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Coupling an ocean wave model with a global aerosol transport model: A sea salt aerosol parameterization perspective

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[1] A new approach to sea salt parameterization is proposed which incorporates wind-wave characteristics into the sea salt emission function and can be employed globally and under swell-influenced conditions. The new source function was applied into Navy Aerosol Analysis and Prediction System model together with predictions from the global wave model Wave Watch III. The squared surface wind velocity U_{10} and the wave's orbital velocity $V_{orb}=\pi H_s/T_P$ are shown to be the key parameters in the proposed parameterization. Results of the model simulations are validated against multi-campaign shipboard measurements of the sea salt aerosol. The validations indicate a good correlation between V_{orb} and the measured surface concentrations. The model simulations with the new parameterization exhibit an improved agreement with the observations when compared to a wind-speed-only approach. The proposed emission parameterization has the potential to improve the simulations of sea salt emission in aerosol transport models. **Citation:** Witek, M. L., P. J. Flatau, J. Teixeira, and D. L. Westphal (2007), Coupling an ocean wave model with a global aerosol transport model: A sea salt aerosol parameterization perspective, *Geophys. Res. Lett.*, *34*, L14806, doi:10.1029/2007GL030106.

1. Introduction

[2] Sea salt aerosol is one of the most abundant components of the atmospheric aerosol, with an estimated mass emission from 0.3 to 30 teragrams (10^{12} kg) per year [*Lewis and Schwartz*, 2004]. It exerts a strong influence on radiation, cloud formation, meteorology and chemistry of the marine atmosphere. An accurate understanding and description of these mechanisms is crucial to modeling climate and climate change.

[3] Recent studies [*Andreas*, 1998; *Guelle et al.*, 2001; *Lewis and Schwartz*, 2004] revealed large uncertainties in simulating the life cycle of the sea salt aerosol. Emission parameterizations available in the literature differ by several orders of magnitude in predicting number and mass production. There is no agreement about the size distribution of emitted particles. The observed uncertainties put into question the legitimacy of parameterizations based solely on atmospheric parameters such as wind speed or wind friction velocity. It has been suggested [e.g., *Xu et al.*, 2000; *Zhao and Toba*, 2001; *Stramska and Petelski*, 2003] that ocean wave characteristics like significant wave height H_s, peak wave period T_p or wave steepness could serve as good candidates for emission parameterization. However, simultaneous measurements of sea-salt aerosol properties and H_s or T_p are not common. On the other hand there is the possibility for the development of more sophisticated approaches based on numerical global ocean wave models. Such models provide wave quantities such as H_s, T_p and allow for investigations of their impact on the sea salt emission.

[4] Recently some wave-state-dependent sea salt emission parameterizations were proposed. *Zhao and Toba* [2001] relate the whitecap ratio W to the nondimensional breaking wave parameter $R_b = u_*^2/\nu\omega_p$ where u_* is the friction velocity, ω_p is the peak angular frequency of the waves and ν is the kinematic viscosity of air. As an alternative, *Zhao and Toba* [2001] proposed another nondimensional scaling parameter, $R_h = u_* H_s/\nu$, which incorporates the significant wave height H_s into the whitecap ratio parameterization. However, both functions are limited to the case of wind-waves in local equilibrium with the wind. There are often conditions in the open ocean, where swell is predominant. Independent studies of the sea surface roughness [*Taylor and Yelland*, 2001; *Drennan et al.*, 2005] show that the presence of swell acts, on average, to significantly decrease the effective wave steepness and hence the mean roughness compared to that for pure wind-sea. This, consequently, affects the momentum transfer between air and sea and the wave breaking probability.

[5] Another example is the study of *Petelski et al.* [2005], where the sea spray emission parameterization in the form $F_E = A \cdot (H_s^{1/2} \cdot U_{10}^2)^{2/3} + B$ is proposed. Here F_E is the emission flux expressed in μgm^{-2}s^{-1}, H_s [m] is the significant wave height, U_{10} [m/s] is the wind speed at 10 meters above the sea surface and the coefficients $A = 1.2 \times 10^{-6}$; $B = -1.6 \times 10^{-7}$ are in units defined by the above listed units of F_E, H_S and U_{10}. This expression was determined specifically for the Baltic Sea and is not supposed to be applied over open oceans globally.

2. Approach

[6] Our approach is based on the whitecap method [*Lewis and Schwartz*, 2004, p. 105]. The size-dependent sea salt aerosol production flux over whitecap area only, i.e. the differential whitecap aerosol productivity, is taken after *Monahan et al.* [1986, equation (4)]. Integrated over dry particle sizes it gives the sea salt mass emission per unit area per unit of time and the multiplication by the fraction W of

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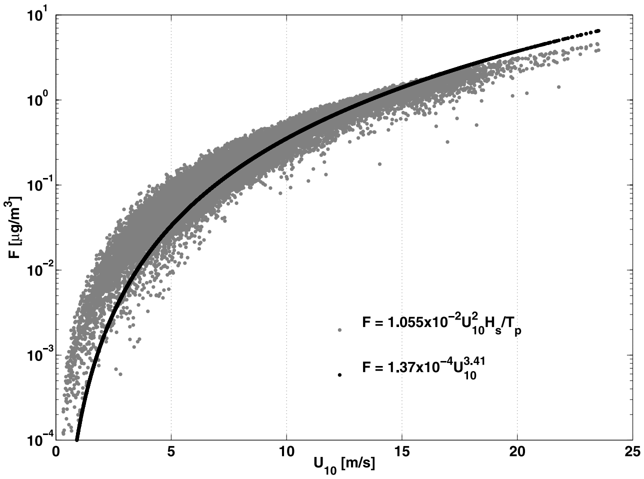

Figure 1. Sea salt mass emission as a function of surface wind velocity. Black points represent the reference (Monahan's) parameterization whereas gray points represent the proposed parameterization.

the sea surface covered by whitecaps completes the emission parameterization. The whitecap ratio W is defined as

$$W = aU_{10}^2 \frac{H_s}{T_p},$$

where U_{10} [m/s] is the wind speed at 10 meters above the sea surface, H_s [m] is the significant wave height, T_p [s] is the peak wave period, and a [s^3/m^3] is a constant. The parameter H_s/T_p is proportional to the dominant wave's orbital velocity $V_{orb}=\pi H_s/T_p$, which is the velocity of water at the air-sea interface in its circular movement in a wave.

[7] Thus, following the whitecap method approach [*Lewis and Schwartz*, 2004, p. 105], the sea salt mass emitted from the ocean's surface is

$$F = 1.055 \times 10^{-2} \times U_{10}^2 \frac{H_s}{T_p}.$$

[8] F is expressed in $\mu gm^{-2}s^{-1}$ and is defined for particles with dry radius between $0.05 \leq r_{dry} \leq 4$ microns.

[9] The new source function is implemented into the Navy Aerosol Analysis and Prediction System (NAAPS) model [*Christensen*, 1997; *Witek et al.*, 2007]. NAAPS is a global off-line aerosol and pollution transport model that operates at 1 degree horizontal resolution and 24 vertical terrain-following sigma levels. The model was modified to incorporate output data from the global wave model Wave Watch III (WW3) [*Tolman*, 1999]. The parameters that were used in NAAPS were the significant wave height H_s and the peak wave period T_p.

[10] Results of the simulations are validated against multi-campaign shipboard measurements of sea salt surface mass concentrations carried out by the NOAA Pacific Marine Environmental Laboratory (PMEL). The experiments considered here are Aerosols99-INDOEX, ACE-Asia, NEAQS-2002 and NEAQS – ITCT 2004. Chemical measurements of sub- and super micron mass concentrations were carried out on board of the NOAA research vessel R/V Ronald B. Brown. The temporal resolution was about 6 hours; the observations covered parts of the Pacific, Atlantic and Indian Oceans.

3. Results

[11] Figure 1 presents a comparison of emission values obtained with the new and the wind-speed-only dependent [*Monahan et al.*, 1986, equation (12); *Witek et al.*, 2007] source functions. A sample output data from the global 1×1.25 degree WW3 model (date: 7-Aug-2004, 12UTC; source: NOAA archives, ftp://polar.ncep.noaa.gov/pub/history/waves) was used as a source of U_{10}, H_s and T_p. The new parameterization produces large scatter in emissions for a given wind velocity. Emission varies over one order of magnitude at 5 m/s and the spread gradually decreases as the wind speed increases. Such variation could partially explain large scatter in emissions predicted by existing parameterizations [*Andreas*, 1998; *Lewis and Schwartz*, 2004]. Lower emission in the high wind speed regime concurs with previous suggestions [*Andreas*, 1998; *Witek et al.*, 2007] that Monahan's parameterization might overestimate emission under strong wind speed conditions.

[12] A detailed analysis of measured and modeled sea salt surface mass concentrations from Aerosols99 and INDOEX experiments was performed. Figure 2 presents the PMEL group measurements and the model results from the southern Atlantic Ocean (Aerosols99-Leg 1). Figure 3 presents similar results but for data from the Indian Ocean (INDOEX). Figure 3 (top) shows the observed and modeled sea salt surface mass concentrations during the cruise. Two independent transport model simulations were performed: one with the reference Monahan emission source function (dotted line) and the second with the proposed parameterization (dashed line). In Figure 3 (bottom), left axis, shows measured surface wind speed (solid line), averaged over the aerosol filter collection period (typically 6 hours) and the model wind velocity (dotted line). The right axis in Figure 3 (bottom) (dashed line) shows the wave's orbital velocity V_{orb} during the cruise.

[13] A first-glance evaluation of the results reveals a good correlation between the wave's orbital velocity and the measured sea salt mass concentrations. Episodes of increased V_{orb} correspond to higher aerosol loadings on days 29th, 34th and 36th. Lower values of V_{orb} correspond to minimum observed sea salt mass concentrations. Such behavior is often observed despite local wind conditions. For instance, around day 31 and 57 the winds were strong enough (over 6 m/s) to expect increased aerosol concentrations. Such increase is not observed suggesting that low V_{orb} might have suppressed aerosol production. Figure 3 illustrates another episode between days 76 – 82 and shows a possible influence of the orbital velocity as a factor driving the sea salt emission. During the episode surface wind velocity gradually decreased from 11 to about 6 m/s. The surface sea salt mass concentrations exhibit an opposite trend, rising from about 7 to 13 μgm^{-3}. This increase corresponds well with the changes in V_{orb}. Transport model simulations show that the proposed emission parameterization is able to capture the trend of the surface sea salt mass concentrations change during this episode, surpassing the wind-speed-only parameterization in accuracy.

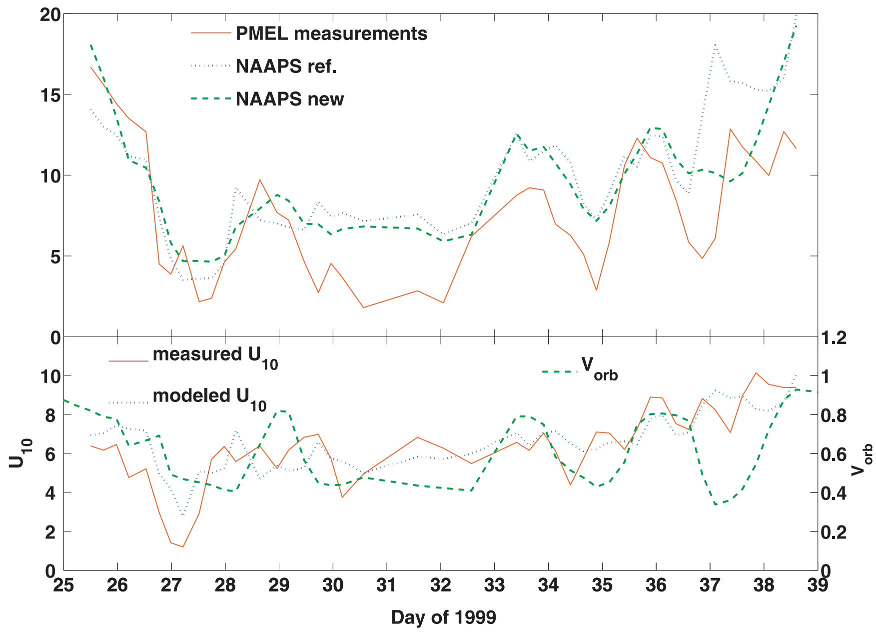

Figure 2. (top) Sea salt surface mass concentrations during Aerosols99 (Leg 1, Southern Hemisphere only) experiment. Solid line represents PMEL group observations; NAAPS results from two simulations, one with reference emission parameterization and the other with the proposed emission scheme are represented by dotted and dashed lines, respectively. (bottom) Left axis, ship measurements (solid line) and NOGAPS (dotted line) surface wind velocities; right axis, wave's orbital velocity (dashed line) ($V_{orb} = \pi H_s/T_p$).

[14] In Table 1 correlation coefficients between the PMEL group sea salt measurements and the NAAPS model results are presented. Cases where no precipitation was observed were selected. For most analyzed campaigns, with the exception of INDOEX, an improved or similar correlation is observed. The lower INDOEX correlation, however, is in contradiction with the previous analysis that indicated a better agreement with observations (see Figure 3). This may indicate a limited ability of the correlation coefficient to fully characterize the model's performance. Therefore, a detailed investigation of concentration trends is needed to properly evaluate the model's performance.

4. Discussion and Conclusions

[15] The squared surface wind velocity U_{10} and the wave's orbital velocity $V_{orb} = \pi H_s/T_p$ are shown to be key parameters for a proposed parameterization of the sea salt

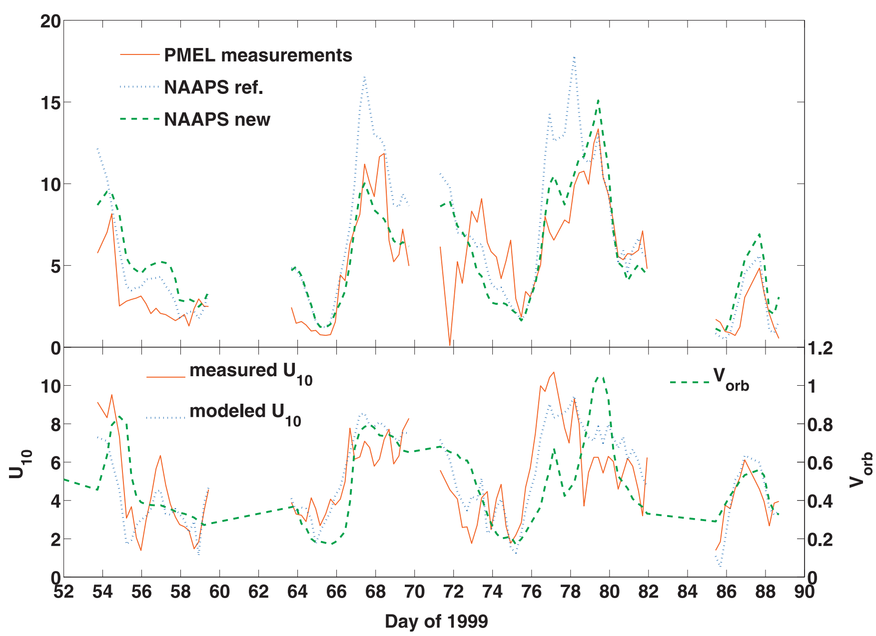

Figure 3. Same as Figure 2 but for INDOEX experiment.

Table 1. Correlation Coefficients Between the PMEL Group Sea Salt Aerosol Observations and the NAAPS Results From Two Simulations for Each of the Experiments[a]

	Aerosols99	INDOEX	ACE-Asia	NEAQS-2002	NEAQS-2004
Number of observations	48	83	37	39	52
Old	0.72	0.84	0.57	0.45	0.94
New	0.79	0.77	0.62	0.47	0.93

[a]'Old' stands for the NAAPS simulation with the reference emission function. 'New' stands for the NAAPS simulation with the proposed emission parameterization. The numbers of free of precipitation comparison points for each of the experiments are also shown.

emission. The parameter V_{orb}, although new in such application, can be inferred from some previous papers. Studies of *Zhao and Toba* [2001] and *Petelski et al.* [2005] suggest that emission is proportional to the significant wave height ($F \propto H_s$). Their arguments are additionally supported by the fact that H_S is proportional to the square root of the total wave energy E. Higher E implies larger dissipation, reflected by more frequent wave breaking and thus enhanced aerosol production.

[16] However, the inverse proportionality to the peak wave period ($F \propto H_P^{-1}$) is not well documented in the literature. The wave period is proportional to the square root of the length L of a wave, therefore H_s/T_p is related to the wave steepness $S = H_s/L$. A more quantitative argument can be derived from statistical analysis of output data from the wave model. A correlation coefficient between the surface wind velocity U_{10} and a combination of the H_s and T_p values ($H_s^x T_p^y$, where x and y ranged between [−3, 3]) was computed. The highest correlation (results not shown) was found when $x = 1$ and $y = -1$. This indicates closer relationship between U_{10} and H_s/T_p rather than between U_{10} and H_s alone.

[17] The presented parameterization for the sea salt emission function, due to the high correlation between V_{orb} and U_{10}, preserves characteristics of previously published wind-speed-only parameterizations. At the same time it introduces additional variability, as shown in Figure 1, dependent on wave characteristics and wave-state development. The computed orbital velocity correlates well with observed trends of the sea salt surface mass concentrations, often giving better agreement than that based on surface wind velocity only. Such behavior indicates a potential for the use of V_{orb} in improving emission parameterizations. Another novel aspect of this work is that the new source function was applied into NAAPS model together with predictions from the global wave model WW3. Parameters that were used in NAAPS were significant wave height H_s and peak wave period T_p. Results of the simulations were validated against multi-campaign shipboard measurements of the sea salt aerosol, including Aerosols99-INDOEX, ACE-Asia, NEAQS-2002 and NEAQS – ITCT 2004. Validations indicate good correlation between simulated and measured sea salt surface mass concentrations. Further research should be undertaken to validate these findings and to assess the usefulness of V_{orb} in sea salt emission parameterization as well as usefulness of coupling between transport models and global wave models.

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References

Andreas, E. L. (1998), A new sea spray generation function for wind speeds up to 32 ms^{-1}, *J. Phys. Oceanogr.*, *28*, 2175–2184.
Christensen, J. H. (1997), The Danish eulerian hemispheric model—A three-dimensional air pollution model used for the arctic, *Atmos. Environ.*, *31*, 4169–4191.
Drennan, W. M., P. K. Taylor, and M. J. Yelland (2005), Parameterizing the sea surface roughness, *J. Phys. Oceanogr.*, *35*, 835–848.
Guelle, W., M. Schulz, and Y. Balkanski (2001), Influence of the source formulation on modeling the atmospheric global distribution of sea salt aerosol, *J. Geophys. Res.*, *106*, 27,509–27,524.
Lewis, E. R., and S. E. Schwartz (Eds.) (2004), *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements and Models—A Critical Review*, *Geophys. Monogr. Ser.*, vol. 152, AGU, Washington, D. C.
Monahan, E. C., D. E. Spiel, and K. L. Davidson (1986), A model of marine aerosol generation via whitecaps and wave disruption, in *Oceanic Whitecaps and Their Role in Air-Sea Exchange Processes*, edited by E. C. Monahan and G. MacNiocaill, pp. 167–174, Springer, New York.
Petelski, T., J. Piskozub, and B. Paplinska-Swerpel (2005), Sea spray emission from the surface of the open Baltic Sea, *J. Geophys. Res.*, *110*, C10023, doi:10.1029/2004JC002800.
Stramska, M., and T. Petelski (2003), Observations of oceanic whitecaps in the north polar waters of the Atlantic, *J. Geophys. Res.*, *108*(C3), 3086, doi:10.1029/2002JC001321.
Taylor, P. K., and M. J. Yelland (2001), The dependence of sea surface roughness on the height and steepness of the waves, *J. Phys. Oceanogr.*, *31*, 572–590.
Tolman, H. L. (1999), User manual and system documentation of WAVEWATCH-III version 1.18, *NOAA/NWS/NCEP/OMB Tech. Note 166,* 110 pp.
Witek, M. L., P. J. Flatau, P. K. Quinn, and D. L. Westphal (2007), Global sea-salt modeling: Results and validation against multicampaign shipboard measurements, *J. Geophys. Res.*, *112*, D08215, doi:10.1029/2006JD007779.
Xu, D., X. Liu, and D. Yu (2000), Probability of wave breaking and whitecap coverage in a fetch-limited sea, *J. Geophys. Res.*, *105*, 14,253–14,259.
Zhao, D., and Y. Toba (2001), Dependence of whitecap coverage on wind and wind-wave properties, *J. Oceanogr.*, *57*, 603–616.

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