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Attempt of regarding the effect of wind gustiness of the sea dynamic roughness as a factor of mass exchange through air-sea interface

ABSTRACT: The investigations carried out during the 5th Antarctic Expedition of the Polish Academy of Sciences allowed to collect the data concerning specificity of the dynamics of sea-salt nuclei dispersed in the Antarctica region. At the established measuring point measurements at three levels were carried out, basing on which the required profile of the wind characteristics at different heights a.s.l. were obtained.

KEY WORDS: Antarctica, wind gustiness, sea roughness, H. Arctowski Station.

1. Introduction

The phenomenon of spray of marine aerosol from the sea surface into atmosphere was investigated from the viewpoint of the action of several mechanisms of drop emission from the sea (1, 4, 10), The complex relationship of this spray from the aerodynamical roughness of the sea surface remains unexplained further on. In the work of Garbalewski and Berek (3), to be true, a semi-empirical relationship between concentration of marine particles in by-water air and the roughness parameter as well as of other hydro-meteorological parameters is presented. Nevertheless, this relationship was checked only on an example of low and medium wind speeds (up to 15 $m. s^{-1}$). Up to now there is a lack of any exact theory explaining this relationship and its connection with other aero-hydro-dynamical parameters of air-sea interface. This lack is related particularly to the range of stormy wind speeds, unclear being the effect of characteristics of wind stresses connected with rapid increments of speed module and with wind direction changes. Investigations concerning these questions had been initiated already in the work of Garbalewski and Marks (5). They prove that the wind stress effects the spray of particles from sea, drops carried of sea can constitute a natural index of this effect. In the present work the problem considered is subjected to the further analysis. The investigations were carried out in the Admiralty Bay region on the King George Island (Antarctica), where a rather strong intensity of storms and rarely encountered variability range of all the aero-hydrodynamical parameters is taking place.

2. Theory of the effect of wind gustiness on changes of the aerodynamical roughness of sea surface

Most works concerning the parameter of the aerodynamical roughness of sea surface (z_0) can be considered as an attempt of developing of the formula of Charnock (2). A principal difficulty in these considerations constitutes a precise determination of the value of proportionality coefficient m_0 assumed as a constant value:

$$z_0 = m_0 \frac{u_x}{g} \tag{1}$$

where: u_x — friction velocity

g — acceleration of gravity

The results of measurements of the wind gradient and pulsation elements of over the sea surface and the attempts of interpretation of values measured from the viewpoint of local dynamic character of the vertical wind profile above sea surface encouraged various authors (3, 11, 12) to speculate about more adequate adaptation of the constant m_0 to conditions fulfilling the equation (1). According to various estimates the m_0 value has been assumed within the range of 0.011–0.04 (4, 12, 13). On the other hand, Kitaigorodsky regards m_0 as a variable depending on the wind undulation development connecting its value with high-frequency undulation spectre (7). Non the less, there is in the literature a considerable divergence in estimation of the m_0 value. It can be presumed that this divergence would follow partly from difficulties connected with carrying out comparable gradient measurements of wind speed above sea. Also a number of aero-hydrodynamical factors connected with the observation place can affect the m_0 value. In addition, still unexplained remains the effect of nonuniformity of the field of wind and of the field of wind waves on the formation of aero-hydrodynamics of air-sea interface.

According to the theory (2), m_0 as a constant dimensionless coefficient, could depend only on $Re_\sigma = \varrho/\varrho_w$ and v/v_w

where: Re_σ — Reynolds' number for the scale of capillary waves,
ϱ, ϱ_w — density of air and water, respectively,
v, v_w — kinematic coefficients of air and water viscosity.

To define m_0 value, let us compare the formula of Charnock (1) with the law of logarythmic distribution of wind speed over sea surface in the following form:

$$u(z) = \frac{u_x}{x} \ln \frac{z}{z_0} \qquad z_0 \leqslant z \leqslant L \tag{2}$$

where: $u(z)$ — wind speed at the z level,
u_x — friction velocity
x — Karman's constant
L — length scale of Monin-Obukhov

Thus we obtain the dependence

$$m_0 = \frac{z \cdot g}{u_x^2} e^{-\frac{u(z)\, x}{u_x}} \tag{3}$$

The calculations at the first approach of the u_x value can be performed using the Deacon and Webb's formula:

$$u_x = u_{1000} \sqrt{\frac{1 + 7 \cdot 10^4\, u_{1000}}{1000}} \tag{4}$$

where: u_{1000} — wind speed in cm. s^{-1} at the level of 1000 cm above sea.

Determination of m_0 value allows to assume the empirical function of Charnock as a basis of determination of the wind stress effect on changes of the roughness parameter z_0. This follows, namely, from the assumption that rapid wind speed increments during wind gusts should be responsible to a considerable extent for changes of aerodynamical roughness of sea surface. Seeking after an analytical expression of these changes the task can be reduced to solution of the differential equation:

$$\frac{dz_0(u_x, u, t)}{dt} = \frac{dz_0}{du_x} \frac{du_x}{du} \frac{du}{dt} \tag{5}$$

While differenting the dependence (5) and using the equation for the wind stress coefficient $c_{10} = \left(\frac{u_x}{u_{10}}\right)^2$ the equation:

$$\frac{dz_x(u_x, u, t)}{dt} = \frac{2m_0}{g} \frac{u_x^2}{u_{10}} \frac{du}{dt} \tag{6}$$

can be obtained, where: u_{10} — wind speed at the height of 10 m a.s.l.

As concerns the finite differences, the equation assumes the following form appropriate for direct numerical caleulations:

$$\frac{\Delta z_0}{\Delta t} = \frac{2m_0}{g} \frac{\bar{u}_x^2}{\bar{u}_{10}} \frac{\Delta u}{\Delta t} \tag{7}$$

Hence at the moment u_{max}, we obtain:

$$z_0 (u_{max}) = z_0 (\bar{u}_{10}) + \frac{\Delta z_0}{\Delta t} \Delta t \tag{8}$$

and thus:

$$z_0 (u_{max}) = z_0 (\bar{u}_{10}) + \frac{2m_0}{g} \frac{\bar{u}_x^{2}}{\bar{u}_{10}} \Delta u \tag{9}$$

In the further part of our considerations we arrive to the question of connection between z_0 changes and the wind gustiness coefficient g_t For this purpose, basing on the equation (1), the dependence:

$$\frac{z_0 (u_{max})}{z_0 (\bar{u}_{10})} = \frac{u_{x\,max}^2}{\bar{u}_x^2} \tag{10}$$

can be obtained, from which it follows that:

$$\frac{z_0 (u_{max})}{z_0 (\bar{u}_{10})} \cong g_t^2 \tag{11}$$

and thus

$$z_0 (u_{max}) = z_0 (\bar{u}_{10})\, g_t^2 \tag{12}$$

where the wind gustiness coefficient is:

$$g_t = \frac{u_{max}}{\bar{u}_T} \tag{13}$$

where: u_{max} — the maximum wind speed for the given stress,
u_T — mean wind speed for the chosen period T.

Now let us try to subject the dependence obtained in such a way to the experimental checking as below.

3. Programme and conditions of measurements

The respective investigations were carried out by the 5th Antarctic Expedition of the Polish Academy of Sciences at the H. Arctowski Station in the period from January 20 to March 20, 1981. The results quoted in the present paper constitute one of the elements of the research item concerning recognition of specificity of the dynamics of maritime systems dispersed over the Antarctica territory. The programme of measurements carried out at the H. Arctowski Station is presented schematically in Table I. (Pol. Pol. Res. No. 4, p...)

The measuring stand has been established on a rocky promontory in the coastal zone of the Admiralty Bay. The registration of characteristics of the vertical wind profile was performed (carrying out measurements

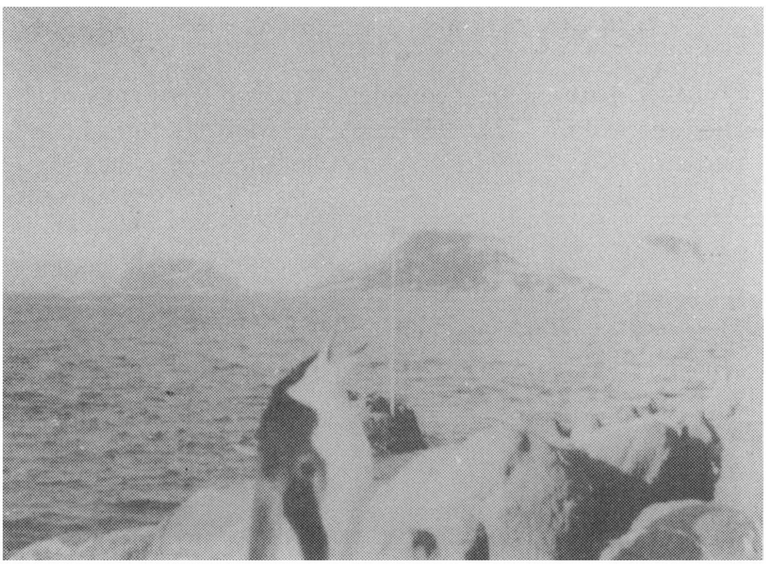

Fig. 1. Measuring pole established on a small island (Admiralty Bay)

at three heights of about 1; 5 and 10 m a.s.l.), at simultaneous continuous recording wind direction changes accomplished from the measuring pole established on a small rocky island (Fig. 1) at the distance of about 30 m from the coastal line.

Half-way of the works of the 5th Expedition the pole was destroyed by a strong storm and its functions were taken up by the reserve pole mounted on the platform (Fig. 2).

Parallely with wind measurements, observations of short-term fluctuations in concentration of particles in the suspension form of drops in air were carried out. The number and size of drops were registered by means of original staining catcher (at application of erythrosine as stain). This method could be applied even under conditions of the strongest storm. These special measurements were applied by simultaneous observations from the meteorological station being in the composition of the outfit of the WMO (World Meteorological Organization) network, laying at the distance of about 200 m from the place of measurements.

The data obtained from measurements carried out during strong storms constituted a basic material for the investigations on the wind gustiness effect on sea spray. W and NW storms came, what, taking into account

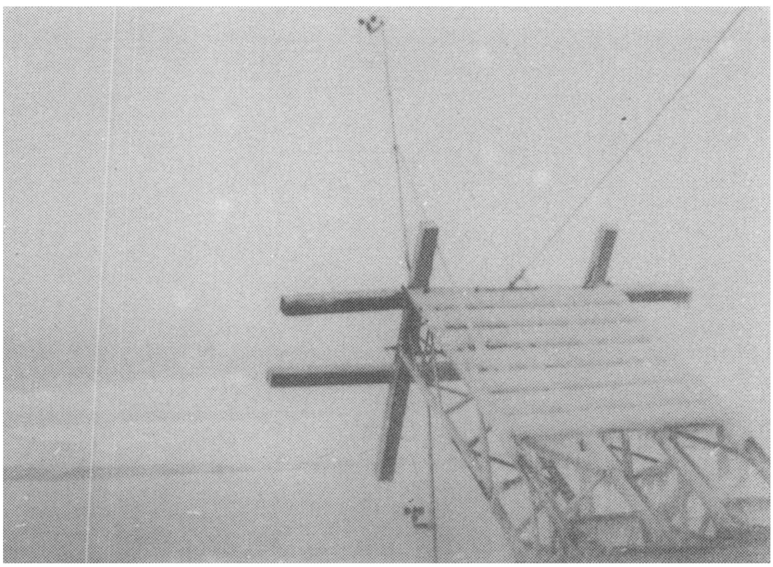

Fig. 2. Measuring pole mounted on a platform

the position of the Admiralty Bay in relation to the island, allowed to presume that the share of synoptical processes in the region of investigations was, as a rule, determined by local small-scale factors as far as the mąss and energy exchange between sea and air were concerned. However, it is to stress that measurements of the spray drops from the sea surface took place only under conditions of occurrence of an undulating ice field in the coastal zone. In such away the effect of intensified spray of drops in the zone of surf caused by breaking waves against coast rocks could be eliminated. It appeared, namely, that the ice fièld strip of about 20 m in width adjoining the coast of the Admiralty Bay, dissipated so strongly the energy of wind mass that the above effect could not practically occur.

4. Wind gustiness characteristics and its connection with the spray of drops from sea surface to air

While investigating the wind gustiness effect on the dynamic roughness (z_0) and the mass exchange between sea and air connected therewith, the correlation analysis for three measuring horizons (10, 5 and 1 m a.s.l.) typical for stresses of wind speed increments (Δw_{max}) and changes of their direction angle ($\Delta \varphi_{max}$) was carried out (Fig. 3). In spite of a wide

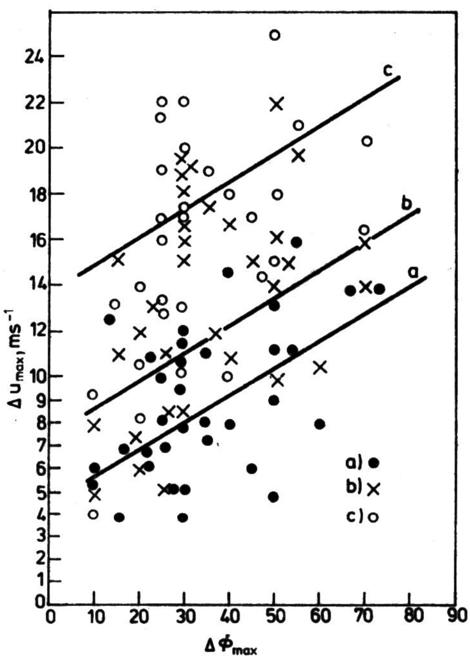

Fig. 3. Correlation of Δu_{max} and $\Delta \psi_{max}$ obtained from wind speed measurements in the coastal zone of the Admiralty Bay. Points a, b, c are related to the measurement results at the height of 1, 5 and 10 m a.s.l.; regression curves for which mean value of angular coefficient has been assumed (in view of deviations only at the place after point) were calculated on the basis of the equations:

a) $\Delta u_{max} = 4.77 + 0.12\, \Delta \varphi_{max}$,

b) $\Delta u_{max} = 7.55 + 0.12\, \Delta \varphi_{max}$,

c) $\Delta u_{max} = 13.82 + 0.12\, \Delta \varphi_{max}$

dispersion of experimental points the equations of regression lines were derived by the method of least squares, the results obtained proving a tendency to growth of Δu_{max} in the function of $\Delta \varphi_{max}$. Similarly expressed dependence was obtained for derivatives of these values after time (Fig. 4). The regression line calculated similarly for three horizons illustrates the correlation of increment speed:

$\Delta u_{max}/\Delta t$ and changes of $\Delta \varphi_{max}/\Delta t$

These results prove a connection of the speed increments of $\Delta u_{max}/\Delta t$ with the changes of $\Delta \varphi_{max}/\Delta t$. It is to emphasize that during measurements wind stream could be observed even visually owing to streaks and coils

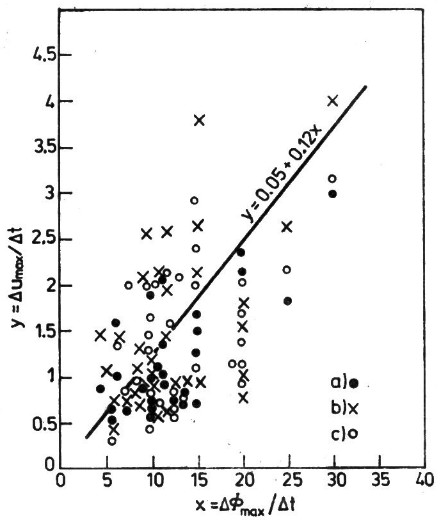

Fig. 4. Correlation of derivatives of $\Delta u_{max}/\Delta t$ and $\Delta \varphi_{max}/\Delta t$ obtained from the wind gustiness simultaneously for three measuring horizons. Points a, b, c are related to the measurement height of 1, 5 and 10 m a.s.l.

of water dust. Such situations connected with intensified water dust spray during wind gusts constituted the subject of a vivid interest in the present investigations. Concentration of air-suspended drops was recorded using the staining catcher. This method allowed to register drops of the size of over 100 μm in dia.

The mass of drops was then converted into the mass of salt (NaCl) contained in them, what allowed to regard the salt concentration values (q) as a conservative characteristics of dispersed systems. Connection of this characteristics with the Δu_{max} parameter was analyzed (Fig. 5). The q concentration changes in the function of u_{max} were presented in a similar way (Fig. 6, curve a). In either case regression lines of changes of q values in the function of Δu_{max} and u_{max} were calculated.

While analyzing the wind gust dynamics, fluctuations of the lateral quistiness coefficient $g_t = \frac{u_{max}}{\bar{u}_T}$ were investigated. The respective calculations were made for gusts with the duration time of $t \geqslant 10$ s, averaging the wind speeds at the time $T = 600$ s for the measuring height of 10 m a.s.l. The dependence of q on the gustiness coefficient $g_{t \geq 10\,s}$ is presented in Fig. 6 (curve b). The regression lines proving the q value growth along with increasing values of $g_{t \geq 10\,s}$ were obtained.

It is to stress that all the measurements as analyzed here were

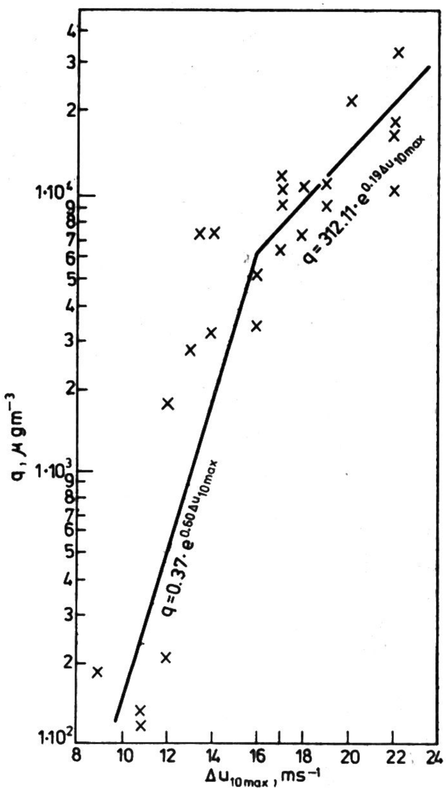

Fig. 5. Salt mass (NaCl) increase q carried off sea with water drops during storms in the function of maximum Δu_{max} speed increments in the coastal zone of the Admiralty Bay

carried out during storms at a well-developed field of wind waves. Then averaged values of $\bar{u}_T$ at the time of $T = 600$ for the height of 10 m a.s.l. lay within the interval of 14–20 m/s.

The obtained lines of regresion of the variable q against Δu_{max}, u_{max} and $g_{t \leq 10\,s}$ (Fig. 5 and 6) were of a similar character. While analyzing the course of all curves, a tendency to their break upon surpassing the wind speed of about 20 m/s could be proved. This fact can be explained by change of the mechanism of spray emission from the sea surface to atmosphere, in our case after wind reached the speed of about 20 m/s.

It is well-known from literature (4, 10) that a rapid jump in concentration of sea-salt particles in the surface air layer upon surpassing the wind speed of about 8 m/s can occur. This fact has been proved by Monahan (10), who investigated the concentration of drops and salt particles at the height of about 0.5 m a.s.l., while intensified the effect of the phenomenon of spraying with the occurrence of foam crests over the sea surface. In our investigations we have proved as well the occurrence of this

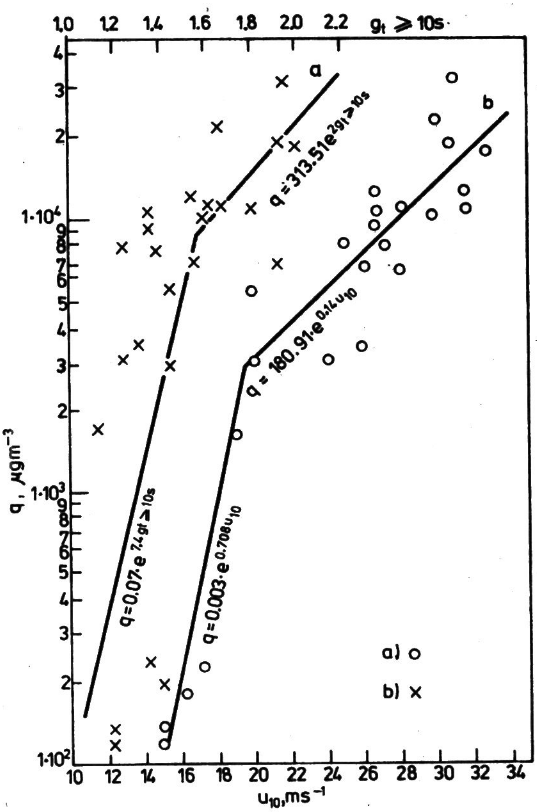

Fig. 6. Dependence of q — volumetric concentration of salt (NaCl) mass in the surface air layer on the speed of u_{10} (a) and the wind gustiness coefficient $g_{t \geq 10\,s}$ (b)

mechanism; however, one can presume that during wind gusts the mechanism of sucking and dissipation of the roughness elements would begin to predominate. It is, as a matter of fact, therefore that the present investigations concerned the range of strong and stormy winds, during which a continuous formation of foam crests over sea surface could be observed. More efficient as far as the spray of the first drops is concerned, would be the mechanism connected with bursting bubbles, which becomes usually inferior in relation to the mechanism of spraying big drops.

While analyzing Figs. 5 and 6, the predominance of mechanisms leading to increase of the spray of drops from the sea surface during wind gusts within the speed range from 15 to about 20 m/s can be observed. On the other hand, upon surpassing the wind speed of 20 m/s a decrease of the spray intensity (breaks of curves in Figs. 5 and 6) occurs. This fact allows to a certain extent to explain subsequent considerations on the changes in aerodynamical roughness of sea surface.

5. Experimental investigations on the wind gustiness effect on the parameters of aerodynamical roughness of sea

In calculations of the wind gustiness effect on the z_0 parameter averaging of speed characteristics of $\bar{u}_{10}$ and u_* at the time $T = 600$ s for gusts with the duration of $t \geqslant 10$ was applied. First of all, in accordance with dependence (3), the value of dimensionless coefficient of $m_0 = 0.03$ was determined. It is to emphasize that the obtained value of m_0 is typical for the case of the wind waves analyzed and lies within the limits of values calculated for this case by other authors.

Fixing the m_0 value in present investigations allows to assume the empirical formula of Charnock as a basis for determination of wind stresses on changes of z_0 parameter. In accordance with this assumptions $z_0\,(u_{max})$ values for the wind stress recorded were calculated at the first approach from the derived differential equation (9). The values of $z_0\,(u_{max})$ obtained in such a way were then compared with measured values of the concentration of salt mass q contained in water drops sprayed from sea surface into surface air layer during stormy wind stresses (Fig. 7, curve a). An attempt to derive the equation of the regression curve for all experimental points did not allow to adapt them well to their distribution. In this connection the regression lines were obtained similarly as in Figs. 6 and 7, suspecting the spray efficiency change at wind speeds of about 20 m/s. Thus the empirical points were appropriately divided into two groups for $u_{10} > 20$ m/s and $u_{10} < 20$ m/s. Curves (Fig. 7 of similar characteristic courses like those presented in Figs. 5 and 6 have ben obtained.

In the next part of our considerations we arrive to the question of connection between the changes of z_0 and wind gustiness coefficient $g_{t \geqslant 10\,s}$ (equation 11). In accordance with the dependence (12) z_0/u_{max} values were calculated and the results obtained were compared with q values measured during particular wind gusts. Such an approach allowed to find the next couple of the equations of regression lines (Fig. 7, curve b). Thus the both calculation methods as described above allowed to get

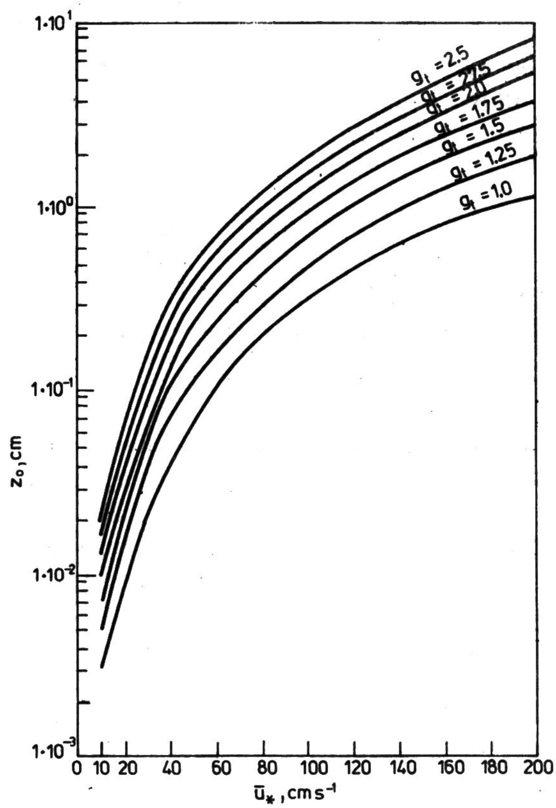

Fig. 7. Increase of q values in consequence of the spray of drops during wind gusts in the function of z_0 changes:

a) values of the roughness parameter were calculated from the equation $z_0(u_{max}) = $
$$= z_0(\bar{u}_{10}) + \frac{2m_0}{g}\frac{u_x^2}{\bar{u}_{10}}\Delta u,$$

b) values of the roughness parameter were calculated from the equation
$z_0(u_{max}) = z_0(u_{10})\, g_{t \geqslant 10\,s}^2$

similar results, since a and b curves in Fig. 8 have the similar course and lie nearby. From that it can be concluded that the dependence (12) can be assumed as generally valid for the description of z_0 changes during wind stresses.

Being guided by the above assumption, diagrams of changes of z_0

parameter in the function of different $\bar{u}_x$ values (Fig. 8) and of different coefficients of horizontal wind gusts $g_{t \geq 10\,s}$ (Fig. 9) were calculated. It should be explained that the diagrams plotted are of a general character and concern situation of developed field of wind waves ($m_0 = 0.03$). Also the possibility of occurrence in them of wind gusts with extremely

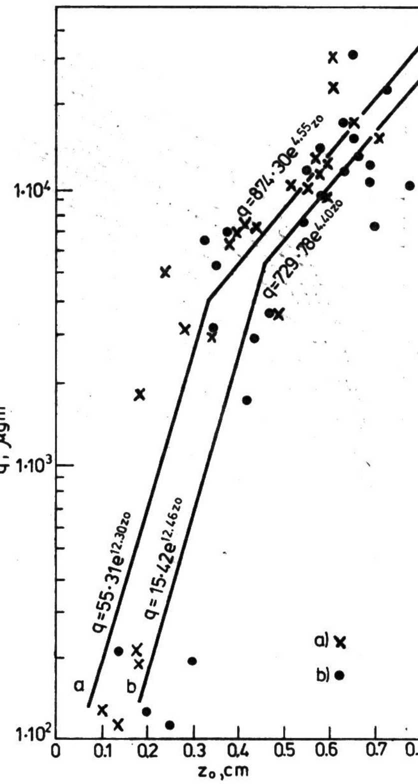

Fig. 8. Diagram of changes of z_0 parameter for different values of the wind gustiness coefficient $g_{t \geq 10\,s}$ in the function of friction rate $\bar{u}_x$

high values of $\bar{u}_x$ and $g_{t \geq 10\,s}$ was taken into consideration, what under real conditions would be hardly possible. The investigations of Goptarev (6) and Garbaleewski and Marks (5) on wind gustiness prove unanimously that in by-water air layer over the sea surface, as a rule, a decrease of horizontal wind gustiness values of $g_{t \geq 1\,s}$ and $g_{t \geq 10\,s}$ along with increasing wind speed would occur. At the same time the frequency of wind gusts of $g_{t \geq 10\,s}$ distinctly decreases (5) while decrease of the $g_{t \geq 10\,s}$ value under storm conditions was observed only at an increase of the wind speed of over 15 m/s. Along with the wind speed increase over 20–25 m/s the value of $g_{t \geq 10\,s}$ approximates unit.

While analyzing the diagram of z_0 changes in the function of $\bar{u}_x$ and $g_{t \geq 10\,s}$, it can be found that the highest absolute Δz_0 increments can be realized at wind gustiness characterizing by lower values of mean friction rate (Fig. 8). On the other hand, along with increase of $\bar{u}_x$ values, particularly within the interval of its high values, decrease both $g_{t \geq 10\,s}$ values and absolute Δz_0 increments (density of curves for high friction

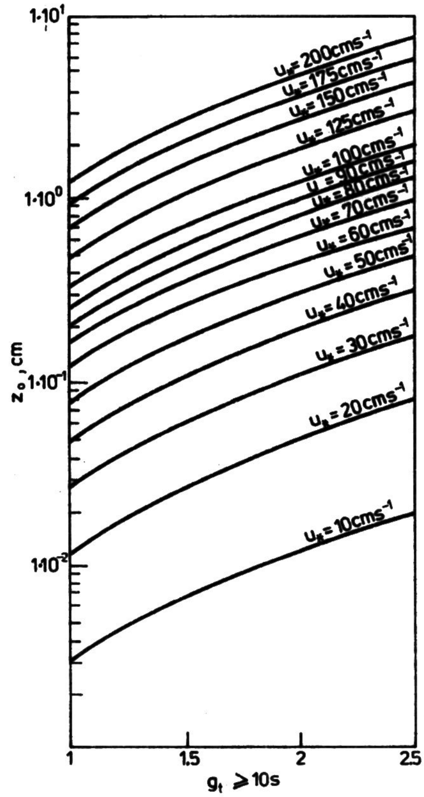

Fig. 9. Diagram of changes of z_0 parameter for different values of friction rate $\bar{u}_x$ in the function of the wind gustiness coefficient

rates $\bar{u}_x$ in Fig. 9). Experimentally found rapid changes in the increment of maritime salt concentration in air (q) along with increase of the value of u_{10} over 20 m/s (break of curves in Figs. 5 and 6) can be theoretically corroborated at a more examination of Fig. 8.

In view of integral connection of wind gustiness characteristics within the range of increments of speed modulus and with wind direction changes accompanying them (Fig. 3 and 4) it appeared very difficult to investigate z_0 changes separately for both these values. It seems that even very through model investigations could only slightly approximate the phenomena investigated. From the above it can be concluded that when choosing only one from among both wind gustiness characteristics, in fact both would be taken into account. Thus the speed modulus increments were chosen while regarding them as basic values for wind gusts Such an assumption is in agreement in its essence with the meteorological definition of wind gusts.

The presented proposal of estimating z_0 changes taking into consideration wind gusts and the effect of z_0 on the spray of sea mass particles should be regarded as one of the methods of determining summary roughness of sea surface. The results obtained allow to state that the concentration of marine aerosol in the surface air layer can play the role of a sensitive index of sea roughness changes, even for short-term nonuniformities of the wind field.

In view of the hitherto lack of the investigations of such kind, there is hardly possible to compare many-sidedly the results obtained in the work. The presented proposal of estimating changes of the parameter of sea surface roughness z_0, should be regarded as the first attempt of such investigations initiating the need of search after ways of their further development.

6. Conclusions

A connection between the eddy particulate air-sea mass exchange and the changes occurring under the effect of wind gusts and aerodynamical roughness of sea surface has been found. The calculated regression lines for these changes show a similar course for all characteristics of wind gustiness and z_0 parameter changes. The conclusion drawn previously (5) as to the break of regression lines for changes in the dependence of q on u_{10} value upon surpassing the speed of $u_{10} \approx 20$ m/s has been corroborated. This theoretical assumptions can be substantiated on the basis of worked out diagrams of changes of the z_0 parameter of sea surface roughness.

The functional dependence of changes of the z_0 parameter values for sea allows to take into account quantitatively the effect of fluctuations of the wind gustiness coefficient $g_{t \geq 10\,s}$ and the friction velocity $\bar{u}_x$. The presented considerations constitute the first attempt of defining such a relationship. The results of the presented analysis allow to develop earlier investigations concerning wind gustiness effect on fluctuations of intensity of eddy particulate air-sea mass exchange, carried out in the Antarctic region (5). The results obtained should be regarded as an initial approach to and the basis of the further development of investigations of such kind.

7. Резюме

В работе установлено существование связи между турбулентным аэрозольным обменом массы между морем и атмосферой с одной стороны и изменениями происходящими под влиянием порывистости ветра и аэродинамической шероховатости моря с другой. Проведен расчет линий регрессии этих изменений со сходным ходом для всех характеристик порывистости и изменений параметра z_0.

Получена функционная зависимость изменений значений параметра z_0 для моря, делающая возмосным количественное учитывание влияния колебаний значений коэффицента порывистости $q_t \geqslant 10$ s.

8. Streszczenie

W pracy stwierdzono występowanie ewidentnego związku między turbulentną aerozolową wymianą masy między morzem i atmosferą a zmianami występującymi pod wpływem porywistości wiatru aerodynamicznej szorstkości powierzchni morza. Obliczono linie regresji tych zmian które mają podobny przebieg dla wszystkich charakterystyk porywistości i zmian parametru z_0.

Uzyskano funkcyjną zależność zmian wartości parametru z_0 dla morza pozwalającą na ilościowe uwzględnienie wpływu wahań wartości współczynnika porywistości $q_{t \geqslant 10\,s}$.

9. References

1. Blanchard D. C. — The electrification of the atmosphere by particles from bubbles in the sea. Progr. Oceanogr., Vol. 1, Acad. Press, New York, 1963.
2. Charnock H. — Wind stress on a water surface. Quart. J. Roy. Met. Soc., Vol. 81, 1955.
3. Garbalewski C., Berek H. — O możliwości wykorzystania stężeń jąder soli morskiej w atmosferze przy wyznaczaniu parametru szorstkości powierzchni morza. Oceanologia PAN, No. 7, Sopot, 1977.
4. Garbalewski C. — Dynamika morskich układów rozproszonych. Zakład Oceanologii PAN, Sopot, 1980.
5. Garbalewski C., Marks R. — Badania dynamiki morskich układów rozproszonych podczas 5-tej Wyprawy Antarktycznej na Stacji im. H. Arctowskiego. Sesja: „Meteorolog. i klimat. badania M. Bałtyckiego i innych akwenów w aspekcie potrzeb żeglugi i gospodarki morskiej". WSM W. Gdynia, 1981 — tezy; Zbiór prac WSSW Gdynia, 1982.
6. Goptarev N. P. — Nekotorye rezultaty izmerenii profila vetra na morskikh platformakh. Trudy GOJN, vyp. 36, Moscow, 1957.
7. Kitaigorodsky S. A. — Fizika vzaimodeistvia atmosfery i okeana. Gidrometeoizdat, Leningrad, 1970.
8. Marks R. — Zjawiska emisji i przenoszenia aerozolu morskiego w rejonie fiordu Hornsund na Spitsbergenie. Zeszyt V Sympozjum Polarnego, No. 2, Gdańsk, 1978.
9. Melville W. K. — Wind stress and surface roughness over breaking waves. J. Phys. Oceanogr., 1977.
10. Monahan E. C. — Sea spray as a function of low elevation wind speed. J. Geophys. Res., Vol. 73, No. 4, 1968.
11. Roll H. U. — Physics of the Marine Atmosphere. Academic Press, 1965.
12. Wu J. — Wind stress and surface roughness at air-sea interface. J. Geophys. Res., 1969.
13. Wu J. — Wind-stress coefficients over sea surface near neutral conditions — a revisit. J. Phys. Oceanogr., 1980.

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