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SHORT COMMUNICATION

Addendum to "Sea spray aerosol flux estimation based on long-term variation of wave statistics": estimation based on long-term variation of wind statistics☆

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Summary This note provides estimates of the mean whitecap coverage and the mean sea spray aerosol flux based on long-term wind statistics from the Northern North Sea. Here the improved sea spray aerosol production flux model by Callaghan (2013) is used. The results are compared with those in Myrhaug et al. (2015) based on long-term wave statistics from the Northern North Sea and the North Atlantic.

1. Introduction

Myrhaug et al. (2015) (hereafter referred to as MWH15) provided estimates of the mean sea spray aerosol flux based on long-term variation of wave statistics using the whitecap method applying the limiting steepness and threshold vertical acceleration criteria. Here the long-term wave statistics represented open ocean deep water waves in the Northern North Sea and the North Atlantic. This note is supplementary to MWH15 with the purpose of demonstrating how similar results for the mean sea spray aerosol flux can be obtained by using estimates of the whitecap coverage based on long-term variation of wind statistics. Moreover, the whitecap method used in MWH15 has been replaced by the Callaghan (2013) improved sea spray aerosol production flux model.

The whitecap coverage, which is defined as the area of whitecaps per unit sea surface, has often been used to

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quantify the occurrence of breaking wind waves at sea. There are many parameterizations of whitecap coverage available in the literature; comprehensive reviews are given in Anguelova and Webster (2006), Massel (2007) and de Leeuw et al. (2011). Parameterizations are based on U_{10} and u_*. Here U_{10} [m s^{-1}] is the mean wind speed at the 10 m elevation, and u_* [m s^{-1}] is the friction velocity equal to the square root of the vertical flux of horizontal momentum at the sea surface. However, when plotting the whitecap coverage versus U_{10} and versus u_* it is often found that the data scatter is larger when plotted versus u_* than when plotted versus U_{10} (see e.g. Sugihara et al., 2007). This is attributed to the larger uncertainties in estimating u_* than measuring U_{10}. Therefore the parameterizations in the present study are based on U_{10}. Other important factors affecting the whitecap coverage are the stratification of the near-surface air boundary layer and the state of development of surface waves, see e.g. Sugihara et al. (2007) and Myrhaug and Holmedal (2008). Reviews of whitecap coverage at sea and how it is linked to marine aerosol production are given by Massel (2007), de Leeuw et al. (2011) and Callaghan (2013).

2. Whitecap coverage and sea spray aerosol flux estimation based on long-term variation of wind statistics

2.1. Whitecap coverage estimation

The following whitecap coverage (W_c) parameterizations will be considered here to demonstrate the use of wave statistics.

The Monahan and O'Muircheartaigh (1980) (hereafter referred to as MO80) parameterization is widely used and recognized (de Leeuw et al., 2011), given as fraction,

$$W_c = 3.84\times10^{-6}U_{10}^{3.41}. \tag{1}$$

The Callaghan et al. (2008) (hereafter referred to as C08) parameterization is based on data collected in the North East Atlantic inside a geographical area defined by 9.5°W, 13°W, 55.5°N and 57.5°N, given in percent,

$$\begin{aligned} W_c &= 0.00318(U_{10}-3.70)^3; \quad 3.70\,\mathrm{m\,s^{-1}} < U_{10} < 10.18\,\mathrm{m\,s^{-1}} \\ W_c &= 0.000482(U_{10}+1.98)^3; \; 10.18\,\mathrm{m\,s^{-1}} < U_{10} < 23.09\,\mathrm{m\,s^{-1}} \end{aligned} \tag{2}$$

It should be noted that the wave statistics in BGGS07 (Bitner-Gregersen and Guedes Soares, 2007) Data Sets 1 to 5 used in MWH15 is from the same ocean area, i.e. from the North Atlantic.

According to Eqs. (1) and (2) the whitecap coverage is given for a known value of U_{10}. The long-term variation of the whitecap coverage can be obtained from available wind statistics, i.e. from long-term distributions of U_{10}. Different parametric models for the cumulative distribution function (*cdf*) or the probability density function (*pdf*) of U_{10} are given in the literature. A recent review is given in Bitner-Gregersen (2015), where the joint statistics of U_{10} with significant wave height H_s and spectral peak period T_p are presented. In the present article the long-term statistics of W_c are exemplified by using the *cdf* of U_{10} given by Johannessen et al. (2001), where wind measurements covering the years 1973—1999 from the Northern North Sea are used as a database. This database consists of composite measurements from the Brent, Troll, Statfjord and Gullfaks fields as well as the weather ship Stevenson. Model data from the Norwegian hindcast archive (WINCH, gridpoint 1415) have been filled in for periods where measured data were missing. Thus a 25-year long continuous time series has been used (see Johannessen et al. (2001) for more details), upon which the *cdf* of the 1-h values of U_{10} is described by the two-parameter Weibull model

$$P(U_{10}) = 1-\exp\left[-\left(\frac{U_{10}}{\alpha}\right)^{\beta}\right]; \quad U_{10}\geq 0, \tag{3}$$

with the Weibull parameters

$$\alpha = 8.426, \qquad \beta = 1.708. \tag{4}$$

It should be noted that the wave statistics in MGAU05 (Moan et al., 2005) used in MWH15 is from the same ocean area as the wind statistics, i.e. from the Northern North Sea.

If $x = U_{10}$ is defined for $x_1 \leq x \leq x_2$, then x follows the truncated Weibull *cdf* given by

$$P(x) = \frac{\exp\left[-\left(\frac{x_1}{\alpha}\right)^{\beta}\right]-\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]}{\exp\left[-\left(\frac{x_1}{\alpha}\right)^{\beta}\right]-\exp\left[-\left(\frac{x_2}{\alpha}\right)^{\beta}\right]}; \quad x_1\leq x\leq x_2. \tag{5}$$

Now the long-term statistics of W_c can be derived by using this *cdf* of $x = U_{10}$. A statistical quantity of interest is the expected (mean) value of W_c given as

$$E[W_c(x)] = \int_0^{\infty} W_c(x)p(x)\,dx, \tag{6}$$

where $p(x)$ is the probability density function (*pdf*) of $x = U_{10}$ given by $p(x) = dP(x)/dx$ where $P(x)$ is given in Eq. (5). Then the integral in Eq. (6) can be calculated analytically by using the results in Abramowitz and Stegun (1972, Chs. 6.5 and 26.4)

$$\begin{aligned} E[x^n] &= \int_{x_1}^{x_2} x^n p(x)\,dx \\ &= \frac{\alpha^n}{N}\left\{\Gamma\left[1+\frac{n}{\beta},\left(\frac{x_1}{\alpha}\right)^{\beta}\right]-\Gamma\left[1+\frac{n}{\beta},\left(\frac{x_2}{\alpha}\right)^{\beta}\right]\right\}, \end{aligned} \tag{7}$$

$$N = \exp\left[-\left(\frac{x_1}{\alpha}\right)^{\beta}\right]-\exp\left[-\left(\frac{x_2}{\alpha}\right)^{\beta}\right], \tag{8}$$

where $\Gamma(s, t)$ is the incomplete gamma function, and n is a real number (not necessarily an integer). It should be noted that $\Gamma(s, 0) = \Gamma(s)$ where Γ is the gamma function, and $\Gamma(s, \infty) = 0$. Here the results are exemplified by using the parameterizations of W_c in Eqs. (1) and (2). The results are

$$\mathrm{MO80}: \quad E[W_c] = 1.10\%, \tag{9}$$

$$\mathrm{C08}: \quad E[W_c] = 0.76\%. \tag{10}$$

The estimate in Eq. (9) is obtained by integrating from zero to infinity, while the estimate in Eq. (10) is obtained by integrating from $x_1 = U_{10} = 3.70$ m s^{-1} to infinity, i.e. giving a 6% larger value than by integrating to $x_2 = U_{10} = 23.09$ m s^{-1}.

The corresponding results obtained in MWH15 (see the results for the MGAU05 data (Northern North Sea) and the

BGGS07 Data Sets 1 to 5 (North Atlantic) in Table 5) are denoted as $E[F_{cov}]$ by using the limiting steepness criterion (Criterion 1) and the threshold vertical acceleration criterion (Criterion 2). It appears that some of the example estimates based on the wind statistics agree well with some of the estimates based on the wave statistics, i.e. (1) the MO80 wind statistics estimate of 1.1% agrees well with the mean value of the estimate corresponding to BGGS07 Data Sets 1 to 5 using Criterion 2 of 1.2%; (2) the C08 wind statistics estimate of 0.76% agrees well with the estimate corresponding to MGAU05 using Criterion 1 of 0.77% (which is larger than the estimate using Criterion 2 of 0.58%).

2.2. Sea spray aerosol flux estimation

Rather than pursuing the method used in MWH15, a recent improved method given by Callaghan (2013) (hereafter referred to as C13) will be used. Thus, following C13, Eq. (1) in MWH15 should be rewritten to explicitly include the time scale of the decaying whitecap area as (i.e. using the notation in C13 by taking $\log r \equiv \log_{10} r$ and $r \equiv r_{80}$)

$$\frac{dF(r)}{d(\log r)} = \frac{dE(r)}{d(\log r)} \cdot \frac{W_c}{\tau}. \tag{11}$$

Here the term on the left hand side of the equation is the number of particles produced per unit ocean surface area and unit time per radius size bin. The first term on the right hand side of the equation is the number of particles produced per whitecap area per radius size bin, W_c is the whitecap per unit ocean surface area, and τ is a characteristic whitecap time scale which cannot be incorporated in the first term on the right hand side of the equation to produce an estimate of the rate of particle production per whitecap area. Here the droplet radius r is taken to represent r_{80}, i.e. the droplet radius in equilibrium with the atmosphere at a given ambient relative humidity of 80%. Moreover, following C13 the first term on the right hand side of Eq. (11) is given by

$$\frac{dE(r)}{d(\log r)} = 29419r(1 + 0.057r^{3.45}) \cdot \exp\left\{ \begin{matrix} 3.68\exp[-5.33(0.433 - \log r)^2] \\ -4.7\ln r[1 + \Theta r]^{-0.017r^{-1.44}} \end{matrix} \right\}, \tag{12}$$

with the unit m^{-2}, where Θ is an adjustable parameter with 30 as a typically assigned value. The whitecap coverage in % is given in Eq. (2) (see C13 for more details).

Now it follows that

$$\frac{dF(r)}{dr} = \frac{r^{-1}}{\ln 10} \frac{dF(r)}{d(\log r)}, \tag{13}$$

with the unit $m^{-2}\,s^{-1}\,\mu m$, and consequently the total flux for particles with radii in the interval r_1 to r_2 is

$$F(r) = \int_{r_1}^{r_2} \frac{r^{-1}}{\ln 10} \frac{dF(r)}{d(\log r)} dr, \tag{14}$$

with the unit $m^{-2}\,s^{-1}$. The volume flux with unit $m\,s^{-1}$ is obtained by multiplying Eq. (14) by the factor $(4\pi/3)r^3$.

The total expected volume aerosol flux of $r = r_{80}$, $E[F(r)]$, can now be estimated based on the long-term wind statistics used in Section 2.1. The results are obtained by multiplying Eq. (14) with $E[W_c] = 0.76\%$ from Eq. (10) and dividing by $\tau = 5.3$ s (see C13). By integrating $r = r_{80}$ over the range 0.8—10 μm (as in MWH15) the result is

$$E[F(r)] = 0.83 \times 10^{-12}\,m\,s^{-1}. \tag{15}$$

The corresponding results obtained in MWH15 by using Criteria 1 and 2 (see the results for $E[f_{vol}^{(tot)}]$ corresponding to MGAU05 in Table 4) are $15.3 \times 10^{-12}\,m\,s^{-1}$ and $11.5 \times 10^{-12}\,m\,s^{-1}$, respectively. The mean values corresponding to BGGS07 Data Sets 1 to 5 are $34.2 \times 10^{-12}\,m\,s^{-1}$ and $23.9 \times 10^{-12}\,m\,s^{-1}$, respectively. Thus, it appears that the present result in Eq. (15) is significantly lower than those obtained in MWH15. This is mainly due to the inherent features of the improved sea spray aerosol production flux model by C13.

3. Summary

Estimate of the long-term sea spray aerosol flux based on long-term variation of wind statistics from the Northern North Sea is provided by adopting the improved Callaghan (2013) model. Overall, some of the example estimates of the mean whitecap coverage based on the wind statistics agree with those obtained in Myrhaug et al. (2015) based on wave statistics. However, the total mean volume aerosol flux based on the improved Callaghan (2013) give significantly lower value than those obtained in Myrhaug et al. (2015), which is mainly due to the inherent features of the first model.

Overall, this work provides a procedure which can be applied to calculate the whitecap coverage and sea spray aerosol flux based on long-term statistical information of the wind climate.

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