Papers

Dependence of the surf zone aerosol on wind direction and wind speed at a coastal site on the Baltic Sea

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Abstract

Since 1992 lidar-based measurements have been carried out under various meteorological conditions and at various times of the year. The aerosol optical properties were determined in the marine boundary layer as a function of altitude using such factors as wind direction, duration and velocity and aerosol size distribution and concentration. It was confirmed that in all cases, the total aerosol concentration, size distribution and aerosol extinction increase with wind speed but decrease with altitude. In the range of wind velocities from 1 to 15 m s^{-1} the mean aerosol optical thickness of the atmosphere (VIS) obtained from the lidar varied from 0.1 to 0.38 for offshore winds and from 0.01 to about 0.1 for onshore winds, while the Ångström parameter for VIS oscillated around 0.65 for onshore winds and around 1 for offshore winds. Both parameters depended strongly on the history of the air mass above the Baltic Sea. Such aerosol optical thicknesses are in agreement with those obtained by other researchers in the Baltic Sea area.

1. Introduction

In the marine boundary layer aerosol deposition fluxes are created as a result of aerosol particle fallout. Therefore, deposition flux along with

turbulent and emission fluxes are responsible for the spatial distribution of aerosol concentrations above the sea surface. In unit volume of air, aerosol fallout influences particle concentration and size distribution, while turbulent diffusion results in the input of particles emitted from the sea surface. As a result, under stable hydrometeorological conditions, stationary conditions are created within the unit volume, which are characterized by a constant concentration and size distribution of aerosol particles. Changes in hydrometeorological conditions result in the distortion of stationary conditions and hence, in varying intensities of turbulent or deposition fluxes (Zilitinkevitch et al. 1976). Such changes are directly related to changes in emission flux. These in turn lead to changes in particle size distribution and a decrease or increase of aerosol concentration in unit volume with falling or rising wind speeds.

In coastal areas, aerosols in the zone of direct interaction between the atmosphere and the ocean surface are characterized by rapid temporal and spatial changes in concentrations. The spectrum of marine aerosol size distribution functions is complex and depends strongly on the weather conditions in the marine boundary layer, especially on the speed, duration and direction of the wind, and also relative humidity. Additionally, it depends indirectly on the sources of aerosol generation (proximity of land) and the history of the air mass. The impact of various meteorological conditions on aerosol parameters, including the atmospheric optical thickness in the Baltic Sea, has been investigated by a number of scientists (Weller & Leiterer 1988, Villevalde et al. 1989, Gulyaev et al. 1990, Smirnov et al. 1995, Kuśmierczyk-Michulec & Darecki 1996, Kuśmierczyk-Michulec & Rozwadowska 1999).

The aim of the present work is to discuss the dependence of aerosol parameters and their optical properties in the coastal area, particularly in the surf zone, on the different wind conditions in the area. The results were obtained using an ensemble of instruments: an FLS-12 lidar, a laser particle counter and a Microtops II ozonometer. The lidar method is especially useful as it quickly measures the physical properties of marine aerosols over distances greater than the limits of the surf zone. By employing several wavelengths, the lidar provides very accurate information about the size distribution of aerosol particles and their concentrations under a variety of weather conditions and at different altitudes above the sea surface.

2. Experimental site and instrumentation

Measurements were carried out in different seasons in the coastal areas of the southern Baltic Sea (Fig. 1).

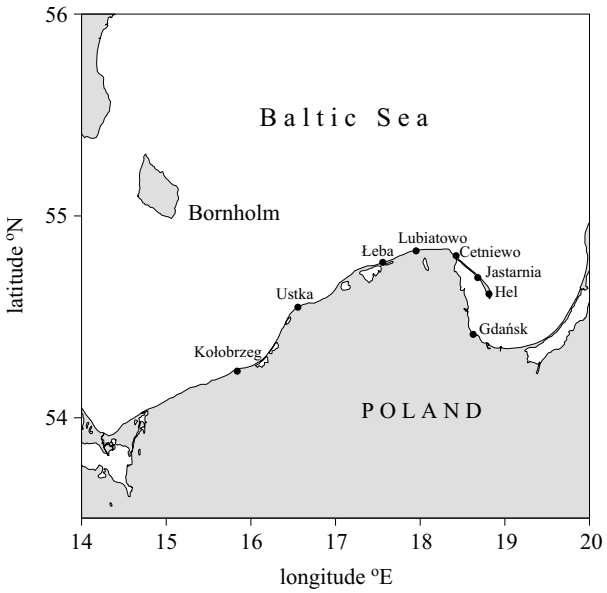

Fig. 1. Location of measuring stations

Wind speed and direction as well as wet- and dry-bulk temperatures were recorded, together with other supporting information. The air temperature varied from 275°K to 296°K, the air pressure from 990 hPa to 1018 hPa, the relative humidity from 65% to 96%, and the wind speed from 1 m s^{-1} to 15 m s^{-1}.

The FLS-12 lidar system used in the aerosol concentration measurements was installed in a van and stationed on the top of the dunes at a fixed distance from the sea (Zieliński et al. 1999). The inclination of the lidar was easily changed, which enabled the marine boundary layer to be examined at various altitudes.

The FLS-12 lidar is a tunable laser system designed for remote sensing of the air in the VIS spectrum range (320–670 nm). The source of UV pumping for the dye laser is an XeCl excimer laser (308 nm). During the experiments the lidar collected aerosol backscattered data every 50 ns, that is every 7.5 m along the optical path, and three wavelengths of 430 nm, 560 nm and 670 nm were employed. A more detailed description of the FLS-12 lidar can be found in Zieliński & Zieliński (2002). The lidar measurements were calibrated by simultaneous measurements with six stage cascade impactors and a laser particle counter (CSASP-HV-100) (Zieliński 1998). For comparison, aerosol optical thicknesses obtained with the Microtops II ozonometer at 1020 nm are also presented in the plots.

3. Theory

The comparative method, introduced by Potter (1987), was used to derive the optical parameters of aerosols at every point along the sensing path z_i. The aerosols were assumed to consist of both optically homogeneous, non-absorbing, spherical water droplets and non-homogeneous, absorbing particles of unknown origin (Zieliński 1998, Zieliński et al. 1999).

Since the relation between the extinction coefficient and the number of particles is linear, then for a given wavelength and size distribution function it depends mainly on the value of $< Q(\lambda) >$; this, however, also depends on the refractive index of the aerosol particles. For calculations of $< Q(\lambda) >$, a refractive index of 1.33 ($\lambda = 550$ nm), characteristic of coastal Baltic waters with a salinity of $S = 7$ PSU, was applied to marine aerosols, while an arbitrary refractive index of 1.48–0.01i was used for the mixture of marine and continental aerosols.

Non-linear minimization was used to derive the parameters that determine the size distribution and total aerosol concentration at particular altitudes h_i for particles of radii from the range of $r \in [0.5\ \mu\text{m};\ 5\ \mu\text{m}]$. The range of aerosol particle sizes results from the fact that particles with radii $r < 0.5\ \mu$m have very little impact on scattering, especially in the case of light of wavelength 400 nm. As there are very few particles with radii $r > 5\ \mu$m, their impact on scattering is also insignificant. Therefore, the aerosol concentrations determined by means of the lidar method for particles from 0.5 to 5 μm in radius are accurate and encumbered with only a small error.

The value of the extinction coefficient ε_{ij} at an arbitrary point z_i and wavelength λ_j as obtained from lidar measurements is described by the formula:

$$\varepsilon_{ij}\,(z_i,\,\lambda_j) = \pi \int_{0.5}^{5} r^2\, Q\,(r,\,\lambda_j)\; n\,(r,\,z_i,\,h_i)\, dr \qquad [\text{km}^{-1}], \tag{1}$$

where r is the particle radius and $Q(r, \lambda_j)$ is the extinction efficiency in the Mie theory

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

and the distribution function is described as follows:

$$n\,(r,\,z_i,\,h_i) = a\,(z_i,\,h_i)\, r^2 \exp\left(-b\,(z_i,\,h_i)\, r\right), \tag{3}$$

where $a,\ b > 0$ are distribution parameters.

These parameters determine the size distribution and total aerosol concentration N_c at point z_i and altitude h_i as follows:

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

$$N_r\,(z_i,\,h_i) = N_c\,(z_i,\,h_i)\,f(r) \qquad [\mathrm{m}^{-3}], \tag{5}$$

where $N_r(z_i,\,h_i)$ is the number concentration of aerosol particles in the size range $r,\,r+dr$.

For the aerosol component (with $h_0 = 0$), the aerosol optical thickness τ_A can be determined as a visibility function in an analytical form as follows (Zieliński et al. 1999):

$$\tau_A\,(\varepsilon,\lambda) = \left(\frac{3.912}{V(\lambda)} - 0.0116\right)\left(\frac{0.55}{\lambda}\right)^{\beta} \quad \times$$

$$\times \quad \left[H_1\left(1 - \exp\left(-\frac{5.5}{H_1}\right)\right) + 12.5\exp\left(-\frac{5.5}{H_1}\right) + H_2\exp\left(-\frac{5.5}{H_1}\right)\right], \tag{6}$$

where $H_1 = 0.886 + 0.0222\,V(\lambda)$ [km] and $\mathrm{H}_2 = 3.77$ km; $V(\lambda) = \frac{3.912}{(0,\lambda)}$ – horizontal visibility.

On the basis of the size distribution function and aerosol concentration at the sea surface it is possible to determine the aerosol optical thickness in the atmosphere τ_A as a function of wind speed and direction. The analysis of the variations of this parameter along with variations of wind conditions were carried out for average values of the Mie coefficients (Król 1985). Parameter β from formula (5) was derived theoretically as follows (Zieliński et al. 1999):

$$\beta = \frac{\log\dfrac{<Q\,(\lambda = 550)>}{<Q\,(\lambda)>}}{\log\dfrac{550}{\lambda}}, \tag{7}$$

where

$$<Q\,(\lambda)> = \frac{\int_{0.5}^{5} Q\,(r,\lambda)\,f\,(r)\,dr}{\int_{0.5}^{5} f\,(r)\,dr}. \tag{8}$$

The aerosol optical thickness was also calculated using VIS light wavelengths and the Ångström parameters γ and α (Bokoye et al. 1997):

$$\tau_A\,(\lambda) = \gamma\left(\frac{\lambda}{1000}\right)^{-\alpha}. \tag{9}$$

The aerosol concentrations were derived from the backscattered lidar signal and are encumbered with an error of ±30%. This is no less than

the error ensuing from the measurement of aerosol concentrations with the laser particle counter used to calibrate the results obtained with the lidar (Piskozub et al. 1994, Zieliński et al. 1998).

4. Results and discussion

The results of the lidar-based studies in the coastal area of the Baltic Sea confirmed that the marine aerosol concentrations varied with offshore distance over the breaker zone, and there were distinct maxima due to enhanced production in this area as a result of breaking waves. For offshore winds no changes in aerosol concentrations with offshore distance over the breaker zone in Lubiatowo were detected (Fig. 2). In Fig. 2 it is practically impossible to determine any variations in concentration over the measuring distance for offshore winds. Such winds blew for a period of up to 35 hours, so the marine boundary layer was well mixed. They carried significant amounts of admixtures, thus resulting in higher concentrations when compared with concentrations obtained for onshore winds, regardless of the fact that the onshore winds blew at speeds over 4 times greater. In the case of onshore winds it is possible to determine the limits of the breaker zone (from c. 40 m to c. 130 m offshore), where the production of marine aerosols due to breaking waves is significantly higher than outside this zone.

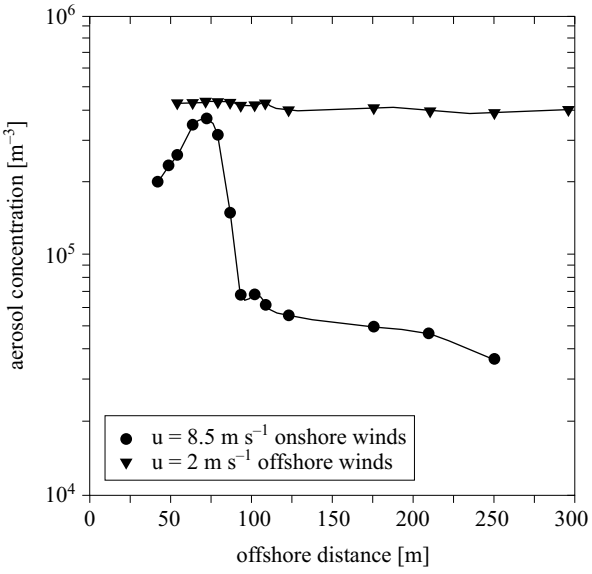

Fig. 2. Variations in aerosol concentration with offshore distance for winds from two directions

The aerosol concentration gradients were determined for the breaker zones at two measurement stations. The results of those measurements are presented in Fig. 3.

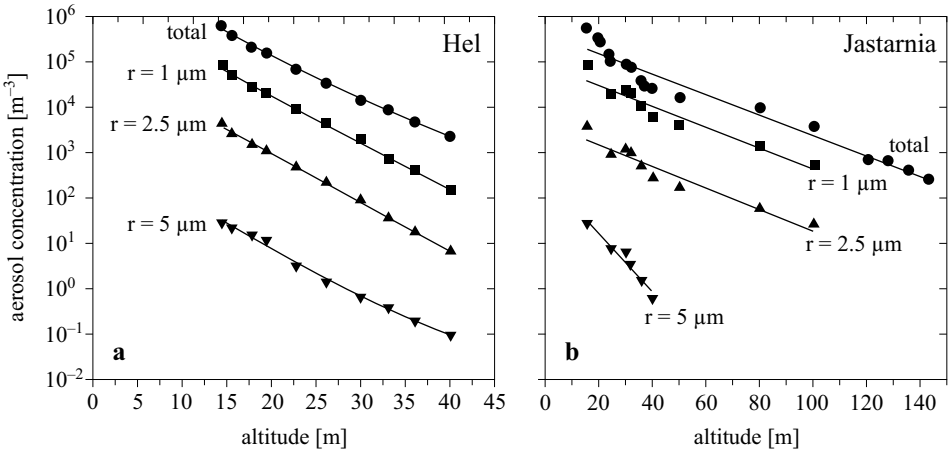

Fig. 3. Variations in aerosol concentrations with altitude at two measurement stations for two wind directions: offshore (a) and onshore (b)

The data were collected at a distance of c. 100 m offshore (the center of the breaker zone) and a wind speed of 9 m s^{-1}. Comparison of the data in the two plots shows that the aerosol concentrations decrease with altitude. However, the concentrations vary in both cases and their decrease with altitude is different for marine aerosols and the mixture of particles. The drop in total aerosol concentration from an altitude of c. 40 m a.s.l. to c. 5 m a.s.l. for the mixture of particles ranges from 10^6 to 10^4 [m^{-3}], while for marine aerosols the range is from 10^6 to c. 5×10^4 [m^{-4}]. The differences are even more obvious for smaller particles of r = 1 μm, for which the ranges over the same altitude difference are from c. 10^5 to 10^2 and 10^5 to 10^4 for offshore and onshore winds, respectively. The total number of particles is dominated by particles of sizes smaller than 1 μm. The contribution of large particles (r = 5 μm) is significant to some extent at small altitudes, c. 25 m a.s.l., while at greater altitudes their contribution is very small, and at altitudes above 70 m a.s.l. these particles are practically non-existent.

The average total aerosol concentrations derived as a function of wind speed and direction at an altitude of 4 m over the sea surface and an offshore distance of c. 110 m (surf zone) are shown in Fig. 4.

The average total aerosol concentration, measured at a distance of c. 110 m offshore (the center of the breaker zone) increases with rising wind speed regardless of wind direction. However, aerosol concentrations for

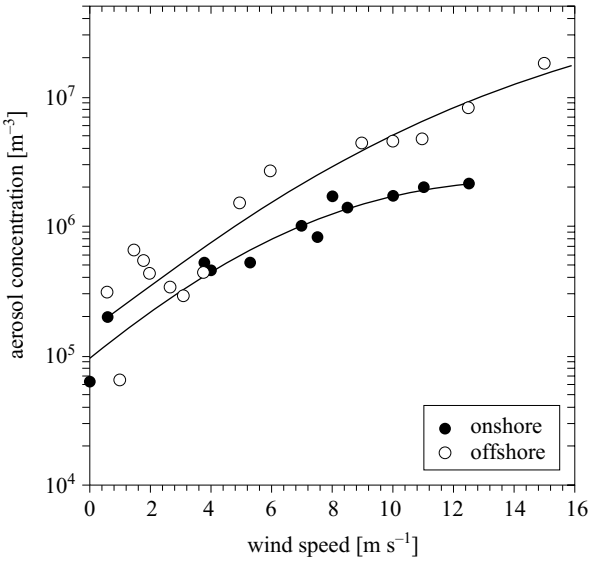

Fig. 4. Variations in aerosol concentration with wind speed and direction

offshore winds are 2 to 2.5 times higher in comparison with those of onshore winds of the same or similar speed. In the case of onshore winds, the aerosol ensemble was comprised mainly of particles of marine origin (salt and water droplets), while the aerosol ensemble with offshore winds was composed of both natural and anthropogenic material. In both cases, the optical properties of the aerosols are different. It can be assumed that the light absorption coefficient in the VIS spectrum range of marine aerosols is close to zero; thus, marine aerosols only have scattering properties in the VIS spectrum range. The same cannot be assumed about a mixture of marine and continental aerosols.

With the aid of eq. 1 and the lidar results, the aerosol extinction was determined for two types of winds. In Fig. 5 the extinction coefficients are plotted against the wind speed for two different wind directions and for three light wavelengths.

The data presented for wavelengths of 400 nm and 550 nm were obtained from lidar measurements, while the data for 700 nm were approximated using the measurement data. In both types of wind direction the extinction coefficient increases together with the decrease in light wavelength and increases with the wind speed (increase in aerosol concentration; see Fig. 4). The extinction values for offshore winds are about three times as high as for onshore winds of the same speeds. This threefold increase in these coefficients for southerly winds is due to the greater concentrations of

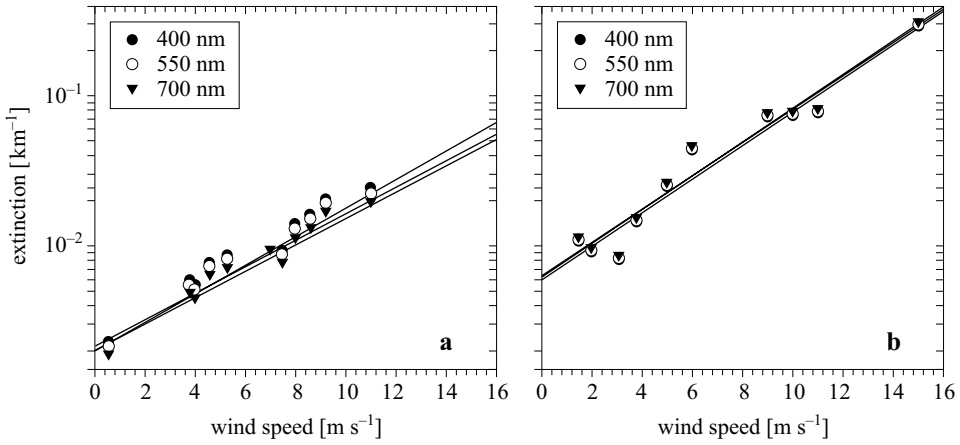

Fig. 5. Variations in aerosol extinction with wind speed and direction for three wavelengths and two wind directions: onshore (a) and offshore (b)

continental aerosols (under the same meteorological conditions as in the case of northerly winds) and their absorbing properties.

The values of the aerosol extinction coefficient for the light wavelength $\lambda = 400$ nm determined for two wind speeds v = 9 m s^{-1} and v = 5 m s^{-1} at three altitudes h = 4 m, h = 15 m and h = 30 m above sea level are presented in Table 1. The data were recorded at a distance of c. 100 m offshore (the center of the surf zone).

Table 1. Aerosol extinction measured in the marine boundary layer of the southern Baltic at three altitudes and for two wind speeds and two wind directions at a wavelength of 400 nm

Altitude	Aerosol extinction [km^{-1}]			
	Offshore winds		Onshore winds	
	v = 9 m s^{-1}	v = 5 m s^{-1}	v = 9.2 m s^{-1}	v = 5 m s^{-1}
h = 4 m	0.0727	0.0246	0.0205	0.0087
h = 15 m	0.0487	0.0204	0.0121	0.00531
h = 30 m	0.0284	0.0167	0.0078	0.00383

The data presented in Table 1 indicate that the aerosol extinctions for winds from southerly directions are around three times as high as for winds of the same speeds but from northerly directions. The three-fold increase in the coefficients for southerly winds is due to the greater concentrations of continental aerosols (under the same meteorological conditions as for

northerly winds) and their absorption properties. For both types of winds the aerosol extinction coefficient decreases with altitude, which reflects the decrease in particle concentrations with altitude (see Fig. 3).

Using the extinction coefficients and applying formula (6), the aerosol optical thickness was derived at an altitude of 4 m a. s. l.; the results are presented in Fig. 6.

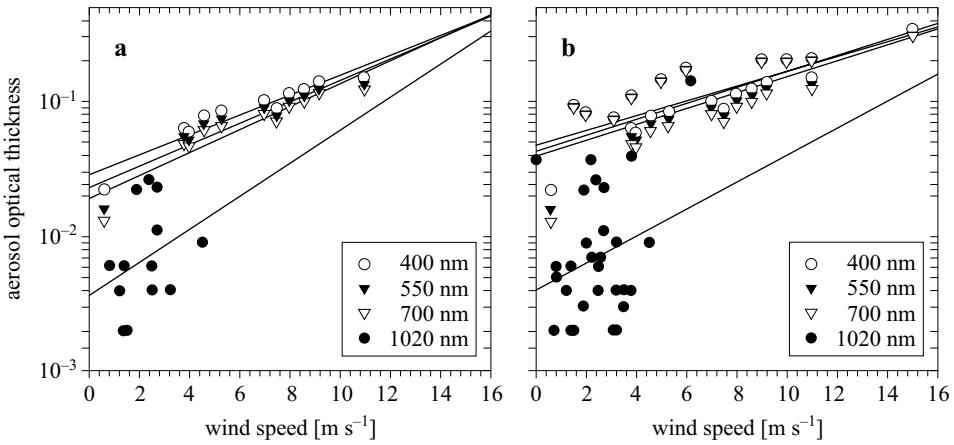

Fig. 6. Variations in aerosol optical thickness with wind speed for three light wavelengths and two wind directions: onshore (a) and offshore (b)

The variations in the aerosol optical thickness are similar to those of the extinction for all three wavelengths.

In the case of onshore winds, aerosol optical thicknesses are some four times smaller than in the case of offshore winds at low wind speeds. However, at high wind speeds the aerosol optical thicknesses are comparable in both types of wind. The aerosol optical thicknesses obtained at 1020 nm with the Microtops II ozonometer were significantly smaller than the values obtained from the lidar at shorter wavelengths. However, the 1020 nm data were obtained for only low wind speeds, during single measurements, and under very clear atmospheric conditions, so it is difficult to compare them with the entire range of wind speeds up to 15 m s^{-1}, especially since the lidar data were collected during numerous measurements.

As the lidar-based measurements were carried out over several years in various months and at different measurement stations, it was possible to derive average values of the aerosol optical thickness for the wavelength of 550 nm and the Ångström parameters α and γ.

The value of the lidar Ångström parameter α ranges from 1.05 to 1.07 for offshore winds, and from 0.67 to 0.72 for onshore winds. One can thus assume that for offshore winds aerosols of terrestrial origin were

dominant, whereas onshore wind aerosols consisted of a mixture of marine and terrestrial particles, the marine fraction being dominant.

In March, September, October and November, for which the number of measurement days in 1996–2000 exceeded 30, mean monthly values of $< \tau_A(\lambda) >$ parameter were determined in the VIS range. The mean values of this parameter for these months and the light wavelength $\lambda = 550$ nm are presented in Table 2.

Table 2. Mean monthly aerosol optical thickness τ_{550} obtained using the lidar technique; results obtained by other authors are also given

Month	$< \tau_{550} >$	Kuśmierczyk et al. (1999)	Hoyninge & Wendisch (1994)	Smirnov et al. (1995)	Persson (1999)
March	0.105	0.111		0.09	0.14
September	0.243	0.236	0.24		to
October	0.216		0.21		0.18
November	0.125	0.11	0.11	0.12	

Like the values reported by Kuśmierczyk-Michulec & Rozwadowska (1999), the lowest mean aerosol optical thicknesses (0.105–0.125) were recorded in March and November; the highest values were obtained in September (0.243). However, these results vary from those obtained by Persson (1999). He carried out his investigations in Swedish coastal areas, and his results indicate that in spring/summer much higher values of this parameter should be expected than in fall/winter.

The values of the Ångström parameter decrease with increasing wind speed. The lidar values of the AOT calculated for the light wavelength $\lambda = 1020$ nm, $< \tau_{1020} >$ range from 0.009 to 0.039 in the range of wind speeds from 0.6 to 6 m s^{-1} for onshore winds, which correlates well with the data obtained from the Microtops II measurements (see Fig. 6a). In the case of offshore winds, the Ångström parameter is close to 1.

5. Conclusions

In the marine boundary layer in the coastal area of the southern Baltic Sea, aerosol concentrations and their optical properties depend strongly on wind speed, direction and duration. It was also found that with onshore winds the breaker zone could be easily distinguished by means of the aerosol concentrations, which were higher there in comparison with those of the open sea. With offshore winds this kind of situation was not recorded. The

ensemble of aerosol particles is dominated by particles of sizes < 1 μm. The contribution of large particles (r = 5 μm) is significant to some extent at small altitudes, c. 25 m a. s. l., while at greater altitudes their contribution is very small, and at altitudes above 70 m a.s.l., these particles are practically non-existent.

The average monthly values of the aerosol optical thickness in the atmosphere obtained using the lidar method confirm the suitability of this method for measuring the optical parameters of the atmosphere above the sea. This method ensures a rapid supply of data which can then be further utilized in statistical studies of such optical parameters as extinction and the thickness of the atmosphere under various weather conditions.

With its VIS sensing range, the FLS-12 lidar used in the investigations is especially suitable for this type of investigation, since most of the extinction occurs in the vicinity of visible wavelengths.

Using the results from the AERONET station in Sopot, the joint experiments with the DLR-Berlin team, which have been carried out since September 2000, will yield a more complete picture of the aerosol concentration patterns in the southern Baltic Sea.

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