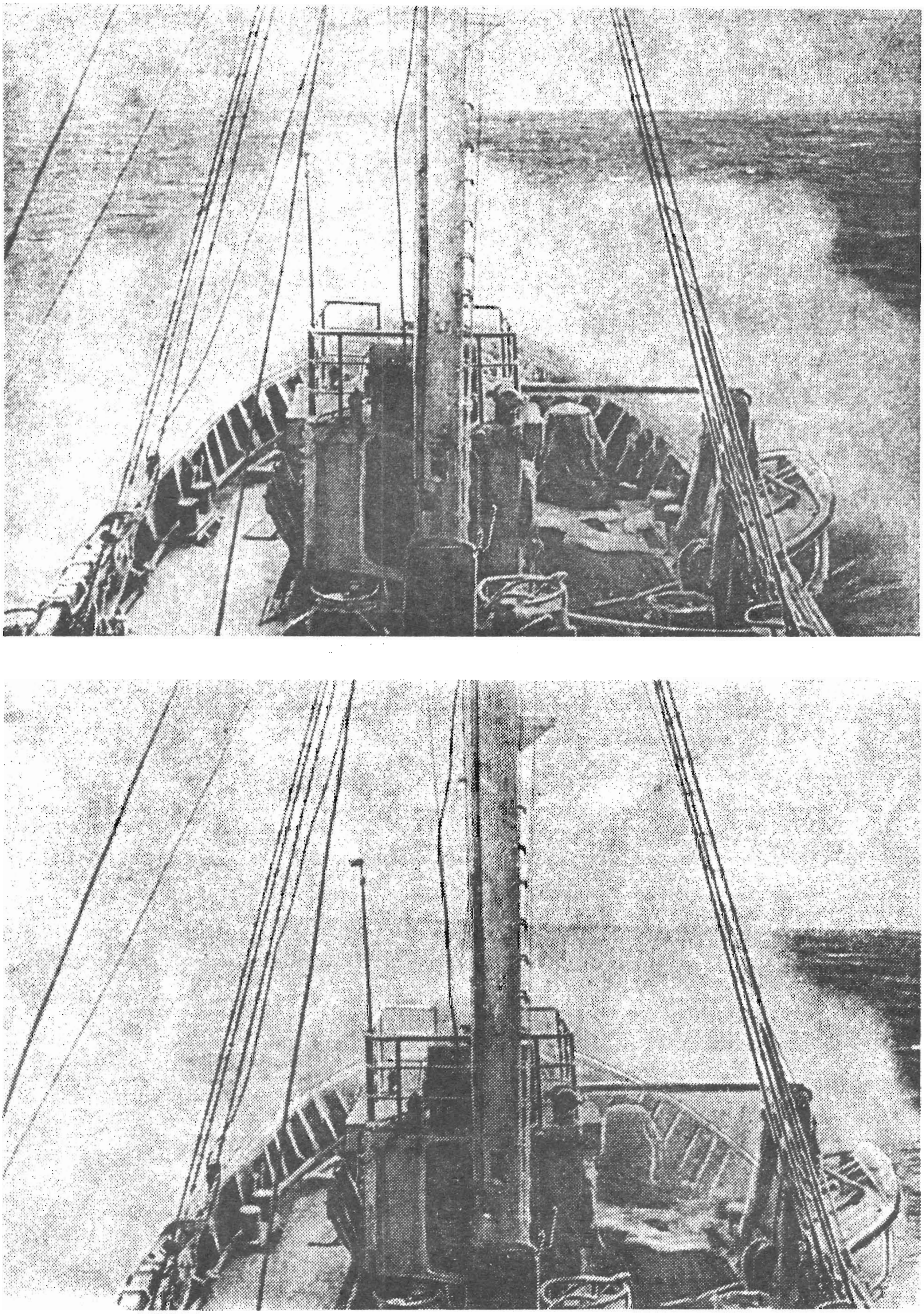
ICING OF SHIPS. PART I: SPLASHING A SHIP WITH SPRAY



Medium fishing vessel splashed with wave-generated spray in moderate sea (according to Panov, 1976).

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ICING OF SHIPS. PART I: SPLASHING A SHIP WITH SPRAY

Wlodzimierz Paul Zakrzewski

Pacific Marine Environmental Laboratory
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FOREWORD

Vessel icing is a severe hazard of high latitude waters. Necessary conditions for vessel icing are an adequate supply of water to exposed structures on the vessel and air temperatures below the freezing point of sea water. Previous work on vessel icing (Kachurin et al., 1974; Stallabrass, 1980; also see Jessup, 1985, and Overland et al., 1986) have concentrated on thermodynamic balances. This report makes a major contribution to the icing problem by providing quantitative estimates of the supply of water to the vessel. We are pleased to publish this report as a contribution to the Marine Services Project at PMEL.

James E. Overland
Carol H. Pease
Marine Services Research Division

CONTENTS

ICING OF SHIPS. PART I: SPLASHING A SHIP WITH SPRAY

Wlodzimierz Paul Zakrzewski*

ABSTRACT. Wind- and wave-generated spray fluxes to an object (cylinder and vertical plate) located on and above the deck of a medium-sized fishing vessel (MFV) are investigated. Using formulas derived for a fully arisen sea, sea-state was defined by the significant wave height, which is a function of wind speed and fetch. Formulas for the liquid water content (LWC) of wind-generated spray are reviewed. It was found that wind-generated spray does not affect an object located on and above the deck of a MFV. Such spray may affect only small ships with low freeboard and low bows in strong winds. Wave-generated spray is the one and only source of water delivery to an object if rain, drizzle, snow, fog, and the flooding of a ship deck by waves is neglected. The wave-generated spray flux was defined using derived formulas of the vertical distribution of the LWC and time of ship exposure to spray originating from spray cloud induced by ship/wave collision. These formulas were derived using published data on a Russian field experiment in the Sea of Japan. The time-averaged water flux to an object can be computed for any given wind speed, fetch, ship speed, and heading angle. These results are applicable for calculating the ice growth rates on medium fishing vessels.

INTRODUCTION

Icing has caused the loss of many small and medium fishing vessels (Shellard, 1974) and has been known to adversely affect the seaworthiness of small cargo vessels (Fig. 1) (Lundquist and Udin, 1977; Zakrzewski, 1980).

Although numerous studies have been conducted on ship icing, those most important in terms of ship operations involve the analysis of ice growth rates on the ship superstructure. To date, the most important research on this subject includes the work of Overland *et al.* (1986), Stallabrass (1980), Wise and Comiskey (1980), Borisenkov and Pchelko (1975), Borisenkov (1969), and Mertins (1968). The thermodynamics of icing seems to be well understood, yet there is a lack of accurate models relating the splashing of a ship with spray to the icing phenomenon. This may, in part, be due to the scarcity of field data by which to test proposed models.

* C-CORE, Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5 Canada

Figure 1.--Dutch tanker m/s *Anna Broere* stranded on the shore near Rozewie (Poland, southern Baltic Sea) when the crew abandoned the ship due to heavy icing in heavy storm on December 31/1 January 1979.

An effort to derive the icing rates of ships as a function of water delivery to the ship will be given in the present paper, with emphasis placed on modeling the splashing of a ship with spray. Medium fishing vessels (MFV) are only considered in this analysis because the published data sets from field experiments are available only for this type of ship. Computations are given for two bodies (cylinder and vertical plate) of unit area (1 m^2), located on the windward side of a ship, within a given range of elevation above the deck of the ship. Neglecting water flux due to snow, fog, drizzle and rain, and the flooding of the ship's deck by waves, the water delivery to a ship with spray is considered. The water drops impinging on a ship are generated both by the wind action and ship/sea interaction.

1. WIND-GENERATED SPRAY

Wind-generated spray is primarily produced through two mechanisms: 1) the direct whipping of wave crests by the wind, and 2) the bursting of air bubbles at the water surface. The latter mechanism is commonly thought to be the primary source of the wind-generated spray.

The water flux to an immobile object is given by Horjen (1983) and Makkonen (1984) as

$$M = E_c \, U \, w \qquad (1)$$

where U is the wind speed, w is the liquid water content (LWC) in the air, and E_c is the collection efficiency. A simple approximation of the collection efficiency was proposed by Stallabrass (1980) for cylinders and vertical plates. He found that

$$E_c = \begin{cases} \dfrac{\xi - 3200}{\xi + 2700} & \text{for cylinder} \\[2ex] \dfrac{\xi - 2800}{\xi + 11700} & \text{for vertical plate} \end{cases} \tag{2}$$

where the nondimensional parameter ξ is equal to

$$\xi = \frac{U^{0.6}\,\phi^{1.6}}{L} \tag{3}$$

where U is the wind speed in the vicinity of an object, ϕ is the water drop diameter (in μm) and L is the characteristic length of an object. For $U = 3\text{-}60$ m/s, $\phi = 20\text{-}1000$ μm and $L = 0.03\text{-}1$ m (cylinder) and $L = 0.03\text{-}3$ m (vertical plate) Stallabrass (1980) obtained a satisfactory correlation (Fig. 2).

1.1 Liquid Water Content in Wind-Generated Spray

The LWC is the least known parameter affecting the spray flux. Very few experimental data are available from which to estimate the vertical distribution of this variable.

Preobrazhenskii (1973) proposed (Fig. 3) for the vertical distribution of the LWC formula

$$w(z) = w_0 \exp(-\beta(z - \tfrac{H}{2})) \quad \text{kg/m}^3 \tag{4}$$

where z is the height (in meters) above the mean water level (MWL), H is the wave height (in meters), and w_0 and β are constants empirically chosen for various wind speeds:

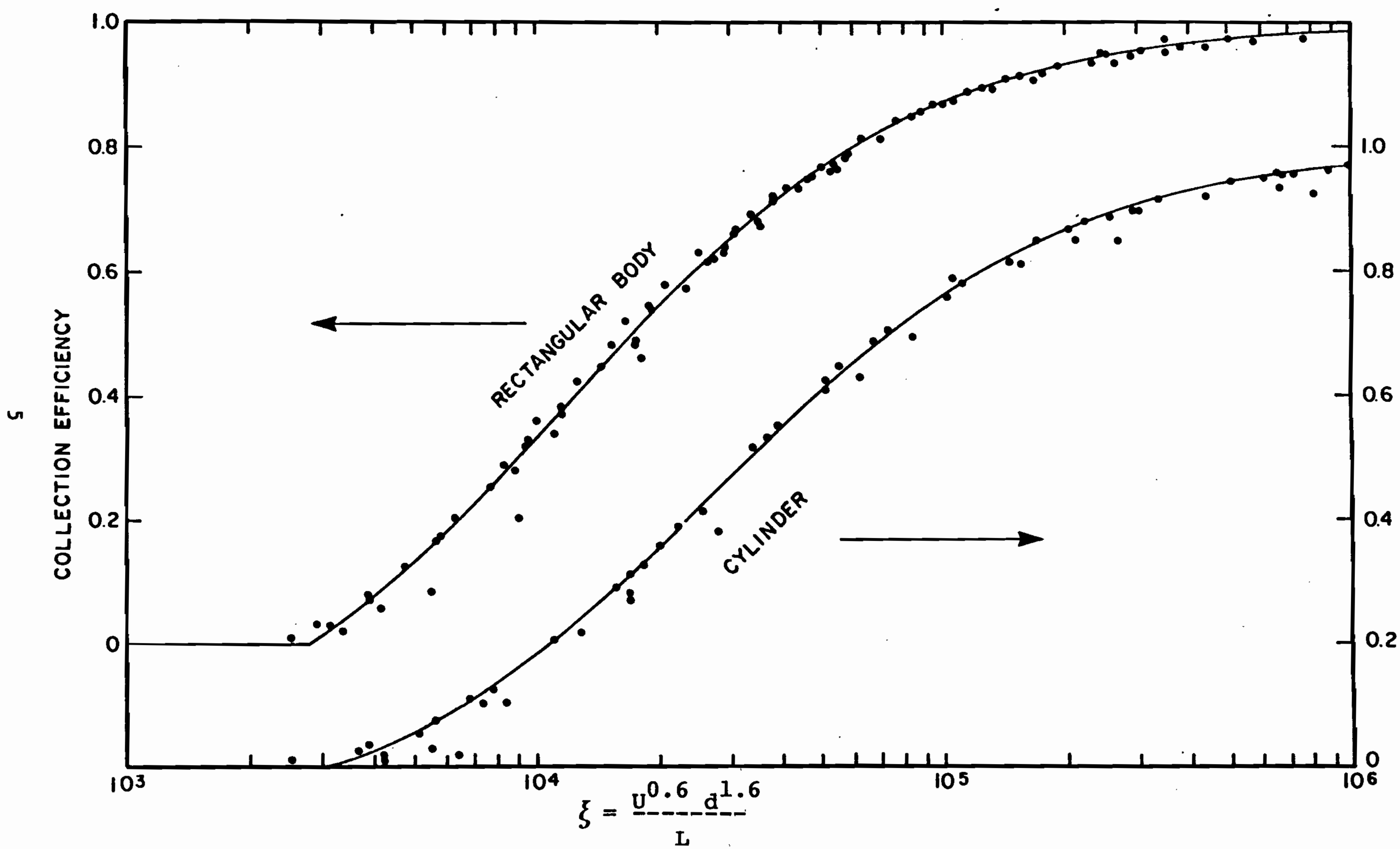

Figure 2.--Collection efficiency of cylinder and rectangular body as a function of parameter ζ (after Stallabrass (1980)).

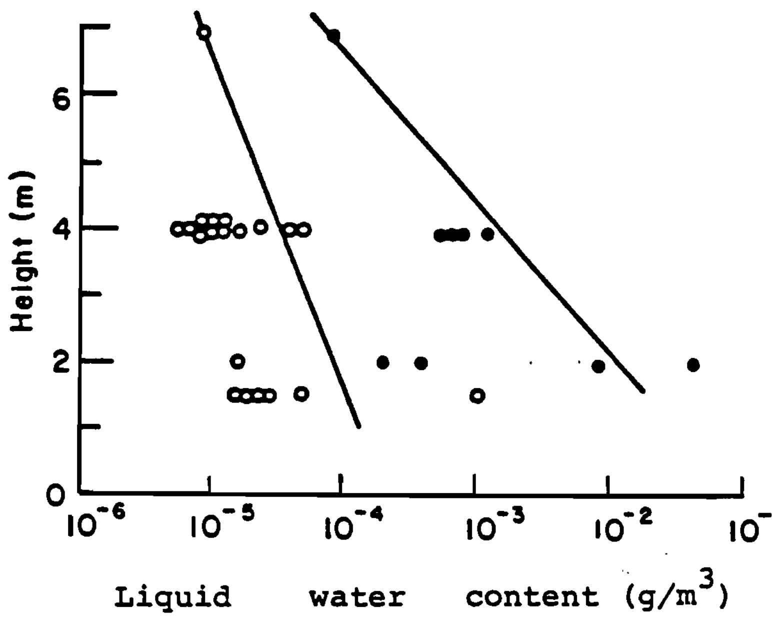

Figure 3.--Liquid water content in the wind-generated spray as a function of the height above the MWL (after Preobrazhenskii (1973), according to Makkonen (1984)).

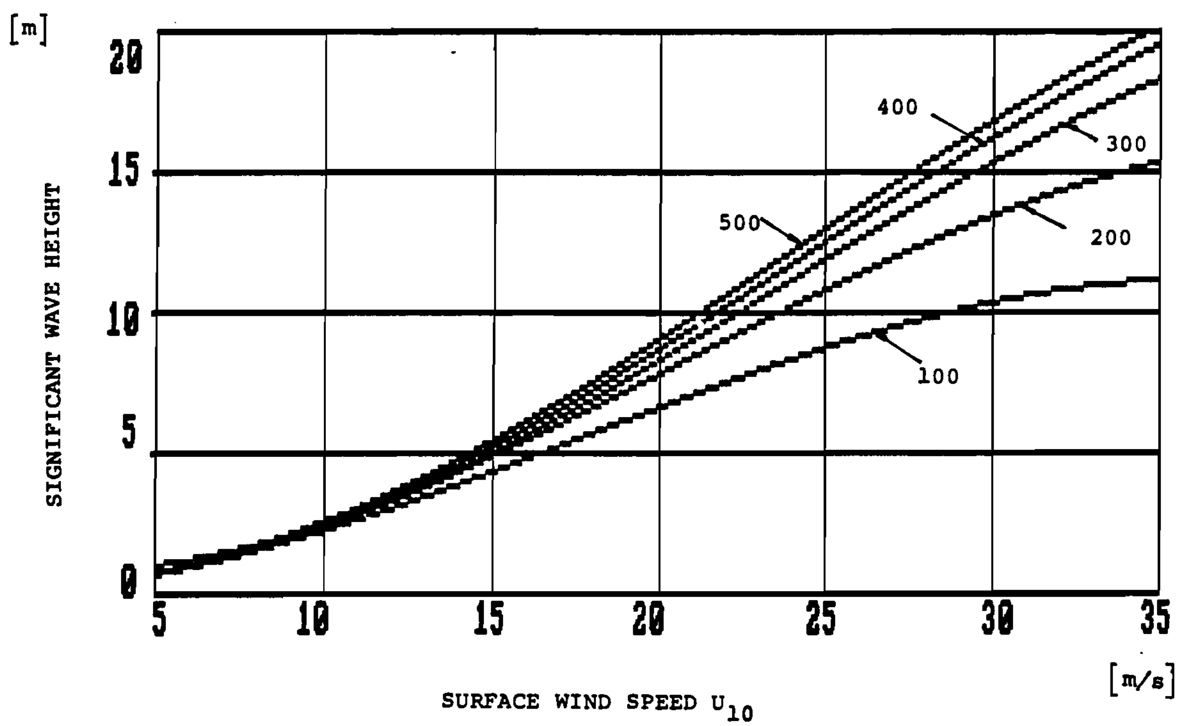

Figure 4.--Significant wave height as a function of surface wind speed U_{10} for a given fetch (in nautical miles).

$w_0 = 10^{-7}$ kg/m³ and $\beta = 0.35$ for moderate winds ($U_{10} = 7$-12 m/s)

and,

$w_0 = 10^{-5}$ kg/m³ and $\beta = 1.0$ for strong winds ($U_{10} = 15$-25 m/s).

According to Eq. (4) the vertical profile of the LWC is a function of the altitude (z) above the MWL, wave height and wind speed. The latter parameter affects the LWC not only directly by the constants w_0 and β which are related to the wind speed, but also by the height of the waves. That is, the height of waves depends on the wind speed, the duration of blowing wind and the fetch. In Figure 4, the significant heights of the wind-driven waves versus wind speed are plotted for fetches of 100, 200, 300, 400 and 500 n.m. These plots are based on the tabulated relationships given in reference [12]. Third- and fifth-degree polynomial regressions fitted the relationships between the wind speed at the level of 10 m and the significant wave height $H_{\frac{1}{3}}$ fairly well

$$H_{\frac{1}{3}}(U_{10}) = B_0 + B_1U_{10} + B_2U_{10}^2 + B_3U_{10}^3 \quad \text{m} \tag{5a}$$

$$H_{\frac{1}{3}}(U_{10}) = B_0 + B_1U_{10} + B_2U_{10}^2 + B_3U_{10}^3 + B_4U_{10}^4 + B_5U_{10}^5 \quad \text{m} \tag{5b}$$

where the constants B_0, B_1, B_2, B_3, B_4, B_5 are listed in Table 1 for a given fetch. These polynomials are only valid for wind speed up to 32.4 m/s, because the field data [12] deals with this range of wind speed.

By substituting the term H given in Eq. (4) by $H_{\frac{1}{3}}(U_{10})$ in Eq. (5a or 5b), we obtain the relationship between the vertical distribution of the LWC and the wind speed measured at the level z = 10 m

$$w(z) = w_0 \exp(-\beta(z - H_{\frac{1}{3}}(U_{10})/2)) \quad \text{kg/m}^3 \tag{6}$$

Table 1.--Constants of the third-degree (a) and fifth-degree (b) polynomial in wind speed to compute significant wave height.

(a)

FETCH (n.m.)	B_0	B_1	B_2	B_3
100	$6.05709\cdot10^{-2}$	$2.89125\cdot10^{-2}$	$2.54698\cdot10^{-2}$	$-4.89792\cdot10^{-4}$
200	$4.21968\cdot10^{-1}$	$-7.75092\cdot10^{-2}$	$3.46928\cdot10^{-2}$	$-5.72020\cdot10^{-4}$
300	1.28311	$-2.26480\cdot10^{-1}$	$4.19756\cdot10^{-2}$	$-6.05377\cdot10^{-4}$
400	$6.09959\cdot10^{-1}$	$-1.32694\cdot10^{-1}$	$3.87922\cdot10^{-2}$	$-5.44265\cdot10^{-4}$
500	$5.59229\cdot10^{-1}$	$-1.34134\cdot10^{-1}$	$4.03976\cdot10^{-2}$	$-5.73259\cdot10^{-4}$

(b)

FETCH (n.m)	B_0	B_1	B_2	B_3	B_4	B_5
100	$8.68869\cdot10^{-1}$	$-4.41178\cdot10^{-1}$	$1.16227\cdot10^{-1}$	$-7.87593\cdot10^{-3}$	$2.62150\cdot10^{-4}$	$-3.34401\cdot10^{-6}$
200	$-7.71688\cdot10^{-1}$	$2.71899\cdot10^{-1}$	$1.07151\cdot10^{-2}$	$-8.30642\cdot10^{-4}$	$5.99481\cdot10^{-5}$	$-1.20460\cdot10^{-6}$
300	-2.31314	$5.96961\cdot10^{-1}$	$-1.71261\cdot10^{-3}$	$-1.75507\cdot10^{-3}$	$1.32954\cdot10^{-4}$	$-2.40288\cdot10^{-6}$
400	$4.86322\cdot10^{-1}$	$-3.41913\cdot10^{-1}$	$1.14635\cdot10^{-1}$	$-8.51850\cdot10^{-3}$	$3.24417\cdot10^{-4}$	$-4.49695\cdot10^{-6}$
500	$6.55261\cdot10^{-1}$	$-3.78443\cdot10^{-1}$	$1.11329\cdot10^{-1}$	$-7.55389\cdot10^{-3}$	$2.75507\cdot10^{-4}$	$-3.75483\cdot10^{-6}$

where $H_{\frac{1}{3}}(U_{10})$ is a third- or fifth-degree polynomial defined in U_{10} by Eq. (5a) or (5b). In Preobrazhenskii's (1973) model, the vertical distribution of the LWC as a function of the wind speed U_{10} was computed for a fetch 200 n.m. (Fig. 5).

Monahan (1968), in his field study measured the spray droplets size distribution on a raft and found that the water drops concentration increased rapidly when the wind speed exceeded a threshold value equal to about 8.5 m/s at an altitude z = 0.47 m above the MWL. This value of wind speed corresponds to a threshold wind speed of approximately 15 m/s at the 10 m level. Following this work, laboratory tests were conducted by Lai and Shemdin (1974), who investigated the effect of wind speed and wave height on the vertical distribution of water drops in a spray. They found that the spectral drop size distribution is a function of the wind speed and drop diameter according to the formula

$$\sigma(\phi,z) = \frac{\gamma(\phi,z)}{U(\delta,\phi)} \qquad \text{No./cm}^4 \tag{7}$$

where U is the local mean wind speed, ϕ is the drop diameter, $\delta\phi$ = 100 μm is the drop diameter interval, and z is the height above the MWL (Fig. 6).

More recently, Itakagi (1979, 1984) presented the LWC vertical distribution by

$$w = \frac{\pi}{6}\,\rho_w \int_{\phi_{min}}^{\phi_{max}} n(\phi)\,\phi^3\,d\phi \qquad \text{kg/m}^3 \tag{8}$$

where ρ_w is the density of sea water, ϕ is the drop diameter and $n(\phi)$ is the number of water drops in the unit volume. $n(\phi)$ was assumed to be a function

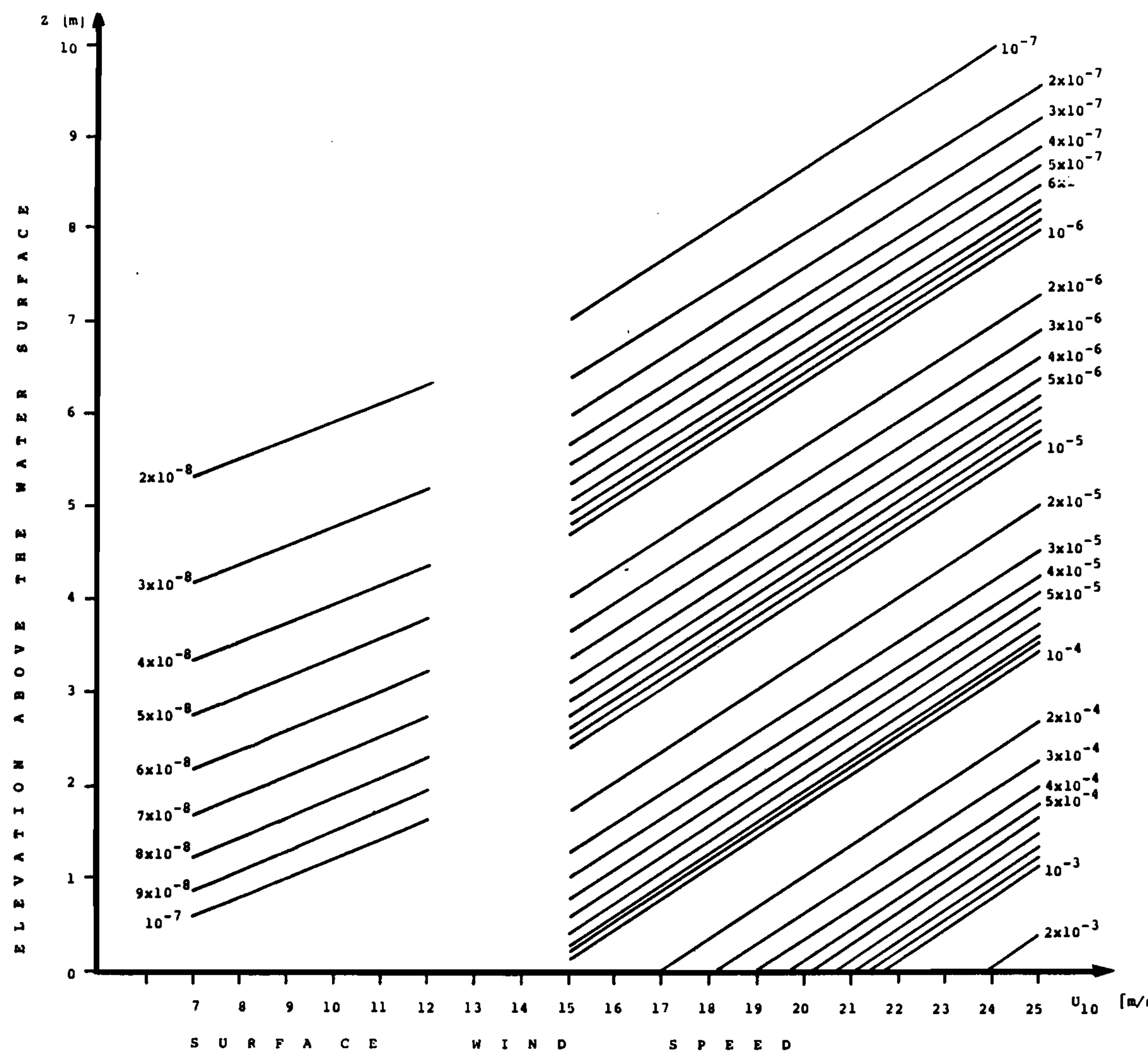

Figure 5.--Liquid water content in wind-generated spray as a function of surface wind speed U_{10} for the fetch 200 n.m.

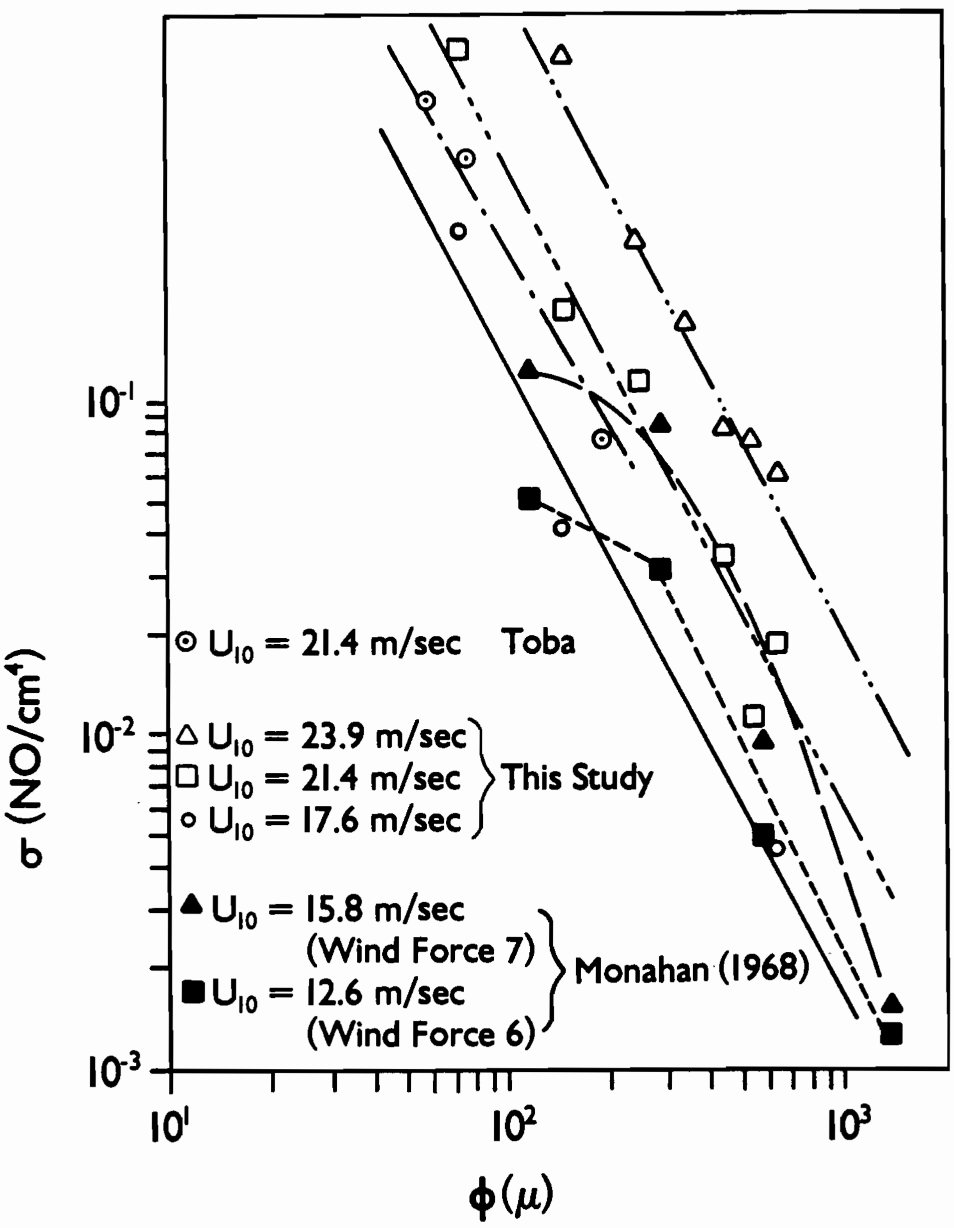

Figure 6.--Spectral drop size distribution as a function of the wind speed and drop diameter by different authors (according to Monahan (1974)).

of the wind speed and the height above the MWL. Basing his model on Lai and Shemdin's (1974), Toba's (1961) and Monahan's (1968) data as well as his own, Itakagi (1979, 1984) found that the size distribution of water drops given by Lai and Shemdin (1974, Fig. 12) could be described by

$$n(\phi,U) = \frac{A(U_{10})}{\phi^2} \tag{9}$$

where $A(U_{10})$, a third-degree polynomial at wind speed U_{10}, is given by

$$A(U_{10}) = -53.5173 + 11.3119\ U_{10} - 0.7934\ U_{10}^2 + 0.01864\ U_{10}^3\ \mathrm{m}^{-2} \tag{10}$$

Using the experimental data of Lai and Shemdin (1974), Itakagi (1979, 1984) calculated the minimum and maximum values of the LWC in unit volume to be ϕ_{min} = 40 μm and ϕ_{max} = 700 μm.

Fitting this data into Eq. (10), he found that

$$w = \frac{\pi}{12}\ \rho_w\ A(U_{10})[(7\cdot10^{-4})^2 - (5\cdot10^{-5})^2] \qquad \mathrm{kg/m^3} \tag{11}$$

For ρ_w = 1025 kg/m³ Eq. (11) becomes

$$w = 1.30818\cdot10^{-4}A(U_{10}) \qquad \mathrm{kg/m^3} \tag{12}$$

where $A(U_{10})$ is determined from Eq. (10). By using Eqs. (10 and 12) one can easily compute the LWC for any given wind speed. However, the vertical distribution of spray is not yet clear. Recently, Horjen (1983) suggested that the size distribution of spray depends on the wave height (H), the diameter of the water drops (ϕ) and the altitude z above the MWL. Hence, Eq. (9) may be rewritten as

$$\sigma(\phi) = g(U_{10}) \frac{H}{z^2\phi^2} \qquad \text{No./m}^{-4} \tag{13}$$

where $\sigma(\phi)$ is the number of drops of certain diameter in unit volume and $g(U_{10})$ is a certain function of wind speed U_{10} at the level of 10 m. Horjen (1983) compared the term $g(U_{10}) \frac{H}{z^2}$ of Eq. (13) with a term $A(U_{10})$ of Eq. (9) and, based on the data from Lai and Shemdin's (1974) laboratory study, found that for a wave height H = 0.035 m and an altitude z = 0.13 m above the MWL, the function $g(U_{10})$ corresponds with the polynomial $A(U_{10})$ as given below

$$g(U_{10}) \simeq 0.5\, A(U_{10}) \qquad \text{m}^{-1} \tag{14}$$

where $A(U_{10})$ is again determined from Eq. (10). It should be noted that the dimension of $A(U_{10})$ in Eq. (10) is in m^{-2} while the dimension of $g(U_{10})$ proposed in Horjen's (1983) Eq. (14) is in m^{-1}. However, since $g(U_{10}) = 0.483$ $A(U_{10})$, Eq. (13) may be written as follows

$$\sigma(\phi) = 0.483\, A(U_{10}) \frac{H}{z^2\phi^2} \qquad \text{No./m}^4 \tag{15}$$

Eq. (8), after substituting $\sigma(\phi)$ into the right-hand side of Eq. (15) and integrating from ϕ_{max} = 700 μm to ϕ_{min} = 50 μm becomes

$$w = 6.3185 \cdot 10^{-5}\, A(U_{10}) \frac{H}{z^2} \qquad \text{kg/m}^3 \tag{16}$$

where $A(U_{10})$ is defined by Eq. (10) and has a dimension of m^{-1}, H is the wave height in meters and z is the altitude above the MWL in meters. The LWC is then proportional to the wave height and wind speed expressed by $A(U_{10})$, and is inversely proportional to the square of the altitude above the MWL. Since wave height depends on wind speed, the vertical distribution of the LWC can be approximated for the waves of significant height by

$$w = 6.3185 \cdot 10^{-5} \, A(U_{10}) \, \frac{H_{\frac{1}{3}}(U_{10})}{z^2} \qquad \text{kg/m}^3 \tag{17}$$

where $H_{\frac{1}{3}}$ (U_{10}) is defined in Eq. (5a or 5b).

Approximating the water drop diameter by the median volume diameter $\phi_{50} = (0.5 \; (\phi^2{}_{max} + \phi^2{}_{min}))^{\frac{1}{2}} = 496$ µm, Eq. (17) becomes

$$w = 3.1886 \cdot 10^{-5} \, A(U_{10}) \, \frac{H_{\frac{1}{3}}(U_{10})}{z^2} \qquad \text{kg/m}^3 \tag{18}$$

For spray of uniform drop diameter ϕ Eq. (17) becomes

$$w = 129.61 \, A(U_{10}) \, \frac{H_{\frac{1}{3}}(U_{10})}{z^2} \, \phi^2 \qquad \text{kg/m}^3 \tag{19}$$

where ϕ is given in meters.

The wind effect on the vertical distribution of the LWC described by Eq. (19) for $\phi = 500$ µm is presented in Figure 7. The LWC varies from about 10^{-7} kg/m^3 to 10^{-2} kg/m^3. Since the course of the isolines of the LWC distribution is rather undulated and not linear at all, one can think that Eqs. (17-19) do not give the consistent values within the entire range of surface wind speed and the altitude above the MWL.

One should be aware that Horjen's (1983) concept of employing flume tank data to LWC predictions may be in error when compared to field measurements. Wind speeds on the order of 20 m/s generate waves 7-8 m high while waves of

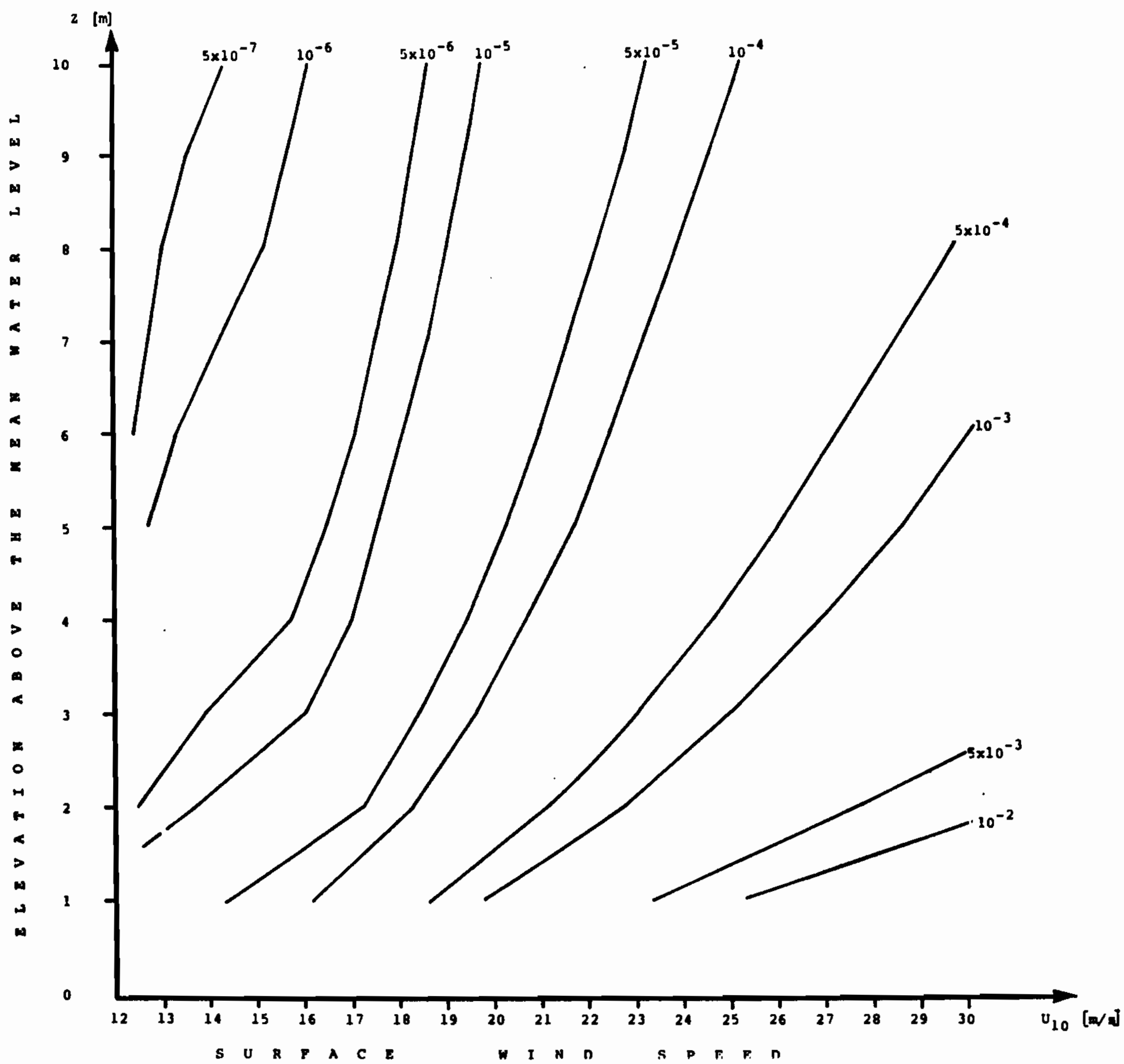

Figure 7.--Liquid water content as a function of wind speed for the water drop diameter ϕ = 500 μm computed using Horjen's (1983) formula.

Lai and Shemdin's (1974) experiment were 3.5 cm high. As a result, Eqs. (16-19) may be somewhat in error. The value of H/z^2 for z = 0.13 m is equal to 2.07 m^{-1} while values of H/z^2 for sea waves a few meters high is equal to >100 m^{-1} (Brown and Roebber, 1985). This indicates that it is better not to apply flume tank data directly to field problems without revising these equations.

Recently, Horjen and Vefsnmo (1984) used Preobrazhenskii's (1973) field data for strong winds (see Fig. 3) and a relationship between the wind speed and whitecap coverage found by Wu (1979a) to give the following approximation of the vertical distributions of the LWC

$$w = w_0(U_{10}/U_0)^{3.8} \exp(\frac{H}{2} - z) \qquad \text{kg/m}^3 \qquad (20)$$

where U_{10} > 15 m/s, U_0 = 15 m/s, and $w_0 = 9.45\cdot10^{-6}$ kg/m³. Results are given in Figure 8 and compare with that of Preobrazhenskii (1973) and Horjen (1983) in Table 2.

Returning to Eq. (1), one can find that the terms E_c and w on the right-hand side of this equation are fairly well approximated by Eqs. (2) and (20), respectively. To compute the mass flux of water coming to the considered objects under consideration we simply have to determine the wind speed U in Eq. (1).

1.2 Local Wind Speed

The distribution of the horizontal wind speed in the lowest 5-20 m of the atmospheric boundary layer follows the logarithmic law first proposed by Prandtl (1933).

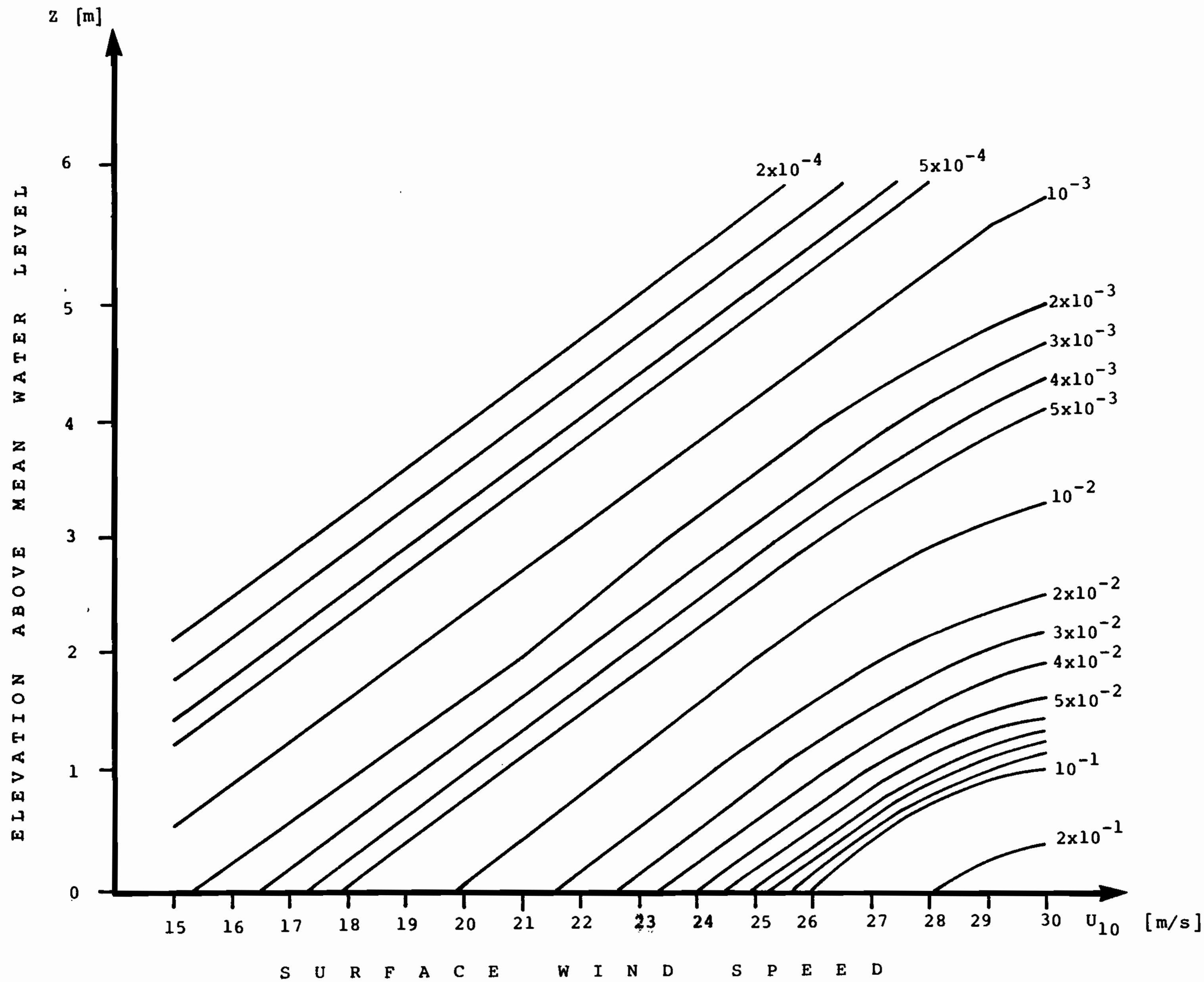

Figure 8.--Liquid water content as a function of wind speed computed using Horjen and Vefsnmo's (1984) formula.

Table 2.--Vertical distribution of the LWC [kg/m^3] ($\times 10^{-8}$) in wind-generated spray in Preobrazhenskii's (1973) (A), Horjen's (1983) (B), and Horjen and Vefsnmo's (1984) (C) models*

Height above MWL [m]	Surface wind speed 15 m/s			Surface wind speed 20m/s			Surface wind speed 25 m/s		
	A	B	C	A	B	C	A	B	C
0	12394	-	175683	55817	-	1054949	298494	-	7051918
1	4559	5768	64630	20534	107213	388094	109810	888022	2594256
2	1677	1443	23776	7554	26830	142772	40397	222227	954373
3	617	642	-	2779	11928	52523	14861	98801	351094
4	227	361	-	1022	6711	19322	5467	55585	129160
5	83	231	-	376	4295	-	2011	35578	47515
6	31	160	-	138	2983	-	740	24708	-
7	11	118	-	51	2192	-	272	18154	-
8	4	90	-	19	1678	-	100	13900	-
9	1	71	-	7	1326	-	37	10983	-
10	1	58	-	2	1074	-	13	8896	-

* These models are described by Eqs. (6), (19), and (28), respectively. Since the vertical distribution of the LWC in Horjen and Vefsnmo's (1984) model is given for the altitudes not larger than 0.5·H (H - wave height), the application of the model is strictly limited for a few meters above the MWL.

$$\frac{U_y}{U_*} = \frac{1}{H} \ln \frac{y}{z_0} \tag{21}$$

where U_y is the wind speed at height y above the MWL, z_0 is a roughness parameter, H is von Kármán constant (H = 0.4), and U* is the shear wind velocity defined as

$$U_* = \sqrt{\tau_a / \rho_a} \tag{22}$$

where ρ_a is the air density, and $\vec{\tau}_a$ is the surface shearing stress. Force $\vec{\tau}_a$ acting on the water surface of unit area is equal to

$$\tau_a = c_a \rho_a U_y^2 \tag{23}$$

where U_y is the wind speed measured at a height y above the MWL and c_a is the aerodynamic friction coefficient defined as

$$c_a = (H/\ln \frac{y+z_0}{z_0})^2 \tag{24}$$

If the wind speed U_y at height z = y is measured the wind speed at any arbitrary level can be found by formula

$$U_z = U_y + \frac{U_*}{H} \ln \frac{z}{y} \tag{25}$$

where U_* is the shear velocity for the wind speed U_y measured at the level of y. To compute the wind speeds for the various altitudes it is the most convenient to refer all wind speed measurements to the level of 10 m above the MWL. Then

$$U_z = U_{10} + \frac{U_*}{H} \ln \frac{z}{10} \tag{26}$$

The shear wind speed can be approximated as

$$U_* = U_{10}\sqrt{C_{10}} \tag{27}$$

where C_{10} is the aerodynamic friction coefficient at a height of 10 m. This variable depends on the wind speed as it was found by Smith (1970) and Wu (1969)

$$C_{10} = \begin{cases} 1.35 \times 10^{-3} \text{ for } U_{10} < 15 \text{ m/s} \\ 2.60 \times 10^{-3} \text{ for } U_{10} \geq 15 \text{ m/s} \end{cases} \tag{28}$$

From Eqs. (21) and (27) the roughness parameter z_0 can be readily found (see also Horjen, 1983)

$$z_0 = 10 \exp(-H \cdot C_{10}^{-\frac{1}{2}}) \tag{29}$$

Then, the roughness parameter is equal to

$$z_0 = \begin{cases} 1.87 \times 10^{-4} \text{ m} \quad \text{for } U_{10} < 15 \text{ m/s} \\ 3.92 \times 10^{-3} \text{ m} \quad \text{for } U_{10} \geq 15 \text{ m/s} \end{cases} \tag{30}$$

By Eq. (25) the wind speed at the level of the crest of the wave of significant height is equal to

$$U_{H_{\frac{1}{3}}} = U_{10} + \frac{U_*}{H} \ln \frac{0.5H_{\frac{1}{3}}}{10} \tag{31}$$

where U^* is shear wind speed and $H_{\frac{1}{3}}$ is the significant wave height.

All terms on the right-hand side of Eq. (1) were approximated above but the flux of wind-driven spray to an object has not been determined yet. To approximate it we must derive the mass of spray originating from a single wave as well as time-averaged spray flux to an object. The latter is necessary if we prove that wind-generated spray affects the objects under consideration.

1.3 Splashing a Ship With Spray Originating From a Single Wave

Let us first consider the conditions under which spray is generated by wind. Direct shearing of the wave crests to produce spray has only been reported for wind speeds greater than 8.0-10.7 m/s (Beaufort number 5 - Table 3). This corresponds pretty well with the threshold wind speed U_{10} = 11.8 m/s producing wind-generated spray given by Itakagi (1984). However, bursting of air-bubbles at the sea surface is the primary source of spray production, and takes place mainly in regions of whitecaps and foam patches* affected by wind turbulence. In general, whitecaps require wind speeds greater than 4-5 m/s (Table 3). This threshold wind speed was confirmed by Gatham and Trent (1968) and Munk (1947) who found no whitecaps for winds up to 3 m/s and an abrupt increase of concentration of oceanic foam patches at wind speed of 5 m/s, respectively. Hence, we will assume that a wind speed of 5 m/s is the threshold value for spray production.

The drops of spray produced by one of the two above mechanisms are quickly picked up by the wind after leaving a boundary layer laying just above the water surface. In order to approximate the movement of the water drops after deputing from the sea surface and boundary layer, we must neglect the effects of inertial and turbulence forces on the spray which are considerably small (Wu, 1979b). Then, we assume that the water drop is affected only by

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* These terms are well defined in Herbers (1984).

Table 3.--Beaufort Scale.

Beaufort Number	Wind Speed (m/s)	Effects Observed at Sea	Term and Height of Waves, in Feet
0	0. 0-0. 2	Sea like mirror.	Calm, glassy, 0
1	0. 3-1. 5	Ripples with appearance of scales; no foam crests.	
2	1. 6-3. 3	Small wavelets; crests of glassy appearance, not breaking.	Rippled, 0-1
3	3. 4-5. 4	Large wavelets; crests begin to break; scattered whitecaps.	Smooth, 1-2
4	5. 5-7. 9	Small waves, becoming longer; numerous whitecaps.	Slight, 2-4
5	8. 0-10. 7	Moderate waves, taking longer form; many whitecaps; some spray.	Moderate, 4-8
6	10. 8-13. 8	Larger waves forming; whitecaps everywhere; more spray.	Rough, 8-13
7	13. 9-17. 1	Sea heaps up; white foam from breaking waves begins to be blown in streaks	Very rough, 13-20
8	17. 2-20. 7	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks.	
9	20. 8-24. 4	High waves; sea begins to roll; dense streaks of foam; spray may reduce visibility.	
10	24. 5-28. 4	Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced	High, 20-30
11	28. 5-32. 6	Exceptionally high waves; sea covered with white foam patches; visibility still more reduced.	Very high, 30-45
12	≥32.7	Air filled with foam; sea completely white with driving spray, visibility greatly reduced.	Phenomenal, over 45

the gravity force ($\vec{W}$)

$$W = \frac{4}{3} \pi r^3 \rho_w g \tag{32}$$

and the air drag force ($\vec{F}_a$)

$$F_a = C_{af} \rho_a \pi r^2 U_z^2 \tag{33}$$

where r is the water drop radius, g is the acceleration due to gravity, c_{af} is the air drag coefficient, U_z is the local wind speed, and ρ_a and ρ_w are the air and water densities, respectively.

The speed of flying water drop has two components. The vertical component is provided by gravity and is a uniform downward-directed accelerated motion. The water drop is affected by the air drag force which value decreases with lowered altitude. Its motion in the horizontal direction is not a uniform one. Its speed may be approximated as equal to the local wind speed. As a result, the wind-driven spray moves along the track of variable curvature which radius gradually decreases with lowering altitude.

The source area of spray is located at the top of the wave crest and within the whitecap which covers the back face (leeward side) of the wave (Fig. 9). At present, it is difficult to approximate the location of the down edge of the whitecap relative to a characteristic element of a free-surface of water, say, the wave crest. Some discussion on it has been recently furnished by Herbers (1984) but it is not sufficient to approximate the relationship between whitecap dimensions and the wind speed and/or the wave height. In this analysis, we will maximate the trajectory and the range of water drop transport from a wave crest and/or back face of the wave by only considering that spray originates from wave crest only.

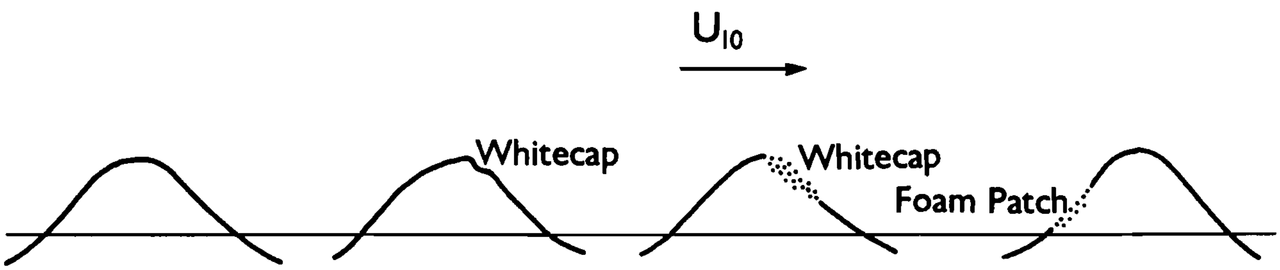

Figure 9.--Formation of the whitecaps (according to Herbers (1984).

Assume a coordinate system located at an unmoving wave crest (Fig. 10). The trajectory of spray flight is given by formula

$$x = U_z \sqrt{\frac{H_{\frac{1}{3}} - 2z}{g}} \quad \text{m} \tag{34a}$$

or

$$z = 0.5\, H_{\frac{1}{3}} - \frac{x^2}{2U_z^2}\, g \quad \text{m} \tag{34b}$$

where z is the altitude above the MWL, $H_{\frac{1}{3}}$ is the significant wave height, g is the acceleration due to gravity, and U_z is the local wind speed at the altitude z. The trajectory of spray originated from the wave crest has been plotted for wind speed U_{10} = 30 m/s in Figure 10. Note that the free-surface of the sea is presented there for the moment of start of the water drop motion.

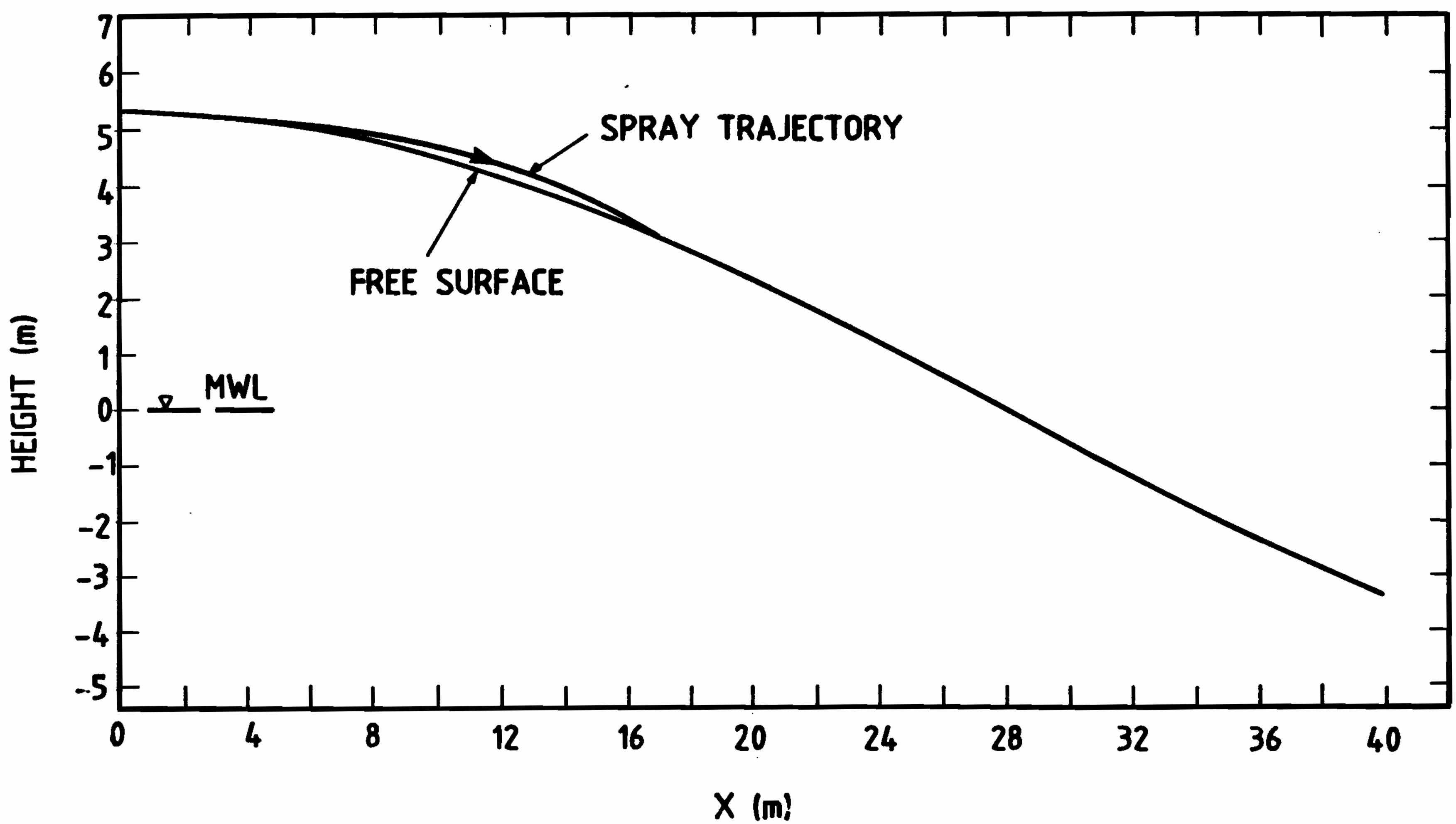

Figure 10.--Spray trajectory of water drops whipped off from the wave crest for the fetch 100 n.m. and wind speed U_{10} = 30 m/s. The wave crest is not moving.

However, in contrast to our simplified model, the wave is propagated and the wave face follows the flying water drop. Hence, the spray motion relative to its parent free-surface of the sea should be considered. The waves propagate in a deep sea with the speed equal to [12]:

$$C_w = 1.559\ P_w \qquad \text{m/s} \tag{35}$$

where P_w is the period of wave. Based on field data given in reference [12], the period of the significant wave in a fully arisen sea has been presented as the third- and fifth- degree polynomials in wind speed U_{10} measured at the level of 10 m above the MWL

$$P_w = C_0 + C_1U_{10} + C_2U_{10}^2 + C_3U_{10}^3 \qquad \text{sec} \tag{36a}$$

or,

$$P_w = C_0 + C_1U_{10} + C_2U_{10}^2 + C_3U_{10}^3 + C_3U_{10}^3 + C_4U_{10}^4 + C_5U_{10}^5 \quad \text{sec} \tag{36b}$$

where C_0, C_1, C_2, C_3, C_4 and C_5 are the constants listed in Table 4 for a given fetch. Assume that a frame of reference is fitted to the wave crest and moves with it. The free-surface may be described using the first-order and the second-order theory of Stokes by formulas (McCormick, 1973), respectively.

$$z = \frac{H}{2}\cos(k\cdot x - \omega t) \tag{37a}$$

and

Table 4.--Constants of the third-degree (a) and fifth-degree (b) polynomial in wind speed to compute the period of significant wave.

(a)

FETCH (n.m.)	C_0	C_1	C_2	C_3
100	2.47228	$3.65216 \cdot 10^{-1}$	$-8.25092 \cdot 10^{-3}$	$9.10275 \cdot 10^{-5}$
200	3.72794	$3.01975 \cdot 10^{-1}$	$-2.32187 \cdot 10^{-3}$	$-1.66139 \cdot 10^{-5}$
300	4.32180	$3.02850 \cdot 10^{-1}$	$-1.05829 \cdot 10^{-4}$	$-6.49383 \cdot 10^{-5}$
400	5.02971	$2.83395 \cdot 10^{-1}$	$1.29923 \cdot 10^{-3}$	$-7.99624 \cdot 10^{-5}$
500	5.14604	$3.35937 \cdot 10^{-1}$	$-4.21257 \cdot 10^{-4}$	$-5.64720 \cdot 10^{-5}$

(b)

FETCH (n.m.)	C_0	C_1	C_2	C_3	C_4	C_5
100	4.68269	$-6.29590 \cdot 10^{-1}$	$1.47148 \cdot 10^{-1}$	$-1.06925 \cdot 10^{-2}$	$3.39925 \cdot 10^{-4}$	$-3.96520 \cdot 10^{-6}$
200	$-2.41866 \cdot 10^{-1}$	1.64186	$-1.67453 \cdot 10^{-1}$	$9.40820 \cdot 10^{-3}$	$-2.52521 \cdot 10^{-4}$	$2.56951 \cdot 10^{-6}$
300	2.92959	$6.97189 \cdot 10^{-1}$	$-3.75184 \cdot 10^{-2}$	$1.36520 \cdot 10^{-3}$	$-1.85457 \cdot 10^{-5}$	$-1.45308 \cdot 10^{-8}$
400	$-8.14976 \cdot 10^{-2}$	1.58956	$-1.20539 \cdot 10^{-1}$	$5.08323 \cdot 10^{-3}$	$-9.81111 \cdot 10^{-5}$	$6.44218 \cdot 10^{-7}$
500	4.68527	$4.02249 \cdot 10^{-1}$	$6.62677 \cdot 10^{-4}$	$-5.85091 \cdot 10^{-4}$	$2.55276 \cdot 10^{-5}$	$-3.66318 \cdot 10^{-7}$

$$z = \frac{H}{2} \cos(k \cdot x - \omega t) + \frac{H^2}{4} \frac{\pi}{2\lambda} \frac{\cosh(k \cdot D)}{\sinh^3(k \cdot D)} \cdot \tag{37b}$$
$$\cdot [2 + \cosh(2kD)] \cos(2k \cdot x - 2\omega t)$$

where λ is the wavelength given by formula

$$\lambda = 1.5616 \; P_w^2 \qquad \text{m} \tag{38}$$

k is the wavenumber $(2\pi/\lambda)$, D is the water depth, $H_{\frac{1}{3}}$ is the significant wave height, x and z are the coordinates, t is time, and ω is given by formula

$$\omega = (k \cdot g \cdot \tanh(kD))^{\frac{1}{2}} \tag{39a}$$

or,

$$\omega = (2\pi/p_w)^{\frac{1}{2}} \tag{39b}$$

where g is acceleration due to gravity.

Eqs. (37a and 37b) are restricted to deep sea, and to fulfill this criterion the water depth D has to satisfy equation

$$D \geq 0.5 \; \lambda \tag{40}$$

For wind speed up to 31 m/s and fetch up to 500 n.m. the minimal sea depth is equal to about 150 m. If the speed of the wave propagation C_w is approximated by Eq. (35), the trajectory of spray flight with respect to the free-surface of sea is given by formulas

$$x = (U_z - C_w) \sqrt{\frac{H_{\frac{1}{3}} - 2z}{g}} \qquad \text{m} \tag{41a}$$

or

$$z = 0.5\ H_{\frac{1}{3}} - \frac{x^2}{2(U_z - C_w)^2}\ g \qquad \text{m} \tag{41b}$$

whose notation are the same as for Eqs. (34a and 34b). For wind speed U_{10} = 30 m/s and fetch 100* n.m the wave and the trajectory of spray flight are presented in Figure 11. One can see that for these extremely severe weather conditions (within the range of the use of Eq. (5a) or (5b)), wind-generated spray is driven by wind up to 20 m from its source area. However, one must not forget that the source area of spray is not only located at the top or the wind-whipped crest of the wave but also forms the extensive whitecap covering the rolling wave†. In fact, wind-generated spray is blown by wind from the back face of the wave and flies above the sea surface. In general, it may be treated as a total spray flux over the sea surface within the maximal range of the water drop flights. That is, this flux is formed by many "solitary" trajectories of water drops. For the large whitecap covering the back face of a wave between its crest and the level of, say, $0.60 \cdot H_{\frac{1}{3}}$, the trajectories of spray flight are presented for wind speed U_{10} = 30 m/s, and a fetch of 100 n.m. in Figure 11. As the altitude of the source area of spray decreases, the range of water drop flight decreases because the wind speed decreases with lowering altitude according to Eq. (26).

Let us now determine how wind-generated spray affects an object located on the deck of a ship moving through the waves (Fig. 11). Such an object will be affected by spray if the spray trajectory crosses the trajectory of the

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* The speed of the wave propagation is smallest for this fetch.

† Under described weather conditions.

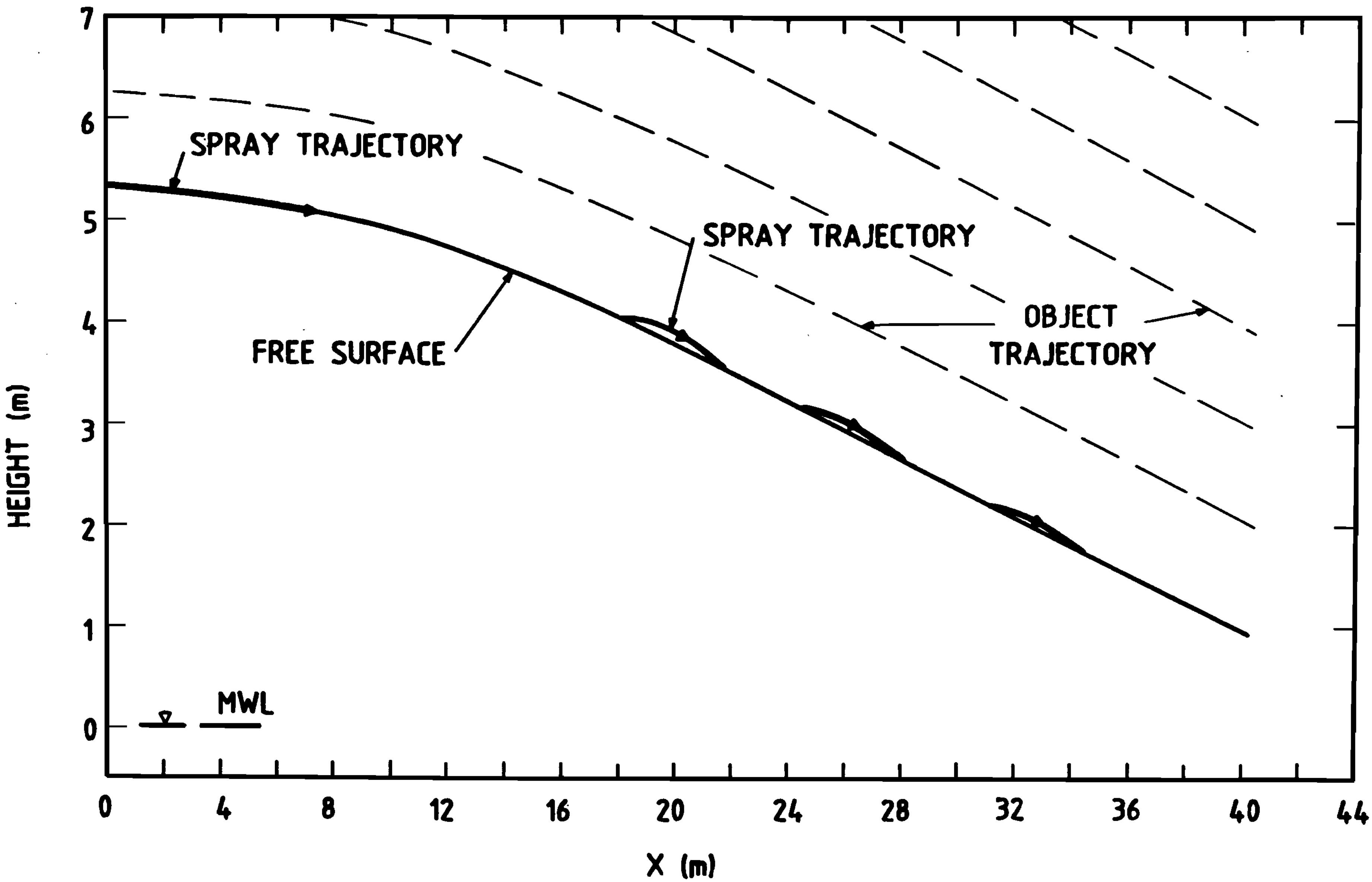

Figure 11.--Spray trajectories for the moving wave crest and wind speed 30 m/s and fetch 100 n.m.

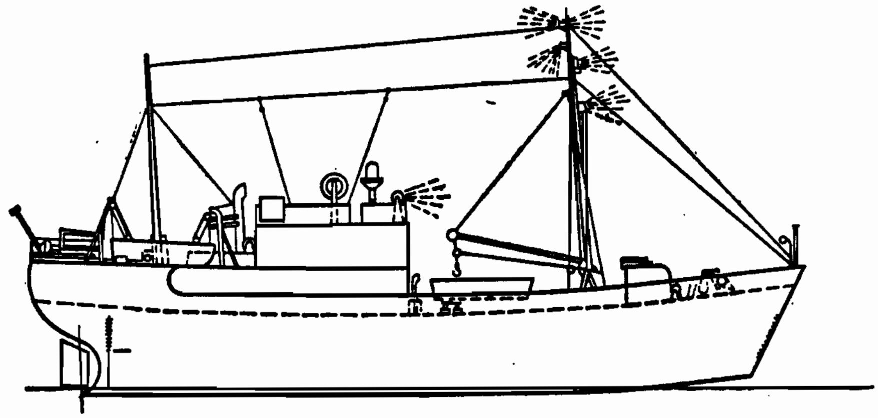

Figure 12.--Soviet medium fishing vessel (38.5-39.5 m length overall; 7.2-7.3 m breadth; displacement 418-462 tons) (according to Aksjutin (1979)).

motion of the object. Neglecting ship motion relative to the free-surface of the sea except that of ship steaming, the trajectory of motion of an object relative to the MWL may be described using the first-order and second-order Stokes theory. For an object elevated h' above the deck of a ship of freeboard h, these formulas are, respectively,

$$z = h + h' + \frac{H}{2}\cos(k\cdot x - \omega t) \tag{42a}$$

and

$$z = h + h' + \frac{H}{2}\cos(kx - \omega t) + \frac{H^2}{4}\cdot\frac{\pi}{2\lambda}\cdot\frac{\cosh(k\cdot D)}{\sinh^3(k\cdot D)}\cdot \cdot [2 + \cosh(2kD)]\cos(2k\cdot x - \omega t) \tag{42b}$$

where the terms are the same as for Eq. (37a) and (37b) and (h+h') is the elevation of the object above the free-surface of the sea. The trajectory of the object is presented with dotted lines for the altitudes z = (h+h') = 1, 2, 3, 4 and 5 m above the free surface in Figure 11. For the MFV of length overall about 40-50 m (Fig. 12) the freeboard is usually equal to 2.5-3.5 m. Thus, it is larger than the maximal altitude of the wind-driven spray during its flight from the top of the wave crest above the sea surface in extremely high seas. As a result, one can easily conclude that the wind-driven spray does not affect the object on the deck of the MFV or above it. This allows us to agree that wave-generated spray seems to be the one and only source of water delivery to the MFV if water flux due to rain, snow, and fog is neglected. On the other hand, it is worthwhile to check if the wind-generated spray is the primary source of water impinging on a marine offshore structure as assumed by Itakagi (1984).

2. SPLASHING A SHIP WITH WAVE GENERATED SPRAY

Wave-generated spray is produced by ship/wave interactions. Almost each wave impact on a ship produces a cloud of spray which becomes wind rafted and splashes the ship. If the ship reaches with the waves the spray splashes her but rarely. In this section, water delivery due to wave impacts on a ship which steams by waves ($\alpha > 90°$)* is considered. Some spray originates from the crests of interference waves generated by ship motion, but this mechanism of water delivery will be neglected here.

To calculate the time-averaged water flux to an object located on deck of a ship near her windward side we have to 1) examine the water delivery to a ship resulting of the single wave impact on the ship, and 2) find the frequency of generation of the spray cloud.

2.1 Effect of a Single Wave Impact on a Ship

The cloud of spray induced by the ship/wave interaction at the moment of impact is affected by wind and drifts with the air stream. Spray generated on

* Heading angle (α) is defined as equal to the angle between the ship heading and direction normal to the wave crest. $\alpha = 0°$ for ship passing the waves and $\alpha = 180°$ for ship going precisely adverse the waves.

the windward side of ship splashes her on its way to the sea surface. Assuming an isotropic structure in the spray cloud, the mass of water delivered to an object can be approximated by a formula similar to Eq. (1) and is given per unit area by the formula

$$m = E_c \cdot w \cdot U \cdot \Delta t \qquad \text{kg/m}^2 \tag{43}$$

where E_c is the collection efficiency, w is the LWC, U is the local <u>relative</u> wind speed and Δt is the time of exposure of an object to a spray.

<u>Collection efficiency</u> is approximated by Eqs. (2) and (3).

<u>The liquid water content</u> is rather weakly defined due to very scarce field data.

The simplest presentation of the LWC distribution above the sea surface after wave impact on a ship is that of Katchurin *et al.* (1974). They assumed that the LWC is a function of wave height only:

$$w = \xi \cdot H \qquad \text{kg/m}^3 \tag{44}$$

where H is the wave height and ξ is a constant. No methodology is given in this reference except a note that the constant for a MFV steaming by the waves ($\alpha \geq 140°$) with the speed of 6-8 knots was assumed to be equal to 10^{-3} kg/m^4. As the significant wave height $H_{\frac{1}{3}}$ is a function of wind speed and fetch (Eq. (5a)) the LWC corresponds with the wind speed according to the formula

$$w = \xi \, (B_0 + B_1 U_{10} + B_2 \cdot U_{10}^2 + B_3 U_{10}^3) \qquad \text{kg/m}^3 \tag{45}$$

where constants B_0, B_1, B_2 and B_3 are listed in Table 1 for a given fetch. A more sophisticated equation has been proposed by Borisenkov (1972), who argued that the LWC is a function of modal diameter of water drops (ϕ_m) and modal value of probability density (f_m) of water drops of such a diameter:

$$w = \frac{20\pi\rho_w e^2}{2^6} f_m \phi_m^4 \qquad g/cm^3 \tag{46}$$

where dimension of ρ_w is in g/cm³, ϕ is in cm and f_m is in cm^{-4}.

In their report Brown and Roebber (1985) mentioned that there are no published measurements of the vertical distribution of wave-generated spray. However, going through Soviet publications on icing, one such report has been found. Based on the field experiment carried on in the Sea of Japan Borisenkov *et al.* (1975) approximated the vertical distribution of the LWC by the formula

$$w = 2.36 \cdot 10^{-5} \exp(-0.55\ h') \qquad cm^3/cm^3 \tag{47}$$

where h' is the elevation (in meters) above the deck of the MFV. The dimension of w is cm³/cm³ as this value gives the volume of water in a unit volume of air. Assume ρ_w = 1025 kg/m³ and converting the dimension of w to kg/m³, Eq. (47) becomes

$$w = 2.302 \cdot 10^{-2} \exp(-0.55h') \qquad kg/m^3 \tag{48}$$

Aksjutin (1979) and Panov (1976) recommended the above given formula for wide use and its application to any air/sea conditions. However, Eqs. (47) and (48) were experimentally derived for the Russian MFV *Narva* steaming by waves at the angle α = 110-90° with a speed of 5-6 knots while the wind speed was equal to 10-12 m/s. This data set indicates that Eq. (48) cannot be used for the approximation of vertical distribution of the LWC above any ship under any air/sea conditions because the ship/wave interaction during this experiment considered the generation of spray by the wave impacts on this ship only. If Eq. (48) reflects the LWC distribution above the ship deck in a spray cloud generated by ship/wave collisions it should be proportional to the wave height and to the square of the ship speed relative to the surface of an oncoming wave. This assumption is in agreement with Katchurin *et al.* (1974). Thus, the distribution of the LWC under any condition can be presented for the same type of ship by the formula

$$w = w_0\left(\frac{H}{H_0}\right)\left(\frac{V_r}{V_0}\right)^2 \exp(-0.55h') \qquad \text{kg/m}^3 \tag{49}$$

where H and V_r are the wave height and ship speed relative to wave, respectively. H_0 and V_0 are the wave height and ship speed relative to the wave during the Russian experiment, and w_0 is a constant equal to 2.302 10^{-2} kg/m³ obtained from Eq. (48). If values of H_0 and V_0 are determined, the vertical distribution of the LWC will be easily found for any given wave height H and ship speed relative to wave (V_r), but Borisenkov *et al.* (1975) have not listed these parameters. We shall try to approximate the values of H_0 and V_0 based on other parameters reported by them. First, we shall find the wave height H_0 during the experiment. Wind speed provided by Borisenkov *et al.* (1975) (U_{10} = 10-12 m/s) is sufficient for this purpose if the fetch is known. The experiment was carried on in the Sea of Japan and the fetch equal to 200 n.m. seems to be appropriate. For this fetch and wind speed U_{10} = 11 m/s, the significant wave height given by Eq. (5b) is equal to H_0 = 3.09 m.

Second, the ship speed relative to an oncoming wave is given by the formula

$$V_r = C_w - 0.514\ V_s\ \cos\alpha \qquad \text{m/s} \tag{50}$$

where C_w is the speed of wave propagation, V_s is the ship speed in knots, and α is the heading angle. The speed of wave motion in the sea may be found by Eqs. (35) and (36a) or (36b). For fetch equal to 200 n.m. and wind speed U_{10} = 11 m/s, the period of waves of significant height given by Eq. (36b) is equal to 6.75 sec, and the speed of wave propagation is then equal to C_w = 10.52 m/s. The Russian ship was steaming with a speed V_s = 5-6 knots by waves at an angle α = 90-110°. For V_s = 5.5 knots and α = 100° the ship speed relative to an oncoming wave was equal to 11.01 m/s. Then, Eq. (49) becomes

$$w = 6.1457 \cdot 10^{-5}\ H\ V_r^2\ \exp(-0.55h') \qquad \text{kg/m}^3 \tag{51}$$

H is calculated by Eq. (5a) or (5b) for a given fetch and wind speed. V_r can be obtained by the formula

$$V_r = 1.559\ P_w - 0.514 V_s \cos\alpha \qquad \text{m/s} \tag{52}$$

where V_s (knots) and α are the ship speed and heading angle, respectively, and P_w is given by Eq. (36a) or (36b) and Table 4 for a given wind speed and fetch.

Summary of results is given in Table 5 for wind speed U_{10} of 10, 20 and 30 m/s and certain ship speeds and heading angles. The values of ship speed (5.5, 8.5, 10.7 and 12.5 knots) and heading angle (180, 150, 120 and 90°) were

Table 5.--Vertical distribution of the liquid water content (kg/m³) in wave-generated spray computed by improved Borisenkov *et al.*'s (1975) formula for a given heading angle and ship speed and surface wind speed.

Heading angle (deg)		180				150				120				90
Surface wind speed (m/s)	**Ship speed (knots) / Elevation above the ship's deck (m)**	5.5	8.5	10.7	12.5	5.5	8.5	10.7	12.5	5.5	8.5	10.7	12.5	5.5-12.5
U_{10} = 10	0	.028009	.035007	.040634	.045550	.026409	.032258	.036919	.040967	.022279	.025323	.027679	.029685	.017204
	1	.016160	.020197	.023444	.026289	.015237	.018611	.021300	.023636	.012854	.014610	.015970	.017127	.009926
	2	.09323	.011653	.013526	.015162	.008791	.010738	.012289	.013637	.007416	.008429	.009214	.009881	.005727
	3	.005379	.006723	.007804	.008748	.005072	.006195	.007090	.007868	.004279	.004863	.005316	.005701	.003304
	4	.003103	.003879	.004502	.005047	.002926	.003574	.004090	.004539	.002469	.002806	.003067	.003289	.001906
	5	.001790	.002238	.002598	.002912	.001688	.002062	.002360	.002619	.001424	.001619	.001769	.001898	.001100
	10	.000114	.000143	.000166	.000186	.000108	.000132	.000151	.000167	.000091	.000103	.000113	.000121	.000070
U_{10} = 20	0	.132779	.158940	.179620	.197480	.126712	.148733	.166002	.180836	.110862	.122572	.131532	.139099	.090921
	1	.076607	.091701	.103632	.113936	.073107	.085811	.095775	.104333	.063962	.070718	.075887	.080253	.052457
	2	.044198	.052907	.059790	.065735	.042179	.049509	.055257	.060195	.036903	.040800	.043783	.046302	.030265
	3	.025500	.030524	.034496	.037926	.024335	.028564	.031881	.034730	.021291	.023540	.025261	.026714	.017461
	4	.014712	.017611	.019902	.021881	.014040	.016480	.018393	.020037	.012284	.013581	.014574	.015413	.010074
	5	.008488	.010161	.011483	.012624	.008100	.009508	.010612	.011560	.007087	.007836	.008409	.008892	.005812
	10	.000543	.000649	.000734	.000807	.000518	.000608	.000678	.000739	.000453	.000501	.000537	.000568	.000372
U_{10} = 30	0	.300614	.352042	.392336	.426728	.288603	.332042	.365833	.394697	.257036	.280383	.298149	.313090	.216870
	1	.713439	.203111	.226316	.246316	.166509	.191572	.211067	.227721	.148297	.161767	.172017	.180637	.125123
	2	.100066	.117185	.130597	.142112	.096067	.110527	.121775	.131383	.085560	.093330	.099245	.104219	.072190
	3	.057733	.067610	.075348	.081991	.055426	.063769	.070258	.075802	.049364	.053847	.057259	.060129	.041650
	4	.033309	.093007	.043472	.047305	.031978	.036791	.040535	.043734	.028480	.031067	.033036	.034691	.024030
	5	.019218	.022505	.025081	.027293	.018450	.021227	.023387	.025232	.016432	.017924	.019060	.020015	.013864
	10	.001228	.001439	.001603	.001745	.001179	.001357	.001495	.001613	.001050	.001146	.001218	.001279	.000886

chosen to enable the comparison of spray fluxes computed using our model with that given by Borisenkov *et al.* (1975) and Tabata *et al.* (1963) and Tabata (1969). Based on data given in Table 5 one can see that: 1) the LWC decreases with the increasing height above the ship deck by approximately 1.73 times per other 1 m of the height difference, 2) as wind speed increases the LWC increases: the LWC is more than 10 times larger in wind speed U_{10} = 30 m/s than 10 m/s, 3) the LWC is maximal if ship is moving into the waves (heading angle α = 180°) and diminishes as the heading angle decreases, 4) the LWC increases as the ship speed increases for any heading angle $\alpha > 90°$, and, 5) if ship moves parallel to the wave crests (α = 90°), the LWC does not depend on the ship speed. Four latter tendencies can be seen fairly well in Figure 13.

Local Wind Speed. Water drops are dragged by the wind. On their way to an object they move along a track of varying curvature. If the wind speed follows the logarithmic law given in Eq. (21), the speed of spray in the horizontal plane will gradually decrease (Eq. (26)). Neglecting both the inertia force effect and deflection of the air stream by the ship, the speed of spray in the horizontal plane in the vicinity of an object located at the height h' above the ship deck is equal to

$$U_{h+h'+z} = U_{10} + \frac{U_*}{H} \ln \frac{h+h'+z}{10} \tag{53}$$

where h is the ship freeboard, and U_{10}, H and U_* are the same as for Eq. (26). z is the elevation or the wave surface above the MWL (see Fig. 11), and may be calculated using Eq. (35a) or (35b) for x-coordinate equal to

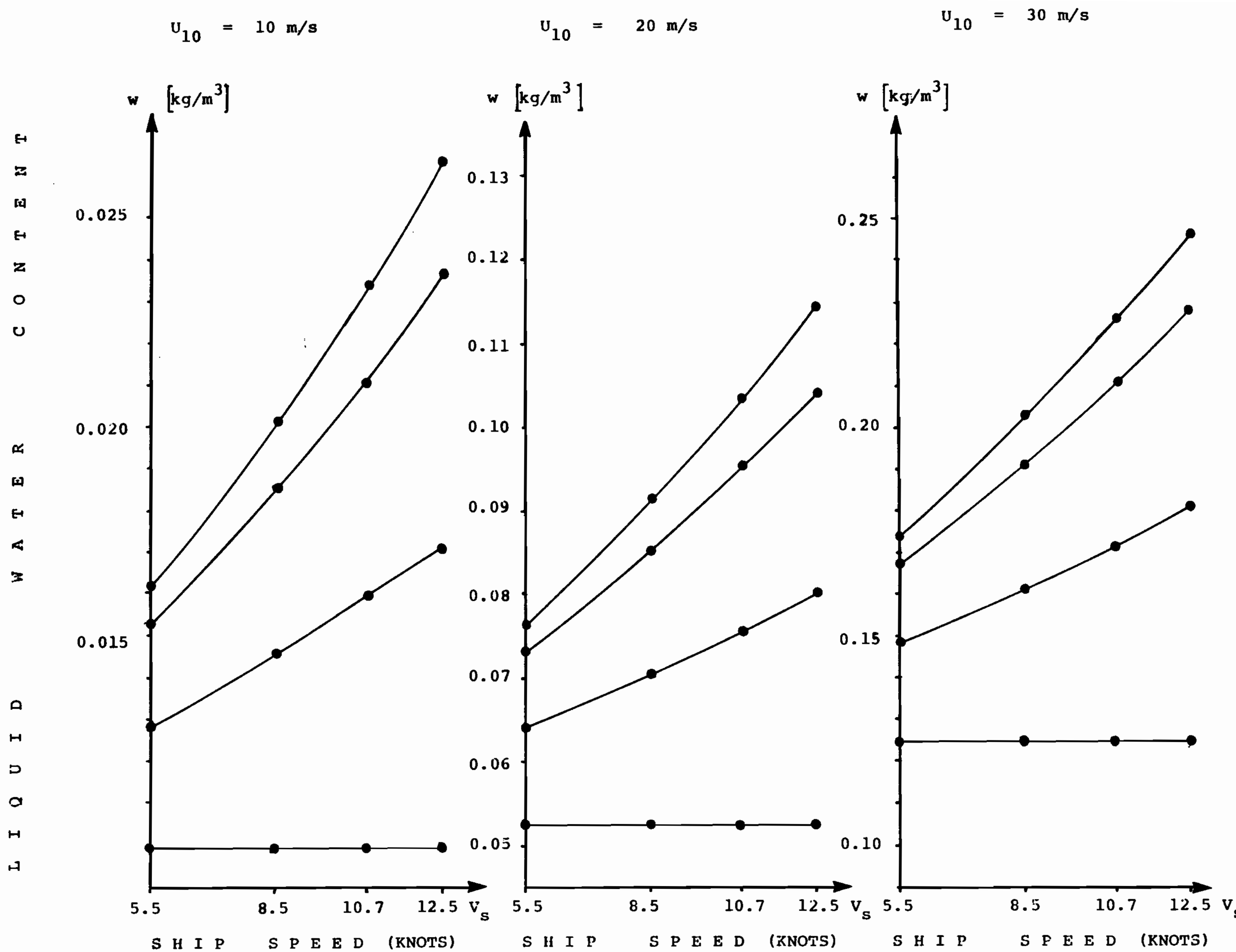

Figure 13.--Liquid water content in wave-generated spray as a function of ship speed and heading angle for an elevation of 1 m above the ship's deck.

$$x = \begin{cases} 0.05\lambda & \text{for wind speed } U_{10} < 15 \text{ m/s} \\ 0.03\lambda & \text{for wind speed } U_{10} \geq 15 \text{ m/s} \end{cases} \tag{54}$$

where λ is the wavelength computed by Eqs. (38), and (36a) or (36b) for given wind speed and fetch. Constants 0.05 and 0.03 were chosen to reflect the location of the ship-wave collision with respect to the wave crest.

However, one must not use Eq. (53) for computing the spray flux if the ship is moving. That is, the flux of spray impinging to the object located at the ship is governed by the local relative wind speed rather than the local wind speed $U_{h'+h+z_s}$ which is given by Eq. (53). The local relative wind speed can be measured on the ship in the vicinity of the object under consideration. This possibility is very convenient during field experiments. However, here we must compute the local relative wind speed. Since the vector of the local relative wind speed ($\vec{U}$) has two components (vector adverse to the ship speed vector, and local wind speed vector given by Eq. (53)), the local relative wind speed affecting the object elevated h' above the ship's deck (or elevated $h'+h+z_s$ above the MWL) is given by the formula

$$U = \sqrt{U^2_{h'+h+z_s} + (0.514V_s)^2 + 2 \times 0.514 \times V_s \times U_{h'+h+z_s} \times \cos(180-\alpha)} \tag{55}$$

where the local wind speed $U_{h'+h+z_s}$ is given by Eq. (53), V_s is the ship speed (in knots) and α is the heading angle.

Time of Ship Exposure to Spray. Δt defines the residence time of a spray generated by wave-ship collision against an object. When the morphology of the spray cloud is unknown due to the lack of field observations we can make a rough approximation of this parameter only. For a given ship the time of ship exposure to a spray should depend on the ship speed relative to the wave at the moment of wave impact, the height of the wave and wind speed. The first two factors affect the extent of spray cloud and its morphology, while the third term determines on the residence time of the spray cloud over a given object as the water drops are affected by the wind form drag force. Thus, formally:

$$\Delta t = f(H, U, V_r) \tag{56}$$

where H is the wave height, U is the local wind speed and V_r is the ship speed relative to an oncoming wave. Let us assume that the dimensions of those terms may be defined as $[\Delta t]$ = sec, [H] = m, [U] = m/s and $[V_r]$ = m/s. If the π-theorem from dimensional analysis is used, we will get

$$[\Delta t] = \frac{[H][V_r]}{([U])^2} \tag{57}$$

Then, Eq. (56) can be written as

$$\Delta t = c\,\frac{HV_r}{U^2} \qquad \text{sec} \tag{58}$$

where c is an empirical constant which depends first of all on the shape and size of ship hull. Hence, for a given type of ship we can find the value of constant c if the values of other terms of Eq. (58) are known. Fortunately, while there are no published results of field observations, two data sets do exist in the literature. First, Borisenkov and Panov (1972) mentioned

Gashin's unpublished report from the Atlantic cruise of MFV "Iceberg" in August-November of 1969, when the ship was affected by swell, and some measurements of spray cloud residence were made. The residence of the spray cloud was given (Δt = 2 sec), but the ship speed, wind speed and wave H height were not. On the other hand, the ship was affected by swell rather than wind wave, and the swell height is not related to the wind speed encountered by the ship during the measurements. As a result, this report is useless for our purposes. Fortunately, however Borisenkov *et al.* (1975) said more about the air/sea conditions under which spray cloud duration was measured on the MFV *Narva* in the Sea of Japan in February of 1973. For a ship speed 5-6 knots, wind speed U_{10} = 10-12 m/s and wave angle α = 90-110°, the measured time of ship exposure to spray was equal to 5.8 sec. If $H_{\frac{1}{3}}$ is the significant wave height, we will get it for a given wind speed U_{10} by Eq. (5a) or (5b). The ship speed relative to an oncoming wave for a given heading angle α and ship speed V_s may be found by Eqs. (52), and (36a) or (36b). The local wind speed U, as defined in Eq. (58), can then be computed for the altitude z+h+h' (h is the freeboard of ship and h' is the elevation of an object above the ship deck), but varies within the time interval Δt as it passes through the wind-driven spray cloud. It is possible to approximate the altitude variation using the set of Eqs. (37a) or (37b) and (54) but we must note that the ship speed after a wave impact on her decreases significantly, especially in heavy seas with large values of heading angle (α > 150°). Thus, we assume that the elevation of an object is uniform for the whole time interval Δt, and equal to the height of the crest of the wave above the MWL ($z = 0.5 \cdot H_{\frac{1}{3}}$). Hence for wind speed U_{10} we have the wave height $H_{\frac{1}{3}}$ = 3.09 m, ship speed relative to an oncoming wave V_r = 11.01 m/s (for α = 100°), and local wind speed U_H = 9.11 m/s. Taken all together, the constant c in Eq. (58) is equal to c = 14.149. Hence, Eq. (58) becomes

$$\Delta t = 14.149 \frac{HV_r}{U^2_{0.5H_{\frac{1}{3}}}} \qquad \text{sec} \tag{59}$$

If the ship speed corresponds with the wind speed as in Table 6, the time of ship exposure to a spray can be easily computed (Fig. 14). In general, the time of ship exposure to the spray cloud depends on the wind speed and heading angle. This decreases significantly as the wind speed increases for heading angle 180° while it varies only slightly for heading angles 150° and 120°. Sharp turn observed in any relationship presented in Figure 14 for the wind speed of 15 m/s is caused mainly by assumed ship speeds (Table 6) and reflect the change of ship response to the waves. If all terms of the right-hand side of Eq. (43) are approximated as above, we will present the water flux to an object as a function of wind speed U_{10}, ship speed V_s and heading angle α, and the elevation of the object above a ship deck h'. For an assumed fetch of

Table 6.--Assumed speed (in knots) of a MFV for a given wind speed and heading angle.

HEADING ANGLE (deg)	SURFACE WIND SPEED (m/s)					
	5	10	15	20	25	30
180*	13.8	12.2	10.4	8.6	6.0	2.1
150	13.8	12.5	10.9	9.0	6.6	3.0
120	14.0	13.0	11.5	9.9	7.8	5.2
90**	14.1	13.8	13.6	12.9	11.1	9.0

* adverse to the waves

** Parallel to the waves

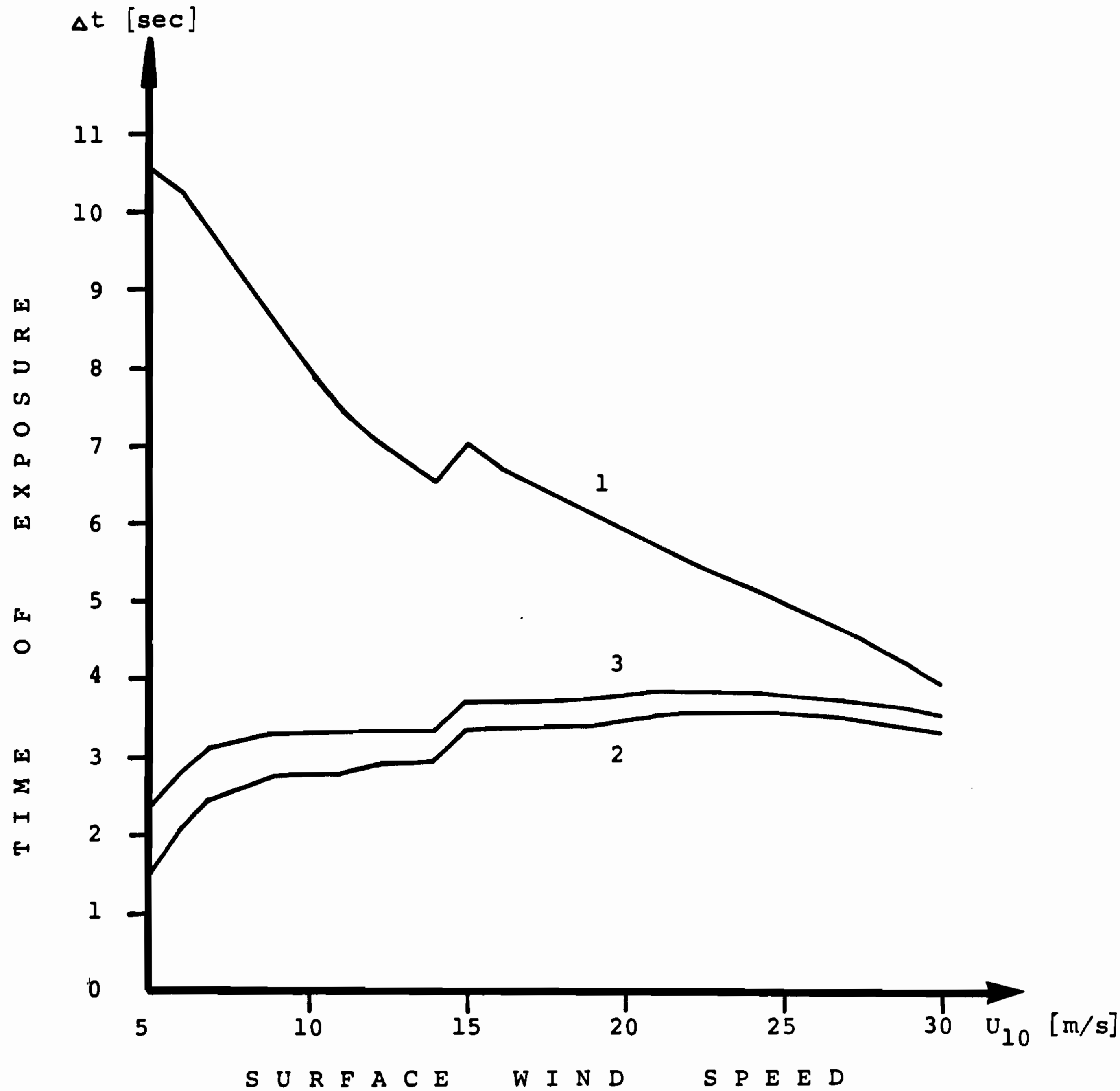

Figure 14.--Time of ship exposure to the spray cloud as a function of wind speed and heading angle (1 - heading angle 180°; 2 - heading angle 150°; 3 - heading angle 120°) for the MFV sailing with speeds given in Table 6.

200 n.m., and ship freeboard h = 2.5 m the results are presented in Table 7. The length of the object was chosen to be equal to L = 1 m. One can readily find that the spray flux to a cylinder is somewhat larger than to a vertical plate. This is directly caused by the collection efficiency. Spray flux abruptly diminishes with the elevation above the ship's deck what is caused both by the transport of spray in the air stream and the wind effect on the wave height. Spray flux depends on the ship speed and heading angle. Spray flux is largest for ship sailing into the waves ($\alpha = 180°$) and diminishes with decreasing heading angle. As ship speed increases the spray flux increases for any heading angle $\alpha > 90°$ while for the heading angle $\alpha = 90°$ the spray flux does not depend on the ship speed.

It is interesting to approximate the total amount of sea water coming to the MFV with a spray originating from a single wave. Since the theory of wave-generated spray movement is rather complex (see Panov *et al.*, 1975) and there are no published data sets available from which the empirical relationships between the forcing factors (air/sea conditions, ship motion parameters and the movement of the wave-generated spray) can be derived, we can make only a rough approximation of the total mass of spray reaching the entire MFV. Borisenkov *et al.* (1975) approximated the total amount of the liquid water content in the spray cloud induced by the single ship/wave collision to be equal to 300 litres. No information is given on the method used for making this approximation. During this experiment, the Soviet MFV *Narva* (39.5 m length overall, 7.3 m breadth) was sailing with the speed $V_s \cong$ 5.5 knots in the moderate sea (wind speed $U_{10} = 11$ m/s; $H_{\frac{1}{3}} = 3.09$ m) and the heading angle was equal to $\alpha = 100°$. For these sea/air conditions and so small heading angle (the ship was sailing almost parallel to the wave crests) we can assume that the total mass of the spray flux coming through the

Table 7.--Wave-generated spray flux (kg/m²) originating from a single wave and coming to the object located on the windward side of a MFV (heading angle ≤ 150°) and near the ship's bow (heading angle 180°) at the elevation of 1 m above the ship's deck.

OBJECT			CYLINDER			VERTICAL PLATE		
WIND SPEED (m/s)			10	20	30	10	20	30
SHIP HEADING (deg)	SHIP SPEED (knots)							
180		5.5	1.0383	8.3879	22.6934	0.9407	7.8525	21.5625
		8.5	1.4508	10.9853	28.7593	1.3144	10.2842	27.3261
		10.7	1.8143	13.1975	33.8356	1.6437	12.3552	32.1494
		12.5	2.1533	15.2141	38.4076	1.9509	14.2431	36.4936
150		5.5	0.9506	7.8196	21.3470	0.8613	7.3206	20.2832
		8.5.	1.2834	9.9442	26.3437	1.1627	9.3095	25.0309
		10.7	1.5713	11.7254	30.4656	1.4236	10.9771	28.9474
		12.5	1.8367	13.3318	34.1415	1.6640	12.4809	32.4401
120		5.5.	0.7366	6.3993	17.9423	0.6673	5.9909	17.0482
		8.5	0.8926	7.4395	20.4415	0.8087	6.9647	19.4229
		10.7	1.0200	8.2700	22.4148	0.9241	7.7422	21.2978
		12.5	1.1329	8.9938	24.1207	1.0264	8.4198	22.9187
90	SHIP SPEED (knots)	5.5--12.5	0.4998	4.7529	13.9054	0.4528	4.4495	13.2125

"window" of arbitrary chosen height of 10 m and spread from the ship's bow to the back wall of the superstructure (see Fig. 12). The length of this "window" is equal to about 30 m. Using Eqs. (43), (51) and (55) one can find that about 100 kg of sea water have been delivered to the MFV *Narva* with the spray generated by any single wave/ship collision under given air/sea conditions.

If a ship moves into the waves and wind ($\alpha = 180°$) the wind-driven spray cloud splashes her from the bow towards the superstructure (see Fig. 12). For a ship moving into the waves the length of the spray catch "window" is equal to the ship breadth. The total mass of spray originating from the single wave/ship impact and delivered to the ship *Narva* moving into the waves with the speed of 5.5 knots under the same air/sea conditions is equal to about 45 kg. The total mass of spray splashing a ship in high seas is much larger (Fig. 15). This can be easily computed using our Eq. (43).

2.2 Time-Averaged Flux of Wave-Generated Spray

To determine time-averaged spray flux to an object located on a ship, the frequency of the wave impacts on a ship and the mass of water delivered with the spray from a single wave are necessary. The problem of water flux originating from a single wave was solved earlier (Eqs. 43, 49, 53, 55 and 59), so at present we will discuss the frequency of generation of spray clouds by ship-wave interaction. To roughly approximate this value we assume that a spray cloud is only generated at the moment of ship collision with an oncoming wave. Then, the time interval between any two subsequent wave-ship collisions is equal to

$$P_r = \frac{\lambda}{1.25\sqrt{\lambda} - 0.514\ V_s\ \cos\alpha} \quad \text{sec} \tag{60a}$$

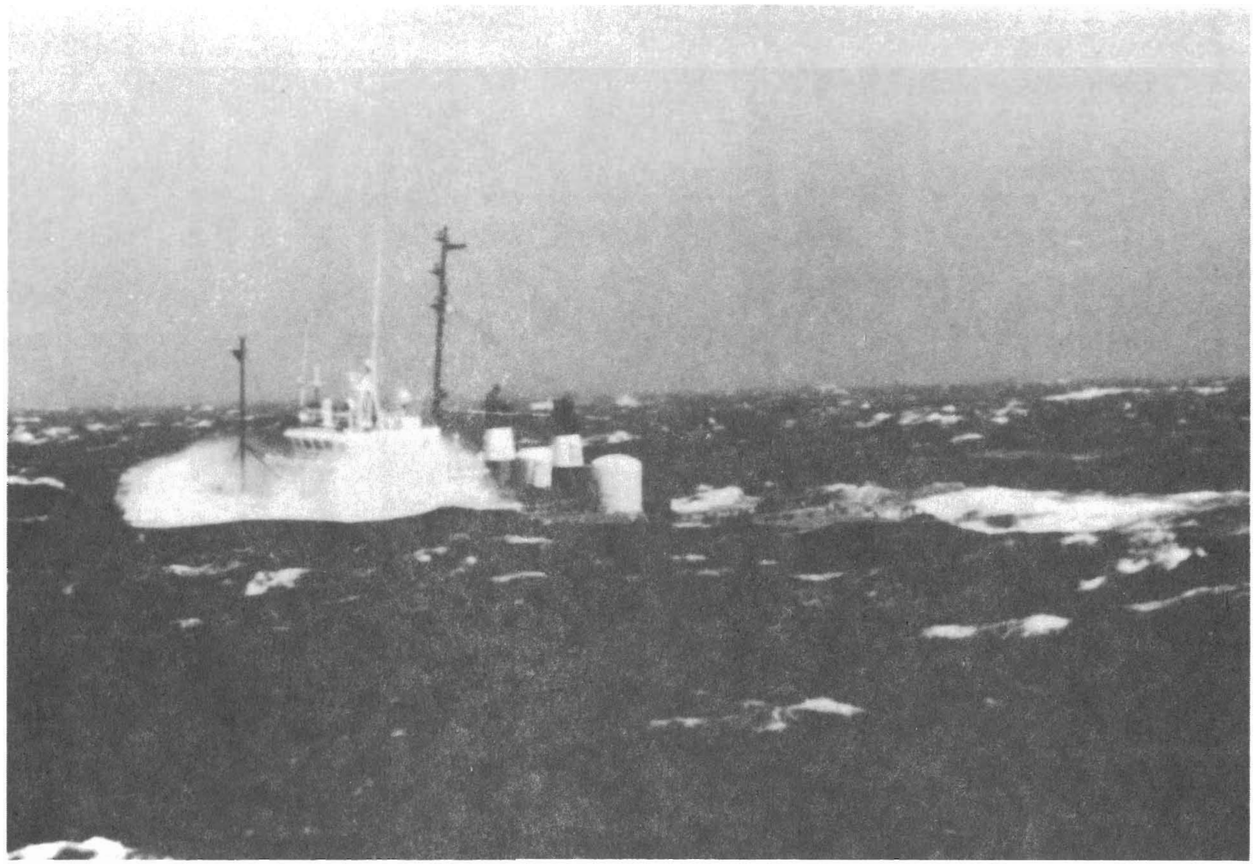

Figure 15.--Clouds of spray generated by ship/wave interaction in heavy seas (a - Canadian supply vessel in the Labrador Sea; b - Norwegian supply vessel in the Norwegian Sea; c - Norwegian supply vessel in the Norwegian Sea).

NOTE: Photographs given in Figure 15b and 15c were obtained from Ivar Horjen (NHL, Trondheim).

b

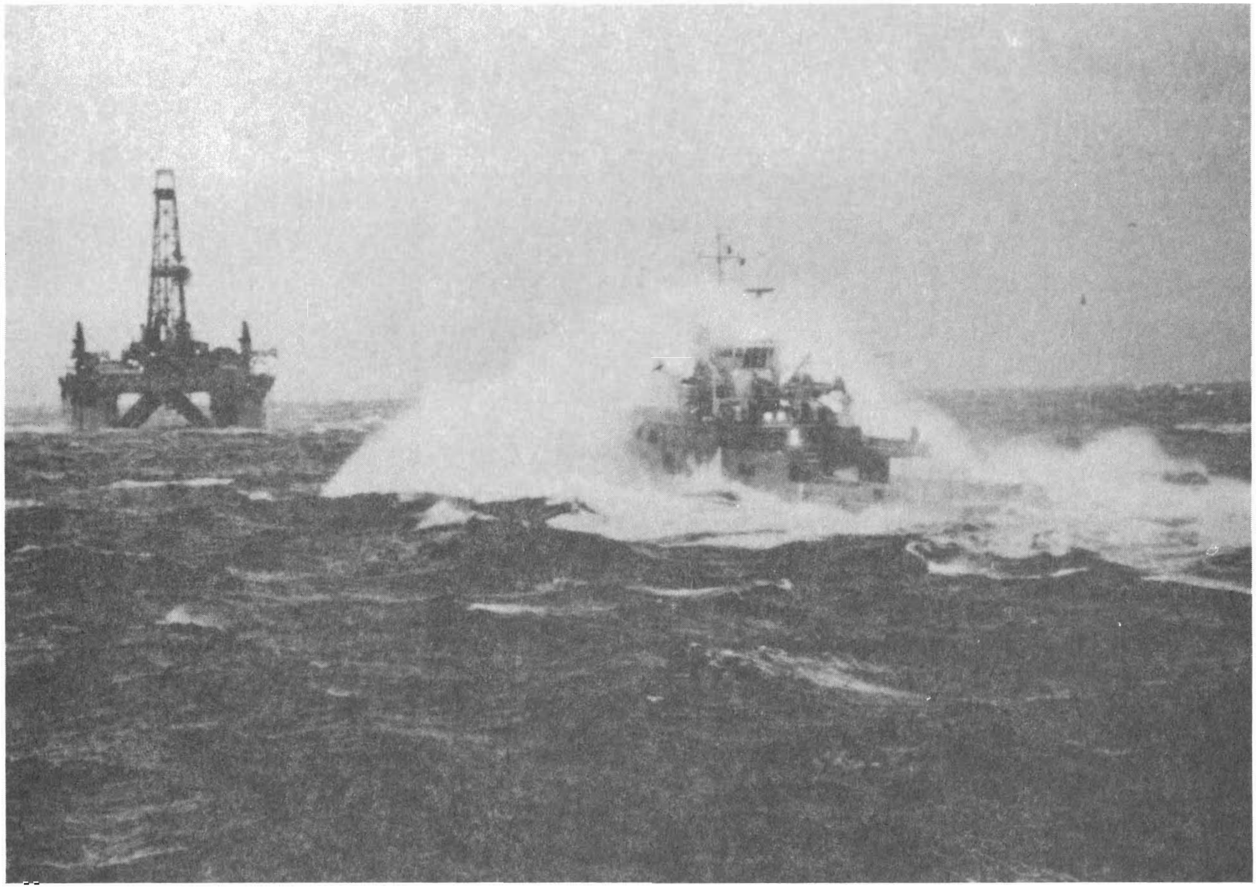

Figure 15.--(continued)

C

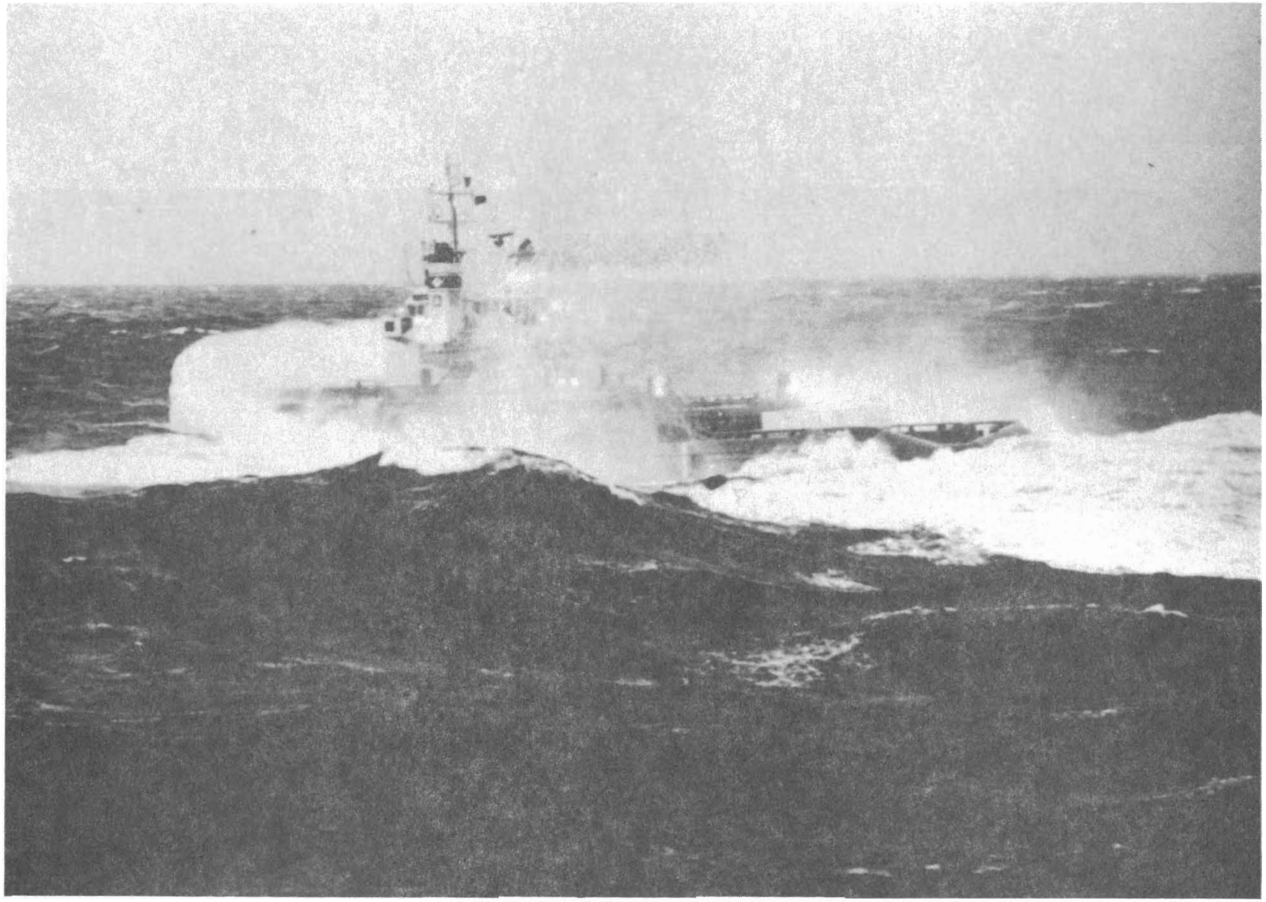

Figure 15.--(continued)

or, using the wind speed U_{10} to determine the wavelength,

$$P_r = \frac{1.5616\ P_w^2}{1.559 \cdot P_w - 0.514\ V_s\ \cos\alpha} \qquad \text{sec} \tag{60b}$$

where λ is the wavelength, V_s is ship speed in knots, α is the heading angle, and P_w is the period of waves of significant height. The number of spray clouds generated per unit time is equal to

$$N = \begin{cases} 60/P_r & \text{for time unit} = 1 \text{ min} \\ 3600/P_r & \text{for time unit} = 1 \text{ hr} \end{cases} \tag{61}$$

where P_r is the time interval between two subsequent ship-wave collisions according to Eq. (60a) or (60b). This relationship is presented for the given ship speeds and heading angles in Figure 16. Thus, the flux of wave-generated spray per unit time is given by the formula

$$M = \begin{cases} 60\ E_c \cdot w \cdot U \cdot \Delta t/P_r & \text{kg/m}^2 \text{ min} \\ 3600\ E_c \cdot w \cdot U \cdot \Delta t/P_r & \text{kg/m}^2 \text{ hr} \end{cases} \tag{62}$$

where E_c is given by Eqs. (2) and (3), w by Eq. (51), U by Eq. (54), Δt by Eq. (59) and P_r by Eq. (60a) or (60b).

Let us now deal with the accuracy of Eq. (62). Panov (1976) and Aksjutin (1979) listed the results of field observations on the frequency of splashing the MFV with spray as a function of wavelength, ship's speed and heading angle. Observed frequencies (N_m) are plotted against theoretical frequencies (N_c) computed from Eq. (61) in Figure 17. As can be seen, a large scatter is evident. The ratio of N_m/N_c varies from 0.25 to 1.24 with a mean value of 0.517. Thus, roughly speaking, the ship is splashed with spray every other wave impact. Hence, one can approximate the frequency of splashing a ship with spray by the formula

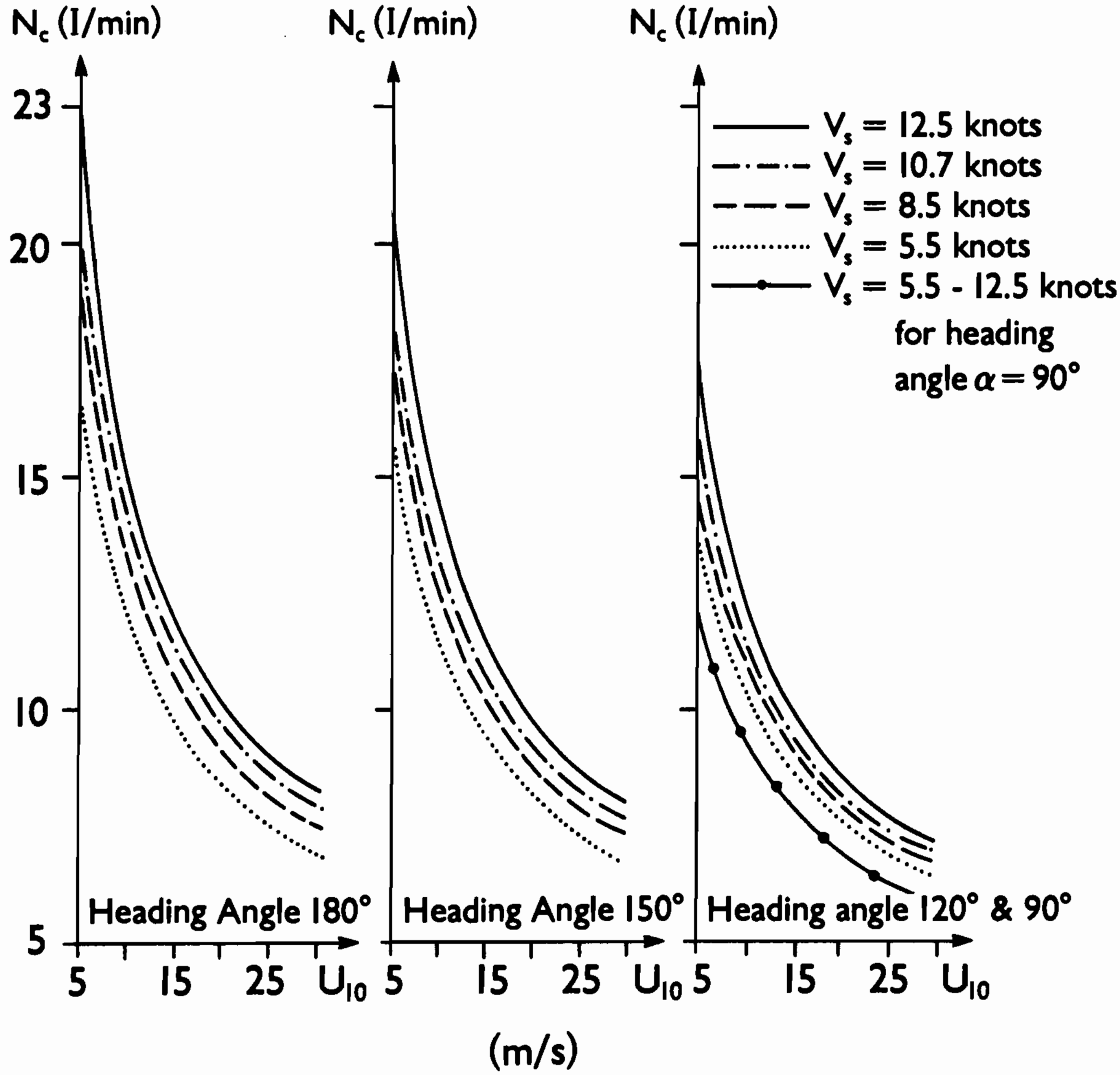

Figure 16.--Frequency of ship/wave collision as a function of wind speed, ship speed and heading angle computed by Eq. (61).

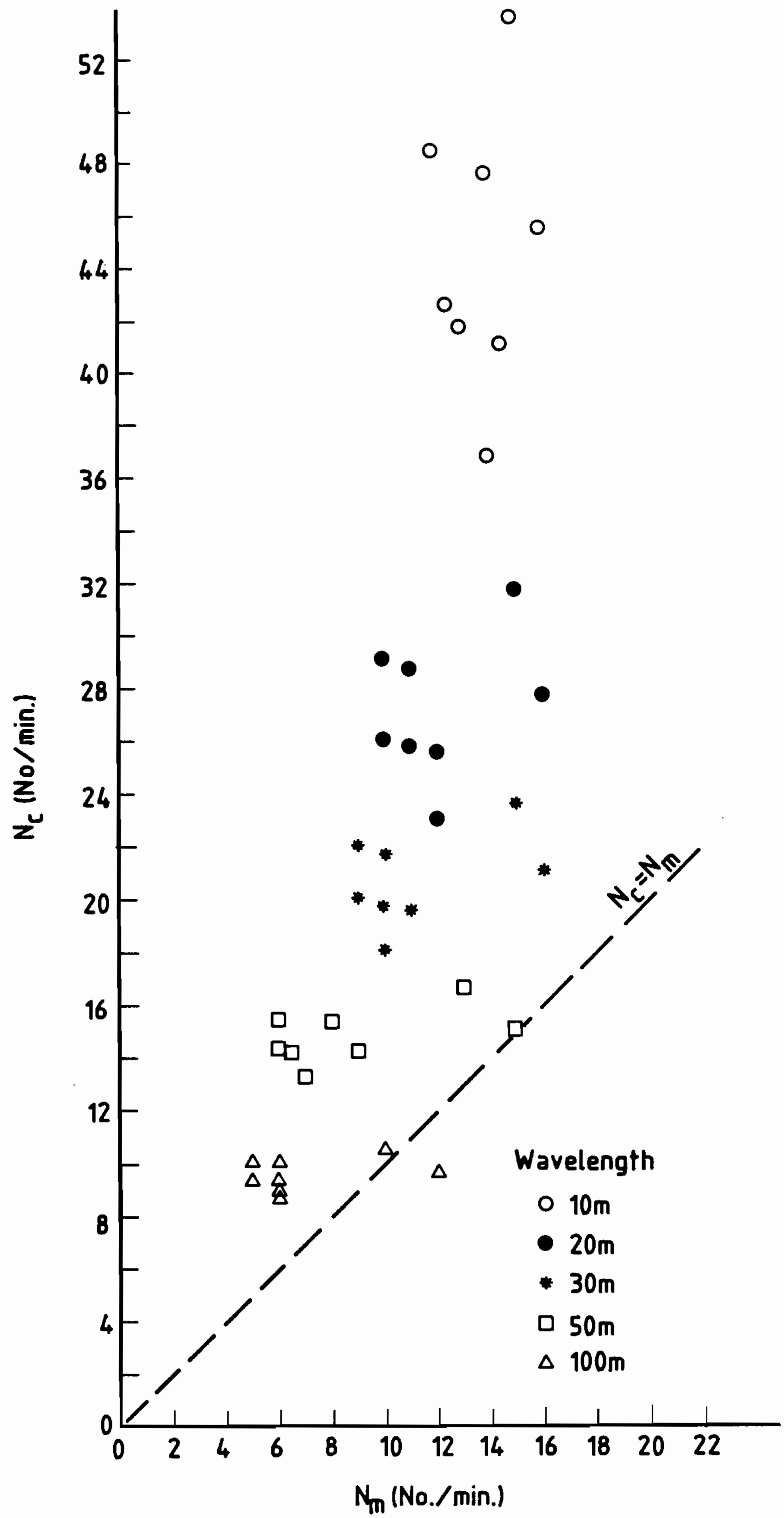

Figure 17.--Frequency of ship/wave collisions computed by Eq. (61) vs. observed frequency of splashing the MFV with wave-generated spray abstracted from Panov (1976) and Aksjutin (1979).

Table 8.--Scaling factor $a = N_m/N_c$ for calibration of Eq. (63)

Wavelength (m)	10	20	30	50	100
a	0.314	0.447	0.543	0.592	0.726

$$N \approx a \cdot 60/P_r \qquad 1/\text{min} \tag{63}$$

where a = 0.517, and P_r is given by Eq. (60a) or (60b). It may be argued that the value of a does not reflect the actual conditions of spray generation due to the large scatter in reprinted values (Fig. 17). The N_m/N_c ratio seems to depend on the wavelength. Thus, scaling factor $a = N_m/N_c$ varies with the wavelength (Table 8). Thus, to improve the accuracy of Eq. (63) a should be chosen for a given wavelength based on Table 8.

However, it should be noted that the behavior of a ship on the sea is not only controlled by ship-wave collisions. Ship behavior is much more complex (Boroday and Necwetaev, 1969; Grochowalski, 1982). Ship rolling, pitch and heave generate spray also. The most intensive spray generation takes place when the ship resonates. For a further discussion of this, see Aksjutin (1979). Spray generation by ship-wave interaction was investigated for the MFV in the Sea of Japan in the late 60's by Kultashev *et al.* (1972). Their results are presented in Figure 18. For a similar type of vessel, Panov (1971) proposed the empirical formula

$$N_s = 15.78 - 18.04 \exp(-4.26/P_r) \qquad \text{min}^{-1} \tag{64}$$

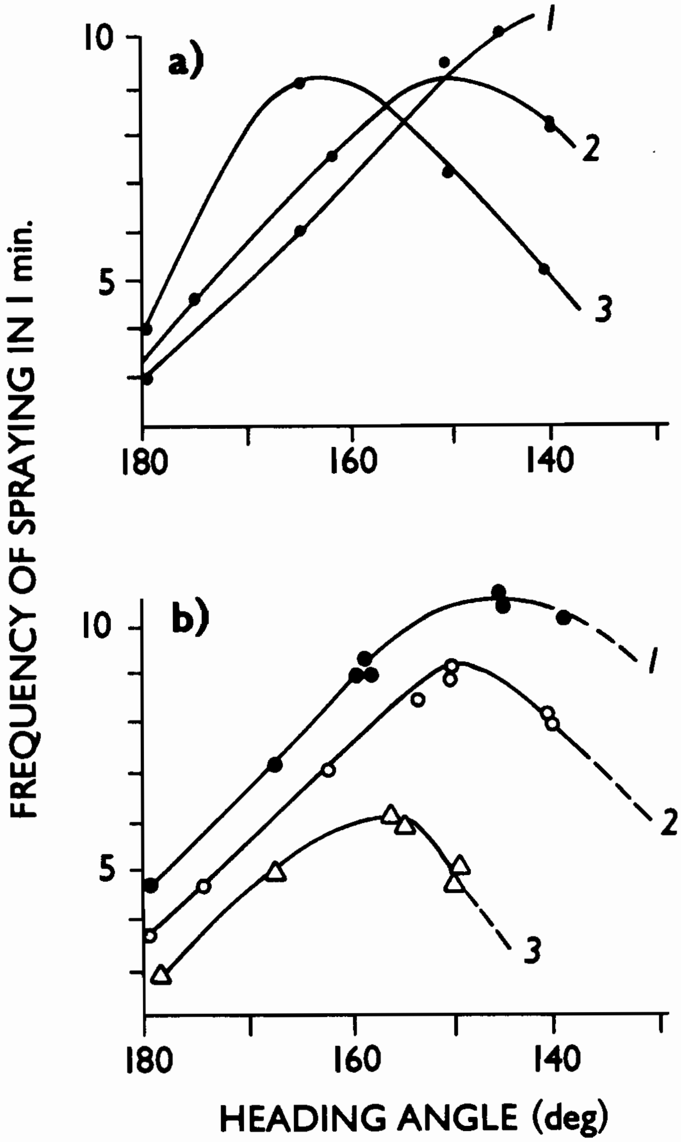

Figure 18.--Frequency of ship/wave collisions observed by Kultashev *et al.* (1975) as a function of heading angle and wave height (a: 1 - wave height 1.0-1.5 m; 2 - wave height 2.0-2.5 m; 3 - wave height 3.0-3.5 m) and ship speed (b: 1 - ship speed 8.5 knots; 2 - ship speed 7.0 knots; 3 - ship speed 5.5 knots).

where N_s is the frequency of splashing a ship with a wave-generated spray, and P_r is given by Eq. (60a or 60b). Eq. (64) is valid for 15 s ≥ P_r ≥ 3.5 s.

As the time-averaged spray flux to an object is proportional to the frequency of generation of the spray cloud, it is worthwhile to check the accuracy of the approximation given by Eq. (64). The field data of Panov's (1971) experiment were listed by Panov (1976) and Aksjutin (1979) and are plotted vs. the frequency of spray splash computed by Eq. (64) in Figure 19. The scatter is significant. The relative error given by formula

$$E_r = \frac{N_s - N_m}{N_m} 100\% \tag{65}$$

where N_s is by Eq. (64) and N_m the observed number of splashes per minute, varies from -44.2% to 54.2% while the mean relative error is equal to ±20%. In general, Eq. (64) overestimates the frequency of splashing by a wave-generated spray. Such tendencies produce no risk of underestimating the potential ice growth rates. The N_m/N_s ratio is fairly close to 1.0 (Fig. 20) and its range is reasonable. The standard deviation of the N_m/N_s increases with the wavelength but only slightly. It is caused by ship behavior in the sea and the more complex ship response to higher waves. Taken all together, Eq. (64) may be used for operational purposes. Finally, the time-averaged spray flux to an object is given by formula

$$M = 60\ E_c \cdot w \cdot U \cdot \Delta t \cdot N_s \qquad \text{kg/m}^3\ \text{min} \tag{66}$$

where N_s is approximated by Eq. (64), and other terms are the same as of Eq. (62).

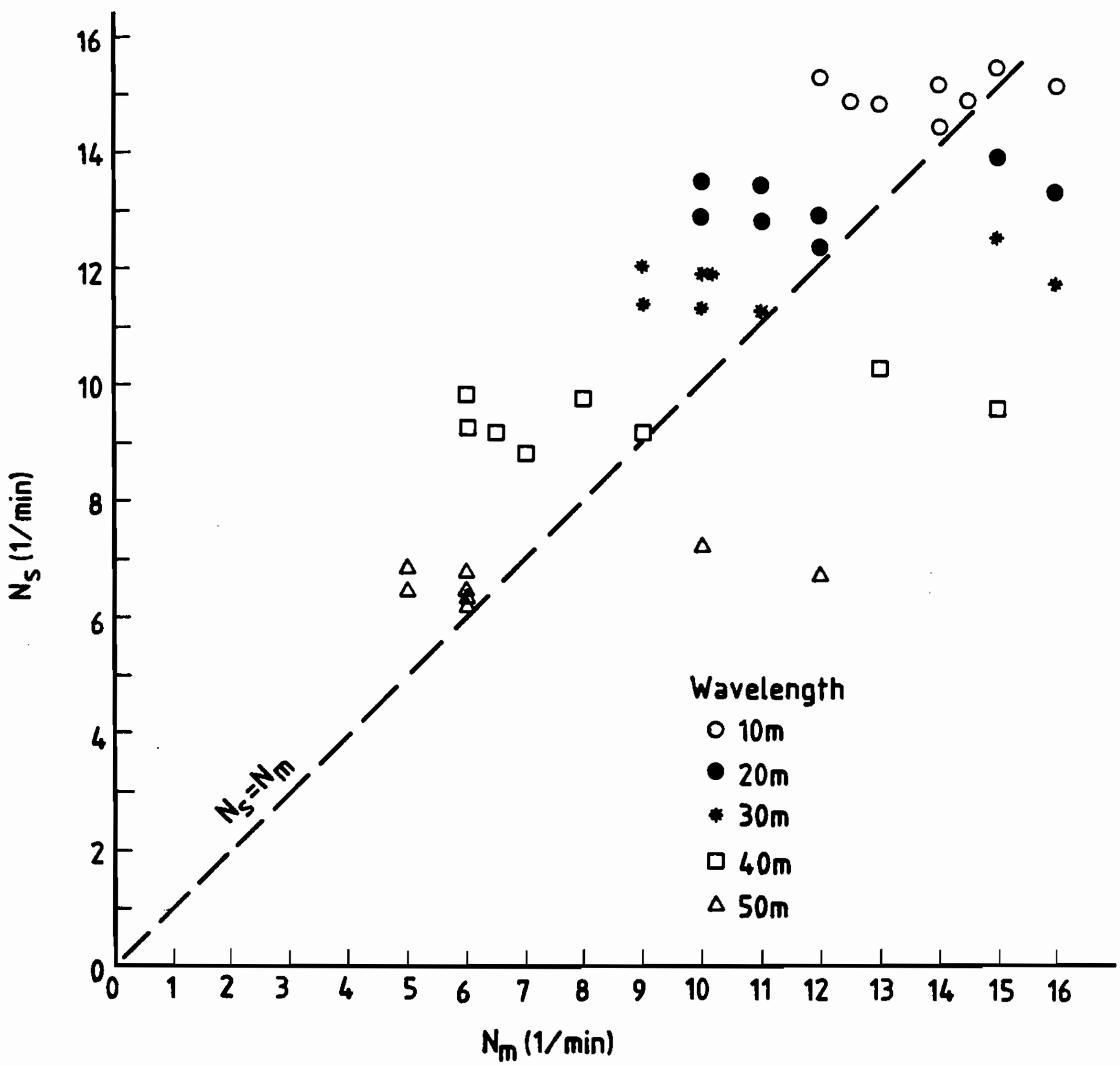

Figure 19.--Frequency of splashing the MFV with wave-generated spray computed by Panov's (1971) empirical formula (Eq. 64) vs. observed frequency of splashing the ship with wave-generated spray abstracted from Panov (1976) and Aksjutin (1979).

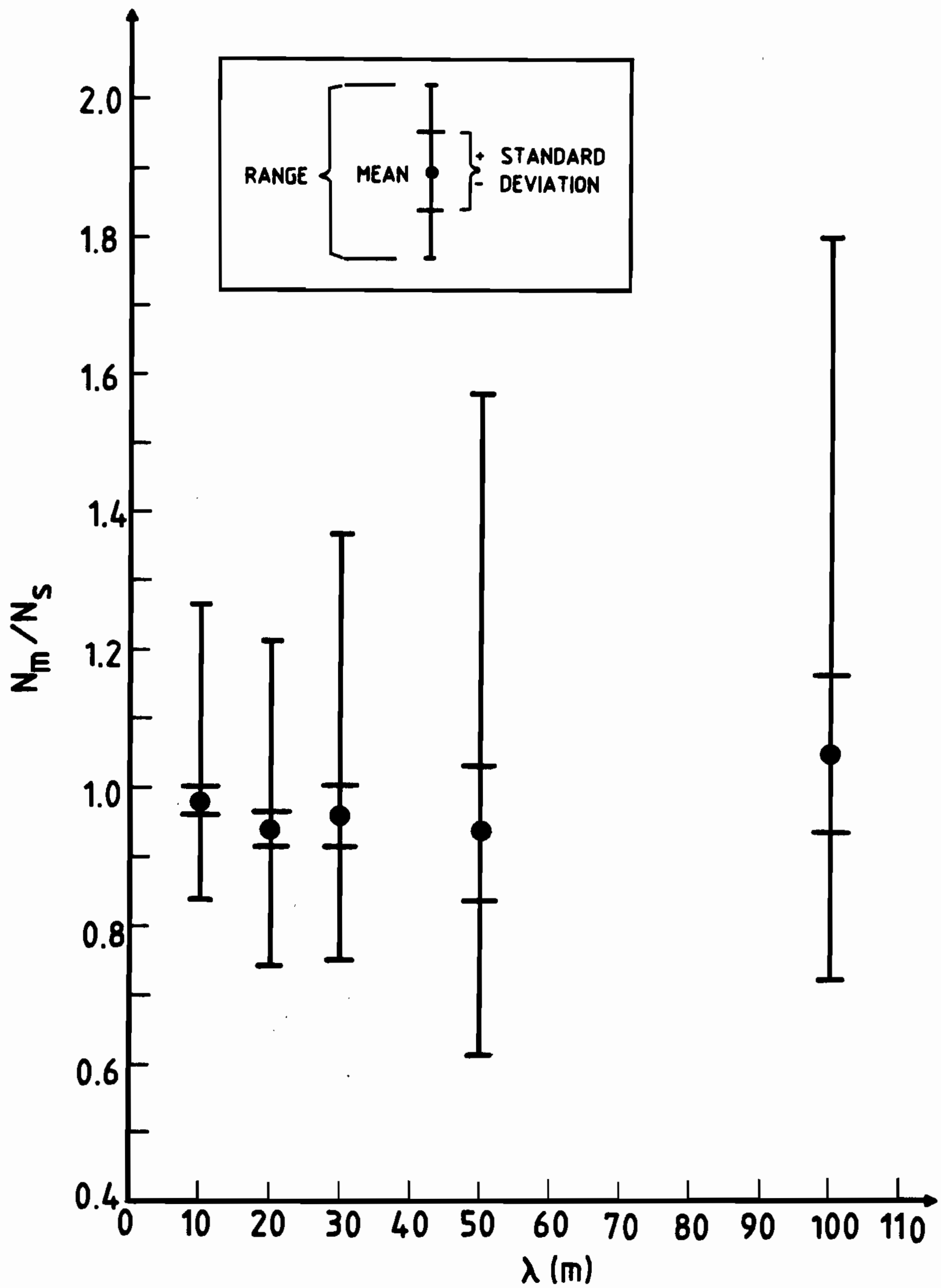

Figure 20.--Some statistics of N_m/N_s ratio (N_m - observed frequency of splashing the MFV with wave-generated spray abstracted from Panov (1976) and Aksjutin (1979); N_s - frequency of splashing the MFV with wave-generated spray computed using Panov's (1971) empirical formula (Eq. 64)).

Spray flux as a function of wind speed and elevation of an object above ship deck (freeboard h = 2.5 m), and ship speed and heading angle is presented in Tables 9 and 10 for objects of cylindrical shape and vertically oriented plate. The length of the object was chosen to be equal to L = 1 m. The results given in Tables 9 and 10 show tendencies similar to that of Table 7. The spray flux increases with increasing wind speed. The spray flux is largest for the ship sailing into the waves and decreases with decreasing heading angle. The spray flux increases with increasing ship speed for any heading angle $\alpha > 90°$ while this does not depend on the ship speed for the heading angle $\alpha <= 90°$. The mass of water delivered with direct spray flux abruptly decreases with the elevation above the ship's deck. Four former tendencies can be easily seen in Figure 21 which presents the direct spray flux coming to the cylinder and vertical plate elevated 1 m above the ship's deck. It should be noted that the spray flux to the cylinder is larger than to vertical plate.

The spray flux to an object is considerably large, especially in high seas. That is, the spray flux exceeds 100 kg/m^2 min if the object is elevated up to 2 m above the ship's deck and the wind speed is very high.

It is worthwhile to compare the results given by our model with experimental data. Unfortunately, there are no published data sets of time-averaged spray flux to a MFV. However, Panov (1976, Fig. 4.6) presented the relationship between the total water delivery to a MFV with the wave-generated spray and the height of the ship's bow. Panov (1976) has given that approximately 1-1.1 m^3 of water is delivered to the entire MFV per minute for the bow height equal to 3.7 m (see Fig. 12), ship speed V_s = 6 knots and the heading angle = 125° and the wave height 6 meters. In our model, wind speed U_{10} = 17 m/s generates the waves of height $H_{\frac{1}{3}}$ = 6.16 m if the fetch is equal

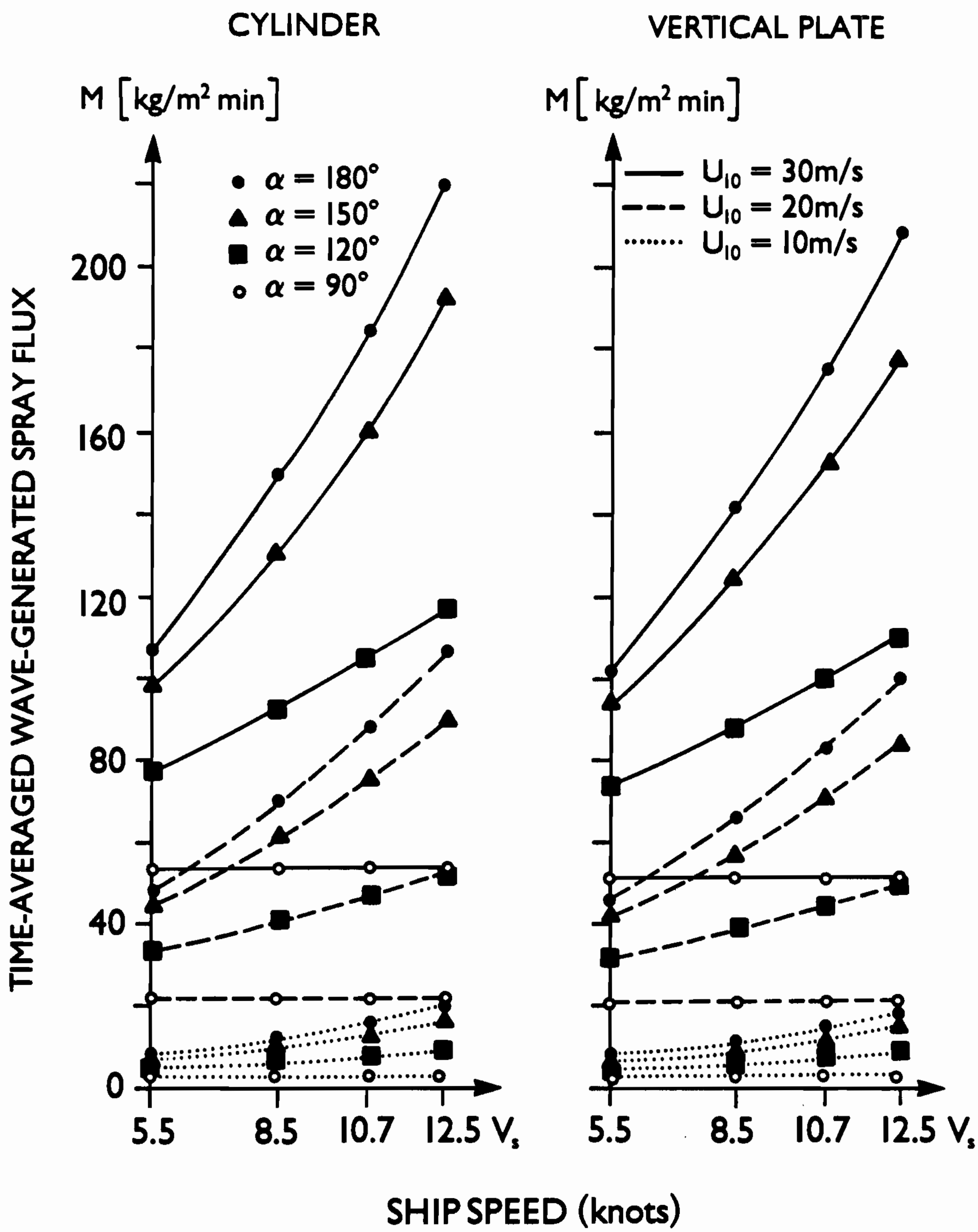

Figure 21.--Time-averaged wave-generated spray flux to cylinder and vertical plate located at the height of 1 m above the MFV's deck as a function of ship speed and heading angle for various wind speeds.

Table 9.--Time-averaged wave-generated flux (kg/m² min) coming to the cylinder located on the bow (heading angle 180°) and on the windward side of a MFV (heading angles ≤ 150°) at the elevation of 1 m above the ship's deck.

HEADING ANGLE (deg)			180				150				120				90
SHIP SPEED (knots)			5.5	8.5	10.7	12.5	5.5	8.5	10.7	12.5	5.5	8.5	10.7	12.5	5.5--12.5
SURFACE WIND SPEED (m/s)	U_{10} = 10	ELEVATION ABOVE THE SHIP'S DECK (m) 0	13.838	21.135	27.947	34.548	12.362	18.110	23.359	28.375	8.898	11.402	13.528	15.463	5.356
		1	8.182	12.497	16.524	20.428	7.310	10.708	13.812	16.778	5.261	6.742	7.999	9.143	3.167
		2	4.813	7.351	9.721	12.017	4.300	6.299	8.125	9.870	3.095	3.966	4.705	5.378	1.863
		3	2.822	4.310	5.699	7.045	2.521	3.693	4.763	5.786	1.814	2.335	2.759	3.153	1.092
		4	1.650	2.521	3.333	4.120	1.474	2.160	2.786	3.384	1.061	1.360	1.613	1.844	0.639
		5	0.963	1.472	1.946	2.405	0.861	1.261	1.626	1.976	0.619	0.794	0.942	1.077	0.373
		10	0.064	0.098	0.130	0.160	0.057	0.084	0.108	0.132	0.041	0.053	0.063	0.072	0.025
	U_{10} = 20	ELEVATION ABOVE THE SHIP'S DECK (m) 0	82.498	118.129	150.385	181.059	75.084	103,528	128,744	152.392	57.259	70.210	80.948	90.565	38.088
		1	48.550	69.520	88.503	106.555	44.187	60.927	75.767	89.684	33.698	41.319	47.638	53.298	22.415
		2	28.492	40.798	51.938	62.532	25.931	35.755	44.464	52.631	19.775	24.248	27.957	31.278	13.154
		3	16.685	23.891	30.415	36.618	15.185	20.938	26.038	30.821	11.580	14.200	16.371	18.316	7.703
		4	9.754	13.967	17.781	21.408	8.878	12.241	15.222	18.018	6.770	8.301	9.571	10.708	4.503
		5	5.695	8.154	10.381	12.498	5.183	7.146	8.887	10.519	3.952	4.846	5.588	6.252	2.629
		10	0.381	0.546	0.695	0.836	0.347	0.478	0.595	0.704	0.264	0.324	0.374	0.418	0.176
	U_{10} = 30	ELEVATION ABOVE THE SHIP'S DECK (m) 0	183.393	253.859	316.535	375.462	168.504	225.172	274.579	320.407	132.252	158.661	180.288	199.492	92.246
		1	107.227	148.427	185.072	219.526	98.521	131.654	160.542	187.337	77.325	92.766	105.411	116.640	53.935
		2	62.607	86.662	108.059	128.175	57.524	76.869	93.736	109.381	45.148	54.164	61.547	68.103	31.491
		3	36.513	50.543	63.021	74.754	33.549	44.831	54.668	63.792	26.331	31.589	35.895	39.718	18.366
		4	21.275	29.449	36.720	43.556	19.548	26.121	31.853	37.169	15.342	18.406	20.915	23.142	10.701
		5	12.386	17.145	21.378	25.358	11.380	15.208	18.545	21.640	8.932	10.716	12.176	13.473	6.230
		10	0.821	1.137	1.418	1.682	0.755	1.008	1.230	1.435	0.592	0.711	0.807	0.893	0.413

Table 10.--Time-averaged wave-generated spray flux (kg/m² min) coming to the vertical plate located near the bow (heading angle 180°) and on the windward side of a MFV (heading angle ≤ 150°).

HEADING ANGLE (deg)			180				150				120				90
SHIP SPEED (knots)			5.5	8.5	10.7	12.5	5.5	8.5	10.7	12.5	5.5	8.5	10.7	12.5	5.5- -12.5
SURFACE WIND SPEED (m/s)	U_{10} = 10	ELEVATION ABOVE THE SHIP'S SPEED (m) 0	12.521	19.123	25.287	31.260	11.186	16.386	21.135	25.674	8.051	10.317	12.241	13.991	4.846
		1	7.413	11.322	14.970	18.507	6.622	9.701	12.513	15.200	4.766	6.108	7.247	8.283	2.869
		2	4.365	6.667	8.815	10.898	3.899	5.712	7.368	8.951	2.807	3.597	4.267	4.878	1.689
		3	2.561	3.912	5.172	6.394	2.288	3.352	4.323	5.252	1.647	2.110	2.504	2.862	0.991
		4	1.499	2.289	3.027	3.742	1.229	1.962	2.530	3.074	0.964	1.235	1.465	1.675	0.580
		5	0.876	1.337	1.768	2.186	0.782	1.156	1.478	1.795	0.563	0.721	0.856	0.978	0.339
		10	0.058	0.089	0.118	0.146	0.052	0.077	0.099	0.120	0.038	0.048	0.057	0.065	0.023
	U_{10} = 20	ELEVATION ABOVE THE SHIP'S DECK (m) 0	77.177	110.511	140.686	169.382	70.241	96.851	120.441	142.564	53.566	65.682	75.727	84.724	35.632
		1	45.452	65.083	82.855	99.754	41.367	57.039	70.931	83.960	31.547	38.682	44.598	49.897	20.985
		2	26.690	38.218	48.855	58.577	24.291	33.494	41.652	49.302	18.525	22.715	26.189	29.300	12.322
		3	15.638	22.392	28.506	34.321	14.233	19.624	24.404	28.887	10.854	13.309	15.344	17.167	7.130
		4	9.146	13.097	16.673	20.074	8.324	11.478	14.274	16.895	6.348	7.784	8.975	10.041	4.223
		5	5.342	7.694	9.738	11.724	4.862	6.704	8.337	9.868	3.708	4.546	5.242	5.864	2.466
		10	0.358	0.513	0.653	0.786	0.326	0.449	0.559	0.661	0.248	0.305	0.351	0.393	0.165
	U_{10} = 30	ELEVATION ABOVE THE SHIP'S DECK (m) 0	174.187	241.116	300.646	356.614	160.045	213.869	260.796	304.324	125.613	150.696	171.238	189.479	87.616
		1	101.883	141.030	175.849	208.586	93.611	125.093	152.541	178.001	73.472	88.143	100.158	110.827	51.247
		2	59.507	82.372	102.709	121.829	54.676	73.064	89.095	103.966	42.913	51.482	58.500	64.731	29.932
		3	34.716	48.055	59.920	71.074	31.897	42.625	51.977	60.653	25.035	30.034	34.128	37.764	17.462
		4	20.233	28.008	34.923	41.424	18.591	14.467	30.294	35.350	14.591	17.505	19.891	22.010	10.177
		5	11.783	16.310	20.337	24.123	10.826	8.419	17.641	20.586	8.497	10.194	11.583	12.817	5.927
		10	0.782	1.083	1.350	1.404	0.719	0.960	1.171	1.366	0.564	0.677	0.769	0.851	0.393

to 200 n.m. For this wind speed and the same ship motion parameters we have that approximately 1.3 m^3 of sea water reaches the ship per minute if the trajectories of spray movement with the wind are monitored by a method similar to that given by Eq. (34a) or (34b) for the ship breadth 7.3 m. The length of the spray "window" was chosen to be equal to 15 m for these conditions. This shows that our model gives reasonable approximation of the time-averaged spray flux. On the other hand, Tabata *et al.* (1963)* described the Japanese field experiments during which both the ice growth rates and the intensity of spraying the ship were measured. A few ships were used in these field experiments. The measurements conducted on the patrol vessel *Chitose* (45.0 m length overall; breadth 7.3 m; displacement 407.2 tons) are most valuable for any comparison because the characteristics of this patrol vessel is somewhat similar to the Soviet MFV of the length 39.2 m. To catch the spray splashing the patrol vessel a number of specially designed icing gauges were distributed over the ship. Records of the measurements conducted using the icing gauges located around the machine-gun platform situated about the center of the Chitose's foredeck are valuable for this purpose. The gauges were elevated about 1.8 m above the ship's deck and the height of the ship's foredeck was about 2.7 m above the waterline. Taking these two altitudes together, one can determine that the icing gauge was elevated about 4.5 m above the ship's waterline and this height correlates with the altitude of 2 m above the deck of the MFV of freeboard equal to 2.5 m. Brown and Roebber (1985, p. 97) employed the Japanese data set to present the variation of time-averaged spray flux as a function of vessel speed and heading angle (Fig. 22). The experiment was conducted in rather low seas (wind speed 5-9 m/s; wave height 0.6-1.0 m; wave length 10 m). One can see in Figure 22 that the time-averaged

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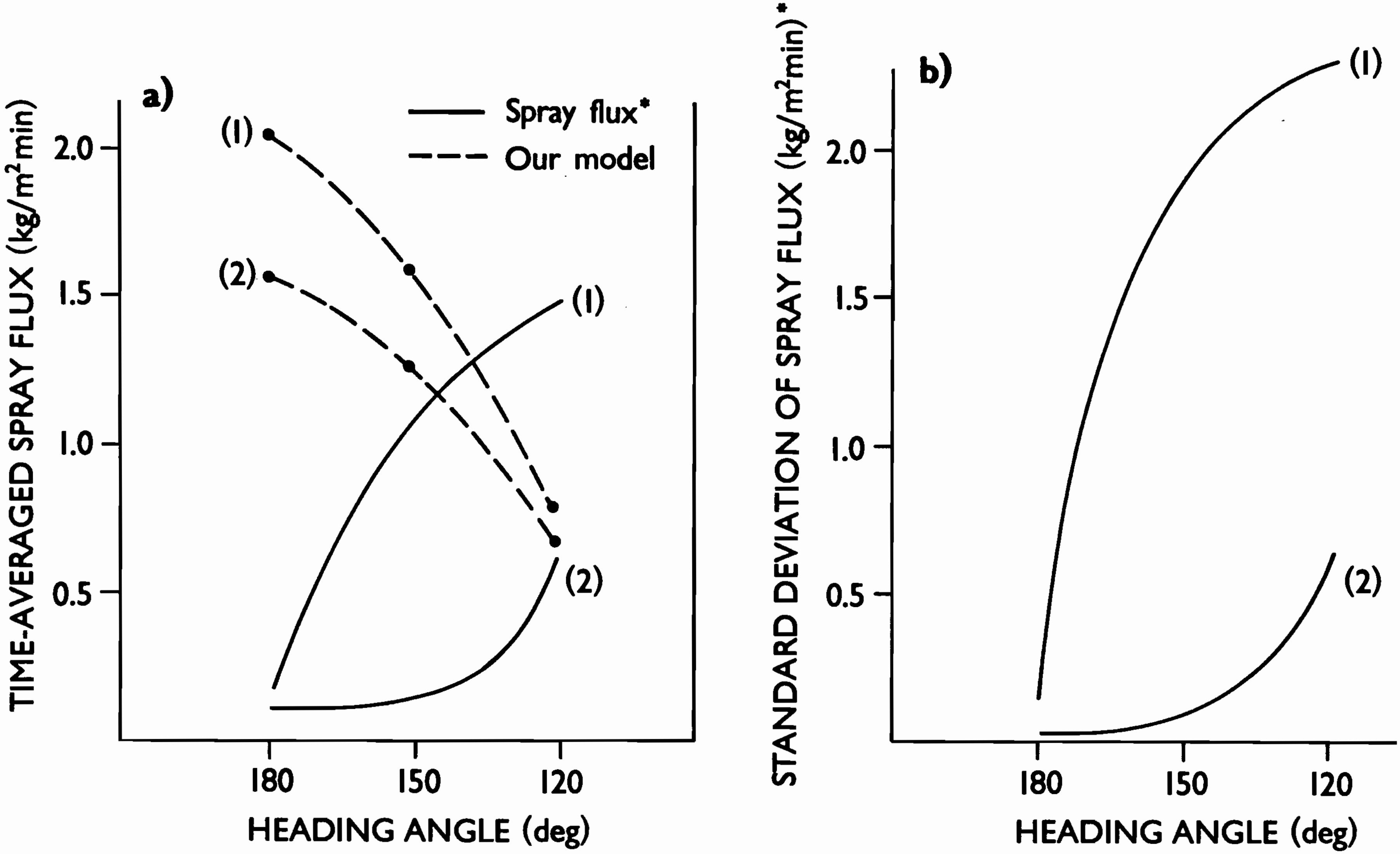
* Available in English in the Defense Research Board translation T93J.



* After Tabata (1969) (according to Brown and Roebber (1985)) and multiplied by 60

Figure 22.--Time-averaged wave-generated spray flux measured by Tabata *et al*. (1963) and Tabata (1969) (according to Brown and Roebber, 1985) for ship speed 12.5-knots (1) and 10.7 knots (2). Observed spray flux reported by Japanese compared with spray flux computed in our model (a). Standard deviation of spray flux observed by Japanese (b).

spray flux increases with the ship speed. However, contrary to our model, the spray flux given by the Japanese increases with the decreasing heading angle. The time-averaged spray flux to cylinder located 2 m above the MFV's deck for wind speed 5 m/s and the wave height $H_{\frac{1}{3}}$ = 0.79 m and ship speed of 10.7 and 12.5 knots is also plotted in Figure 22. One can see that the results given by our model are larger almost by two orders of magnitude than the spray fluxes reported by Tabata (1969) (according to Brown and Roebber, 1985, p. 97). If we neglect here the probable effects of the ship architecture differences among the patrol vessel *Chitose* and the Soviet MFV on the spraying intensity, this can be caused by some circumstances related to the conditions under which the experiment was conducted (calm sea and low winds) and to the method applied for capturing the spray hitting the patrol vessel (very small diameter of the icing gauge). However, Brown and Roebber (1985) gave some information on the standard deviation of the spray flux measured during this experiment (Fig. 22b). This plot indicates that the scatter of data was very large. On the other hand, one can easily see in Figure 22a that the spray flux increment caused by the decrement of the heading angle decreases for the ship speed of 12.5 knots while this abruptly increases for the ship speed of 10.7 knots. These opposite tendencies of the spray flux variation with the heading angle and ship speed seem to speak for the incoherence of the data rather than for the linear relationship between the spray flux and the heading angle for ship sailing with the certain speed within the range of 10.7-12.5 knots.

Taken all together, we think that during the field experiments which will be hopefully launched in the near future, the direct spray fluxes will be carefully investigated using some spray-capture devices of much larger working surface area than the icing gauges used by Tabata *et al.* (1963) and Tabata

(1969). The models of the spray movement should be also developed and verified in the field experiments. Some studies should be made on the wind speed distribution over the ship for various heading angles and air/sea conditions. This will make it possible to determine the ship hull and superstructure effect on the wind field in the vicinity of the ship.

3. TOTAL SPRAY FLUX

Time-averaged total spray flux to an object is equal to

$$M = M_a + M_w \qquad kg/m^2 \text{ min} \tag{67}$$

where M_a and M_w are the time-averaged wind-generated and wave-generated spray fluxes, respectively.

It was proven that wind-generated spray does not affect objects located on and above the deck of the MFV. Thus, the total spray flux to the objects under consideration is that of wave-generated spray only. This spray flux to a cylinder and vertical plate located on and above the deck of the MFV is given in Tables 9 and 10 and Figure 21.

CONCLUSIONS

1. Medium fishing vessels are not affected by wind-generated spray even in heavy seas.
2. Wave-generated spray is the only important source of sea water flux apart from rain, drizzle, snow, fog, and direct flooding of a ship deck by waves.
3. The liquid water content (LWC) is the least known parameter involved in the spray flux to an object.

4. There are very few field data available which present the vertical distribution of the LWC in both wind- and wave-generated spray.

5. Flume tank data cannot be used to define the vertical distribution of the LWC in the field by simply applying scaling factors.

6. Horjen and Vefsnmo (1984) proposed a formula for vertical distribution of the LWC in a wind-generated spray (Eq. 20). This formula seems to fit available field data best among the proposed formulas.

7. Wave-generated spray flux originating from a single wave collision with a ship is a function of collection efficiency, the LWC, local wind speed and the time of ship exposure to the spray (Eq. 43).

8. Vertical distribution of the LWC in the wave-generated spray is a function of the elevation above the ship deck, wave height and ship speed relative to an oncoming wave (Eq. 49).

9. Borisenkov *et al.*'s (1975) empirical formula for the LWC vertical distribution above the deck of a ship has been improved and adopted for any air/sea conditions (Eq. 51).

10. Using Russian field data from the Sea of Japan, the empirical relationship between the time of ship exposure to a cloud of wave-generated spray and the wave height, ship speed relative to an oncoming wave and wind speed has been derived.

11. Time-averaged spray flux to an object is a function of mass flux from a single wave impact to a ship (Eq. 43) and the frequency of ship/wave collisions. This latter parameter is fairly well approximated by Panov's (1971, 1976) empirical formula (Eq. 64), while the simple relationship between the frequency of ship/wave collisions and the wavelength, ship speed and heading angle (Eq. 60a) is less accurate even when a scaling factor for various wavelengths is applied (Eq. 63 and Table 8).

12. Spray flux to a cylinder is larger than to a vertical plate. Since the spray flux increases with increasing wind speed, ship speed and heading angle, the spray flux is largest for the ship sailing into the waves with high speed in heavy seas. Under extremely heavy air/sea conditions, the spray flux to the objects elevated up to 2 m above the ship's deck exceeds 100 kg/m^2 min.

13. The need of launching a field experiment for collecting data (vertical distribution of the LWC, direct spray fluxes, spectral size distribution of spray drops, morphology of the spray clouds, and ice growth rates) is evident.

14. As the ice growth rates of a ship depend on the water flux to a ship, the ship designed for navigation in regions prone to icing waters should have minimal surface of all objects exposed to impinging water drops, especially in the bow and deck and foredeck areas. The bow and freeboard should be reasonably high, and the hull of such ships should generate a minimal amount of spray during ship/wave collisions and impacts due to pitch and heave. A bow and board shape which rejects spray from a hull in the horizontal plane is recommended.

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