Temporal and Spatial Characteristics of Surf zone Plumes[1]

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Abstract

One of the goals of the investigation, Electro-Optical Propagation Assessment in the Coastal Environment (EOPACE), is to enhance our understanding of the impact that surf generated aerosols have on the propagation of optical radiation through coastal regions. A bi-static LIDAR system uses a fan beam to illuminate the atmospheric region above the surf which permits measurements of both the vertical and horizontal extent of aerosol plume structures. The scattered radiation is imaged by two sensitive CCD cameras and a digital imaging camera, the latter being available only for the most recent test. Three measurement phases of the experiment program have provided data on the surf generated coastal plumes at two locations and under a range of different meteorological conditions. General spatial and temporal characteristics of these "coastal plumes", are described in this report.

1. Introduction

Judging from the interest in scientific investigations such as MAPTIP [1], VOCAR [2], and EOPACE [3], the coastal environments are of considerable importance. The attraction of the EOPACE program is its focus on the propagation of electromagnetic waves at optical frequencies in the coastal environment.

Toward this study, ARL/PSU (Applied Research Laboratory of The Pennsylvania State University) has provided measurement support using three instruments: (1) a LIDAR, (2) a transmissometer [4], and (3) a temperature mast (included in the April 1997 experiment). The ARL/PSU lidar has obtained data at the two Californian experimental sites: (1) the Scripps Institution of Oceanography (SIO, La Jolla) in 1996 and 1997 and (2) Moss Landing (Monterey) in 1996. Upon the first visit to the SIO (22 January to 5 February 1996), tall vertical structures were revealed by the bi-static LIDAR (Figure 1). These plumes provided a visual depiction of the scatters which decrease transmission. Hence, both the composition and characteristics of these plumes are of interest.

Figure 1: Typical plumes observed over the surf zone at La Jolla, CA, when illuminated by a vertical Argon-ion laser sheet. The picture was taken on 2 February 1996, at 7:15 PM with a low-noise CCD camera. The exposure time was 10 seconds.

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2. Experimental set-up

Figure 2 shows the set-up of the third experiment which, like the first one, was conducted at the SIO (31 March 31 to 11 April 11 1997). The unconventional bi-static LIDAR used a cylindrical lens to transform the incident Argon-ion (514.5 nm) CW laser beam into a vertical laser sheet. The receivers were low-noise high-resolution (16 bits) CCD cameras and one digital video camera. The former allows long integration times to retrieve distribution of the scatterers [5] and the latter to reveal the dynamics of the plumes. The temperature mast was located on the pier in the middle of the surf zone and provided more details about the processes just above the interface. Simultaneously, the SIO kept a record of the meteorological conditions from a weather station at the end of the pier. The distance over which the waves continuously break has been observed to be typically between 200 and 100 meters from the beach end of the 300 meter long pier.

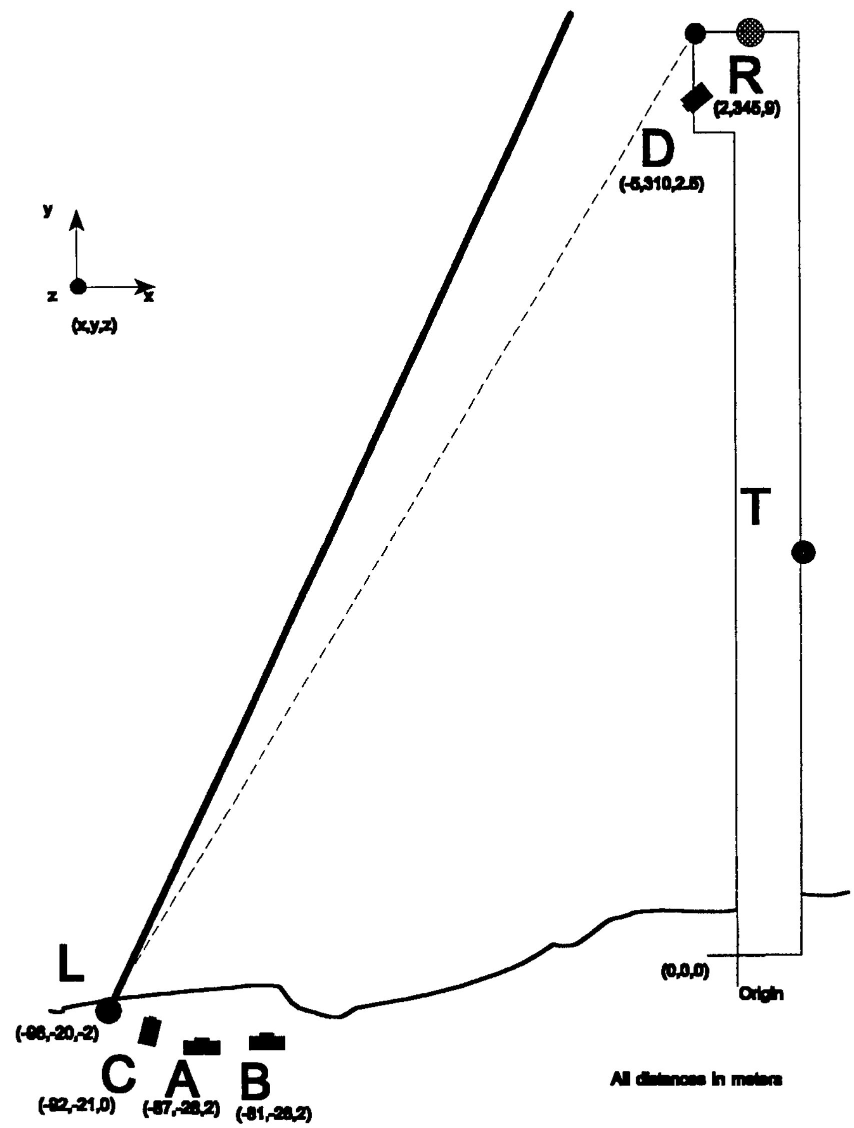

Figure 2: Experimental set-up at La Jolla, CA. L refers to the location of the source for the laser fan (emitter), A and B refer to those of the CCD cameras, C and D refer to those of the digital video camera, T refers to the one of the temperature mast, and R is a fixed reference point of known location which appears in every image.

3. The Coastal Atmospheric Boundary Layer

Considerable effort is currently underway to model the dynamics of coastal environments [6]. Those focusing on the first few tens of meters above the surf zone may validate their models using the ARL/PSU images. Figure 3 shows a sample of a cropped image from one of the CCD cameras and its corresponding projection along the pier. By keeping track of the location of the plumes and their heights under similar atmospheric conditions, one can plot the distribution of those heights versus the distance from the origin of the pier. Figure 4 displays such a plot obtained during the night of 2 April 1997, night during which a

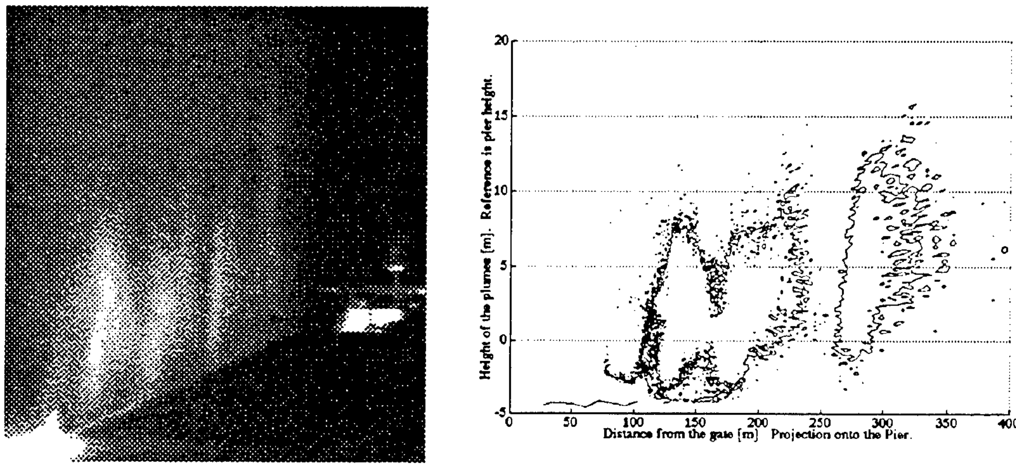

Figure 3: The left-hand side image shows a truncated image captured by the CCD camera positioned at A (see the map of Figure 2) on 2 April 1997, at 11:43 PM. Exposure time was 10 seconds. The structure in the background is that of the weather station at the end of the pier and the bright dot on its top is R, the reference point. The projection of this image onto a vertical plane which is parallel to the pier is shown on the right-hand side plot. The intensity contour chosen to define a plume was set to 3315 digital counts.

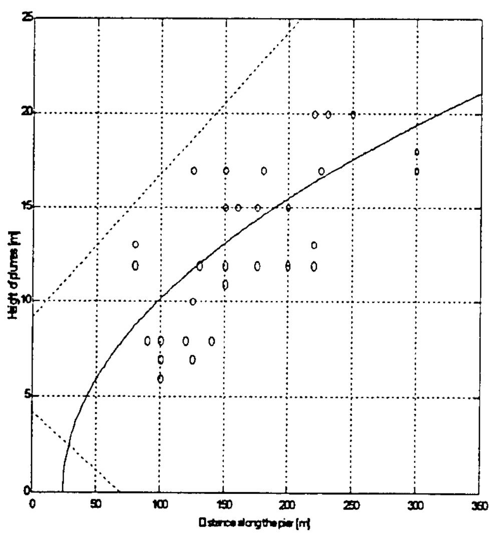

Figure 4: Plume height versus distance from the origin of the pier during the night of 2 April 1997. The tilted dashed lines trace the aperture of the laser fan. The solid line corresponds to a least-square fit of the data points (circles) with the following function: $\text{Height} = \text{Const}\sqrt{\text{Distance} - \text{Origin}}$.

slight offshore wind was present. As the air mass advected from land glides over the warmer surf-zone, a Thermal Internal Boundary Layer (TIBL) develops [7]. Several equations exist to model a TIBL, but most of them can be parameterized as:

$$\text{Height} = \text{Const}\sqrt{\text{Distance} - \text{Origin}} \qquad (1)$$

where the value of *Const* depends on the environmental conditions. The offshore wind acts as a sink for the net flux of particles emanated from the breaking waves. These conditions typically existed from late evening to early morning during the experimental phase (Figure 5a). When the temperature difference between water and land was small, the wind decreased in intensity and the density of the scatterers is approximately symmetrically distributed over the surf zone. Figure 1 shows such a case where the plumes are standing vertically. This particular situation occurred during transitional periods corresponding to a shift in direction of the mean wind (from offshore to onshore and vice-versa) and are depicted in Figures 5b and 5d.

When land temperature is greater than water temperature, onshore wind results. With it comes an TIBL, but located at the land and water intersection. Documentation of a possible internal boundary layer generated by the change of surface roughness between the open-ocean and the surf zone has yet to be satisfactorily supported. One reason is due to the geometry of the bi-static lidar whose vision of the plumes in their full height is impossible close to the transmitter (see dashed lines in Fig. 4). We suspect that an TIBL exists over the entire ocean surface, but that it is only discernible when the aerosol from the surf provides a tracer which can be observed from the laser illumination. The distinctive feature which is believed to form the TIBL is the temperature gradient in the first several meters above the surface, which is governed by the air/sea temperature difference. If this hypothesis is true, then the same kind of plume characteristics will be present during high sea states or when the aerosols are produced in the wake of a

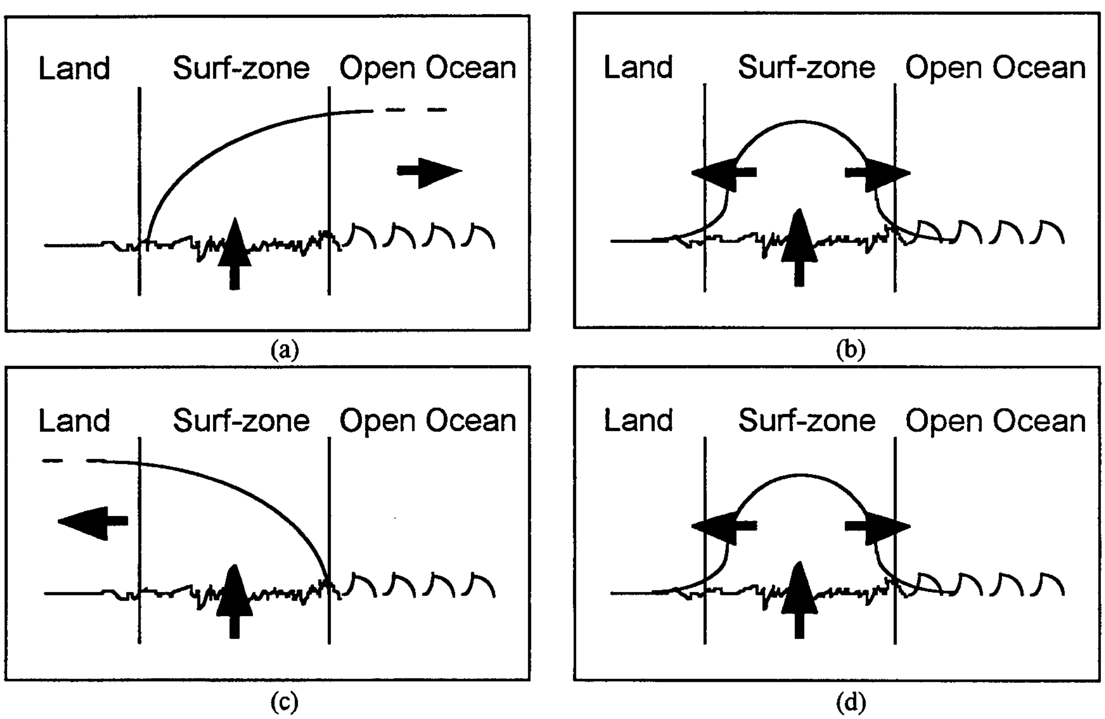

Figure 5: Cyclic temporal changes over the surf zone. (a) Over night (surface temperature of water is greater than the one over land), (b) early morning after sun rise (surface temperature of water and land are approximately equal), (c) later into the morning (surface temperature of water is smaller than the one over land), and (d) early into the night (surface temperature of water and land are approximately equal).

Table 1: Summary of the mean meteorological conditions and resulting plume heights over the surf zone during the three IOPs.

Location	SIO (I)	Moss Landing	SIO (II)
T_{Sea}-T_{air} [C]	3.3	1.7	2
Wind speed [m/s]	3.1	1	1.2
Av. plume height [m]	25	10	11

ship in the presence of air/sea temperature difference. Favorable conditions for the development of the coastal TIBL were between late morning and early evening (Fig. 5c). This time frame renders the observations of the plumes even more challenging because of the presence of the extremely large optical background signal during daytime.

Table 1 reviews the mean meteorological conditions in which all three experimental phases were conducted [8]. Departures from those mean values (all else being equal) reveal interesting features. First, when the wind increases, the plume height decreases. Second, when the temperature difference between the sea and air decreases, so does the plume height. This last effect agrees with Equation 1 for which Raynor et al. and Venkatram [7] have parameterized the proportion constant as follows:

$$\text{Const} \propto \left|T_{\text{Land}} - T_{Water}\right|^{1/2} / \text{Wind} \qquad (2)$$

We have observed that the tallest plumes occurred with calm winds and large temperature gradients.

We have argued that the plumes scale with the depth of an internal boundary layer. This gives us a better idea of the atmospheric conditions which will likely entrain the scatterers, provided that the wave activity produces them in sufficient quantity to render the plumes visible. A reliable source of ejected and spayed droplets, i.e., scatterers, are the breaking waves. Because not all breaking waves produce the same amount of aerosols, two of their categories are of interest: plungers and spillers. As waves turn into plunging breakers, trapped pockets of air entrained below the water surface eject many aerosols (i.e., water droplets) as the bursting air bubbles reach the surface. Spilling breakers are more gentle, surface bursting bubbles remain mainly at the surface. Under similar atmospheric conditions, plunging breakers produced more scattering[4] than spilling ones.

Hence, three variables seem to be appropriate to predict the height of the plumes: wind speed, temperature difference, and breaker type.

4. Temperature Mast

One way to assess whether atmospheric stability influences the height reached by the plumes is to measure the thermal vertical structure of the region above the surf zone. This aim motivated the installation of the mast, equipped with 7 thermistors, in the middle of the surf zone (Fig. 2). Figure 6 sketches the mast and provides the height for each sensor relative to the pier level. Once the data gathered, another analysis has been undertaken because of the necessity to refine and enhance some of the data sets required to estimate the Richardson number over the surf zone. Again, it is necessary to note that the height of the plumes is affected by the intensity level chosen to define a "plume". This number depends on the intensity of the scattering by the plumes and the exposure time to capture them.

Relative comparison between the environmental characteristics and the mean height of the plumes consists of the computation of (1) the mean temperature and the standard deviation of the mean temperature over all the sensors at each point in time (this is equivalent to assuming that each sensor sees one realization of the same random variable) and (2) the time-average for both the mean and the standard

[4] We imported the images into MATLAB where the function `contour` delimited the plumes. The subjective part of the analysis was to define the intensity levels corresponding to what we defined as being "plumes". Once a number had been selected (for a given exposure), it became a reference for the other cases.

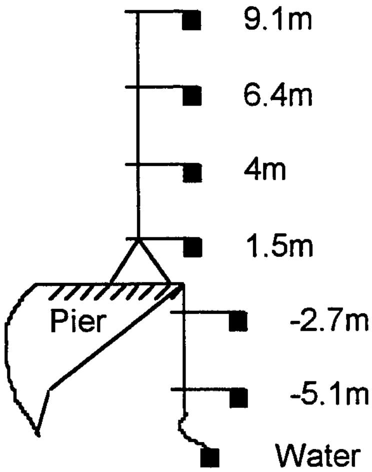

Figure 6: The temperature mast was located in the the middle of the surf zone where it captured several profiles. Heights are referenced to the pier. Water level was approximately -10 meters.

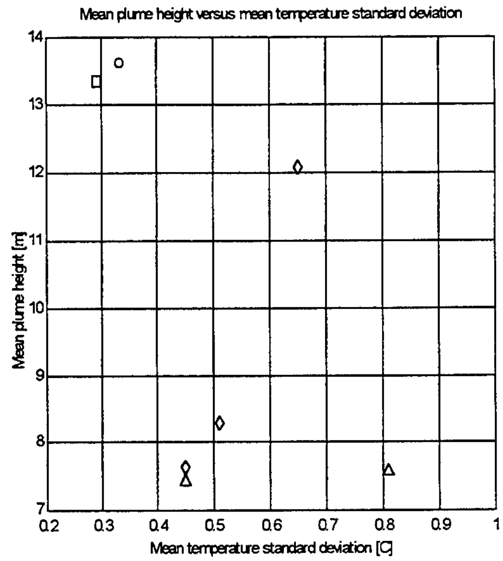

Figure 7: Mean height of the plumes for 2-10 April, 1997, as a function of temperature standard deviation. With a 10 sec exposure, squares refer to a 3315 contour-level and triangles to one of 4200. With a 30 sec exposure, diamonds refer to a 4200 contour-level and circles refer to one of 3500.

deviation of the mean temperature (which is equivalent to invoking ergodicity to expand the total number of realizations). Table 2 summarizes the results of this processing. Figure 7 plots the plume height versus the standard deviation of the mean temperature for this third experiment.

Before formulating hasty conclusions on the problem at hand, it is essential to realize that Table 2 allows comparison within the same group only. More work is required to compare results between different groups.

First, both the diamonds and the triangles reveal that the taller the plumes the higher the standard deviation of temperature. Second, the mean temperature results from a complicated process which takes

Table 2: Summary of the results from the processing of the plume heights and the data taken on the mast of temperature sensors.

Day/Month/ Year	Time (PST)	Symbol (Fig. 7)	Mean plume height [m]	Mean temperature [C]	Mean temperature std. deviation [C]
2 April 97	23:35-23:38	square	13.3	11.0	0.29
2 April 97	23:54-00:00	circle	13.6	10.9	0.33
7 April 97	19:50-19:55	diamond	7.6	16.7	0.45
7 April 97	21:43-21:50	diamond	8.3	16.1	0.51
9 April 97	00:20-00:26[5]	diamond	12.1	16.9	0.65
9 April 97	01:04[6]	triangle	7.6	17.0	0.81
9 April 97	20:21-20:24	triangle	7.4	16.5	0.45

[5] The plumes were analyzed over this time, but the closest set of temperature data was taken on 8 April from 23:54 to midnight. The meteorological and oceanographic conditions were stationary from one time segment to the next.

[6] The plumes were analyzed at this time, but the closest set of temperature data was taken from 01:19 to 01:25. The meteorological and oceanographic conditions were stationary from one time segment to the next.

into account both the air and the droplets inside the plumes. The temperature sensors located upwind and outside the surf zone give an actual air temperature (relatively free of surf-zone generated droplets) considerably lower than the mean temperature measured by the sensors on the mast (by 2 degrees Celsius). The only other potential thermal source is the water itself whose "bottom" temperature (defined by the SIO as being 3.5 meters below the mean lower low water level) remains around 17 degrees Celsius. Hence, the measured temperature results from a mixture of air and water droplets, the latter of which interacts with the thermal sensors through the processes of deposition and evaporation. This result confirms that the content of the plumes is sea water in nature. Contamination of temperature sensors by water has been reported by Friehe [9] who has noticed the spiky signature of the measurements.

An increase in the temperature fluctuations requires that there is "enough" time for some of the water to evaporate and that there is a significant amount of water coming suddenly into contact with the thermistors. The physical processes which promote this behavior need to be further analyzed.

Out of curiosity, the analysis of the plume heights for a different intensity level has been investigated. Once this level set to 4200 (the same as for the triangles and diamonds), neither the circle nor the square of Figure 7 resolve plumes. Notice that their standard deviations are the smallest of all the data points.

Therefore, we conclude that there is a strong correlation between the mean standard deviation of temperature and the mean plume height. However, the mean temperature is not a constant indicator of the plume height.

5. Conclusion

Our study shows that an internal boundary layer provides a means of estimating the height of the surf zone plumes. The physics behind such a boundary seems to include wind speed, buoyancy forcing, and, possibly, changes in surface roughness. The study of boundary layers is rendered difficult by the nesting[7] of boundary layers over the surf zone.

The meteorological conditions seem to prepare the atmosphere to accept any aerosols to form plumes, but the major contributor of aerosols is the surf zone itself via its breaking waves which eject significant amounts of water droplets. The brightest and tallest plumes are observed in the presence of larger temperature difference between air and water, minimum wind, and plunging breakers. Further studies of the effect of turbulence is necessary to determine whether it promotes tall plumes or shreds them. Our next step is to simulate those effects using Large Eddy Simulations [10] and compare the outputs of the model to our experimental data.

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[7] If one accounts for all the phenomena generating their own boundary layer, one faces an infinite number of intricate boundary layers, some developing, others blending in, but several boundary layers coexist, especially over the surf zone.

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