# Aerosol production in the surf zone and effects on IR extinction

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**SUMMARY**
The aerosol production in the surf zone, as determined from measurements, at two sites along the California coast is presented. The data used were collected during three EOPACE (Electro-Optical Propagation Assessment in Coastal Environments) measurement campaigns in 1996 and 1997. Particle counters were deployed at both the end and the base of two piers which extended into the ocean, beyond the surf zone. For winds from the sea, a clear increase in aerosol concentration was measured, between the particle counters at the end and the base of the piers. Aerosol concentrations were measured at the base of the piers at three heights, which allowed for the estimation of the aerosol production in the surf zone. Taking into account the different whitecap ratios, the surf zone aerosol source function derived from the data compares well with previously reported open-ocean source functions, in agreement with the common bubble (film and jet drops) origin. Wind speeds measured during the experiments were up to about 9 m/s; therefore, the source function presented here applies to the bubble part of the source spectrum only. Infra-red extinction coefficients were computed from the aerosol concentrations, using a Mie scattering code. Extinction values may be up to two orders of magnitude larger than in the unperturbed oceanic air mass; the vertical gradients in extinction are also much stronger than those reported for open-ocean conditions. A simple aerosol dispersion model, using observed surf zone aerosol production rates, predicts that air masses up to several km from the surf zone may be significantly affected by the surf-produced aerosol. For winds from land, this proves the importance of the surf zone in assessing the performance of electro-optical systems in coastal areas.

## 1. INTRODUCTION

Aerosols in the marine atmospheric boundary layer and their effects on a variety of processes have been investigated in the past decades by various research groups. One of the effects of the maritime aerosol that has attracted attention was their influence on the propagation of electro-magnetic radiation at wavelengths in the atmospheric transmission windows in the IR[1], both for military applications and, more recently, also for climate. Until the 1990's, the open ocean was considered most important. However, many experiments were conducted with the instrumentation ashore. The effect of the nearby surf zone was considered negligible. Experiments where aerosols were measured both ashore and on a ship to assess the influence of the surf on the aerosol concentrations close to the shoreline indicated that the surf was unimportant[2].
However, during the ONR (Office of Naval Research) aerosol workshop in Monterey, in May 1994, a simple calculation by Monahan (UCONN), showed the possible impact of the aerosol produced in the surf zone[3]. This calculation was based on aerosol production by a whitecap, and a realistic assumption as regards the equivalent whitecap coverage of the surf zone and its horizontal extent. The importance of this (then hypothetical) effect was recognised and included as an applied research topic into EOPACE (Electro-Optical Propagation Assessment in Coastal Environment), the work programme of which was formulated in the following year[4]. EOPACE started in October 1995. Three Surf experiments (Surf-1, 2 and 3) were conducted as part of EOPACE to determine the production of aerosol over the surf, in a variety of environmental conditions at coastal sites in California: La Jolla, near San Diego, in January/February 1996 (Surf-1) and in March 1997 (Surf-3), and in Moss Landing, Monterey Bay (March 1996, Surf-2). 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[4].

In this paper, results are presented from the analysis of data collected by TNO Physics and Electronics Laboratory (TNO-FEL) and the University of Sunderland (CMAS) in the three EOPACE Surf experiments, extending the work presented by de Leeuw et al.[5]. Other results were presented by Gathman & Smith[6].
The present analysis shows that, over the surf, the aerosol concentrations may increase by up to two orders of magnitude, depending on the height above sea level and aerosol size. The largest increase is observed for aerosols with diameters of about 10 μm (the largest aerosol in the present, corrected data set).
The vertical aerosol concentration gradients observed during the surf experiments provided the necessary data to measure the aerosol production in the surf zone. A clear dependence

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on wind speed was observed, with higher fluxes observed at higher wind speeds, probably resulting from more efficient upward turbulent transport. Taking into account the different whitecap area between the surf zone and the open ocean, the aerosol source function derived here agrees well with previously reported source functions for open-ocean conditions, for aerosol sizes up to about 10 μm, in agreement with the common origin, i.e., breaking waves. The present data set does not cover the spume domain, as the wind speeds did not exceed 9 m/s.
The infrared (IR) extinction coefficients calculated from the aerosol size distributions similarly show an increase of up to two orders of magnitude over the surf zone. Extinction gradients are presented and compared with results for open-ocean conditions. Estimates of the effect of the increased extinction on transmission across the surf are presented for on-shore winds. For off-shore winds, an extensive study, involving advection of the surf-produced aerosol and size-dependent dispersion and deposition, is necessary for the assessment of the surf effect on the performance of EO systems, along lines of sight that intersect the surf zone. Estimates of the horizontal extent of the surf produced aerosol in off-shore winds are derived with a simple dispersion model. In future work, a more comprehensive model will be applied to this problem.

## 2. EXPERIMENTAL SETUP

### 2.1 Experiment sites

The measurements were performed at the piers of the Scripps Institute of Oceanography (SIO), La Jolla, San Diego (Surf-1 and Surf-3) and Moss Landing, Monterey (Surf-2). 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 one of three particle counters at the end of the piers provided background size distribution 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. Table 1 lists the most important instruments and their locations.

| Instrument | Type | Position | Average height above mean sea surface | Parameter measured |
|---|---|---|---|---|
| PMS1 | ASAS-300A and CSAS-100-HV | Base of Pier | 12 m (Surf-1,3)<br>7 m (Surf-2) | Aerosol size distribution<br>0.16-32 μm |
| PMS2 | CSASP-200 | Base of Pier | 15 m (Surf-1,3)<br>11.2 m (Surf-2) | Aerosol size distribution<br>0.2-20 μm |
| PMS3 | CSASP-100-HV | Base of Pier | 7 m (Surf-1,3)<br>5 m (Surf-2) | Aerosol size distribution<br>0.5-47 μm |
| PMS4 | FSSP-100 | End of Pier | 11 m (Surf-1,3)<br>6 m (Surf-2) | Aerosol size distribution<br>0.5-47 μm |
| Rotorod | - | Variable | 1-9 m (Surf-1,3)<br>1-6 m (Surf-2) | Aerosol size distribution<br>D>13 μm |
| BMS | - | Variable | -0.36 m | Bubble size distribution<br>D>30 μm |
| Sonic anemometer | Solent research type | various | various | Wind speed and direction (20 Hz) & turbulence;<br>Turbulence profiles & wave effects on air flow |
| Cup anemometer | Thies | Base of Pier | 12.5 m (Surf-1,3)<br>11.5 m (Surf-2) | Wind speed |
| Wind vane | Thies | Base of Pier | 12.8 m (Surf-1,3)<br>11.5 m (Surf-2) | Wind direction |
| Rotronic | MP440 | Base of Pier | 12 m (Surf-1,3)<br>7 m (Surf-2) | Air temperature & RH |
| Rotronic | MP440 | Base of Pier | 13.2 m (Surf-1,3)<br>11.2 m (Surf-2) | Air temperature & RH |
| Nephelometer | - | Base of Pier | 12 m (Surf-1,3)<br>7 m (Surf-2) | Aerosol scattering |
| Pyranometer | Kipp | Base of Pier | 12 m (Surf-1,3)<br>6.6 m (Surf-2) | Irradiation |
| Rain detector | - | Base of Pier | | Rain occurrence |
| Barometer | Honeywell 142PC30A | Base of Pier | 11 m | Atmospheric pressure |

Table 1. Instrumentation used during the Surf experiments. Aerosol sizes refer to the diameters measured.

## 2.2 Particle counter (inter)calibration

All particle counters were size calibrated with particles with well-defined diameters. To remove any remaining differences among the instruments, a instrument comparison test was performed prior to the Surf-1 and Surf-3 experiments. During the test, all particle counters were operated for several days at the same location. The size distributions measured during this period were averaged to obtain a common mean, and inter-instrument correction curves were defined as the deviation of each instrument from this common mean. These correction curves were applied to the data of the subsequent experiments.

Unfortunately, there was no such instrument comparison period prior to the Surf-2 experiment. Instead, correction curves were obtained from the Surf-2 data directly. It was assumed that the data from the counters at the base of Moss Landing represent the true size distributions (these counters had been calibrated at the laboratory with aerosol of known size distributions). The difference between the data from pms4 (at the end of the pier) and pms1 (at the pier base, at comparable height) is then equal to the pms4 instrument correction *minus* the surf effect for onshore winds, while for winds from land this difference equals the instrument correction *plus* the surf effect. Hence, the instrument correction factor for pms4 can be obtained from the average difference between pms1 and pms4, for both onshore and offshore winds. Correction curves for pms4 that were obtained in this way showed a smooth dependence on aerosol size.

## 3. AEROSOL CONCENTRATIONS

Figure 1 presents part of the data set, 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 first four days of the Surf-1 experiment (January 24 through 27, 1996). These 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.

Wind speed was generally low, usually less than 2 m/s with occasional short periods of higher wind speeds of up to 4 m/s. These wind speeds are still too small to cause significant production of sea spray aerosol over the open ocean. The wind direction followed the general sea breeze pattern, with offshore winds (easterly wind directions) during the night and morning, quite suddenly changing to onshore flow late in the morning and back to offshore before sunset. Relative humidity varied between 70% and 100%, while air temperatures were between 8 °C and 17 °C. Significant wave height varied between 0.5 and 1.5 m, and the wave period slowly decreased from 11 s in the first few days, to 5 s around day 28 (after which it increased to more than 15 s).

As expected, an obvious correlation is observed between the aerosol concentration and wind direction. During westerly winds, a strong increase in aerosol content with respect to the background was observed. The concentrations varied significantly among the three probes, the highest concentrations measured by pms3 which was situated closest to the sea surface. When the wind was from land, the three probes at the pier base measured similar aerosol concentrations (as expected) and the surf generation was visible as an enhancement of the concentrations measured with pms4.

No clear dependence of the aerosol concentration on meteorological parameters other than wind direction and wind speed are apparent from figure 1. It is expected that significant wave height and wave period are key elements in the aerosol production, but no clear correlation has been found. Although variations in these parameters were relatively small during the experiments, significant variations in the width and activity in the wave breaking zone were observed. The text in the middle panel in figure 1 gives a rough indication of the rigour or activity in the surf zone. The first two days of the Surf-1 experiment a 'normal' surf zone was observed of about 100 m wide. During day 26 the surf zone gradually narrowed and whitecapping decreased, but, due to a simultaneous increase in wind speed and concurrent enhanced transport, this is not readily visible in the aerosol concentrations at the pier's base.

The aerosol gradients, as derived from the data presented in figure 1, show a peculiar feature. The concentrations are highest at the lowest sampling point of about 7 m above sea level (pms3), and then decrease with height. However, in onshore winds, the concentrations at 12 m were often observed to be somewhat lower than at 15 m. The particle counters at 12 m were mounted above the deck of the pier (pms1).

In contrast, the more detailed profiles of giant particles (D>13 μm), measured with the Rotorod rotating impaction samplers, do not show a decrease in aerosol concentration near the pier deck. The Rotorod samples were taken at height intervals of 1 m, requiring about 20 minutes for a complete profile. It is noted that the Rotorod profiles were measured at some distance from the Pier (upwind), whereas the data presented in figure 1 for the 12 m level were measured with pms1 mounted at about 1.5 m above the pier deck on a wooden box, near the railing.

It is presumed that heating of the Pier deck by solar radiation resulted in the observed reduction in relative humidities, which in turn induced a shift in the particle size distribution to smaller diameters. Hence, the observed concentrations will have been smaller, thus causing the dip in the concentration profile at 12 m. This view is supported by the observation that during offshore winds the concentrations showed the expected decrease with height (cf. figure 1, usually between 8 p.m. and 11 a.m.). The kink was observed only during the afternoon, when the Pier deck was warm. Indeed, the humidity and temperature sensors mounted close to the box at heights of 12 and 13.2 m above sea level, showed significant differences (in fact the relatively low humidities and high temperatures near the box were the reason for having a second sensor somewhat further away from the pier surface).

## 4. SURF ZONE AEROSOL SOURCE FUNCTION

The data presented in the previous section can be 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.

An example of the effect of the surf on the aerosol size distributions is presented in figure 2, showing aerosol size distributions measured simultaneously with all four aerosol counters in on-shore wind. The difference between the data from pms4 (representing the background concentration) and the data from the counters downwind from the surf can be

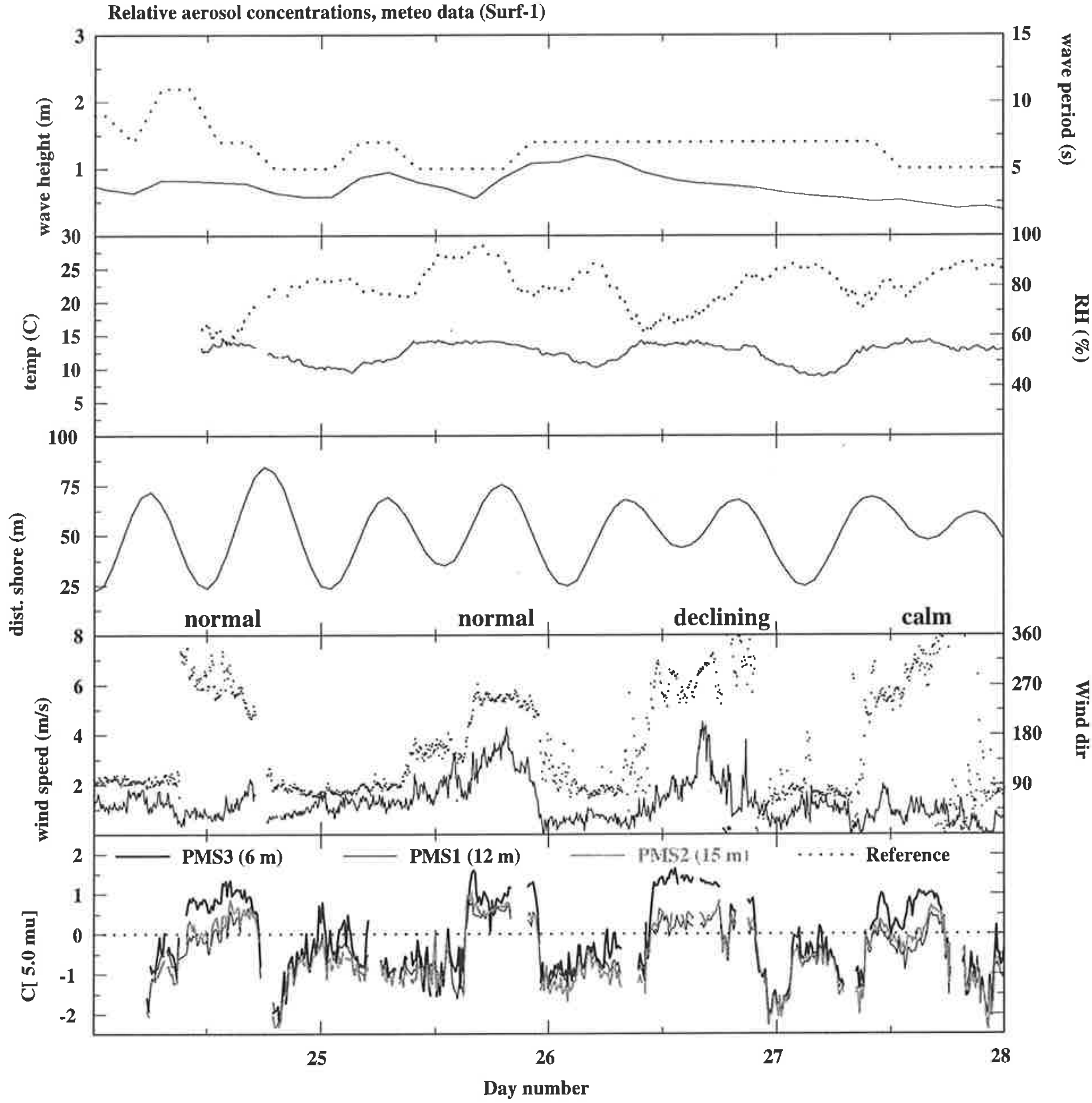


Figure 1. Relative aerosol concentrations (diameter 5 μm) and relevant meteorological parameters during the first four days of the Surf-1 experiment. The bottom panel shows aerosol concentrations (in $^{10}$log format) at the base of the Scripps Pier relative to those from the particle counter at the end of the Pier (pms4): $^{10}$log(pms1,2,3) - $^{10}$log(pms4). For onshore winds (westerly winds, during the afternoons), pms4 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 are plotted as dotted lines. There is a strong correlation of aerosol concentration with wind direction. During winds from sea, aerosol concentration may be up to 100 times higher than in the air mass unaffected by the surf zone. In the middle panel (showing tide, or distance to the water line) the rigour of the surf is indicated. The declining activity in the surf zone on day 26 cannot be readily correlated with a decrease in aerosol concentrations at the pier's base, due to a simultaneous increase in wind speed.

attributed entirely to generation in the surf zone. The surf effect on the aerosol content is largest for large diameters, as can be seen in figure 2.

To obtain an estimate of the overall production in the surf, the surf contributions to the aerosol concentrations were averaged for all periods of on-shore winds during three surf experiments. The results for the Surf-1 and Surf-3 experiments are shown in figure 3, for diameters of 1, 5 and 10 μm and wind speeds up to 2 m/s. The data clearly show the variation of the aerosol concentration with height, with gradients increasing with particle size. The concentrations near 12 m are not shown, for reasons discussed above. The results in figure 3 suggest that at the base of the pier the surf-produced aerosol extends to heights of about 30 m. This height compares well with lidar observations of the surf-produced aerosol plumes (R. Philbrick, unpublished results). It should be stressed that

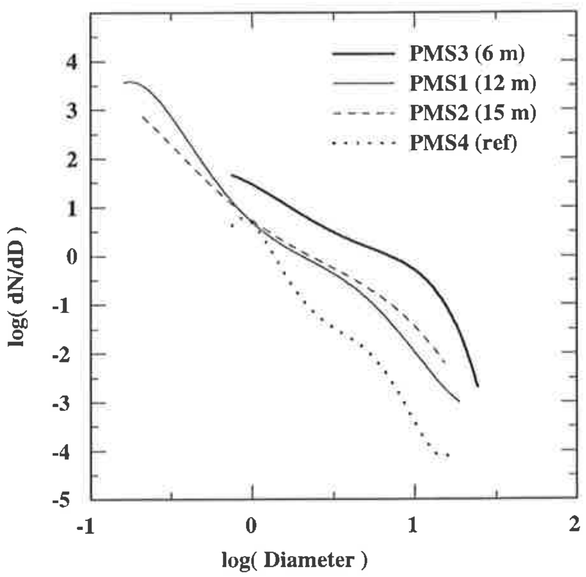


Figure 2. Typical aerosol size distribution ($cm^{-3}/\mu m$) measured during onshore winds. The surf-produced aerosol causes higher concentrations at pms1-3. This effect is larger for larger diameters.

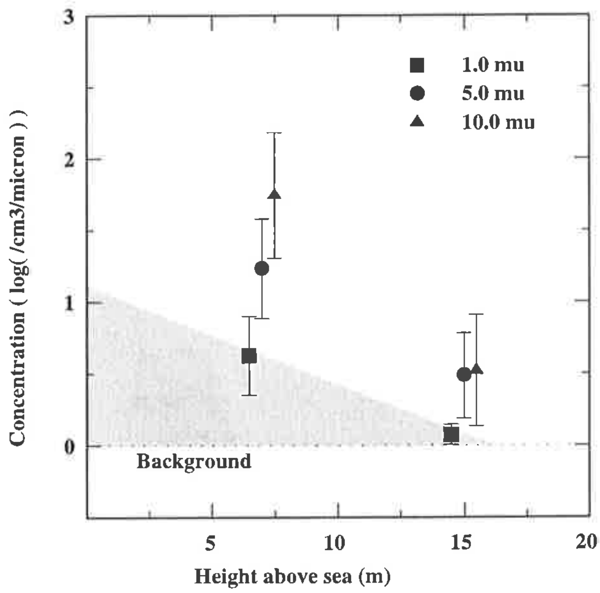


Figure 3. Average increase in aerosol concentrations, for wind speeds up to 2 m/s during the Surf-1 and Surf-3 experiments. Shown are averages of concentrations at two heights at the base of the Scripps pier, relative to the background concentration. Aerosol concentration increases sharply towards sea level, with gradients increasing with particle size.. The shaded area corresponds with the number of 1μm particles generated in the surf zone. Data shown are from pms2 (7 m height) and pms3 (15 m height).

figure 3 shows the enhancement of the aerosol concentrations downwind from the surf zone.

Data like those in figure 3 are used to estimate the total number of aerosol produced by the surf, as a function of aerosol size. It is assumed that the aerosol height profile is logarithmic, which is expected for an equilibrium situation[7]. Obviously, close to the source there will be no equilibrium between production and removal. However, the limited data that are presently available do not allow for a more sophisticated approach.

The horizontal aerosol flux downwind from the surf zone $dF/dD$ is given by the expression

$$\frac{dF}{dD}(D) = \frac{u}{L}\int_0^{z_{\max}}\left(\frac{dN}{dD}(z,D) - \frac{dN}{dD}_{bg}(D)\right)dz$$

where $dN/dD$ is the aerosol concentration as a function of height $z$ and aerosol diameter $D$, $dN/dD_{bg}$ the concentration in the well-mixed air before it enters the surf zone, $u$ the wind speed at the base of the pier and $L$ the width of the wave breaking zone. The background concentration, for onshore winds, is measured with the particle counter at the pier's end, pms4. $dN/dD(z,Z)$ is obtained by fitting a logarithmic profile to the data measured at the base of the pier, as explained above. The aerosol numbers are integrated between sea level and the height at which the concentrations have returned to the background value ($z_{max}$). In figure 3 the area over which the 1 μm particles are integrated is indicated by the shaded area. The horizontal flux over the beach near the base of the pier is obtained by multiplying the aerosol number by the wind speed $u$. The additional assumption is made that this flux is due completely to production in the surf zone, and, therefore, that the vertically integrated horizontal flux over the beach equals the vertical flux integrated over the whole surf zone. Thus, particle deposition between the surf zone and the pier base is ignored. A division by the width of the surf zone $L$ normalises the surface flux to a value independent of $L$ (units $m^{-2}s^{-1}\mu m^{-1}$).

Figure 4 shows the aerosol number and volume fluxes, obtained from data from the Surf-1 and Surf-3 experiments at wind speeds up to about 9 m/s. The aerosol sizes represent the size upon formation derived from the relation between $r_{80}$ (radius at 80% humidity) and $r_0$ (radius upon formation), $2r_{80} = r_0$(Ref. 8). The humidity during the Surf experiments was never significantly different from 80% during onshore winds.

Figure 4 shows that the surface flux of particles of 0.8 μm in diameter increases by about a factor of 10 between the lowest and the highest wind speeds. For larger particles the wind speed effect appears to be smaller. Since the suspension is more efficient at higher wind speeds, i.e. larger particles remain airborne longer[9], this finding suggests that fewer larger particles would be produced at higher winds. This suggestion seems unlikely and hence the observed wind speed effect on the surface flux of the largest particles is probably an artefact which may be caused by the statistics in the measurements of the largest particles. Wave height (and, hence, surf activity) is assumed independent of wind speed, which is a reasonable assumption for the relatively low wind speeds encountered during the experiments and the sea-breeze conditions at La Jolla.

The volume flux shows a clear maximum at a diameter of just over 10 μm. This finding is consistent with the bubble origin of the aerosol since the peak concentration of jet drops is expected near 10 μm[10]. The data in figure 4 (top) do not show a clear wind speed dependence of the position of this

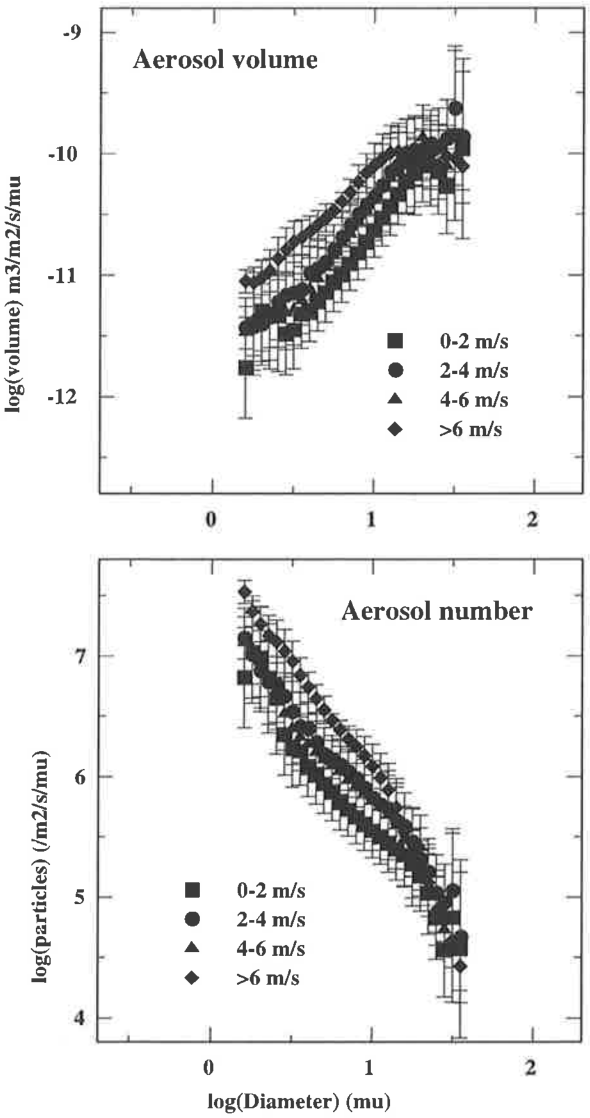


Figure 4. Aerosol fluxes *dF/dD(D)* from Surf-1 and Surf-3 data. Top: aerosol volume ($m^3/m^2/s/\mu m$); bottom: aerosol number ($/m^2/s/\mu m$) produced in the surf zone. The data have been arranged as a function of wind speed. The diameter refers to the diameter upon production.

maximum, in accordance with the assumed bubble origin of the aerosol.

The aerosol source function as presented in figure 4 is valid for the surf conditions near the SIO Pier. Extrapolation to other locations requires knowledge on the physical mechanisms determining the surf characteristics and their effects on the production of sea spray aerosol. Efforts are underway to describe these effects (see below).

Assuming a 100% whitecap cover in the surf zone[11], the surf data can be related to open ocean conditions and compared with published results on the surface source function. Such data were compiled by Andreas et al.[12]. These data are reproduced in figure 5. All source functions in figure 5 apply to a wind speed of 20 m/s; comparison with the surf aerosol source function in Figure 4 requires a correction for the difference in whitecap coverage between the surf and open ocean at a wind speed of 20 m/s. Monahan & O'Muircheartaigh[11] give an empirical relation between the open-ocean whitecap coverage and wind speed

$$A(W) = 3.84 \cdot 10^{-6}\, U_{10}^{3.41}$$

with $A(W)$ the fraction of sea surface covered by whitecaps, and $U_{10}$ the wind speed at 10 m height. According to this relation, the whitecap coverage at 20 m/s wind speed is about 10%. For a proper comparison between the open-ocean and surf aerosol source functions, the source function found in this study is divided by a factor of 10. The results are shown in figure 5, together with the aerosol source function obtained from the Surf-2 (Monterey) data. For the Surf-2 experiment, a surf width of 30 m was assumed. Error bars for the Surf-2 source function are larger, due to the smaller data set.

The two surf source functions obtained in the present study compare well with the open-ocean source of Miller[13]. The bubble part of the Monahan et al.[14] source function also agrees well with the Surf-1,2,3 source functions. The sharp increase in the source function of Monahan et al.[14] near a diameter of 20 μm is due to spume drops. The fluxes predicted by the source function of Smith et al.[15], also shown in figure 5, are too low in the size range considered here.

Recent studies by Petelski & Chomka[16] and Chomka & Petelski[17] provide a comparison with aerosol production in the surf zone at a location on the Baltic coast; their fluxes (several

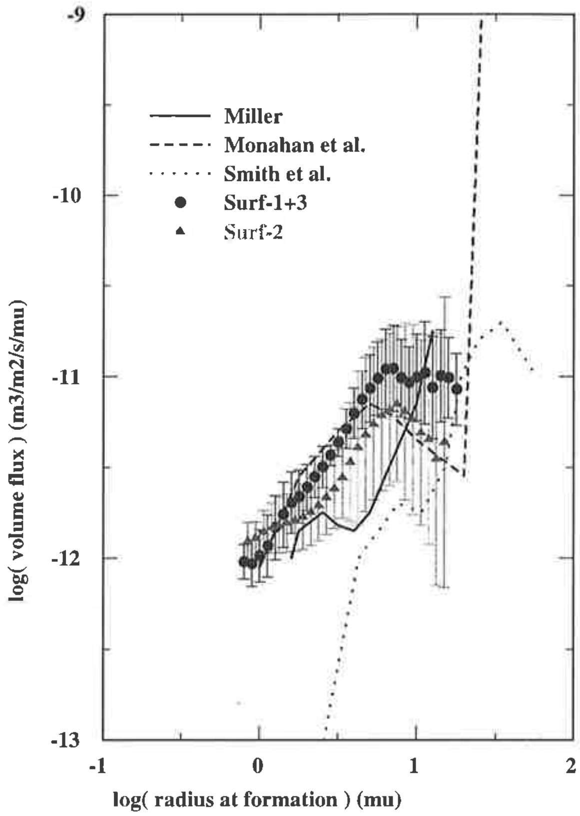


Figure 5. Aerosol source functions. The surf zone aerosol source function, corrected for whitecap ratio of 10% (wind speed 20 m/s), as derived from the Surf-1,3 and Surf-2 experiments have been inserted. There is good agreement with the source function of Miller[13] and Monahan et al.[14]. Also shown is the source function of Smith et al.[15].

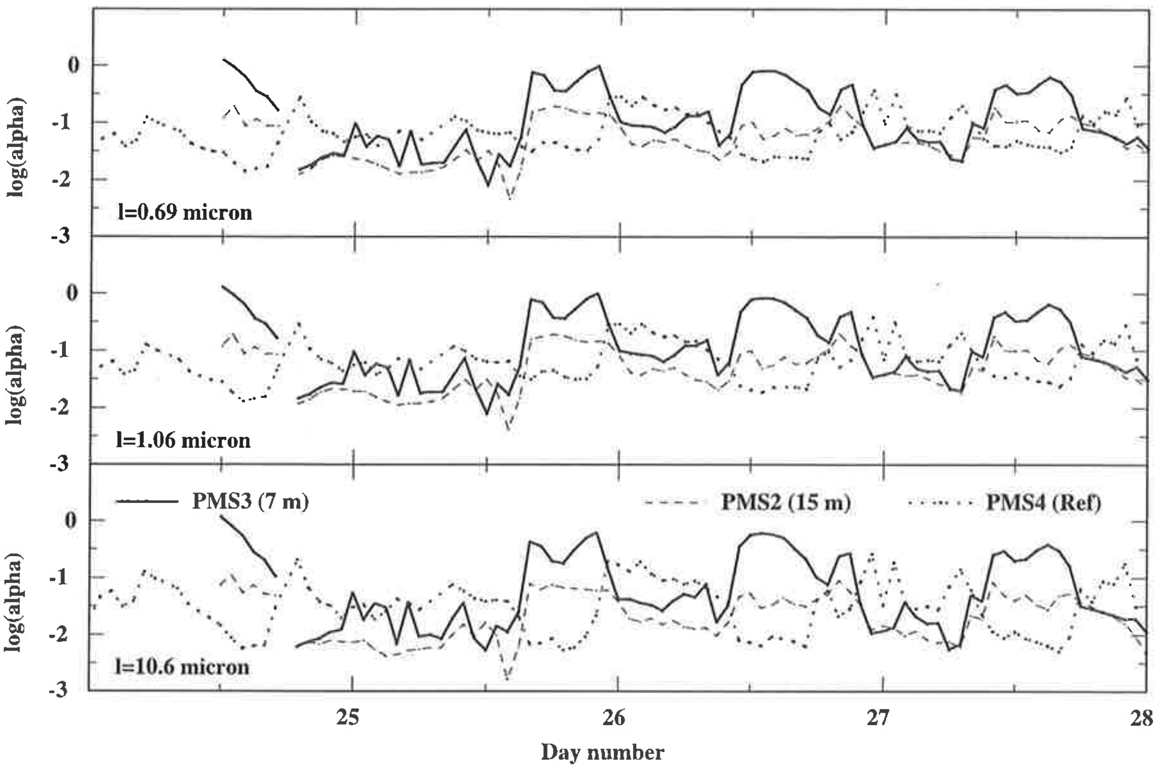


Figure 6. Extinction coefficients ($\alpha$ in $km^{-1}$) computed from the aerosol data in figure 1, for wavelengths 0.69, 1.06 and 10.6 µm. Not shown are data from pms1, for reasons discussed in the text.

hundreds of µg/m²/s) are of the same order of magnitude as those presented here, integrated over the size range in the figures.

## 5. IR EXTINCTION PROFILES

Extinction coefficients at five wavelengths in the visible and infra-red (IR) atmospheric transmission windows were computed from the aerosol size distributions using a Mie[18] code. Results for wavelengths of 10.6, 1.064 and 0.69 µm are shown in figure 6, for the same period as in figure 1. The data from pms1 are not shown, because they were affected by the hot pier surface. The surf effect is obvious in figure 6, with significant vertical gradients during the afternoons, when the extinction behind the surf zone was up to two orders of magnitude larger than over the open ocean. This effect is most pronounced for the longer wavelengths. Note that the effect of the surf on the extinction is present not only for winds from sea (during the afternoons), but also for winds from land. During the nights and mornings, the extinction at 7 and 15 m above sea level was similar, but the extinction at the end of the pier (pms4) was consistently higher. Effects of water vapour are not included in these calculations. Due to evaporation, the water vapour concentrations may also have been enhanced over the surf, thus increasing the IR absorption.
Extinction profiles for open-ocean conditions, show an (expected) increase of extinction coefficients towards the sea surface[19]. Whereas at the open-ocean almost zero gradients were observed for the lowest wind speeds, stronger gradients occurred for moderate (4-7 m/s) winds, while at high winds the aerosols were well-mixed throughout the surface layer, resulting in negligible extinction gradients. Data such as those shown in figure 6 allow the estimation of the average extinction gradient in the surf zone, as a function of both wavelength and wind speed.
Figure 7 shows the mean extinction profiles derived from the Surf-1 and Surf-3 data, as a function of wind speed. The extinction profiles in figure 7 are shown up to the height where the background extinction is attained (between 20 - 40 m above mean sea level). The background extinction coefficients vary between 0.1 and 0.01 $km^{-1}$. The profiles do not show that this background extinction value increases with increasing wind speed, as would be expected.
In contrast with the open ocean, where aerosol production is more directly related to wind speed, surf zone production may be high, even for low wind speeds, resulting in significant extinction gradients to heights of 20 to 40 m above sea level. Whereas Gathman[19] found a ratio between the extinction at 10 m and 1 m above mean sea level of only about a factor of 1.5, in these data this ratio ranges from 2 (6-8 m/s wind speed) to almost 10 (0-2 m/s wind speed) just downwind from the surf zone. At 5 m above mean sea level, the extinction coefficient in the air just downwind from the surf zone is about a factor of 60 (0-2 m/s winds) to 6 (6-8 m/s winds) higher than just upwind from the surf zone (derived from the data from pms4). The data show little dependence of the extinction gradient on wavelength. The strong correlation with wind speed is further emphasised in figure 8, which presents the average extinction gradient versus wind speed. The values show the behaviour expected for the case of a strong, nearby surface source of aerosol, with increasing dilution for higher wind speeds.

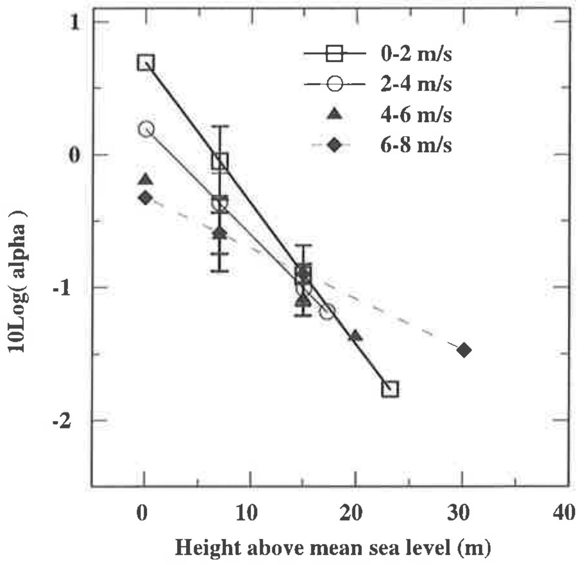


Figure 7. Profiles of log(extinction) versus height above mean sea level; the unit of extinction is $km^{-1}$. Curves are shown for four wind speed intervals; the wavelength is 4.0 μm. Data used are from the Surf-1 and Surf-3 experiments, for winds from sea only.

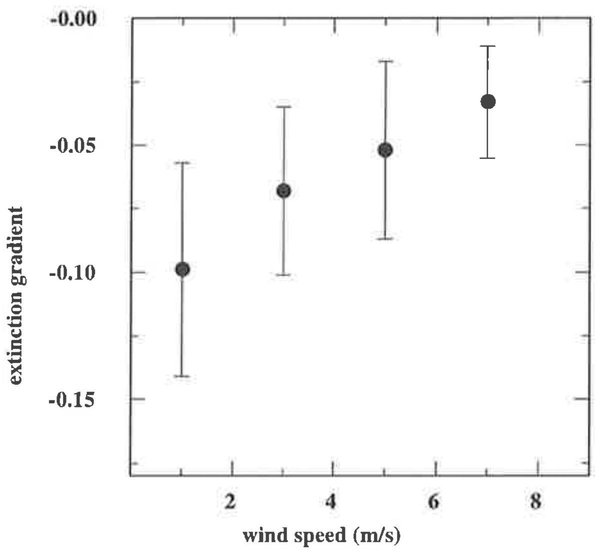


Figure 8. Extinction profile slope as function of wind speed. Shown are the slopes of the profiles from figure 7.

## 6. AEROSOL DISPERSION

The extinction coefficients in figures 6, 7 and 8 apply only to the base of the pier. For an assessment of the effect of surf-generated aerosol on the performance of electro-optical systems for lines of sight intersecting the surf zone, path-integrated (and range-dependent) extinction or transmission needs to be taken into account.
Two examples are presented which show the effect of the surf-produced aerosol on the transmission for both on-shore winds and winds from land.

### 6.1 Winds from sea

In this case, only the aerosol produced in the surf zone and transported across the shoreline up to the point where the electro-optical sensor system is situated needs to be taken into account. Consider a transmission path of 10 km length, crossing a surf zone with an effective width of 300 m obliquely. Assume that the background extinction coefficient is 0.05 $km^{-1}$ (the average background value in figure 7), while the extinction over the effective surf is enhanced by a factor that varies between 3 and 300. Transmission losses, relative to the situation where the surf has no influence of the extinction, were calculated as a function of the angle of incidence of the path through the surf zone. The results are shown in figure 9. The curves are labelled with the enhancement factor of the extinction coefficient in the surf zone: '10' corresponds to a surf zone in which the extinction is 10 times higher than in the unperturbed air mass. The figure shows that the increase of the aerosol extinction over only the surf zone, by realistic values of about 2 orders of magnitude (see figure 6), causes rather dramatic losses in transmission.

### 6.2 Off-shore winds

In off-shore winds, the effect of the surf on the transmission may be much more serious, as the surf-produced aerosol may be transported over considerable distances. Hence they may influence the extinction along the entire transmission path. In the following, a simple aerosol model is applied in a first attempt to estimate the down-wind dispersion of the surf-produced aerosol and the resulting effect on extinction.
As a first approximation of the dispersion of aerosol produced in the surf zone, the diffusion equation for a line source in a simplified atmosphere is solved analytically. The application of a line source model is justified by considering the surf as a source with a relatively small vertical extent (maximum 30 m, as derived from data as displayed in figure 7, situated along the coast line. With this hypothesis, the model was formulated for aerosols emitted from a continuous crosswind line source located at the land-sea transition. The mean concentration downwind from a line source at a height $h$ is given by

$$\langle c(x,z)\rangle = \frac{q(zh)^{1/2}}{\sigma_z^2 u}\exp\left[-\frac{\left(z^2+h^2\right)}{2\sigma_z^2}\right] I_{-1/2}\left[\frac{zh}{\sigma_z^2}\right]$$

where $x$ is the downwind distance from the source, $z$ the measuring height, $u$ the mean wind speed, $q$ the source strength, $I_{-1/2}$ is the modified Bessel function of the first kind of order -½. $\sigma_z^2=2K_{xx}\,x/u$, where $\sigma_z$ is the vertical dispersion coefficient and $K_{zz}$ is the vertical turbulence coefficient. The wind speed and the vertical turbulence coefficient are assumed constant with height[20].
Particle deposition is taken into account by modifying the source strength $q(x)$ with a reduction term which is dependent on the distance from the source[21]

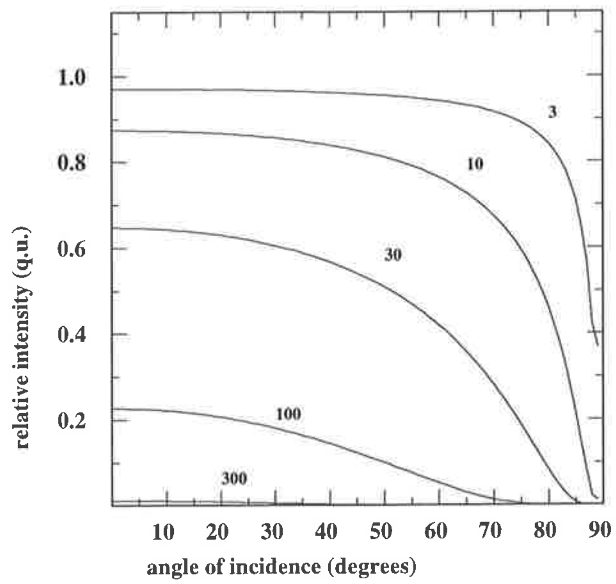


Figure 9. Path-integrated extinction losses in on-shore wind, plotted as function of the angle between the transmission path and the normal to the shore line. The total length of the transmission path is 10 km, the effective width of the surf zone is 300 m. The labels indicate the extinction in the surf zone: '10' represents a surf zone in which the extinction is 10 times higher than the background value. Background extinction is set to 0.05 km$^{-1}$.

$$\frac{q(x)}{q(0)} = \left[ \exp \int_0^x \frac{dz}{\sigma_z \exp\left(h^2 / 2\sigma_z^2\right)} \right]^{-\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{v_d}{u}\right)}$$

where $v_d$ is the wind speed dependent particle deposition velocity. The model applies only in neutral conditions. Deposition velocities were calculated using the expression of Slinn and Slinn[22].

The average concentrations derived from the Surf-1 data were used as input to the model. To account for the vertical extent of the surf, these concentrations were extrapolated to heights of 1-30 m, and the model was applied for a series of release heights, with the receptor point fixed at a single level of 10 m. The concentrations arriving at the receptor point from the various release heights were then integrated to obtain the actual concentrations of the surf-produced aerosol at the receptor point. The distance between the source and the receptor point was varied from 10 m up to 25 km. The calculations were made for aerosols with diameters of 1-10 µm, and wind speeds of 2 and 10 m/s. An example of the results for wind speed of 2 m/s is shown in figure 10. Close to the source the concentrations increase somewhat due to mixing of the particles from several heights to the receptor height, then a gradual decrease is observed. Even at 25 km from the source, the concentrations are decreased only by about one order of magnitude. This implies that the surf-induced enhancement of the aerosol concentrations in off-shore winds may have serious consequences for the transmission over sea.

It may be argued, that in off-shore winds the surf production of aerosol may be much lower than in on-shore winds. However, in this calculation concentrations were used which were measured at an average distance of 50 m downwind from the surf, in wind speeds that usually did not exceed 2 m/s. Hence, the surf was mainly due to swell. Also, the data in figure 1 show that, in off-shore winds, the concentrations of the aerosols at the end of the pier are appreciably enhanced over those measured at the base of the pier , which in fact is due to the enhancement of the concentrations by the surf production.

The model was derived with the assumption that the wind speed and the vertical turbulence coefficient are constant with height. Although this leads to errors only at short distances (up to about 500 m) from the source[23], this calculation should only be regarded as a first attempt to estimate the influence of surf-produced aerosol. In the future, more comprehensive models will be applied to take into account the vertical extent of the aerosol, the wind profile and associated vertical mixing, as well as other potential processes in the marine boundary layer that may affect the aerosol, other than advection, dispersion and deposition.

The effect on extinction can be found with this model, as the concentrations as a function of height and distance from the surf zone can be computed. In general, it can be expected that the strong extinction gradients observed near the surf zone gradually disappear as the air mass moves away from the surf zone and becomes better mixed. Figure 10 shows that at a distance of 25 km, concentrations may be as high as 10% of the concentrations measured just downwind from the surf zone.

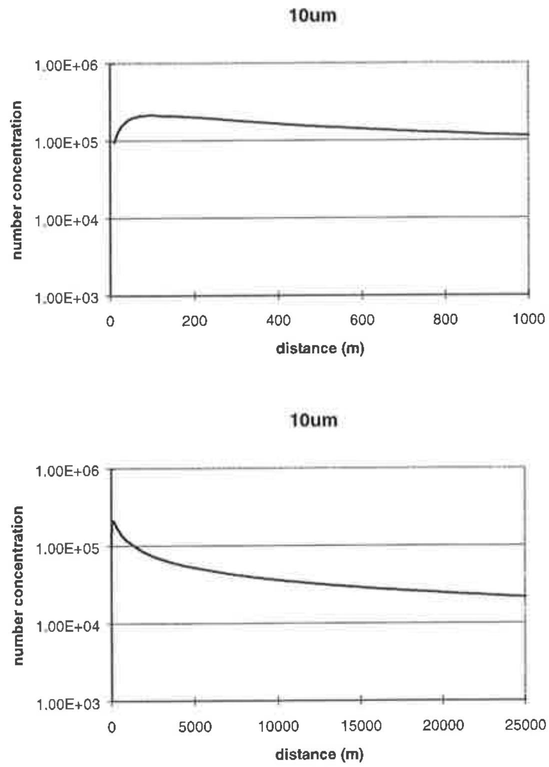


Figure 10. Aerosol concentrations for particles of 10 µm in diameter, calculated as a function of distance from the surf using the aerosol transport model described in the text.

## 7. DISCUSSION AND CONCLUSIONS

The analysis of the aerosol measurements obtained during the EOPACE Surf experiments show that, in the diameter range between 0.5 and 10 μm, the aerosol concentrations increase by up to two orders of magnitude due to production in the surf zone. A clear correlation is observed between wind speed and the aerosol flux downwind from the surf zone. The data from the three particle counters that were used in the height interval between about 7 and 15 m above mean sea level suggest that at an average distance of 50 m from the surf the maximum height attained by the surf produced aerosol is between 20 and 30 m.

The aerosol source functions which were derived from the three data sets not only agree well between the La Jolla and Monterey sites, but also compare well with surface fluxes previously reported for open-ocean conditions. All source functions used in the comparison apply to aerosol produced from bubbles (film and jet drops). Prior to the comparison with open-ocean aerosol surface fluxes, the only scaling applied to the surf source functions is a correction for whitecap ratio, which is considerably higher in the surf zone than at the open ocean, even at wind speeds of 20 m/s. The good agreement among the surf and open-ocean aerosol source functions suggests the existence of a single, well-defined bubble source function, expressed in aerosol produced per unit white cap. This result indicates that the whitecap ratio is an important parameter controlling the aerosol flux from the sea surface. Application to different conditions and locations is then a matter of measuring the local whitecap ratio. On the open ocean, wind speed is most likely to control the whitecapping ratio, while in surf zones the swell is probably more important than the local wind speed and direction. This is especially true for the sites of the Surf experiments, where winds follow a sea breeze pattern and are generally too low to significantly affect wave breaking.

This study is continuing to derive a model describing the effect of the surf on the aerosol production. The relation between the incoming wave field (direction of arrival, spectral content) and the rigour of the surf zone will be considered. Currently available software predicts the wave energy dissipation in the surf zone, which is the key parameter controlling aerosol production[17]. Preliminary results suggest that such an approach is viable, as the aerosol production is similar at very different surf zones, for comparable levels of wave energy dissipation.

The effect of surf-produced aerosol on IR extinction has been shown to be considerable. Not only do the data suggest a large effective width of the surf zone, but they also show that the extinction coefficients over the surf may be two or three orders of magnitude larger than in the unperturbed oceanic air. A more complete description of the surf effect on IR propagation requires detailed modelling of the size-dependent aerosol dispersion. Examples of the first attempts to apply such an aerosol transport model were presented. It is realised that this model may be an oversimplification of the real situation with developing wind and wave fields in off-shore winds, as well as temperature and humidity gradients that will affect the aerosol physics. For future application, more comprehensive models will be developed.

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**References.**

[1] Fairall, C.W., Davidson, K.L. and Schacher, G.E., "Meteorological models for optical properties in the marine atmospheric boundary layer", *Opt. Eng.* **21**, pp. 847-857, 1982.

[2] Kohnle, A. and J.H. Richter, "Result of the Fall 1981 North Sea measurements", *NATO AC/243 (Panel IV/RSG.8) Report 1983-01*, 1983.

[3] Goroch, A.K. and Geernaert G.L. (Editors), "Coastal Aerosol Workshop Proceedings", *Naval Research Laboratory, Report Number NRL/MR/7542--95-7219*, 138pp, NRL Monterey, Monterey, CA, 93943, June 1995.

[4] Jensen, D.R., "EO propagation assessment in coastal environments (EOPACE)", NCCOSC RDTE DIV, Code 543, San Diego, CA 92152-7385, USA, May 1995.

[5] de Leeuw, G., Neele, F.P., van Eijk, A.M.J., Vignati, E., Hill, M.K. and Smith, M.H., "Aerosol production in the surf zone and effects on IR extinction", *SPIE proceedings volume 3125,* 14-27, 1997.

[6] Gathman, S.G., and Smith, M.H, "On the nature of surf-produced aerosol and their effect on electro-optical systems", *SPIE Proceedings Volume 3125*, 2-12, 1997.

[7] Goroch, A.K., Burke, S. and Davidson, K.L., "Stability effects on aerosol size and height distributions", *Tellus*, **32**, 245-250, 1980.

[8] Andreas, E., "Sea spray and the turbulent air-sea heat fluxes", *J. Geophys. Res.*, **97**, 11429-11441, 1992.

[9] de Leeuw, G., "Modeling of extinction and backscatter profiles in the marine mixed layer", *Appl. Optics*, **28**, 1356-1359, 1989.

[10] Cipriano, R.J., and. Blanchard, D.C, "Bubble and aerosol spectra produced by a laboratory 'breaking wave'", *J. Geophys. Res.*, **86**, 8085-8092, 1981.

[11] Monahan, E.C., and O'Muircheartaigh, I.G., "Optical power-law description of oceanic whitecap coverage dependence on wind speed", *J. Phys. Oceanogr.,* **10**, 2094, 1980.

[12] Andreas, E.L, Edson, J.B., Monahan, E.C., Rouault, M.P. and Smith, S.D., "The spray contribution to net evaporation from the sea: a review of recent progress", *Boundary Layer Meteorol.*, **72**, 3-52, 1995.

[13] Miller, M.A., "An investigation of aerosol generation in the marine planetary boundary layer", M.S. thesis, 142 pp., Dep. of Meteorol., Pa. State Univ., University Park 1987.

[14] Monahan, E.C., D.E. Spiel and K.L. Davidson, "A model of marine aerosol generation via whitecaps and wave disruption", *in* "Oceanic whitecaps", edited by E.C. Monahan and G. Mac Niocaill, pp. 167-193, Reidel, 1986.

[15] Smith, M.H., Park, P.M. and Consterdine, I.E., "Marine aerosol concentrations and estimated fluxes over the

sea", *Quart. J. Roy. Meteorol. Soc.,* **119**, 809-824. 1993.

[16] Petelski, T. and Chomka, M., "Marine aerosol fluxes in the coastal zone - BAEX experimental data", *Oceanologia*, **38**, 469-484, 1996.

[17] Chomka, M. and Petelski, T., "Modelling the sea aerosol emission in the coastal zone", *Oceanologia*, **39**, 211-225, 1997.

[18] Mie, G., "Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösingen", *Ann. Phys.* **25**, pp. 377-445, 1908.

[19] Gathman, S.G., "Aerosol profiles near the sea surface during MAPTIP", *in* "Propagation assessment in coastal environments", AGARD CP **567**, paper 20, 1995.

[20] Seinfeld, J.H., "Atmospheric Chemistry and Physics of Air Pollution", Wiley, 1986.

[21] Hanna, S.R., Briggs, G.A. and Hosker, R.P. Jr., *Handbook on Atmospheric Diffusion*, Published by U.S. Department of Energy, DOE/TIC-11223 (DE82002045), 1982.

[22] Slinn, S.A., and Slinn, W.G.N., "Predictions for particle deposition on natural waters", *Atmospheric Environment,* **14**, pp. 1013-1016, 1980.

[23] Smith, F.B., "The problem of deposition in atmospheric diffusion of particulate matter", *Journal of the Atmospheric Sciences* **19**, pp. 429-434, 1962.

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# E-O Propagation, Signature and System Performance Under Adverse Meteorological Conditions Considering Out-of-Area Operations

(La propagation, la signature et les performances des systèmes optroniques dans des conditions météorologiques défavorables, compte tenu des opérations hors zone)

*Papers presented at the Sensors & Electronics Technology Panel Symposium held at the Italian Air Force Academy, Naples, Italy, 16-19 March 1998.*

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