Papers

The characteristics of aerosol formation over the sea as an index of climatic activity of the ocean *

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Energoactive ocean regions
Marine aerosol
Whitecaps

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Abstract

The problem of estimation of the ocean active centers is presented, using Atlantic Ocean as an example. A synoptic analysis of these centers is carried out on the basis of the foam coverage of the ocean and aerosol emission. The possibilities of application of the presented methods for such an analysis are discussed in connection with the growing needs of modelling the climatic variability of ocean and atmosphere.

1. Introduction

Progress in the field of discovering the synoptic and climatic variability of the ocean achieved owing to international dynamics experiments (MODE, POLYMODE, *etc* – *The mid-ocean...*, 1978) enabled broadening the model investigations of this variability. Multilevel models of currents taking into account the interaction of sea with atmosphere and accompanying, momentum exchange, heat exchange, *etc* (Robinson *et al*, 1977; Semtner and Mintz, 1977; Seidov, 1980) have been already developed. Recent modelling of synoptic and climatic ocean variability, however, is still at its initial development stage. Model experiments are carried out on the basis of schematic and idealized assumptions, and an exact role played by the individual factors is still not well recognized. The problem becomes especially complicated when modelling concerns the relationships between the local climatic ocean variability and variations of atmosphere climate in a macroscale.

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Development of this up-to-date direction of investigations requires further discovering and specification of the interdependences between the variability of hydrophysical fields structure, as well as synoptic and large-scale variability of atmospheric characteristics of the oceans. In order to achieve this goal it is necessary to take more precisely into account the geographical factors of synoptic variability of the structural parameters of the atmosphere-ocean system and to further increase the knowledge on physics of atmosphere-sea interaction.

Marine aerosol characterisitcs also deserve special attention in the investigations of the synoptic characteristics of the climatic ocean activity. They refer to the variability of the share of spray and sea salt particles in the mass, moisture and heat exchange, as well as to the influence of the changes of the general aerosol background on variations of the radiation balance of atmosphere and ocean. At the same time they characterize the spatial variety of activity of dynamic states of interaction of various ocean regions with the atmosphere, probably corresponding to the variety of the climatic activity of the ocean on a synoptic scale. The above statements are testified by the current results of macroscale and synoptic analyses of ocean as a source of atmospheric particulates (Patterson *et al*, 1980; Garbalewski, 1983; Monahan, 1985). Although according to other opinions (Prospero, 1979) only small differences in concentration of sea salt particles occur in the surface air, they seem sufficient for distinguishing the centers of increased ocean activity. For example, Lannefors *et al* (1982) indicate the existence of active regions of generation and reduction of aerosol background in the Arctic region. It is only that the need is growing for theoretical and experimental investigations of such differences, not only in the light of local characteristics, but through synoptic comparisons taking into regard their connection with the mechanisms of general atmosphere circulation.

An evaluation of the anticipated possibilities lying in this direction of investigations from the viewpoint of discovering new and defining more accurately the recent relationships characterizing the climatic activity of the Atlantic Ocean is given below. The considerations are limited mainly to the regions extending from Arctic latitudes (*ca* 80°N) to middle southern latitudes (*ca* 40°S). These regions are partly included in the long-term plan of research cruises of r/v 'Oceania' expected to be carried out within the recent five years by the Institute of Oceanology of the PAS.

2. Synoptic variability of the aerosol mass exchange in the ocean regions

It is natural to assume that aerosol mass and heat exchange between the sea and the atmosphere cannot be uniform within the entire ocean region. A number of physical properties – first of all different dynamic characteristics of various regions, but also variations in thermal air currents, water density and salinity – result in occurrence of large differences in both hydrophysical and aerosol characteristics. Investigations of the influence exerted by these differences on the dynamics of marine particulate fluxes constitute an important part of the entire problem.

It seems that the effect of small-scale processes of atmosphere and water interaction on the characteristics of the aerosol source fields and turbulent vertical mass exchange constitute the most important reason and the main set of factors determining the regional properties of every sea area. Hence, the assumption of occurrence of a uniform layer of air and water contact can rather be valid only for restricted ocean regions.

Spatial distributions of the values of the spray emission flux (F_0) evidence the synoptic non-homogeneities of marine aerosol characteristics in the Atlantic Ocean. These distributions were calculated on the basis of long-term mean monthly observational data (*Morskoy atlas*, 1953). The proportionality of the F_0 flux to the tangential wind stress, *ie* the square of friction velocity ascertained previously (Garbalewski, 1977) constituted a basis for such calculations. It has been proposed to carry out the calculations according to the following half-empirical formulae (Garbalewski, 1983):

$$F_0 = \alpha \, \mathrm{Re}_* \, \varrho_w u_*, \tag{1}$$

$$q_0 = \alpha \, \mathrm{Re}_* \, \varrho_w q_n, \tag{2}$$

where:
u_* – friction velocity,
Re_* – Reynolds' roughness,
ϱ_w – water density,
q_n – salinity.

Basically, the data on monthly or annual distribution of u_*^2 and U^2 mean wind characteristics are insufficient for the calculations. Blanchard (1963) indicated the difficulties related to deriving the U^2 values, differing from the square of the U values taken from the climatologic maps of mean wind velocities. In practice, however, according to some authors (Spillane *et al*, 1985) the need of exact fitting the U value not always exists, especially in case of more statistic evaluation of the oceanic distributions.

The value of α in equation (1) was determined experimentally (Garbalewski, 1977, 1983), mainly during the GATE-74 international experiment in the middle Atlantic (Fig. 1), to be equal to $2.2 \cdot 10^{-9}$. For a comparison, the value of α for a semi-salty sea (Baltic) equals to $0.5 \cdot 10^{-9}$.

The existence of a few regions of increased aerosol emission activity in the Atlantic has been established as a result of the analysis of mean monthly values of the F_0 flux obtained for January (Fig. 2*A*) and July (Fig. 2*B*). In January the active region of hydrodynamic exchange occurs in the middle latitudes of the ocean. This region extends along the European coast from

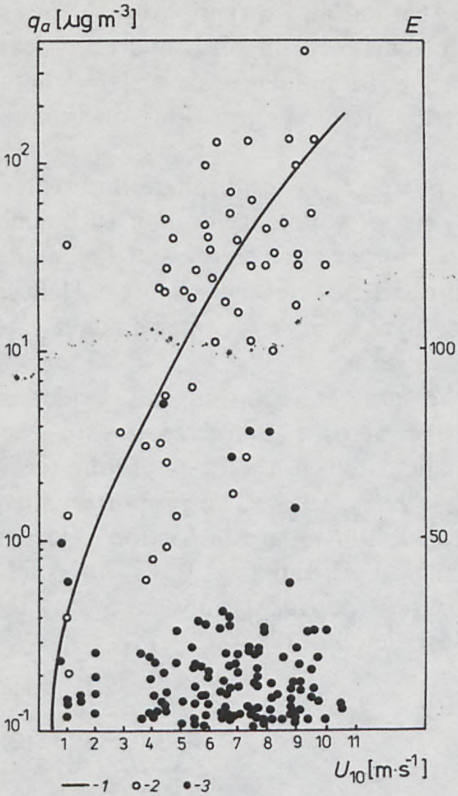

Fig. 1. Comparison of the dependence of concentration of sea salt particle mass and Sahara dust in the surface air on the wind velocity (Garbalewski, 1980)
1—calculated on the basis of the equation (1), *2*—results of micromorphometric measurements of sea salt particles, *3*—results of photometric analysis of the aerosol background samples, mainly Sahara dust (*E*—light attenuation degree)

the North Sea to the middle part of the northern Atlantic. It is shifted in its northern part to the Norwegian coast, while its active maximum lies in the central part of the northern Atlantic. Generally, geographical location and configuration of the region of active particulate emission in middle ocean latitudes distinctly indicates the connection between this region and flow of the Gulf Stream.

The occurrence of two regions of increased mass transfer activity in the intertropical region of the ocean can be noticed at the same time. They are much weaker and indicate the correlation with activity of the northern and Southern trade winds, respectively. The region related to the northern trade wind is larger. Similarly, a second region of increased activity is formed in the southern trade wind zone, south of the equator. This active center, however, is smaller than the northern one but it is noticeable. It is not directly connected with the maximum activity belt occurring in the southern

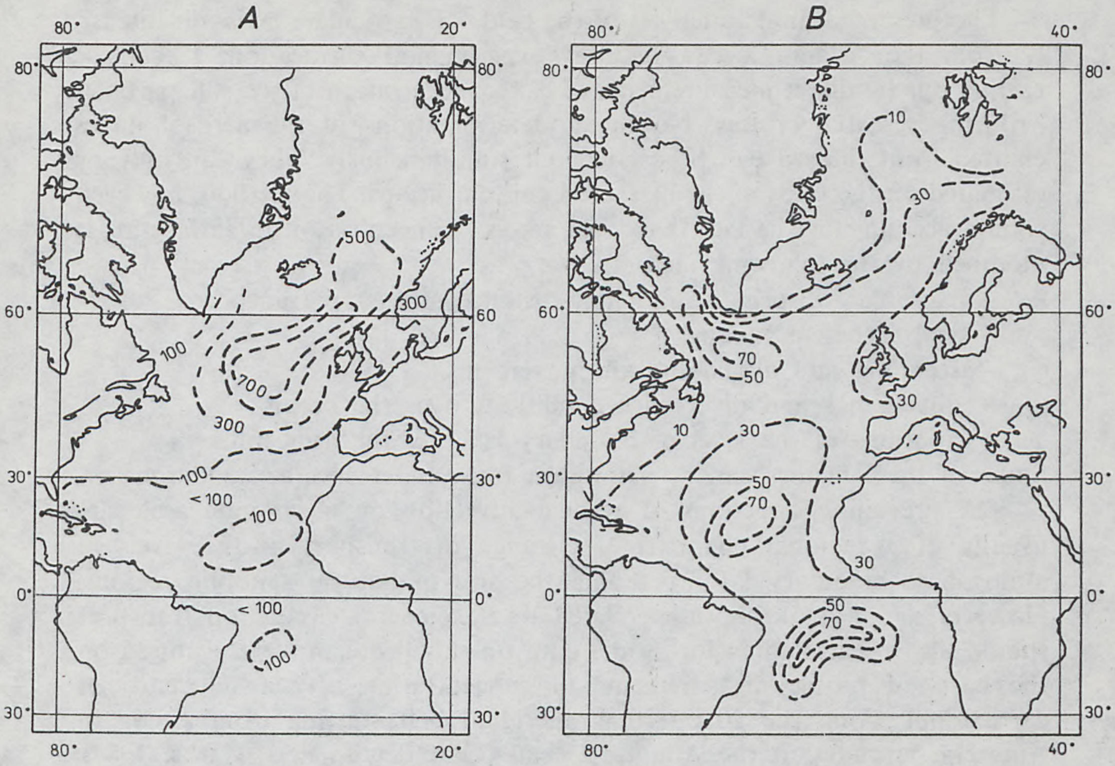

Fig. 2. Active centers of aerosol exchange in the Atlantic determined on the basis of calculated F_0 fluxes [$\mu g\ m^{-2} s^{-1}$] A – in January, B – in July

part of western transport over the ocean (Garbalewski, 1983; Garbalewski and Marks, 1987).

The values of the F_0 flux in July are generally smaller by an order of magnitude than in January. Domination of the vast northern center is reduced. At the same time, similarly to January, the existence of three main centers of activity of mass and energy exchange is observed. They are nearly equal in July with respect to the intensity of the F_0 fluxes and to their extent. Considerably weaker and reduced region of activity in middle latitudes is shifted from the central part of the northern Atlantic to the west, and it is almost thrusted between Greenland and Newfoundland. A significant increase in activity of the intertropical centers is observed at the same time. The region related to the activity of the northern trade wind is shifted slightly west compared to its January position. Increased activity center occurring south of equator extends vastly in the direction of the parallel of latitude and is distinctly separated from the southern maximum activity belt (not depicted in Fig. 2).

The presented model analysis of the fields of particulate emission intensity from the Atlantic ocean requires experimental verification. It can be carried out by direct measurements of q_0 – concentration of sea salt particles – during research cruises. No direct determinations of the aerosol fluxes emitted from the sea can be carried out simultaneously. They can only be estimated on the basis of the measured concentrations. The method, however, should account for the fact that local aerosol concentration in surface air is modified by the following factors:

– macroscale dispersion and long-distance advection transport,
– local turbulent mixing,
– ascending and discending air movements,
– convergence and divergence conditions over the ocean,
– variations of the level of boundary layer of the atmosphere.

Some of these factors can be significant only under specific conditions.

The prevailing directions of aerosol advection on a synoptic scale are usually of a regional character; the range of transport at the levels of atmosphere boundary layer reaching the size of natural synoptic regions. However, larger scale motions related to the general circulation transport should also be accounted for. Some data on this problem were acquired on the basis of profile measurements of concentration of sea salt particles carried out along the 20°E – 30°W meridian belt starting from Arctic to Antarctic latitudes in the Atlantic Ocean (Garbalewski and Marks, 1987). Different and relatively short observation period (northern summer 1977 and winter 1980 – 1981) did not allow acquiring universal results; measurement data (Figs. 3 and 4), however, indicate the regional character of the aerosol ocean efficiency partly confirming the expectations. This concerns mainly the effect of atmospheric convergence zones over the ocean on advective transport. The indices of advection proposed in the paper – A_q and A_N – for mass and number of particles, respectively, defined as the ratio of mean regional aerosol concentration to local concentration, were equal to 28.5 in the equatorial doldrums, *ie* being 10 times higher than in both trade wind zones, and over 25 times higher than in the northern region of western transport. It is worth noticing that in the 35° – 40° and 60°N latitudes the advection index over the ocean is close to unity which indicates prevalence of local aerosol component in this region.

Vertical convection – turbulent dispersion in the boundary layer of the atmosphere, reaching few hundreds m over the ocean, should cause a local decrease of concentration of particles in surface air. Hence, if advection can result mainly in overestimation of the aerosol emission fluxes calculated on the basis of aerosol concentration, then it should be expected that turbulent diffusion causes underestimation of these fluxes. Due to this it is proper to use parallelly the methods of estimation of the aerosol ocean efficiency based on synoptic hydrophysical and wind characteristics and on determination of the concentration of sea salt particles.

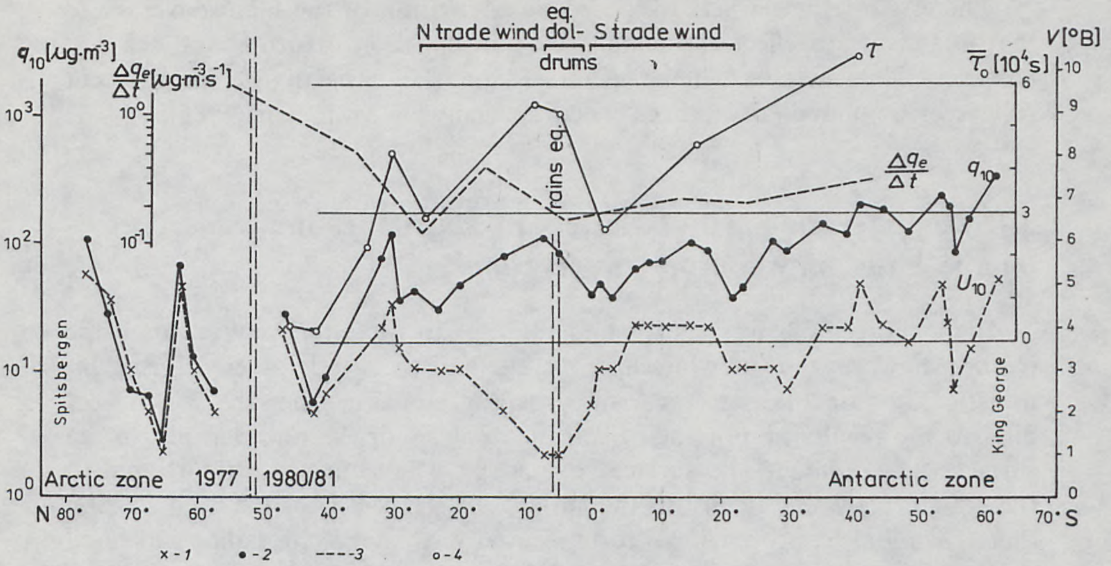

Fig. 3. Volume concentration of the mass of sea salt particles (q_{10}) and wind profile in the surface air determined on the basis of the measurements in the meridian profile (20°E – 30°W) over the Atlantic (Garbalewski and Marks, 1987)

1 – changes in wind velocity (*U*), *2* – course of the measured q_{10} values, *3* – distribution of the changes in local concentration of the mass of sea salt particles ($\Delta q_e/\Delta t$), calculated from equation (2), *4* – distribution of the local changes of residence time (τ_0) of particles in surface air over the ocean calculated from equation (2)

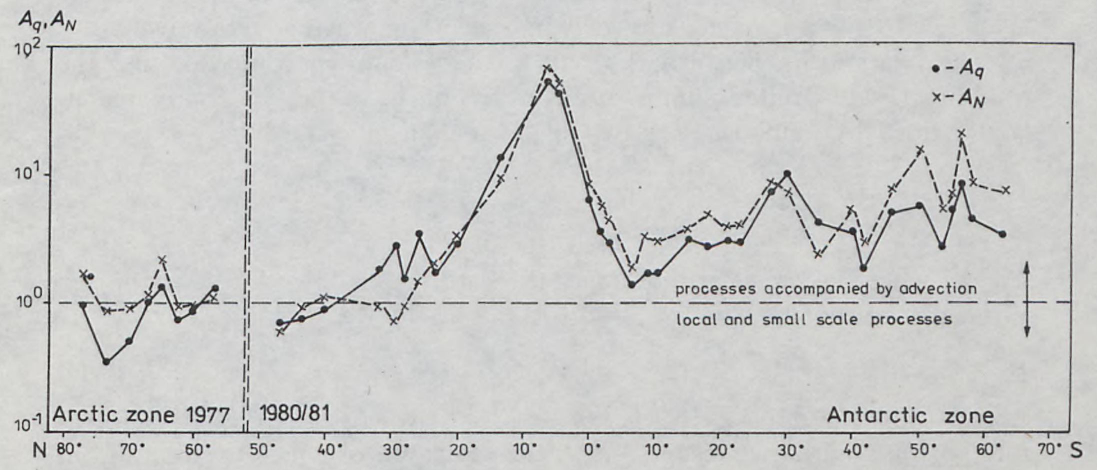

Fig. 4. Meridional (20°E – 30°W) distribution of the value of coefficient of advection for mass (A_q) and number (A_N) of sea salt particles in the surface air over the Atlantic Ocean (Garbalewski and Marks, 1987)

There is one more method, based on estimation of the foam coverage of the ocean, due to effect the foam exerts on emission of drops and sea salt particles. This method will be evaluated on the basis of the most recent results of a number of authors, and espacially of Monahan (1985).

3. Synoptic variability of the ocean activity estimated on the basis of whitecaps observations

Blanchard (1963) was the first to attempt to quantitatively evaluate the relationship between the whitecap coverage and the wind velocity during his investigations on the effect of foam on spray emission from the sea. According to the results he obtained from the analysis of the photographs of sea surface the W_c value – the surface covered by whitecaps – is proportional to the square of wind velocity in the surface air. Hence, he drew a conclusion that W_c should be proportional to tangential wind stress. Monahan indicated the influence of the atmospheric equilibrium on the dependence of W_c on wind velocity. Formation of whitecaps is much more intensive under the conditions of unstable equilibrium than of stable conditions at the same wind velocity. If also the dependence of W_c on the rate of energy dissipation (ε) in the high-frequency part of waving spectrum, found by Cardone (1969), is accounted for, then it can be concluded that W_c is determined by four parameters, *viz* wind velocity, the extent of its action at the sea, atmospheric equilibrium conditions, and the ε parameter. According to Wu (1979) under the conditions of neutral atmospheric stratification and fully developed waving, at infinite wind extent and duration of whitecap coverage, the value of W_c is proportional to the product of Uu_*^3 – wind velocity in the surface air layer (*ca* 10 m asl) and energy of wind spent on waving, respectively.

The relationship between the total area of foam in whitecaps and the total flux (F_s) of emitted number of drops (N) of the radius r is approximatelly described by a model proposed by Monahan *et al* (1983):

$$\frac{\partial F_s}{\partial r} = \frac{W_c + (\partial N/\partial r)}{\tau\, W_s(0)}. \tag{3}$$

To calculate the whitecap coverage, the rate of wind work W_t at the sea surface is defined by

$$W_t = \varrho_w C_D(U, DT)\, U^3. \tag{4}$$

Above C_D is the drag coefficient, $D_T = T_w - T_a$, where T_a is the air temperature, $W_s(0)$ is initial whitecap surface, the reduction of which (resulting from drop emission) is proportional to τ – exponential time constant of its decay. These values were determined by an experimental simulation of the process in a standard tank (Monahan *et al.* 1982).

Hence, the following formula found practical application:

$$W_c = 6.667 \cdot 10^{-6} W_t. \tag{5}$$

By means of equation (5) Spillane *et al* (1985) calculated mean monthly foam coverage of the ocean.

Further investigations allowed to establish that threshold Beaufort force U_B, starting from which the whitecaps begin to form, is a function of T_w – sea surface temperature – and atmospheric stability. The dependence of foam coverage of sea on temperature T_w and wind velocity U after exceeding the U_B velocity has been investigated by Bortkovskii (1983). His results are presented in Figure 5. The observed increase of W_c with the increase of T_w at

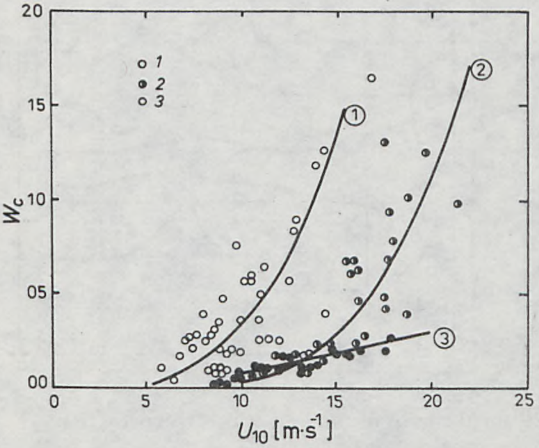

Fig. 5. Dependence of the sea surface covered with foam and whitecaps on the wind velocity U (acc. to Borkovskii, 1983)
1 – water temperature $T_w = 27°C$ (curve 1), *2* – water temperature $T_w = 3-15°C$ (curve 2), *3* – water temperature $T_w \leqslant 3°C$ (curve 3)

a constant wind velocity can be elucidated by a shift of the spectrum of the size of air bubbles in water accompanying the change in water temperature. It is consistent with the preliminary hypothesis according to which air bubbles in warmer water (being of smaller size) require more time to reach sea surface than in colder water (larger bubbles).

Monthly isopleths of whitecap coverage calculated by Spillane *et al* (1985) for January and July (Fig. 6*A*, *B*) do not account for a temperature correction. A constant temperature characteristic of warm seas (laboratory determined value of the coefficient corresponded to the temperature $T_w \simeq 19°C$) was assumed. Evaluation of the resultant error, however, is difficult without a comparison of the calculated fields with observational data. On the other hand visual estimation of the ocean fields of the W_c value or even photographing can be a source of even greater errors.

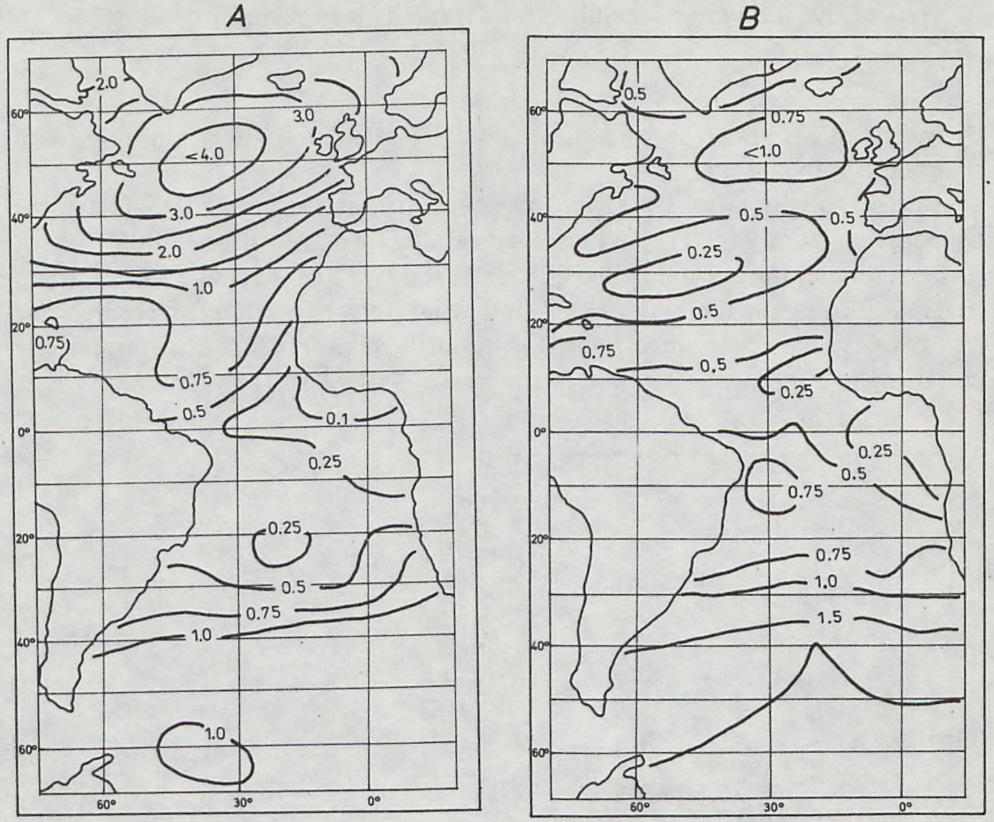

Fig. 6. Regions of oceanic activity determined on the basis of data on whitecap coverage [%] of the ocean (Spillane *et al*, 1985, changed)
A – January, *B* – July

The calculated fields of ocean coverage by foam allowed determination of the geographical distribution of active exchange centers in the Atlantic Ocean in January and July. It follows from the comparison of Figure 6*A*, *B* with Figure 2*A*, *B* that in general it is similar to the distribution of the centers determined on the basis of the calculated spray emission fluxes in the same months. The analysis of noticeable deviations and differences is presented in Table 1. The differences probably arise from worse (so far) accuracy of the method based on determination of W_c fields (due, among others, to not accounting of the temperature differences). Further development of this method will probably allow determination of active centers and their dynamics with greater accuracy.

At the present stage application of both the described methods confirms the correctness of distinguishing three active centers in the investigated area, *viz* one vast center in the northern Atlantic and two smaller ones forming in

Table 1. Comparison of the general characteristics of ocean activity obtained on the basis of flux F_0 and surface W_c data

Characteristics of the centers	North Atlantic center	N trade wind center	S trade wind center
January			
Characteristic values:			
flux F_0 [$\mu g\ m^{-2}\ s^{-1}$]	500–700	100	100
surface W_c [$^0/_0$]	3.0	0.75	0.25
Geographical location and extent of:			
F_0 field	Vast center in the middle ocean regions of the western transport zone, extending to the Norwegian Sea	Distinct active center in the middle region of the ocean the ocean	Small center at the ocean close to Brasilian coast, separated from the maximum activity belt
W_c field	Vast center in the middle ocean regions of the western transport zone, extending to the Norwegian Sea	Blurred center in the middle part of the N trade zone at the ocean	Blurred center merging with the southern maximum ocean activity belt
July			
Characteristic values:			
flux F_0 [$\mu g\ m^{-2}\ s^{-1}$]	50–70	50–70	50–70
surface W_c [$^0/_0$]	0.75	0.50	0.75
Geographical location and extent of:			
F_0 field	Center strongly reduced compared to January and shifted westwards	Vast center in the central part of the ocean	Distinct vast center in the zone in middle regions of the ocean
W_c field	Center strongly reduced compared to January without a distinct westward shift	Vast (noticeable, although not depicted) active center in the zone in the middle regions of the ocean	Blurred center merging with the southern maximum ocean activity belt

the regions of northern and southern trade winds, respectively. These centers change their geographical position and their extent does not remain constant, as follows from a comparison of mean monthly data for January and July. Comparison of results obtained using methods based on F_0 and W_c indicates that the centers are not equally well defined. Hence, there exists a necessity of carrying out a detailed analysis of the principal features and resolving power of both methods.

Both the described methods are interdependent and partly complementary one to another. Both are promising in the discussed area. It seems that aerosol method is suitable for a wider range of dynamic conditions. It allows carrying out observations of atmosphere and sea interaction characteristics at the stages preceding occurrence of whitecaps. On the other hand, the method based on observation of whitecaps concerns stages of an increased sea activity which constitutes the primary aim of the discussed research. Moreover, a parallel action of two or even more mechanisms of drop emission from the sea should often be taken into account in a case of the former method. These are mainly the mechanisms of drop emission by breaking air bubbles at the sea surface and blowing away cloudlets of water dust by stronger wind

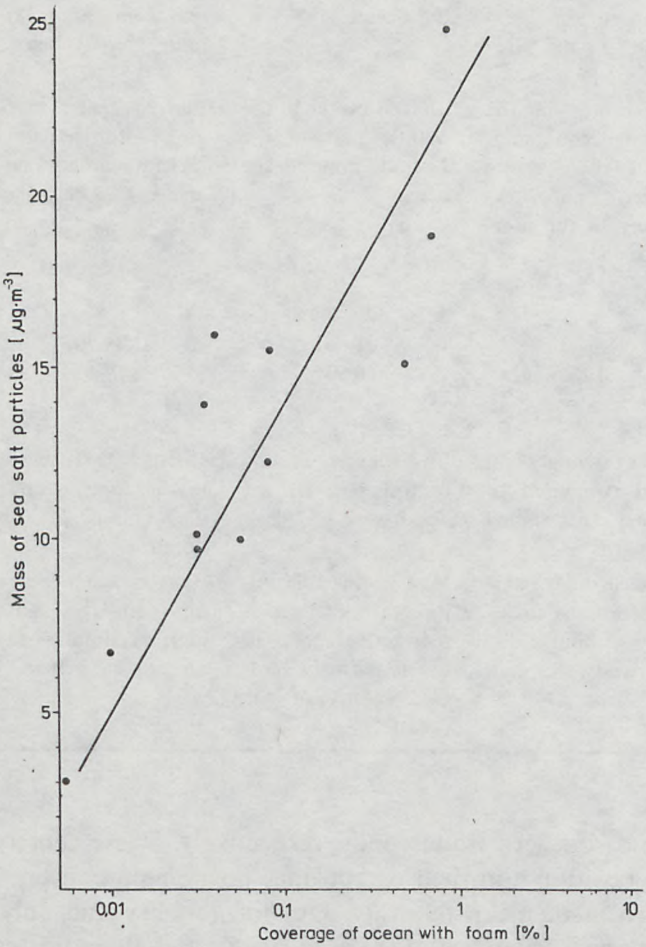

Fig. 7. Concentration of the mass of marine aerosol in the surface air as a function of the changes of foam coverage of the ocean (acc. to Marks, 1987)

gusts. In the case of whitecaps, however, only one mechanism prevails, *viz* formation of foam bubbles at wave crests resulting from capture of air by folding crests and its immediate escape in the form of streams of bubbles speeding upwards. The main shortcoming of the method based on determination of sea salt particles is the difficulty in distinguishing between local and advective component while the method based on determination of the number of whitecaps allows carrying out 'purely' local observations. The latter method, however, requires further development of an observation technique. A recently used technique of photographing the sea surface leads to approximate evaluations which are relatively less accurate than direct determination of the concentration of sea salt particles using impactors. The latter method, however, is suitable only for total evaluations since it does not allow a separate estimation of the share of the whitecaps component. According to specialists, also application of a video camera coupled to a computer does not yield very good results in recording W_c. This opinion is at variance only with the data of Marks (1987) for northern regions of northern Atlantic; in this case, apart from recording the coverage of ocean with foam, the concentration of marine aerosol in surface air was parallelly determined. The correlation between the concentration of sea salt particles and W_c characteristics obtained by Marks (Fig. 7) indicate that the applied method of recording whitecaps yields, in general, an accuracy similar to the method of marine aerosol determination.

4. Conclusions

The share of one of the parameters of climatic variability, *viz* particulate air-sea exchange of moisture and heat, in the energy balance of the active centers in the ocean can be estimated basing on the characteristics of marine aerosol and whitecaps coverage. Some fundamentals for such estimations have been created so far in the literature; they can constitute an initial stage for the development of special investigations within the scope of climatic activity of the ocean.

The comparison of results of estimation of ocean regions by various methods presented above indicates the usefulness of their application for long-term investigations of the aerosol exchange in space and time as well as filling up the existing gap in the field of the characteristics of the time-space synoptic variability of this exchange. Investigations in this field mean expanding the research on the variability of interdependences between the ocean and the atmosphere. Not only relatively close relations should be examined but also teleconnections in the atmosphere-world ocean system, the Southern Oscillation and its connection with El Niño in the Pacific being a classical example. It seems that the aerosol method can be helpful in such investigations. The results presented in this paper are promising in this sense althogh they require experimental verification of the initially calculated F_0 and W_c fields and carrying out for this purpose special profile measurements at the ocean, first of all from the viewpoint of synoptic variability of aerosol fluxes of heat and moisture exchange in the atmosphere-ocean system.

It would be difficult at the present stage to define more precisely the ocean activity fields and to distinguish secondary variables or regional activity centers, routes of their displacement *etc* at the ocean. These should be the goals of further investigations.

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