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Influence of atmospheric parameters on vertical profiles and horizontal transport of aerosols generated in the surf zone

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HIGHLIGHTS

- The measured vertical distributions of surf generated aerosols are discussed.
- The behavior of aerosols during transport is analyzed.
- Influence of atmospheric stability is demonstrated.
- The EOF methods allowed for separation the surf aerosols from aerosols advected.

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ABSTRACT

The vertical and horizontal transport of aerosols generated over the surf zone is discussed. Experimental data were collected during the second campaign of the Surf Zone Aerosol Experiment that took place in Duck NC (USA) in November 2007. The Empirical Orthogonal Function (EOF) method was used to analyze the vertical concentration gradients, and allowed separating the surf aerosols from aerosols advected from elsewhere. The numerical Marine Aerosol Concentration Model (MACMod) supported the analysis by confirming that the concentration gradients are more pronounced under stable conditions and that aerosol plumes are then more confined to the surface. The model also confirmed the experimental observations made during two boat runs along the offshore wind vector that surf-generated aerosols are efficiently advected out to sea over several tens of kilometers.

1. Introduction

With 70% of the Earth' surface covered by oceans, sea-salt is the most abundant aerosol species in the atmosphere. The sea salt aerosols are important in a variety of processes, such as marine stratocumulus microphysics and chemistry (e.g., O'Dowd et al., 1999). They affect the radiative transfer balance of our planet both directly (scattering) and indirectly (cloud condensation nuclei), which makes them a (ill-defined) factor in climate change models (e.g., Charlson et al., 1992). Hence, it is vital to reliably estimate the concentration of sea salt in the atmosphere.

Nearly 50 years ago, Woodcock (1962) published extensive data on sea-salt concentration as a function of altitude and wind speed. Many authors followed in his footsteps, with experimental (e.g., Chaen, 1973; Blanchard and Woodcock, 1980; Blanchard et al., 1984; De Leeuw, 1986; Stramska, 1987; Petelski and Piskozub, 2006; and others) and modeling efforts (e.g., Toba, 1965; Gathman and Davidson, 1993; Van Eijk et al., 2002). It was found that the concentration and vertical distribution of the aerosols are strongly dependent on wind speed (due to production and dispersion processes, see below) and that the concentration gradient varies with particle size. Small particles are more easily drawn upward, hence the average concentration gradients are much less pronounced for the smaller sizes than for the larger ones (e.g., De Leeuw, 1986; Piazzola and Despiau, 1997).

Sea-salt aerosols are generated from breaking waves (e.g., Blanchard, 1963). Wave breaking is especially abundant in the surf

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zone, which led Monahan (1995) to suggest that the surf zone is a high-intensive production zone as compared to Open Ocean. Since the surf zone also represents a localized line source, it is ideal for studying vertical and horizontal dispersion of sea-salt aerosols. However, whereas wave breaking in the open ocean is predominantly determined by the wind speed and the fetch, i.e., the distance an air mass has traveled over water (e.g., Lewis and Schwartz, 2004), other factors such as the bathymetry may become dominant (Van Eijk et al., 2011) in the surf zone. This implies that the production of sea-salt aerosols in the surf zone must be described by a dedicated (not Open Ocean) source function, of which few have been published (e.g., De Leeuw et al., 2000; Clarke et al., 2006; Van Eijk et al., 2011).

The transport properties of aerosols produced in the surf zone have been studied by several researchers. De Leeuw et al. (1997), using in-situ aerosol measurements, and Hooper and Martin (1999), using lidar observations, observed efficient vertical mixing at Scripps Pier with aerosol plumes reaching heights of 20–25 m over a minimal horizontal distance during onshore winds. On the contrary, Porter et al. (2003) and Clarke et al. (2006), using similar methods at Oahu, concluded that the plume heights did not exceed 5 m. For horizontal transport, lidar observations by Kunz et al. (2002) at the Irish west coast and Zielinski (2003) at the Baltic coast suggested that surf aerosols are transported over kilometers from their production zone during offshore flow. Their conclusion was supported by numerical simulations by Vignati et al. (2001). On the other hand, Petelski and Chomka (2000), using impactor measurements at the Baltic coast during onshore flow, concluded that the surf aerosols were not transported more than 82 m inland from the shoreline. While the discrepancies noted above may be (in part) related to difference in environmental conditions, the scarcity of observations and modeling efforts justifies a further study of the transport properties of aerosol generated over the surf zone.

This paper discusses both the aerosol vertical distributions as well as the transport of surf-generated aerosols out to sea. The measurements reported here are part of a larger experimental effort, the Surf Zone Aerosol Experiment (SZAE). The SZAE consisted of two experimental campaigns, both extensively described in Van Eijk et al. (2011). One experiment took place in La Jolla, CA, in the fall of 2006. The second experiment was organized in Duck NC, in the fall of 2007. Relevant experimental procedures for the analysis presented here are summarized in Section 2 of the present contribution. Section 3 describes the methodology and tools for analyzing the data, such as the Empirical Orthogonal Functions method and the numerical MACMod model, which was used to support the experimental results. The results for vertical and horizontal transport are presented in Sections 4 and 5, respectively.

2. Experimental

Data analyzed in this paper were collected at the 560 m long pier of the Field Research Facility (FRF) of the U. S. Army Corps of Engineers (http://www.frf.usace.army.mil/) in Duck, North Carolina, as part of the Surf Zone Aerosol Experiment (see Van Eijk et al., 2011 for details). The vertical aerosol measurements were made over a timeframe of three weeks (16 October–9 November 2007) with several episodes of onshore and offshore flow. The horizontal transport experiment took place during a two day offshore flow event on the 5th and the 6th November 2007.

Aerosol data were obtained with four optical particle counters manufactured by Particle Measuring Systems (PMS): two CSASP-200 probes, a CSAP-100HV and a CSASP-100HV-ER. Each of the CSASP-200 probes was co-located with a 100HV, and the data of the individual probes was merged into a single distribution in the data logger that was subsequently fitted to a 5th order polynomial. This created combined diameter ranges of 0.21–45.5 μm (probes 200 and 100HV) and 0.21–92 μm (probes 200 and 100HV-ER). In the remainder of this paper, the paired probes are referred to as probe 23 and probe 46, respectively. Van Eijk et al. (2011) provides additional information on probe calibration, intercomparison, and storage of raw data.

Meteorological data were collected by the TNO portable meteorological station and included air and sea temperatures, wind speed, wind direction, relative humidity, solar irradiance and rainfall. Data from the aerosol probes and the meteorological station were reduced by averaging over 5 or 10 min, and merged. This provided the data files used in the analysis, which contained the aerosol size distribution and the meteorological conditions at the time of observation. To eliminate humidity effects (the PMS probes collect data at ambient humidity), all size distributions were normalized to 80% humidity (Fitzgerald, 1975) before starting the analysis reported in Sections 4 and 5.

The FRF pier is equipped with the Sensor Insertion System (SIS, see Fig. 1), a crane-like device with two arms that can reach 15–23 m out from the side of the pier. This allows for aerosol measurements at two vertical levels (generally 6 and 16 m above the water) while minimizing the effects of the pier on the air flow. Probe 46, with the largest combined diameter range, was placed on the lower arm. Since the SIS can be positioned anywhere on the pier, it was possible to make measurements downwind of the surf zone in both onshore and offshore flow conditions.

Horizontal transport measurements were made with a commercial fishing boat, the "Wahoo". Aerosol probes 23 and a small meteorological station were mounted on top of the boat's main cabin at approximately 3 m above the water line, while the data logger was inside the main cabin. During steady offshore flow conditions, the "Wahoo" sailed from the end of the pier along the offshore wind vector to a maximum distance of 12 km (Nov 5) and 16 km (Nov 6). Along the track, data was collected at 10 waypoints. At each waypoint, 15 min of data was averaged into a single data file. The experiment started and ended with a 15-min data collection at the end of the pier. The data thus collected was compared to the data of probe 46, which remained on the lower arm of the SIS, just downwind of the surf zone. The changes in concentration between probes 23 and 46 as function of downward distance of the "Wahoo" provided an estimate of the efficiency of horizontal aerosol transport.

3. Methodology

3.1. The analysis methods for the PMS data

Since all aerosol probes had been intercalibrated, vertical gradients in the aerosol concentration can be inferred from the differences in size distributions measured by probes 23 and 46 on the two arms of the SIS. Since there are only two heights, it might seem logical to fit a linear gradient to the observed concentrations. However, many authors assume that the concentration gradient follows an exponential law, as shown by Toba (1965) under the assumption of equilibrium between production and deposition. While in many situations the existence of equilibrium is questionable, especially over the surf zone, we have decided, for the purpose of more easy comparison to other studies, to follow Toba (1965):

$$\frac{\mathrm{d}N(z,\ D)}{\mathrm{d}D} = \frac{\mathrm{d}N\left(z_{ref},\ D\right)}{\mathrm{d}D}\exp\left[\xi(D)\left(z - z_{\mathrm{ref}}\right)\right] \tag{1}$$

where $\mathrm{d}N/\mathrm{d}D$ is the concentration in [$\mu\mathrm{m}^{-1}$ cm^{-3}], D the particle diameter in [μm] at RH = 80%, z and z_{ref} in [m] the tide-corrected heights of probe 23 and 46, respectively, and $\xi(D)$ in [m^{-1}] the aerosol gradient. It is emphasized that eq. (1) only provides the