Variations in the physical properties of surf generated aerosols with altitude

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Abstract

Vertical profiles of marine aerosol size distribution and concentration in the marine boundary layer over surf zones depend strongly on wind speed, direction and duration as well as the sea bottom profile. The measurements in the present study were carried out in various seasons of the year with all these factors being taken into consideration. The data with respect to offshore winds were neglected in the calculations, since in such cases the major aerosol contribution was from terrigenous and anthropogenic particles. It was confirmed that in the range of wind speeds from 1 m s^{-1} to 12 m s^{-1} there were measurable differences in the concentrations, particularly in the size distribution of marine aerosol particles at two stations differing with respect to their sea bottom profiles.

1. Introduction

Coastal areas play an important part as sources of marine aerosols due to the fact that breaking waves occur in this area even at small wind speeds. Breaking waves create whitecaps and sea-spray droplets. These consist of large numbers of air bubbles, which are essential for the large-scale production of marine aerosols (Monahan & Mac Niocaill 1986, Resch 1986). The concentration of air bubbles in breaking waves is four times higher in the surf zone than in the ocean under the same weather conditions. It is these sea-spray droplets and the droplets from bursting bubbles elevated

into the marine boundary layer that constitute a marine aerosol (Blanchard & Syzdek 1988, Wu 1988, Resch et al. 1989, Wu 1990). These mechanisms and sources of marine aerosols have been well described theoretically and well investigated experimentally (Monahan et al. 1983, Wu 1992). Based on the results of many research findings, models have appeared which parameterize the dependence of marine aerosol generation, transport and deposition from the marine boundary layer on various physical parameters of the atmosphere (Burk 1986, Fairall & Davidson 1986, Fitzgerald 1992, Van Eijk & de Leeuw 1992, Gong et al. 1997). Especially well described is the influence of wind speed on the concentration and size distribution of marine aerosols over the ocean. Such models, however, cannot be directly applied to coastal areas, for which data are rather scarce. At present, a complete balance of aerosol fluxes in coastal areas cannot be done. The available data for such areas are incomplete, thereby preventing the determination of the dependence of a particularly important parameter – roughness length – on fluxes of emission and deposition of marine aerosols (Zieliński & Zieliński 1996, Chomka & Petelski 1997, Zieliński 1997). This parameter, as shown in Panin & Krivickiy (1992) for developing and fully developed roughness in coastal areas, depends on the slope and shape of the sea bottom and is important, as it influences particle deposition velocity (Carruthers & Choularton 1986).

Therefore, in coastal areas, and especially in the surf zone, the magnitude of breaking waves influences deposition fluxes, and indirectly, the concentration and size distribution of marine aerosols (Zieliński et al. 1997, Massel 2001). In the present study, the data collected from lidar-based investigations were used to determine the variations in marine aerosol concentrations and size distributions in the surf zone at two stations in the southern Baltic Sea.

2. Theory

Since 1992 measurements have been taken at several stations on the Polish coast of the Baltic Sea (17–19°E and 54.4–55°N) (Zieliński & Zieliński 1996). The locations of the measuring stations are shown in Fig. 1.

The measurements were carried out in different seasons and at two stations in order to detect the influence of the character of the sea bottom (Jastarnia – shallow, smooth bottom with very small inclination and spilling type of wave breaking, Lubiatowo – deeper, greater inclination with underwater dunes, which facilitate better wave breaking conditions, plunging type of wavebreaking) on aerosol size distribution and the level of aerosol concentration in the surf zone. Moreover, wind speed and direction as well as wet and dry-bulb temperatures were recorded, in addition to other supporting

Fig. 1. Location of measuring stations

information. The air temperature varied from 278°K to 293°K, the wind speed from 0.5 m s^{-1} to 19 m s^{-1}, and the wind direction from NE to SW (Zieliński & Zieliński 1996, Zieliński 1997). The data obtained for southerly, i.e. offshore, winds were omitted from the calculations, since in such cases the major contribution was from terrigenous and anthropogenic particles.

The FLS-12 lidar system was installed in a van stationed on the top of the dunes at a fixed distance of about 30 m from the sea. The inclination of the lidar was easily changed, thus enabling the marine boundary layer to be sounded at various altitudes. The FLS-12 is a tunable laser system designed for remote sensing of the air in the VIS spectrum range (400–670 nm). The source of UV pumping for the dye laser is an XeCl excimer laser (308 nm). The backscattered energy from various distances is collected by a Cassegranian configured telescope, which has a 280 mm diameter primary mirror, and is registered by separate channels of a multichannel (8 channels) photoreceiver. A more detailed description of the FLS-12 lidar has been given previously (Zieliński & Zieliński 2002). The backscattered signal was recorded every 50 ns, that is, every 7.5 m along the optical path. The lidar measurements were calibrated by taking simultaneous measurements with six stage cascade impactors and a laser particle counter (PMS-Particle Measurement System). The backscattered signal values for all wavelengths served as the basis for determining the size distribution of aerosol particles and their concentrations at particular altitudes.

The comparative method, introduced by Potter (1987), was used to derive these parameters. It was assumed that aerosols consist of optically homogeneous, non-absorbing, spheres of size $r \in [r_1, r_2]$. Therefore, the extinction coefficient in the lidar equation can be defined as follows:

$$\varepsilon_{ij}(R_i,\, \lambda_j) = \int_{r_1}^{r_2} Q(r_i,\, \lambda_j)\, S(r) dr, \tag{1}$$

where $S(r)$ is the total, geometric cross-section of aerosol particles per unit volume, $Q(r,\, \lambda_j)$ is a dimensionless extinction coefficient, and r is the particle radius. The extinction coefficient can thus be replaced with the scattering coefficient; then, functions $S(r)$ and $Q(r,\, \lambda_j)$ can be written as follows:

$$S(r) = a\, r^2 e^{-br}, \tag{2}$$

$$Q(r_i,\, \lambda_j) = 2 - \frac{4}{\chi} \sin\chi + \frac{4}{\chi^2}(1 - \cos\chi), \tag{3}$$

where $\chi = 2x_j\,(m-1)$; m – relative light refraction coefficient, χ – Mie parameter: $x_j = 2\pi r/\lambda_j$, a, b – distribution parameters. Function $S(r)$ can be described by the Nakajima-Tanassara distribution, widely applied to determine the number of particles in unit volume in the size range from r_i to $r_i + dr$; hence, $S(r) = n(r) = dN/dr$ (Wells et al. 1977). The shape of formulas (2) and (3) allow formula (1) to be solved in an analytical form. Formula (1) can also be used to determine the distribution parameters a and b. These distribution parameters are then used in the determination of aerosol size distribution and its concentration at particular altitudes for particles of sizes $r \in [0.5;\, 5\ \mu\text{m}]$ as follows:

– total concentration,

$$N_c\,(z_i,\, h_i) = \int_{0.5}^{r} n_r\, dr = \frac{a\,(z_i,\, h_i)}{b^2\,(z_i,\, h_i)} e^{[-0.5b(z_i,\, h_i)]}, \tag{4}$$

– particle concentration from the range of sizes r_i, $r_i + dr$,

$$N_r(z_i,\, h_i) = N_c(z_i,\, h_i) f(r), \tag{5}$$

$f(r)$ is a normalized size distribution function,

$$f(r) = be^{[-b(z_i,\, r_i)r]}. \tag{6}$$

3. Results and discussion

For the surf zones at Jastarnia and Lubiatowo aerosol concentrations were determined in the marine boundary layer as a function of wind speed. The surf zones in both areas vary in offshore width due to the different

sea bottom configurations. These differences are manifested in diverse wave breaking patterns, which thus affect the emission of marine aerosol particles. The data collected from lidar-based investigations were used to determine the marine aerosol concentration, size distribution, and vertical gradients of concentration. Fig. 2 shows the variations in total concentration of marine aerosols with wind speed for onshore winds at both coastal stations at an altitude of 4 m.

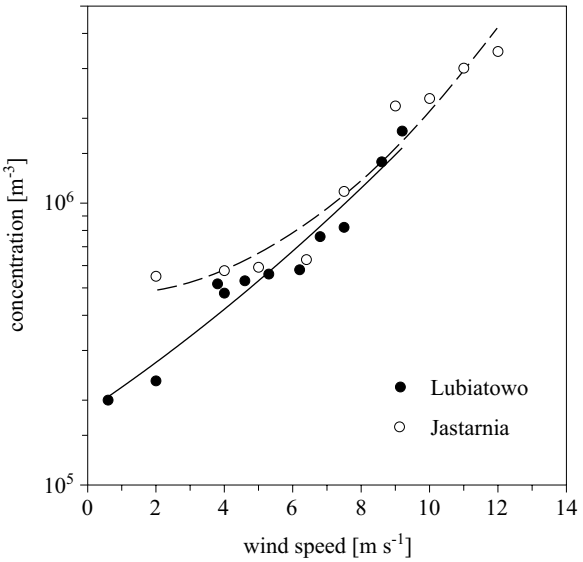

Fig. 2. Variations in aerosol concentration with wind speed

Fig. 2 shows that in both cases, the total marine aerosol concentration increases with wind speed. In the range of wind speeds from 1 m s^{-1} to approximately 8 m s^{-1} the aerosol concentrations in the marine boundary layer were slightly higher for Jastarnia than for Lubiatowo. The difference is highest at very slow wind speeds, almost disappearing at speeds close to 8 m s^{-1}. For wind speeds faster than 8 m s^{-1} the difference is very small; nevertheless, the values obtained for Jastarnia are still slightly higher. These differences may be related to the extension of the surf zone in both areas. An equally simple relationship exists for the changes in total concentration gradient with altitude, shown in Fig. 3. The data were collected at wind speeds of 9 m s^{-1}.

For both stations the total concentration gradient decreases with altitude and the difference between 15 m and 50 m is about 1.5 orders of magnitude. However, the values obtained for Jastarnia were slightly higher than for Lubiatowo, and at an altitude of 50 m a.s.l. the difference was about 20%.

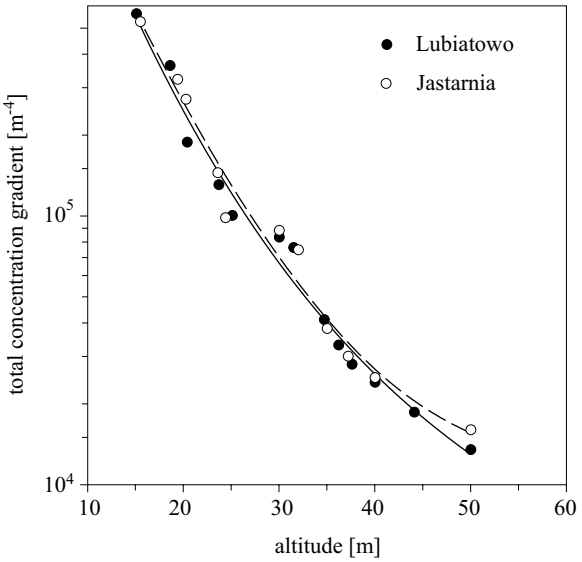

Fig. 3. Variations in aerosol total concentration gradients with altitude

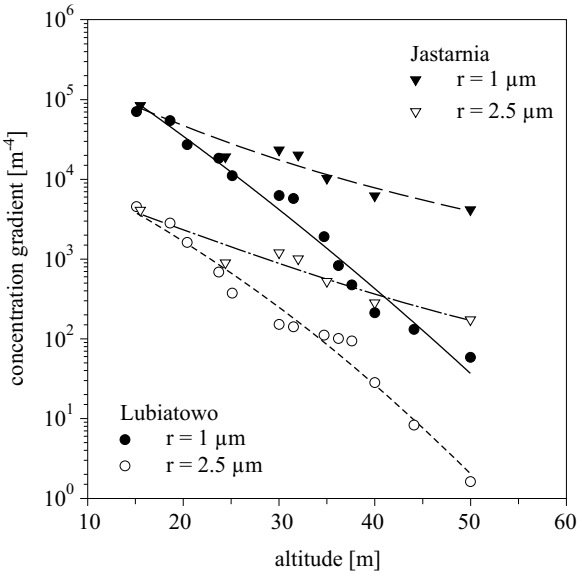

Fig. 4. Variations in aerosol concentration gradients with altitude

The differences are significant when particles of specific sizes are compared, as in Fig. 4.

As in the case of the total concentration gradient, values decrease with altitude at both measuring stations and for particles of both sizes. At lower

altitudes, up to about 20 m a.s.l., the concentration gradients for particles of the same size were comparable at both stations. The difference appears at altitudes above 20 m a.s.l., reaching 2 orders of magnitude at 50 m a.s.l. It was found that at 50 m a.s.l. particles 2.5 μm in size were practically non-existent in the marine boundary layer over the surf zone at Lubiatowo, while at Jastarnia their number was still higher than the number of 1 μm particles at Lubiatowo.

The differences in aerosol concentrations and their gradients determined in the marine boundary layers at Lubiatowo and Jastarnia may be explained by the influence of the sea bottom type on emission and deposition fluxes of aerosols. These fluxes depend on the roughness length parameter, which in coastal areas under various weather conditions is determined by the sea bottom slope or water depth (Panin & Krivickiy 1992). For slow wind speeds, i.e. in the case of developing wave motion, this parameter is proportional to the ratio of the offshore distance to the water depth, while for high wind speeds, i.e. fully developed wave motion, the roughness length parameter is inversely proportional to water depth. For sea bottoms with smaller slopes, under conditions of developing wave motion, the roughness length parameter is smaller than for sea bottoms with steeper slopes. In the latter case, the average emission fluxes are higher than deposition fluxes (Chomka & Petelski 1997). The decrease in deposition fluxes is caused by the decrease in the deposition velocity of particles (Zieliński & Zieliński 1996). For high wind speeds (fully developed wave motion), the roughness length parameter is independent of sea bottom slope, and the sea bottom's influence on average aerosol fluxes is negligible. By assuming that the average aerosol concentration in the marine boundary layer over the coastal area is a result of the balance of the two above-mentioned fluxes, the large differences in concentrations at low wind speeds and small differences at high wind speeds shown in Fig. 2 are readily explained. The changes in aerosol concentration gradients with altitude at Lubiatowo and Jastarnia (Figs 3 and 4) were caused mainly by deposition fluxes, whose values depended linearly on the particle deposition velocity. Such variations in size distribution are presented in Fig. 5. Data were collected at wind speeds of 9 m s^{-1} and at a distance of 100 m offshore (center of the surf zone).

At altitudes of both 4 m a.s.l. and 30 m a.s.l. there are differences in the size distributions with respect to particles with radii from 0.5 μm to 2.5 μm. These differences confirm the sea bottom's influence on aerosol concentration. For particles of radii greater than 2.5 μm these differences disappear, which means that the sea bottom's influence on the concentration of such particles in the marine boundary layer in coastal areas is very small.

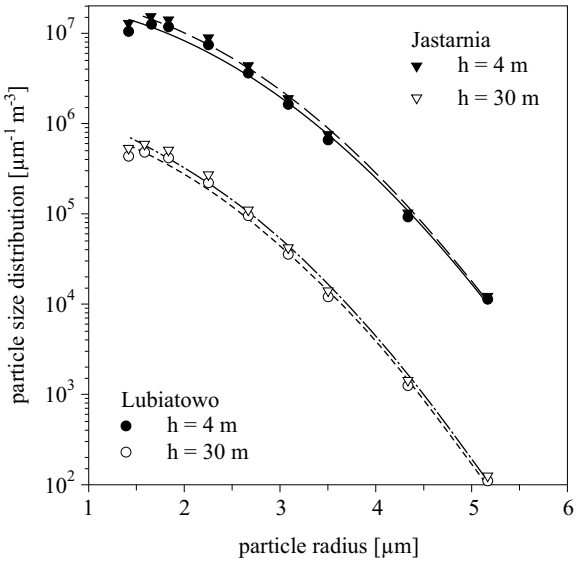

Fig. 5. Variations in aerosol size distribution with altitude

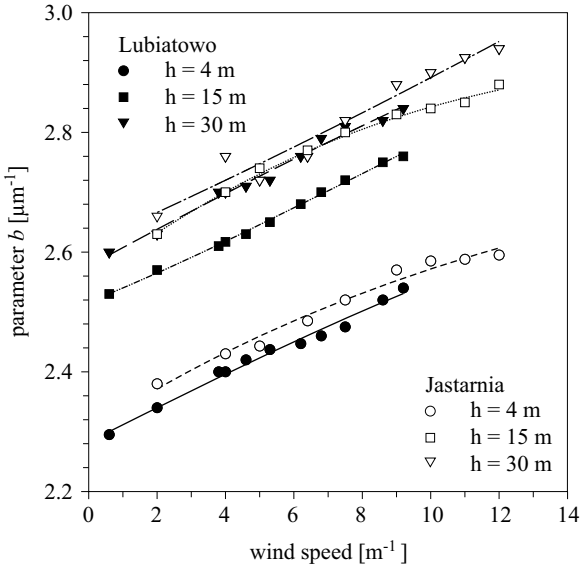

Fig. 6. Variations in distribution parameter b with wind speed and altitude

Owing to the relatively high deposition velocity of such particles (Zieliński 1997), their fluxes bring about a rapid decrease in particle concentration with altitude. Fig. 6 presents variations in distribution parameter b with wind speed at three altitudes at Lubiatowo and Jastarnia.

In all cases, the distribution parameter b increases with wind speed, although there are significant differences with altitude between the two stations. The highest values were obtained for Jastarnia at 30 m a.s.l. and 15 m a.s.l.: they differ by about 0.04 μm^{-1}. In the case of Lubiatowo, the values of parameter b at 30 m a.s.l. were comparable with the Jastarnia values at 15 m a.s.l. The Lubiatowo values at 15 m a.s.l. were lower by about 0.08 μm^{-1} when compared with those at 30 m a.s.l. At altitudes of 4 m a.s.l. parameter b at Jastarnia was higher than at Lubiatowo (0.04 μm^{-1}) and the difference with altitude of 30 m a.s.l. was 0.24 μm^{-1}.

The differences in distribution parameter b confirm that under the same weather conditions in the marine boundary layers, the marine aerosols generated at Lubiatowo and Jastarnia are characterized by different size distributions. The maximum concentration occurs at $r_m = 2/b$. Fig. 7 shows variations in aerosol concentrations as a function of particle size, at a wind speed of 9 m s^{-1}, and altitudes of 4 m a.s.l. and 30 m a.s.l. in the marine boundary layers at Lubiatowo and Jastarnia.

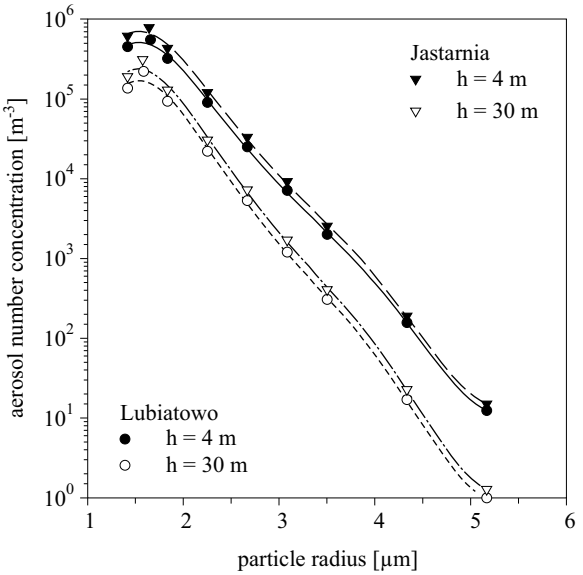

Fig. 7. Variations in aerosol number concentration with altitude

This figure shows distinct maxima of the aerosol size distribution in the investigated areas. With increasing altitude these maxima shift towards particles of smaller sizes (c. 0.8 μm), which confirms the part played by the emission flux in the production of marine aerosols over various sea bottom types. At Jastarnia, the average aerosol concentration is higher

than at Lubiatowo under the same weather conditions. This means that with a gentler sea bottom slope the marine aerosol concentration in coastal area increases. Similar results were obtained by Chomka & Petelski (1997).

4. Conclusions

The experimental results obtained for marine aerosol concentrations in the marine boundary layers of two coastal areas (surf zones) show that the sea bottom configurations influence both marine aerosol concentrations and their size distribution. Under the same weather conditions, concentrations are higher for sea bottoms with gentler slopes than for more steeply sloping bottoms. Mean concentration gradients of aerosols decrease with altitude and are greater for lower wind speeds. This means that at greater altitudes the mean aerosol concentration decreases and depends strongly on wind speed. The total number of particles is dominated by particles < 1 μm in size. It was found that at 50 m a.s.l. particles 2.5 μm in size were practically non-existent in the marine boundary layer over the surf zone at Lubiatowo, whereas at Jastarnia their number was still higher than the number of 1 μm particles at Lubiatowo. Such information must be taken into account if they should be applied to correction algorithms for remote sensing of coastal areas.

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