within the breaker zone,
D_P – width of the breaker zone.

The values of parameters E_P and D_P were obtained using the Thornton & Guza (1983) model, where the sum of all values of was taken to be, and the maximum distance where the wave energy dissipation was > 0.001 (that is dE > 0.001) was taken to be D_P.

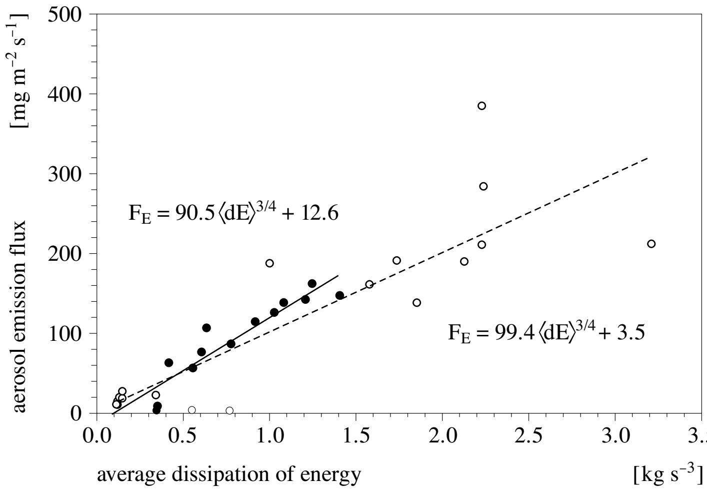

Fig. 7. The emission aerosol flux as a function of wave dissipation based on TABEX (○) and BAEX (●) data

Fig. 7 shows the relation between the aerosol emission flux and the mean wave energy dissipation to the power of 3/4. The white circles represent the data obtained during the TABEX experiments. The regression line determined by those dots is described by the following equation:

$$F_E = 90.5\langle dE\rangle^{3/4} + 12.6. \qquad (9)$$

For comparison, the results obtained during BAEX are marked as black circles. The regression line for these data is described by the formula

$$F_E = 99.4\langle dE\rangle^{3/4} + 3.5. \qquad (10)$$

The correlation coefficient for these values was 0.89. TABEX ′97 proved the correctness of emission parameterisation in the model. Although eq. (1) was obtained on the basis of only 8 dots, it is very close to the analogous one obtained during BAEX.

The coefficient of correlation for the BAEX data was 0.86, and the emission coefficient calculated from the TABEX data is slightly lower than that of the model actually used. The emission coefficient $A_p = 90.5$ is slightly (10%) lower than the one calculated using the BAEX data ($A_p = 99.4$). The difference is equal to the measurement error. Further experiments will permit an increase in the size of the data set under various meteorological conditions, which should enable the emission coefficient to be calculated more accurately.

5. Conclusion

This analysis of the data on the marine aerosol over the coastal zone obtained during the TABEX and BAEX experiments indicates that this zone plays an important part in aerosol emission. The fluxes of aerosol emission from the breaker zone do not directly depend on the wind velocity, but do depend on the wave energy dissipation.

The emission fluxes calculated for the distribution of aerosol concentrations are proportional to the wave energy dissipation to the power of 3/4. This relationship, first obtained for the BAEX data, was confirmed during the TABEX experiments. Both regression equations and correlation coefficients are very close. Aerosol emission within the coastal zone is therefore proportional to the dissipation of wave energy.

The relation was demonstrated under different weather conditions as well as coastal zones (Lubiatowo, Preila). This is a universal rule which should apply to all coastal zones.

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