Quantitative assessment of surf-produced sea spray aerosol

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ABSTRACT

The first results are presented from a quantitative model describing the aerosol production in the surf zone. A comparison is made with aerosol produced in the surf zone as measured during EOPACE experiments in La Jolla and Monterey. The surf aerosol production was derived from aerosol concentration gradients measured downwind from the surf zone, after correction for the background size distribution that was measured upwind from the wave breaking zone. The aerosol production model was originally developed from measurements performed along the Baltic coast[1]. The model predicts the aerosol production from the total energy dissipated in the wave breaking zone, calculated from the coastal bathymetry and deep-water surface wave field. In the present work, the parameterisation of the aerosol production in the wave breaking zone is maintained, but the energy dissipation in the wave breaking zone is calculated using a different model that produces more realistic surf zone widths. Wave data were obtained from buoys off the Californian coast, while bathymetry data were supplied by the Scripps Institute of Oceanography. Observed and predicted aerosol production in the surf zone are in good agreement, for both sites. The predicted aerosol flux reproduces the day-to-day variations and even some of the observed variations on a time scale of several hours.

1. INTRODUCTION

The aerosol produced in surf zones has recently gathered widespread attention. Surf zones are relatively narrow and, in spite of the likely high production, have been considered negligible in accounting for transmission losses of visible and infra-red (IR) radiation across the coastline. Studies taking the surf zone into account with measurements both ashore and on a ship suggested that indeed the surf zone could be ignored[2]. However, recent measurements prove that the effect of the surf on aerosol production may strongly depend on the location and oceanographic and meteorological conditions. For example, the aerosol produced at La Jolla may significantly affect electro-optical propagation across the surf zone, especially for paths oblique to the coast and off-shore winds[3].

The aerosol production in the surf zone has been one of the focal points of recent measurement campaigns along the Californian coast. Aimed primarily at the effectiveness of electro-optical systems in coastal areas, the Electro-Optical Propagation Assessment in Coastal Environments (EOPACE) efforts contained three measurement campaigns that included the study of aerosol production in the surf zone. These three Surf experiments were conducted in a variety of environmental conditions at two coastal sites in California: La Jolla, near San Diego, in January/February 1996 and in March 1997, and in Moss Landing, Monterey Bay in March 1996. The final goal of these experiments was to provide an assessment of the effect of the surf on electro-optical propagation in a coastal environment. It was a common effort of several research groups from the USA, the UK and The Netherlands involving measurements of aerosols, bubbles and meteorological parameters including turbulence and visibility, as well as laser visualisation of the aerosol plumes over the surf, and spectral transmission measurements[3-5]. Initial results on the observed aerosol production at the two sites and computed IR extinction coefficients were presented by De Leeuw et al.[3], Gathman and Smith[4] and Neele et al.[5]. Application of a simple aerosol dispersion model showed that the effect of the surf-produced aerosol may extend to more than 25 km downwind from the surf zone[3]. This result is confirmed by calculations with a coastal aerosol transport model[6]. This illustrates that the surf zone can be an important factor controlling electro-optical (EO) propagation in coastal environments. A physical model describing the surf source function will be an important tool to assess effects on EO systems.

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Recently, Petelski & Chomka[1] and Chomka & Petelski[7] developed a model relating aerosol production in the surf zone to energy dissipated in the wave breaking process, following simple scaling arguments. Aerosol flux measurements performed at a location along the Baltic coast were used to define the constant of proportionality in the model. Below, the application of a wave breaking model to predict the energy dissipation in the surf zones at La Jolla and Moss Landing is described. The surf aerosol production fluxes are calculated using the parameterisation of Chomka & Petelski[7]. The results are in good agreement with the experimental data.

2. AEROSOL PRODUCTION: DATA

The measurements were performed at the piers of the Scripps Institute of Oceanography (SIO), La Jolla, San Diego, in January-February 1996 and March 1997 and Moss Landing, Monterey Bay in March 1996. At both locations, sea breeze conditions govern the wind pattern: winds from land during the night and early morning, light winds from sea during the afternoon. Aerosol probes were installed at both ends of the piers to exploit these conditions. For winds from sea, data from a particle counter at the end of the pier provided background size distributions in the well-mixed air mass before it entered the surf zone. At the base of the piers, three particle counters measured the increase in aerosol concentration due to production in the surf zone, at different heights above sea level. The production in the surf zone can be estimated from the vertical gradient measured by the three counters. Standard meteorological parameters (temperature, humidity, pressure, wind speed and direction) were recorded at various positions on the piers. The reader is referred to refs. [3] and [5] for a detailed description of the experiments and the data processing.

Figure 1 shows an example of the data measured during the experiments, showing clearly the effect of the surf zone on the aerosol concentrations. The lower part in figure 1 shows concentrations of particles with a diameter of 5 μm, during the period of 8 through 11 April, 1997 at La Jolla. The time in the figure is given in GMT, causing the periods of winds from sea to occur in the late evening. The concentrations are relative to the concentrations measured by the particle counter at the pier end which, for westerly (onshore) winds, represent the background aerosol. Also presented in figure 1 are meteorological parameters such as air temperature, relative humidity, wind speed, wind direction and wave height and period. The aerosol concentrations (shown in $^{10}\log$ format) show a clear correlation with wind direction: for westerly winds, the concentrations at the base of the pier (downwind from the surf zone, measured by instruments pms1, pms2 and pms3) are up to one order of magnitude higher than upwind from the surf zone. Strong vertical gradients are observed, with highest aerosol concentrations close to sea level. For winds from land, the surf effect is visible in the higher aerosol concentrations observed at the pier end. The correlation is particularly clear on day 100. In the early morning of this day, the wind turned from NNW to NNE and back several times. This caused the air to arrive from land (for NNE directions), rather than across the surf zone (for NNW directions). This change in trajectory is promptly visible in the aerosol concentrations at the base of the pier, relative to those at the end of the pier.

The data measured during the surf experiments were used to estimate the aerosol production in the surf zone. Combining the data from the three surf experiments, wind speeds up to about 9 m/s are covered. The total amount of aerosol produced in the surf zone can be estimated from the aerosol concentration gradients measured for winds from sea at the base of the piers. The size distributions from the instrument upwind from the surf zone (at the pier end) provide the background aerosol concentrations (before entering the surf zone). The aerosol surf production derived for the La Jolla and Monterey sites was presented in ref. [5], where also the method followed to compute the aerosol source function is illustrated in more detail.

Figure 2 (reproduced from ref. [5]) shows the aerosol source function for the La Jolla and Monterey sites, obtained for wind speeds of 4-6 m/s. Also shown in the figure are several source functions derived from measurements at the open ocean. The open-ocean aerosol source functions apply to a wind speed of 20 m/s; the surf source function has been corrected for the difference in whitecap ratio between the surf (assumed to be 100%) and the open ocean at 20 m/s (10%, using the relation given in ref. [8]). Good agreement is observed between the aerosol source function derived for the La Jolla and Monterey surf zones and those obtained for open-ocean conditions, for aerosol sizes between 1 and 10 μm. Of the source function of Monahan et al.[9] only the droplet-mediated part is reproduced.

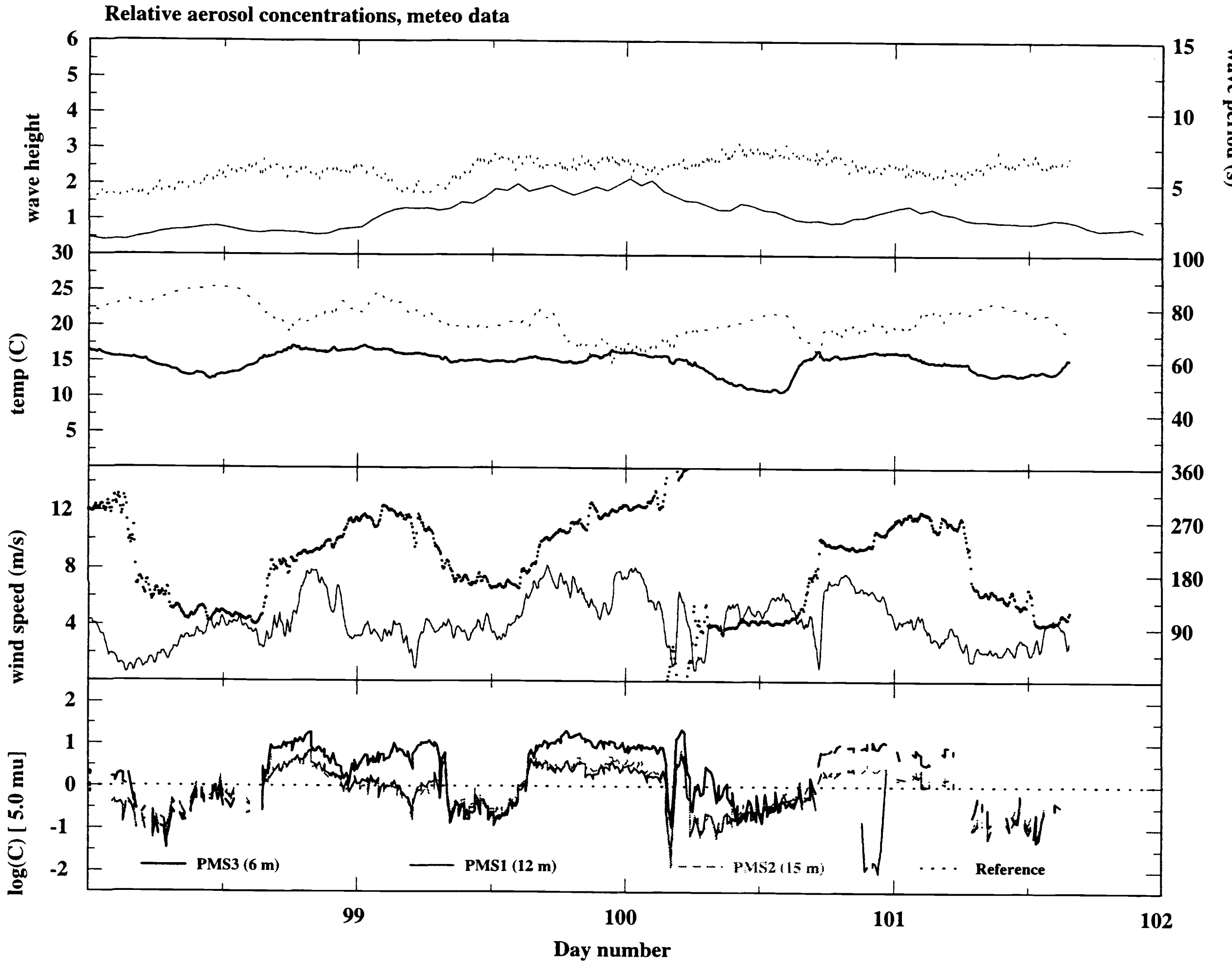

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Figure 1. Example of data measured at the SIO pier at La Jolla. Shown are relative aerosol concentrations (diameter 5 μm) and relevant meteorological parameters in the period of 8 through 11 April 1997. The bottom panel shows aerosol concentrations (in ^{10}log format) at the base of the Scripps Pier relative to those from the particle counter at the end of the Pier (pms4): ^{10}log(pms1,2,3) - ^{10}log(pms4). For onshore winds (westerly winds, during the afternoons), pms4 ('reference') measured the aerosol concentration in the well-mixed air mass before it enters the surf zone. The upper panels show the various meteorological and wave parameters measured during the campaign. Parameters plotted on the left hand side axes are plotted as solid lines, those on the right hand side axes as dotted lines. There is a strong correlation of aerosol concentration with wind direction (see, e.g., day 100). During winds from sea, aerosol concentrations are more than 10 times higher than in the air mass unaffected by the surf zone. The height above mean sea level of the three sensors at the base of the pier is indicated in the legend in the lower panel.

3. AEROSOL PRODUCTION

3.1 Model

The aerosol production in a surf zone can be calculated from the coastal bathymetry and the incoming wave field using the model proposed by Petelski & Chomka[1] and Chomka & Petelski[7] (hereafter referred to as CP97). The model is based on a number of scaling arguments.

CP97 assume that the aerosol is produced mainly by bubbles, entrained in the water by breaking waves. CP97 assume that aerosol production (emission flux F_e) is linearly related to the surface bubble density L_p

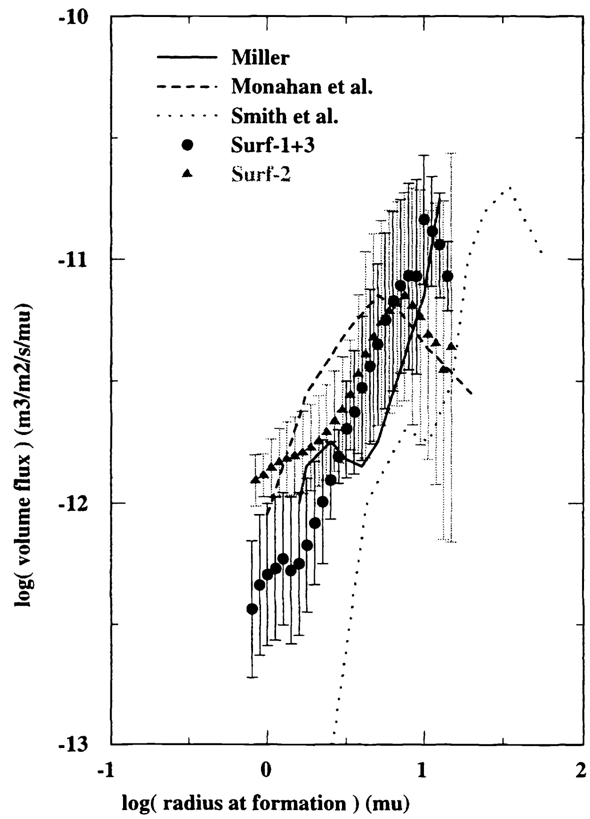

Figure 2. Aerosol source functions for the surf zone and the open ocean. The surf zone aerosol source functions derived from the Surf-1,3 and Surf-2 experiments have been scaled to a whitecap ratio of 10% (wind speed 20 m/s). There is good agreement with the source function of Monahan et al.[9] and Miller[10], while the source function of Smith et al.[11] predicts lower concentrations.

$$F_e = a_1 L_p \tag{3.1}$$

The emission flux is measured in units of μg/m^2/s. The factor a_1 describes the number of aerosol droplets produced per bubble. The bubble density is related to the volume V of the breaking wave:

$$L_p = a_2 \frac{V}{\frac{4}{3}\pi r^3} \tag{3.2}$$

where r is the characteristic bubble radius and a_2 a constant. Wave geometry considerations lead to a relation between the volume V and the wave height reduction ΔH due to the wave breaking

$$V = a_3 (\Delta H)^3 \tag{3.3}$$

with a_3 a constant. The decrease in potential energy (energy dissipation) due to the wave breaking is

$$\Delta E = \rho_w g V \Delta H \tag{3.4}$$

Equations (3.2)-(3.4) can be combined to obtain an expression for L_p as a function of ΔE, which is then inserted in (3.1), yielding

$$F_e = C(< dE >)^{3/4} \tag{3.5}$$

where $<dE>$ is the average energy dissipated per unit area in the surf zone and the constant C contains all constants (including ρ_w and g) from expressions (3-1) to (3-4). CP97 estimated the constant C using measurements of surf-produced aerosol fluxes at a location on the Baltic coast[1], deriving the following relation for the emission flux

$$F_e = 99.4(< dE >)^{3/4} + 3.5 \tag{3.6}$$

For the calculation of the emission flux from equation (3.6) the average energy dissipation in the surf zone needs to be calculated. CP97 use a wave model based on wave energy flux balance theory of Battjes & Janssen[12] and Thornton & Guza[13]. In the present study, the ENDEC* module of UNIBEST wave breaking model is used. This model describes wave refraction and wave energy dissipation by wave breaking and bottom friction. The code is also based on Battjes & Jansen[12]. A description of the UNIBEST-TC model can be found in ref. [14]. The results from using the ENDEC module and those from the wave model proposed by CP97 are compared in Table 1. The inputs to the models were a sea bottom of constant slope (either $\tan\alpha = 0.026$ or $\tan\alpha = 0.065$) and a wave field with significant wave period of 3.5 s and significant wave height of 0.6 m.

Table 1 shows that the width of the wave breaking zone calculated with the wave model used by CP97 is much larger than according to the ENDEC model. In the CP97 model, significant energy dissipation (and, hence, aerosol production) starts at a water depth of about 25 m, for both sea bottom slopes. In contrast, the ENDEC model predicts aerosol production in water depths of 5 m and less. As a rule of thumb, a wave is affected by the sea bottom for water depths less than about 1.6 times the wave period squared. For the waves used in these calculations, this would be about 20 m. This implies that in the CP97 model significant energy dissipation starts in relatively deep water (about 25 m). It does not seem realistic to assume that aerosol production starts at that point, when the waves are not yet significantly affected by the sea bottom. The surf width predicted by the ENDEC model is more realistic. The total aerosol production in the surf zone calculated with the CP97 model is larger than according to the ENDEC model, for both sea bottom slopes. The differences between the CP97 and ENDEC models are further illustrated in Figure 3, which shows the aerosol production profiles perpendicular to the coast, for both wave breaking models, for the sea bottom with a slope of $\tan\alpha = 0.026$.

Table 1. Comparison between the wave breaking models of CP97 and the ENDEC model[14]. The wave field used has dominant wave period of 3.5 s and significant wave height of 0.6 m. The sea bottom has a constant slope of either $\tan\alpha = 0.026$ or $\tan\alpha = 0.065$. The distances are measured from the shore line.

	CP97	ENDEC	CP97	ENDEC
Sea bottom slope	$\tan\alpha = 0.026$	$\tan\alpha = 0.026$	$\tan\alpha = 0.065$	$\tan\alpha = 0.065$
Width wave breaking zone (m)	1100	230	360	85
Total aerosol flux (μg/m/s)	$1.0 \cdot 10^5$	$3.7 \cdot 10^4$	$7.1 \cdot 10^4$	$2.8 \cdot 10^4$
Average aerosol flux (μg/m^2/s)	90	160	200	330
Maximum aerosol flux (μg/m^2/s)	310	810	750	1700
Position maximum flux (m)	250	45	100	11

The results in Table 1 and Figure 3 confirm the conclusions of CP97. The locally highest aerosol fluxes are produced by a steeper sea bottom. However, the total aerosol production is highest for a shallower sea bottom slope, which also causes a wider wave breaking zone. Furthermore, the maximum aerosol production, and the most vigorous wave breaking occur close to the shoreline.

3.2 Application to La Jolla and Moss Landing.

The CP97 model of aerosol emission in the surf zone is applied to the conditions at La Jolla and Monterey. The sea bottom slope at La Jolla was assumed to have a constant slope of $\tan\alpha=0.016$, to sufficiently deep water. For Moss Landing, the average sea bottom slope was $\tan\alpha=0.05$. The wave field data (significant wave height and period) were obtained from NOAA

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* Information about this model is available at http://www.wldelft.nl/mci/en/software/169.shtml (UNIBEST) and http://www.wldelft.nl/mci/en/software/152.shtml (ENDEC module).

and CDIP buoys off the Californian coast♦. For the La Jolla site, buoy 46025 (Catalina island) was used, for Moss Landing data from the CDIP buoy in Santa Cruz harbour. It was assumed that the data from these buoys are representative for the deep water waves causing the surf at the sites where the measurements were made.

During each period with winds from sea, total aerosol fluxes were computed at one-hour intervals. As both piers are oriented roughly West, at right angles to the coast, periods of wind from sea were defined as those intervals when wind direction was

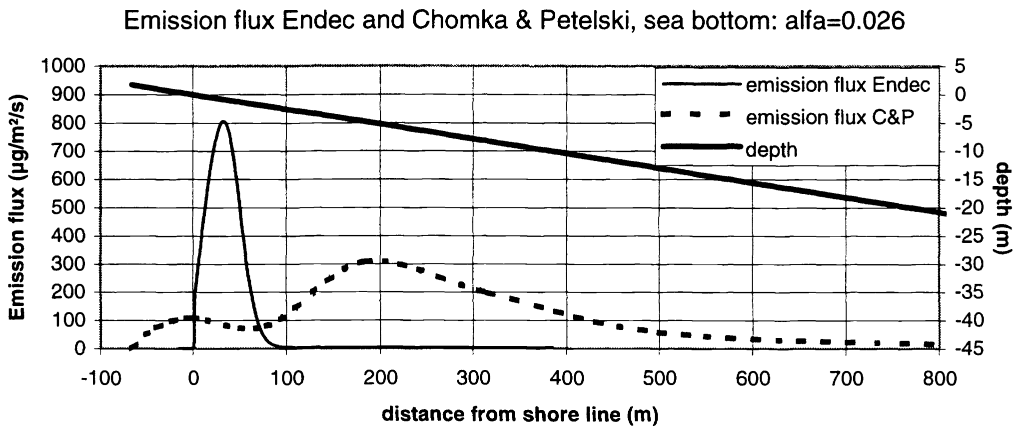

Figure 3. Aerosol emission flux profiles over the wave breaking zone, for a sea bottom profile with a slope of tanα=0.026 (shown as heavy solid line). Shown are the emission profiles predicted by the wave breaking model of CP97 (dashed line) and the Endec model (thin solid line). The Endec model predicts a much narrower wave breaking zone than the CP97 model; aerosol fluxes are locally higher in the Endec results

between 180° and 360°. For wind directions oblique to the coast, the effective surf width increases. To account for this effect, the predicted fluxes were divided by the factor f

$$f = 1 - \frac{|wdir - 270°|}{270°}$$

where *wdir* is the wind direction in degrees. This factor was chosen to avoid singularities of a correction factor like $1/\cos(wdir-270)$.

Figures 4a-c show the results for surf-1, surf-2 and surf-3 experiments. The last panel in figure 4c corresponds with the time period shown in figure 1. The total aerosol production is given in units of µg/m/s, where the length unit is length of shore line. There is generally good agreement between predicted and measured aerosol fluxes. The observed day-to-day variations in the observed aerosol flux are reasonably well reproduced by the model, while at times the model also predicts the correct trend. However, in other cases the model calculations may be up to one order of magnitude different from the observed fluxes. This shows that more research is needed to refine the model. Tests are being made on the prediction of the wave breaking model itself, while on the other hand also the bubble-mediated aerosol production model could be improved.

♦ Wave data from the buoys mentioned in the text are available at http://seaboard.ndbc.noaa.gov/Maps/swstmap.shtml (for the NOAA data) and http://cdip.ucsd.edu/wc/santacruz.html (CDIP data).

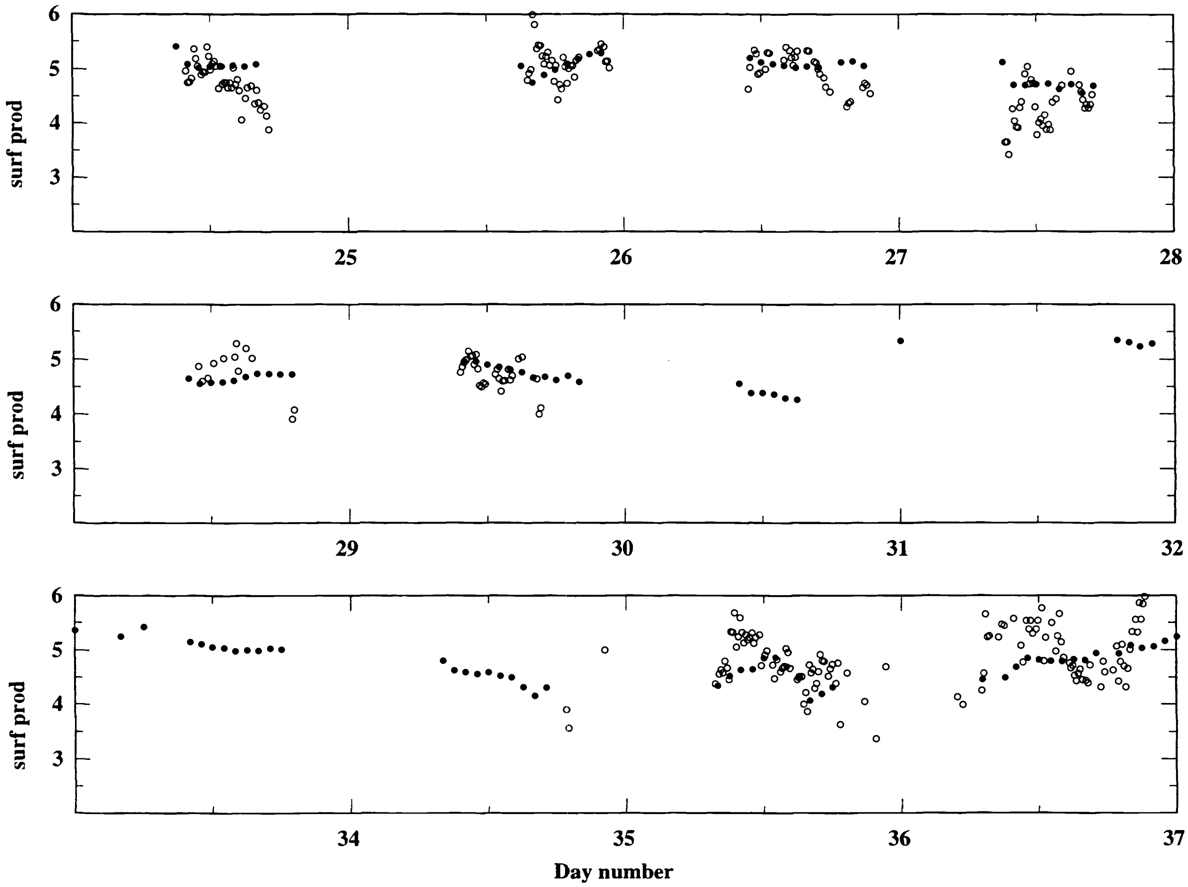

Figure 4. (a) Time serial plots of predicted (solid dots) and observed (open circles) total aerosol fluxes during the Surf-1 experiment. Note the good agreement on days 24 to 29, when even the trend during the day is reproduced by the model.

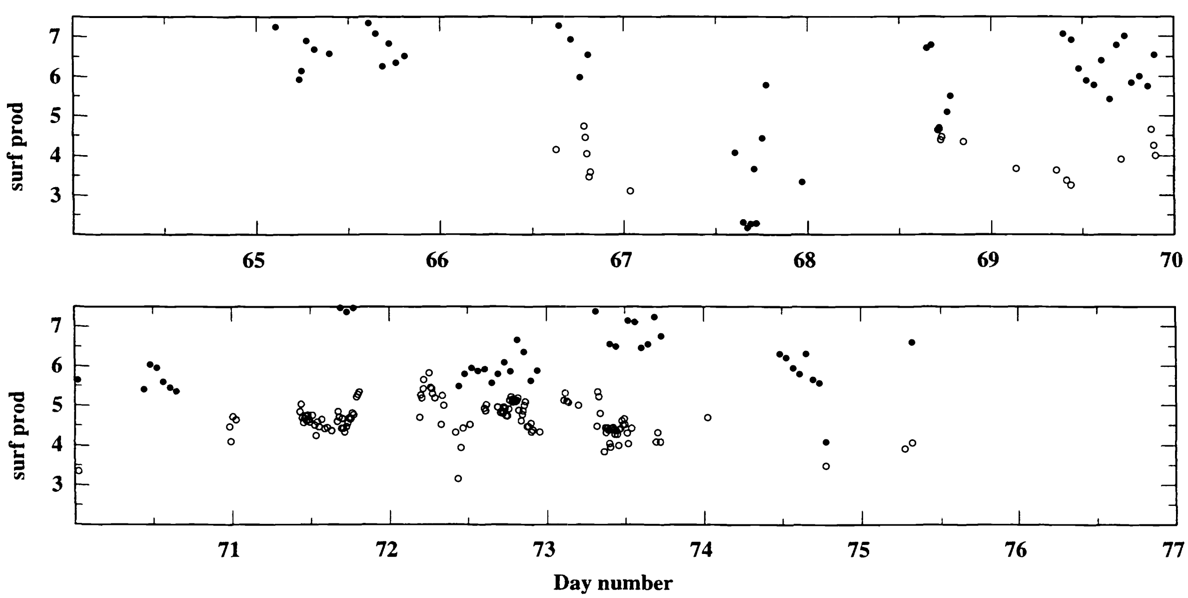

Figure 4. (b) As figure 4a, now for the Surf-2 experiment.

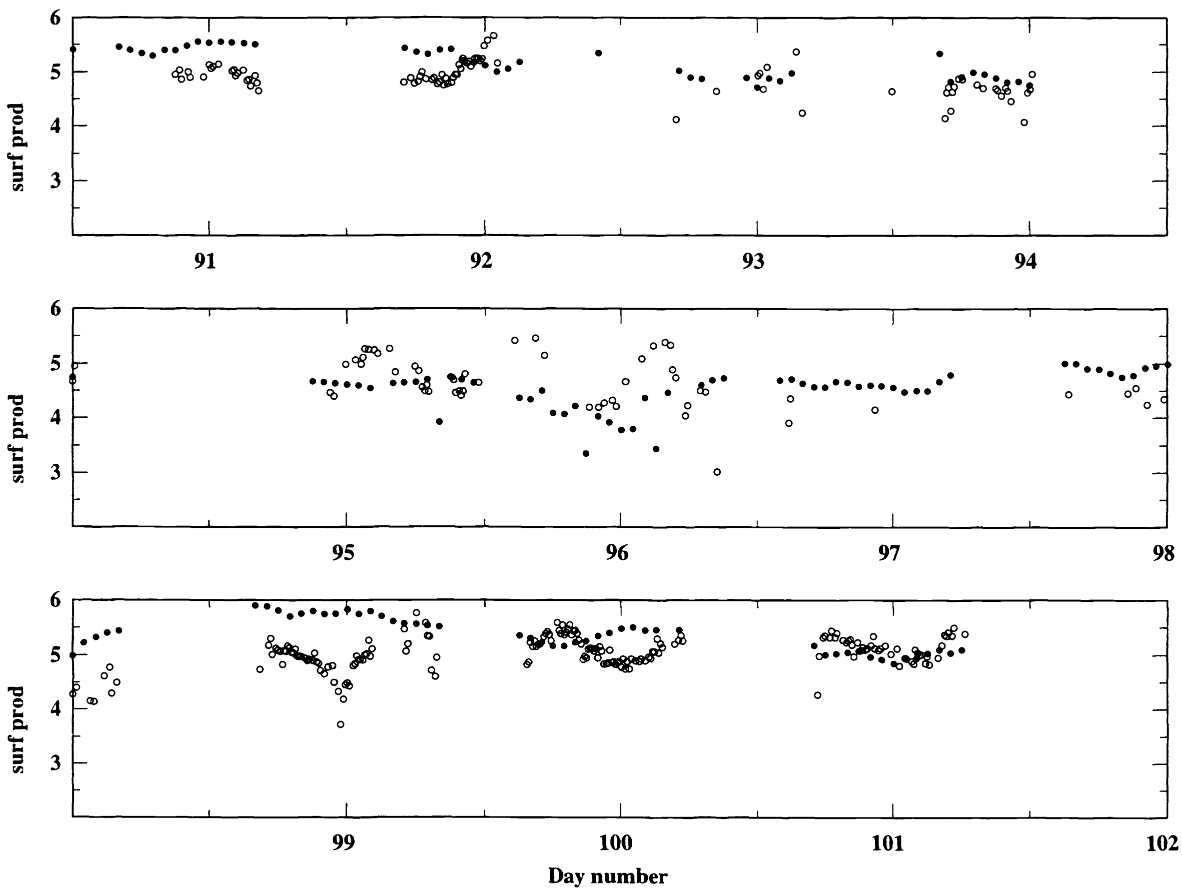

Figure 4 (c). As figure 4a, now for the Surf-3 experiment. The lower panel shows the same time period as figure 1.

The agreement between observed and modelled aerosol production for the Surf-2 experiment in Moss Landing is not as good as for the Surf-1 and Surf-3 experiments. Aerosol production is overestimated by one to two orders of magnitude. The wind-speed corrected aerosol source functions for the Moss Landing and La Jolla sites agree quite well (figure 2), and there is reasonably good agreement between model and data for the La Jolla site. Therefore, it is unlikely that the discrepancy between model prediction and experimental data is due to experimental errors. A source of uncertainty may be the wave data used, which were taken from a buoy near Santa Cruz. The wave data given by a buoy in Monterey bay (NOAA buoy 46042) were not used, as these gave deep-water wave heights in excess of 6 m, while the surf during the experiment did not show evidence for such wave heights. Without wave data representative for the area where the aerosol measurements were made, no definitive conclusions can be drawn. In view of the shape of Monterey Bay, the wave field at the site is likely sheltered from open ocean waves and much energy may already have been dissipated upon arrival at Moss Landing.

The value of the results presented here lies in the fact that they show the generality of the surf-zone aerosol flux model of CP97. The CP97 model was developed for a site along the Baltic coast, using aerosol flux data to determine the constant relating total aerosol flux from breaking waves to the energy dissipated in the surf zone.

4. SUMMARY AND CONCLUSIONS

The results presented in this paper show that the aerosol emission from a coastal wave breaking zone can be reasonably predicted, when the sea bottom profile near the coast and the deep-water wave spectra are known. A relatively simple relation involving the wave energy dissipation[7] describes the total amount of aerosol produced in the surf zone. In the present work, the CP97 model was improved by replacing the wave breaking model proposed by Chomka & Petelski by the ENDEC module of the UNIBEST-TC code. Results from the application of the two wave breaking models showed that the CP97 wave breaking model predicts waves to break in relatively deep water. The wave breaking zone widths predicted by the ENDEC code are more realistic and smaller than those from the CP97 model. Application of the aerosol production model to two sites on the Californian coast shows the generally good agreement between model and observations for both sites.

The model of Chomka & Petelski[7] was developed for the aerosol flux at a site along the Baltic coast. The agreement between model and data for the Californian coast indicates that the approach leads to reasonable results and, more important, shows the generality of the model. The relation between total energy dissipation in the wave breaking process and total aerosol production provides a reasonable description of the aerosol source function. The two most important parameters controlling aerosol production in the surf zone (when spume production is ignored) are the coastal bathymetry and the deep-water surface wave field. Once these parameters are known, the aerosol flux can be reasonably predicted. Apart from these two parameters in the production process, wind speed plays a role in the transport of aerosol to the particle counters. Neele et al.[5] showed that there is a positive correlation between wind speed and aerosol production, which might be explained by a more efficient transport of aerosol. The increase in aerosol production between wind speeds of 0-2 m/s and 6-8 m/s was found to be about an order of magnitude. The current model does not include such a wind dependence. Improvements are expected from a better parameterisation of the aerosol production. Bubble size spectra have been measured in the surf at various occasions, and the results will be used in future efforts in this topic. The effects of wind speed on the transport of the surf-produced aerosol should also be taken into account.

The value of a surf aerosol production model will lie in applications in aerosol transport models which are used, e.g., to predict atmospheric effects on the performance of IR sensor systems. Initial studies show the large impact of the surf aerosol on the aerosol concentrations in the littoral region in off-shore winds[6].

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