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Model of the spume sea spray generation

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[1] A model of the spume spray generation function (SGF) is suggested. Spume droplets are produced by the wind tearing off breaking crests of the equilibrium range wind waves. The injection occurs in the form of a jet which is pulverized into droplets that have a range of sizes with a distribution proportional to the radius to the power 2. Breaking of the equilibrium range wind waves takes place on crests of dominant wind waves, therefore spume droplets are injected into the air at the altitude of the dominant wave crest. A reasonable agreement with the empirical SGFs is found. **Citation:** Kudryavtsev, V. N., and V. K. Makin (2009), Model of the spume sea spray generation, *Geophys. Res. Lett.*, *36*, L06801, doi:10.1029/2008GL036871.

1. Introduction

[2] Sea spray droplets are generated at the sea surface by two main mechanisms: bursting of air bubbles at the sea surface (film and jet droplets), and by the wind tearing off the wave breaking crests (spume droplets). With the wind increasing the second mechanism dominates the generation of droplets. The minimum radii of spume droplets are generally about 20 to 40 μm [*Andreas*, 1998; *Wu*, 1993], and there is no a definite maximum radius. The rate at which spray droplets of any given size are produced at the sea surface - the sea spray generation function (SGF) - is essential for many applications. The SGF is commonly denoted as dF/dr [e.g., *Andreas*, 1998], where r is the radius of a droplet. Its dimension is m^{-2} s^{-1} μm^{-1}. The corresponding volume flux is $4/3\ \pi r^3 dF/dr$, which has units m^3 m^{-2} s^{-1} μm^{-1}. However, existing empirical SGFs differ from each other by several orders of magnitude, and data at very high winds are not available. A comprehensive review is given by *Andreas* [2002]. Although the empirical functions are widely used for application needs, it is appealing to build a theoretical SGF based on the physical laws. Such a function on one hand will help to understand better the physics of the spray generation, and on the other hand will provide a basis to extrapolate the function to the range of the wind speed where data are absent. An attempt to build a theoretical SGF for spume sea droplets is undertaken in the present paper.

2. Generation of Spume Droplets

2.1. Generation by a Narrow Band Breaking Waves

[3] Spume droplets are generated by the wind tearing off the crest of breaking waves and the subsequent injection into the airflow at the altitude of the wave crests, where from they are blown away by the wind, as shown in Figure 1. In order to describe this phenomenon *Kudryavtsev* [2006] (hereinafter referred to as K06) introduced the volume source of the spume droplets generation V_s - the total volume of spray droplets created per unit time and per unit volume of air. The dimension of V_s is m^3 m^{-3} s^{-1}. As argued by K06 the rate of droplets injection by breaking waves in the range of the wavenumber from $\mathbf{k}$ to $\mathbf{k} + d\mathbf{k}$ reads

$$dV_s(z,\mathbf{k}) = F_{0s}\Delta(z - h_b)\Lambda(\mathbf{k})d\mathbf{k}, \quad (1)$$

where F_{0s} in m^3 m^{-2} s^{-1} is the total volume flux (integrated over all droplet radii) of droplets from an individual breaking crest denoted by the zero; $\Lambda(\mathbf{k})$ is the spectrum of wave breaking crests length originally introduced by *Phillips* [1985]; $\Delta(x)$ is a unit function centered around $x = 0$ with width d. Function $\Delta(x)$ simulates the outlet of thickness d of a jet of droplets injected into the airflow from a breaking crest of height h_b (Figure 1a). Since the characteristic slope of breaking waves $kh_b/2$ is about 0.5, h_b is taken here equal to k^{-1}. Due to the self-similarity of breaking gravity waves d is also proportional to k^{-1}. K06 assumed that droplets once generated are immediately entrained into the separation bubble thus $d \cdot k \simeq 1$. Here the initial stage of the droplets generation is considered, when water/foam on the crest of breaking waves is pulverized into droplets that are confined within a thin inner boundary layer (IBL) of thickness $d \sim 0.1\ k^{-1}$. They are then injected into the airflow as a jet of spray. Being torn away from a breaking crest droplets are further accelerated to match the airflow velocity u_s in the vicinity of the wave crest. If F_{0s} is the volume flux of droplets then the force required to accelerate these droplets to u_s is equal to $\rho_w F_{0s} u_s$ (ρ_w is water density). This force is equal to the local turbulent wind stress over the breaking crest, which is proportional to $\rho_a u_s^2$ (ρ_a is air density). Thus $\rho_w F_{0s} u_s \propto \rho_a u_s^2$, and the spume droplets flux reads

$$F_{0s} \propto (\rho_a/\rho_w)u_s. \quad (2)$$

Equation (2) describes the production of droplets from an individual breaking crest. Now we shall consider how droplets once generated are distributed over size.

2.2. Droplet Size Distribution

[4] Following *Kolmogorov* [1949] it is suggested that at high Reynolds numbers sea droplets will be pulverized if the differential pressure force on their surface $\rho_a v_r^2$, where v_r^2 is the scale of turbulent velocity differential over the droplet radius r, exceeds the restoring force associated with the surface tension $\rho_w\gamma/r$ (γ is the surface water tension in m^3 s^{-2}). Then the criteria for the pulverization is that the

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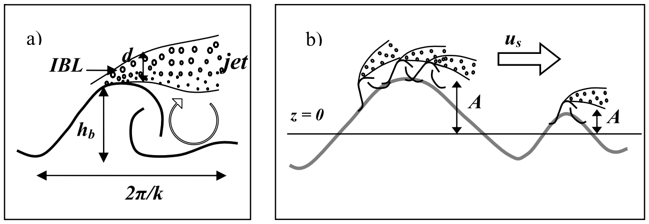

Figure 1. Sketches illustrating the generation of spume droplets. (a) Being pulverized inside the inner boundary layer on the crest of a breaking wave droplets are injected into the airflow at altitude h_b in the form of a jet with the outlet thickness d. (b) Generation of droplets from breaking short waves takes place on crests of dominant waves at the altitude A of the dominant wave crest. u_s is the wind speed at the altitude of the droplets generation.

Weber number $We = (\rho_a/\rho_w)v_r^2 r/\gamma$ should exceed some critical value We_{cr}. Thus the radius scale of droplets in the turbulent flow is

$$r = (\rho_w/\rho_a)We_{cr}\gamma/v_r^2. \quad (3)$$

According to the Kolmogorov-Obukhov theory of the local structure of turbulence the mean square velocity differential v_r^2 over the scale r is

$$v_r^2 = (\nu/\lambda_0)^2 f(r/\lambda_0), \quad (4)$$

where ν is the kinematic viscosity, $\lambda_0 = \varepsilon^{-1/4}\nu^{3/4}$ is the Kolmogorov length scale, ε is the dissipation rate, and f is the universal function with the asymptotic behaviour $f(x) \propto x^{2/3}$ at large x, and $f(x) \propto x^2$ at small x. Since spume droplets have radii $r < \lambda_0$ equation (4) reads

$$v_r^2 \propto \varepsilon\nu^{-1}r^2. \quad (5)$$

Taking into account (5) and the relation for the kinetic energy dissipation rate in the wall boundary layer $\varepsilon = u_*^3/\kappa z$, where u_* is the friction velocity and κ is the von Karman constant, equation (14) reads

$$r \propto (\gamma\nu/\varepsilon)^{1/3} \propto (\gamma\nu z)^{1/3}u_*^{-1}, \quad (6)$$

where ρ_w/ρ_a, We_{cr} and κ are adopted in the proportionality constant. Equation (6) describes the pulverization of water/foam into droplets inside a thin turbulent IBL adjacent to the crest of a breaking wave, where the local shear production of turbulence is balanced by its dissipation. After the pulverization took place droplets are injected into the airflow in the form of a jet. If s_j is the concentration of droplets inside the IBL then their mass flux through the jet outlet is $s_j u_s$. From the mass conservation it follows that this flux has to be proportional to the flux of droplets torn off from a breaking crest (2). Therefore $s_j \propto F_{0s}/u_s$ and by comparison with (2) s_j should have a constant value, which is independent of the wind speed and the scale of breaking waves; each breaking crest identified by a white cap possesses a fixed amount of available water-foam, which can be pulverized to droplets. According to the self-similarity of breaking waves the volume of the pulverized water/foam and the IBL volume, where the produced droplets are spread, are proportional to the breaking wave wavenumber to the power −3. Although the proportionality constant can be very different, the concentration of droplets inside the jet should be a universal constant. The question however remains: what is the distribution of droplets over size inside the jet?

[5] Let us introduce the spectral distribution of droplets over the radius $S(r)$

$$\int_{r<r_0} S(r)dr = s_j, \quad (7)$$

where r_0 is the maximum radius of droplets, which according to (6) are generated at the upper bound of the IBL

$$r_0 \propto (\gamma\nu d)^{1/3}u_*^{-1} \propto (\gamma\nu/k)^{1/3}u_s^{-1}. \quad (8)$$

The second relation in (8) follows from $d \propto k^{-1}$, and the friction velocity u_* is related to the wind velocity u_s that tears off a breaking crest and to which value the torn droplets are accelerated. Since the concentration of droplets inside the jet is constant over height $S(r)dr/dz = s_j/d$, by using (6) we get

$$S(r) \propto 3r_0^{-1}(r/r_0)^2. \quad (9)$$

Thus, the rate of the spume droplets generation from an individual breaking wave (2) accounting for their distribution over size (9) has the following form

$$F_{0s} \propto 3u_s r_0^{-3}\int_{r<r_0} r^2 dr. \quad (10)$$

The generation of droplets by a narrow band breaking waves is thus given by (1) with (10).

2.3. Generation by All Breaking Waves

[6] In order to find the production of droplets by all breaking waves, equation (1) has to be integrated over **k**. Taking into account that $kd = \epsilon \ll 1$, the integral can be approximated

$$V_s(z) \simeq \epsilon F_{0s}z^{-2}\Lambda(k)|_{k=1/z}, \quad (11)$$

where $\Lambda(k)$ is integrated over all directions. A specific distribution of the wave breaking crests length $\Lambda(k)$ is an open question. As most of white caps are generated by breaking of the equilibrium range wind waves, the idea of *Phillips*'s [1985] is adopted that

$$\Lambda(k) \propto k^{-1}(u_*/c)^3 \propto k^{1/2}u_*^3 g^{-3/2}, \quad (12)$$

where $c = (g/k)^{1/2}$ is the phase speed. Equation (12) shows that the main contribution to the total length of breaking crests results from breaking of shortest gravity waves. Not all breaking waves generate the white caps; the shortest ones break without the air entrainment. *Gemmrich et al.* [2007] investigated the wave breaking dynamics by tracing visible white caps. They found that the velocity of the smallest white caps was about 1 m s^{-1} that corresponds to k of order O(10) rad m^{-1}. This value is adopted assuming that the range of waves generating white caps and thus spume droplets is confined by the interval $k < k_b = 10$ rad m^{-1}. Substituting (12) in (11) and replacing k by z^{-1} the following equation for the volume flux of spume droplets is obtained:

$$V_s(z) \propto k_b F_{0s} \left(u_*/c_b\right)^3 (k_b z)^{-5/2} \tag{13}$$

at $zk_b > 1$ and $V_s(z) = 0$ at $zk_b < 1$, where $c_b = (g/k_b)^{1/2}$. Since $F_{0s} \propto u_s$, equation (13) predicts the wind speed dependence of the droplets production proportional to the power 4. As follows from (13) the production of spume droplets has a maximum at $z = 1/k_b$ and attenuates rapidly with height.

[7] The next question is: what is the role of dominant waves, if most of spume droplets are generated by breaking of the equilibrium range wind waves? *Dulov et al.* [2002] found that dominant waves strongly modulate the short wave breaking leading to its enhancement on the long wave crest and suppression in the trough areas. Therefore the production of droplets occurs on the crest of dominant waves, and that droplets being torn from the short breaking waves are injected into the turbulent airflow at the altitude of the dominant wave crests (Figure 1b).

[8] To account for this fact it is suggested that the production of droplets is described as before by (13), where z however is shifted by the amplitude A of dominant waves, i.e. $V_{sA} = V_s(z-A)$. If $P(A)$ is the probability density function of the dominant wave amplitude prescribed by the Rayleigh distribution

$$P(A) = (A/m_{00}) \exp\left(-A^2/2m_{00}\right), \tag{14}$$

where m_{00} is the variance of the sea surface displacement, then the volume source of droplets production averaged over all dominant waves reads

$$V_{sA}(z) \propto F_{0s} k_b \left(u_*/c_b\right)^3 \int_{A<z-1/k_b} [k_b(z-A)]^{-5/2} P(A) dA, \tag{15}$$

where the limit of integration reflects the fact that $V_s(z-A)$ vanishes at $z-A < 1/k_b$. At moderate to high wind speeds the inverse wavenumber k_b^{-1} is of order O(10^{-1})m and is much smaller than the square root of the standard deviation of the sea surface, i.e., $k_b m_{00}^{1/2} \gg 1$. Therefore $P(A)$ in (15) is a slowly varying function of the length scale $1/k_b$, and the integral (15) could be approximately evaluated to

$$V_{sA}(z) = F_{0s} \left(u_*/c_b\right)^3 (z/m_{00}) \exp\left(-z^2/2m_{00}\right) \tag{16}$$

with

$$F_{0s} = 3 c_s u_s r_0^{-3} \int_{r<r_0} r^2 dr, \tag{17}$$

where c_s is a constant adopting all other constants. Since the contribution of breaking waves to the droplets generation reduces rapidly with the decrease of k, see (11) with (12), we suggest that the maximum radius of spume droplets (8) scaled by k_b is a proper estimate of the upper bound of the spume droplets spectrum, i.e.,

$$r_0 = c_r (\gamma\nu/k_b)^{1/3} u_s^{-1}, \tag{18}$$

where c_r is another constant. The generation of droplets takes place on the crest of dominant wind waves, so that u_s is the wind speed at the altitude $z = m_{00}^{1/2}$.

2.4. Spume Droplets Concentration

[9] Experimental data on spume droplets normally do not provide the rate of the droplets production V_s but the droplets concentration at a given altitude. The spray generation function is then assessed indirectly from the mass conservation equation. The rate of the droplets production (16) can be considered as a component of the droplets conservation equation which reads

$$\frac{\partial}{\partial z}[\hat{q}_s - a(r)\hat{s}] = \hat{V}_{sA}, \tag{19}$$

where hat over any quantity states that it is its spectral density in the range from r to $r + dr$, $\hat{s}$ is the droplet volume concentration spectrum - the volume of droplets of radius r per unit volume of air (m^3 m^{-3} μm^{-1}), $a(r)$ is the terminal fall velocity, and $\hat{q}_s$ is the turbulent flux of droplets. If the spectral density $\hat{X}$ of a quantity X is defined, its total value is $X = \int \hat{X} dr$. Assuming that far enough from the sea surface both $\hat{s}$ and $\hat{q}_s$ vanish and introducing the turbulent transfer coefficient for droplets $c_q k_t$, where k_t is the eddy-viscosity coefficient and $c_q = 2$ is the inverse turbulent Prandtl number close to 2 [e.g., *Taylor et al.*, 2002], equation (19) can be rewritten as

$$c_q k_t \partial\hat{s}/\partial z = -a\hat{s} + \hat{F}_s, \tag{20}$$

where $\hat{F}_s$ is the spectrum of the total volume flux of droplets $F_s = \int_z^\infty V_{sA} dz$ (dimension of F_s is m^3 m^{-2} s^{-1}) torn off from breaking waves. Using (16)

$$F_s = F_{0s} \left(u_*/c_b\right)^3 \exp\left(-z^2/2m_{00}\right), \tag{21}$$

where F_{0s} is defined by (17). Since the generation of droplets was already included in the term F_s, the surface flux of droplets must vanish, and equation (20) is solved with the surface boundary condition $\partial\hat{s}/\partial z = 0$ at $z = z_0$, where z_0 is the surface roughness scale. The spectrum $\hat{F}_s$ in (20) has a meaning of the normal SGF dF/dr expressed in terms of the volume flux 4/3 $\pi r^3 dF/dr$. Using (21) and (17) with (18) it reads

$$\frac{4}{3}\pi r^3 \frac{dF}{dr} \equiv \hat{F}_s = 3 c_s u_s \left(\frac{u_*}{c_b}\right)^3 \frac{r^2}{r_0^3} \exp\left(-z^2/2m_{00}\right) = \\ = 3 \frac{c_s}{c_r^3} \frac{k_b}{\gamma\nu} u_s^4 \left(\frac{u_*}{c_b}\right)^3 r^2 \exp\left(-z^2/2m_{00}\right) \tag{22}$$

at $r < r_0$. According to (22) the wind speed dependence of the spectral flux is proportional to the wind speed to the power 7.

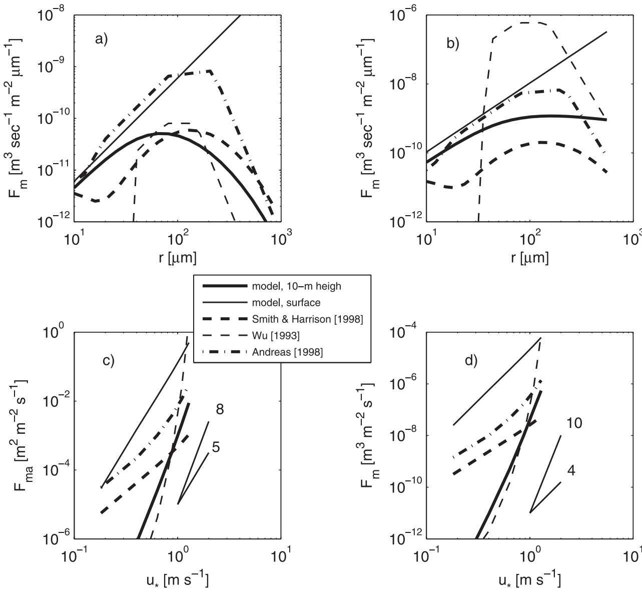

Figure 2. SGF defined by (25) as a function of the droplet radius for the wind speed (a) 20 m s^{-1} and (b) 30 m s^{-1}. (c) Total droplets surface area and (d) droplets volume fluxes as a function of the friction velocity. Lines: see legend. Thin solid lines with a number n on the top indicate the wind dependence u_*^n.

[10] According to the K06 model the effect of droplets on the turbulent atmospheric boundary layer is similar to the effect of the temperature stratification, where the empirical laws in terms of the Monin-Obukhov similarity theory are well established. The eddy-viscosity coefficient k_t reads $k_t = \kappa u_* z/(1 + 5z/L_s)$, where $L_s = u_*^3/\kappa\sigma asg$ is the stratification length scale for spume droplets, $\sigma = (\rho_w - \rho_a)/\rho_a$ is the relative density excess of sea droplets and s is the volume concentration in m^3 m^{-3} (see K06 for more details).

[11] Most of data available on spume droplets were collected at the wind speed less than 30 m s^{-1} and at altitudes of order of tens meters or less. At such conditions $z/L_s \ll 1$, and the solution of (20) reads

$$\hat{s}(z) = \hat{s}_*(z) + \int_{z_0}^{z} (\xi/z)^{\omega/c_q} \hat{v}_*(\xi) d\xi, \quad (23)$$

where $\hat{s}_* = \hat{F}_s/a$, $\hat{v}_* = \hat{V}_{sA}/a$ and $\omega = a/\kappa u_*$ is the normalized fall velocity. The terminal fall velocity a is calculated according to the model by *Andreas* [1989]

$$a = \frac{2r^2 g(\rho_w/\rho_a)}{9\nu\left[1 + 0.158(2ra/\nu)^{2/3}\right]} \quad (24)$$

and z_0 is described by the Charnock relation.

[12] Measurements of the droplet concentration is a standard indirect way to assess empirically the SGF as $\hat{F}_s = a\hat{s}$. Therefore the model calculations of $\hat{s}$ through (23) give a possibility to compare the model results with data.

3. Comparison With Data

[13] The comprehensive review of the available empirical spume SGFs are given by *Andreas* [2002]. It can be seen that the empirical SGFs differ from each other on several orders of magnitude. A more detailed analysis reveals however the possible cause of such difference: all of functions are based on measurements taken in a limited range of the radius, the wind speed and at different heights above the sea level. All of them are extrapolated then to a larger radius, larger wind speed and the surface using some heuristic arguments. As an example, *Wu et al.* [1984] performed measurements from a floating raft close to the water surface and for the radius range $60 < r < 250$ μm, but for the range of the wind speed $6 < U_{10} < 8$ m s^{-1}, where U_{10} is the wind speed at 10-m height. The SGF was extrapolated to the radii up to 500 μm and the wind speed up to 25 m s^{-1}. *Smith et al.* [1993] performed measurements at U_{10} up to 32 m s^{-1}, but for droplets less than 47 μm in the radius of their formation, which is at the lower boundary of the spume droplets range. *Andreas* [1998] derived his function from *Smith et al.* [1993] extending the range of its availability to the domain of spume droplets up to $r = 500$ μm. Such extrapolations of course bring uncertainties in SGFs.

[14] *Smith and Harrison* [1998] (hereinafter referred to as SH98) measured the droplets concentration in the open ocean for the radius up to 150 μm and for the wind speed up to 20 m s^{-1}. Measurements were performed at 10-m level. As we are interested in the comparison of our model with data for droplets generated by high winds, it appears that only measurements by SH98 at radii of about 150 μm and the wind speed 20 m s^{-1} are available for the direct comparison.

[15] Note the following: all empirical SGFs dF/dr for the spume droplets are obtained via measurements of the droplets concentration by multiplying it on the terminal fall or deposition velocity

$$\frac{4}{3}\pi r^3 \frac{dF}{dr} \equiv \hat{F}_m = a\hat{s}, \quad (25)$$

where $\hat{F}_m$ is a measurable SGF. But according to equation (21) the SGF based on the concentration $\hat{F}_m$ equals to model $\hat{F}_s$ only at the surface. At any other height they differ by the turbulent flux term, which is not available from measurements. Keeping that in mind, we shall compare the model and empirical SGFs in terms of the measurable SGF $\hat{F}_m$.

[16] Correspondingly, the total flux of the droplets volume is $F_m = \int_{r<r_0} \hat{F}_m dr$, and the total flux of the droplets surface area is defined as $F_{m_a} = 3\int_{r<r_0} r^{-1}\hat{F}_m dr$. Constants in (17) and (18) are chosen so that to match the level of the SGF function by SH98 at the highest wind speed of 20 m s^{-1}. Constant c_s in (17) is taken as $c_s = 10^{-6}$, and constant c_r in (18) is taken as $c_r = 30$. The comparison between the model and empirical SGF defined by (25) is shown in Figures 2a and 2b.

[17] Though the model SGF level compares well with SH98 data at 10-m height, the maximum of our SGF is shifted to the lower radius. At 30 m s^{-1} the shape of both SGFs is very similar but the model SGF has a stronger wind speed dependence. At 20 m s^{-1} the model surface SGF is somewhat higher than *Wu*'s [1993] and somewhat lower than *Andreas*'s [1998] SGF but has the same radius dependence as both of them up to the radius of about 200 μm. For larger radius both empirical functions have a pronounced

cut off while the model SGF continues to increase up to the maximum radius r_0 defined by equation (18) and has a cut off at this value. Notice, that there are no measurements for droplets larger than 250 μm. At 30 m s^{-1} the modelled function agrees well both in the level and shape (up to r = 200 μm) with the SGF by *Andreas* [1998].

[18] The total surface area flux as a function of u_* is shown in Figure 2c. The model flux at the surface is $F_{m_a} \sim u_*^5$ and consistent with the empirical relation by *Andreas* [1998]. However, the level of the model flux is much higher than empirical ones. This is due to a different cut off of the model and empirical SGFs. At 10-m height F_{m_a} has much stronger wind speed dependence proportional to the power of about 7–8. It is well compared with the flux by *Wu* [1993] but not consistent with the flux by SH98 $\sim u_*^3$.

[19] Figure 2d shows the total flux of the droplets volume. At the sea surface the flux is larger than the empirical fluxes but for largest droplets has the same wind speed dependence as *Andreas*'s [1998], proportional to u_*^4. The flux at 10-m height is smaller than empirical fluxes for moderate winds but reaches the same level at high wind speeds, and its wind speed dependence coincides with the one of *Wu*'s [1993] and proportional to about u_*^{10}. In fact fluxes at the sea surface cannot be measured; the model flux being evaluated at heights between the surface and 10 m will fall between those shown in Figure 2.

4. Conclusions

[20] A theoretical model of the spume sea spray generation is suggested. The model is based on arguments that most of spume droplets are generated by breaking of the equilibrium range wind waves. Spume droplets being torn from an individual breaking wave are injected into the airflow at the altitude of a breaking wave crest. The pulverization of water/foam into droplets takes place in a thin turbulent boundary layer adjacent to a breaking wave crest. Adopting *Kolmogorov*'s [1949] ideas it is shown that the distribution of droplets over radii is proportional to the radius to the power 2. The equilibrium range waves are strongly modulated by dominant wind waves that leads to the enhancement of their breaking, so that the production of spume droplets occurs in the vicinity of the dominant wind waves crests, where from they are injected into the airflow. Solving equation for the droplets concentration the spray generation function can be obtained and compared with empirical functions. Few empirical functions were selected for the comparison and a reasonable agreement in the spectral level, integral flux and shape of the spray generation function is found.

[21] **Acknowledgments.** ONR grant N00014-08-1-0609 is gratefully acknowledged by V.M. V.K. acknowledges support from RFBR grant N08-05-13581.

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