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Parameterization of turbulent exchange in the polar regions

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Abstract. Sea ice plays a significant role in the Earth's climate system. Significant changes are currently taking place in the sea ice cover area. The structure of sea ice also is changed. Based on field measurements, the paper shows the importance of taking into account the morphometric (structural) inhomogeneities of sea ice for modeling its interaction with the atmosphere. The dependence of the drag coefficient and the aerodynamic parameter of roughness on the surface structure is considered. The drag coefficient nonlinearly depends on the ice concentration, the relative area of the puddles, on the width and configuration of the leads, on the spatial location and height of the hummocks, as well as on the atmospheric stability. The parameterizations proposed in the paper can be used to calculate fluxes in weather and climate models.

Introduction

The sea ice cover determines the albedo change, heat and moisture fluxes, as well as the dynamic interaction between the ocean and the atmosphere [1,2]. In polar winter, ice prevents heat exchange, but in the presence of open water areas (polynyas, leads), turbulent heat fluxes increase tens of times due to the large water-air temperature difference [3]. The formation of the thermal regime of the atmospheric near-surface layer is also significantly influenced by phase transformations on the ocean surface associated with freezing of the water surface and melting of ice. An important property of sea ice is its complex surface structure. This is due to the features of ice formation and the drift of ice fields. Each surface inhomogeneity (hummocks, leads, puddles) plays its role both in interaction with the water layer of the atmosphere and in the thermal and radiation regime of the surface. And taking into account these morphometric features is important not only for calculations related to the ice dynamics and thermodynamics, but also for climatic modeling. The most complicated processes of energy exchange are at the margin ice zone, where the ice cover has a pronounced seasonal cycle and the maximum variety of its characteristics is observed [4]. Interest in the study of these areas is due to the fact that it is here that the maximum spatial and temporal variability of the state of drifting ice is observed, which, in turn, play an important role in large-scale oceanic and atmospheric processes. The marginal zones of sea drifting ice (or, in a broader sense, zones of seasonal migration) remain the least explored, especially in winter. The main problems in modeling sea ice and reconstructing its characteristics from satellite measurements arise precisely at the boundaries of the ice cover, for which there are no data from field experiments, and it is impossible to use one or another parameterization to describe processes with a subgrid scale.



To calculate turbulent fluxes in the atmosphere-surface system, so-called aerodynamic bulk formulas are used [5].

$$\tau = \rho C_D U_z^2, \quad (1)$$

$$H = \rho c_p C_H U_z (T_s - T_z), \quad (2)$$

$$L_E = L_s C_E U_z (q_s - q_z). \quad (3)$$

C_D , C_H , C_E — exchange coefficients (Drag coefficient, Stanton number and Dalton number); c_p and ρ — heat capacity and density of air, L_s — specific heat of vaporization τ , H and L_E — turbulent momentum, sensible and latent heat fluxes, U_z , T_z and q_z — wind speed, temperature and humidity at altitude z ; T_s and q_s — temperature and humidity at the surface.

To calculate the characteristics of the air-sea interaction, in particular, heat and momentum turbulent fluxes in models over heterogeneous surfaces, where all spatial inhomogeneities are inside the grid cell, various methods are used, which are called aggregation methods [6]. Two approaches are most often used: parametric and mosaic. In the first, all parameters characterizing the surface and its interaction with the atmosphere (roughness parameter, exchange coefficients, thermophysical properties of the surface) are averaged inside the cell, and the average fluxes for the cell are calculated using formulas (1-3) [7,8]. In the mosaic method [7,9,10], fluxes are calculated for each type of surface, after which the average flux values for the entire cell are calculated, and the flux for each surface is added to the area weight of that surface. Both methods have their advantages and disadvantages [7,11], but in any case, information on the aerodynamic and thermophysical properties of each surface, as well as its spatial distribution, is necessary for calculations.

Sea ice exchange coefficients

The drag coefficient C_D of the ice surface also depends to a very large extent on the shape, geometrical dimensions and placement of the irregularities present on it. The resistance also depends on the state of the snow cover, on the presence of drifting and snowfall, on the atmospheric stability. Therefore, the drag coefficient and the roughness parameter are extremely variable in time and space, and to a large extent depend on meteorological conditions and the distribution of hummocking zones and ice movements, which explains the large scatter of the experimental coefficients and roughness parameters in the Arctic. And knowledge of the coefficient of aerodynamic drag C_D , and the associated roughness parameter z_0 , is necessary when calculating the drift of ice fields, predicting ice conditions, calculating ice pressure on ships and coastal structures.

However, in most modern climate and sea ice models (for example, ECHAM [12] and FESOM [13]), the variability of sea ice surface roughness is not taken into account, and the surface roughness does not depend on the characteristics of sea ice, but the drag coefficient associated with the roughness parameter is often considered constant in space and time, while thin ice, thick ice and ice concentration from full ice cover to 1 point are parameterized in the same way. But the results of measuring the drag coefficient show an increase in its values for uneven ice and in the marginal zones [14,15]. At the same time, studies [16] show that sea ice drift, reproduced from the results of modeling, significantly depends on the method of setting the surface roughness.

In the marginal areas, the ice consists of ice fields ranging in size from a kilometer to several meters. The ice floes are surrounded by open sea water, which sometimes contains wet snow, sludge and crushed ice. The roughness of the surface in this case varies greatly in space, depending on the size of the ice floes and the distance between them.

At present, in regional models (WRF [17], as well as in the COSMO-CLM climate model (<http://www.clm-community.eu>)) parametrizations are used, in which the roughness coefficient is set separately for ice and for water, and the fluxes are aggregated as averaged over two surfaces. This leads to a linear dependence of the drag coefficient on the concentration of sea ice [18]. But in real

conditions, this relationship is not fulfilled [19]. Based on the processing of a large array of data obtained during the SHEBA experiment, it was shown that this dependence is nonlinear [20]. It was established in [21] that momentum transfer in the atmosphere is influenced not only by the resistance of open water and flat ice floes, but also by the shape resistance caused by the edges of ice floes. Taking into account the shape resistance leads to a nonlinear dependence of the resistance coefficient on the concentration of sea ice [22]. The marginal zones occupy a rather small area in comparison with the entire area of sea ice, and the significance of resistance parameterization in them may seem small. But in the same work [20] it was shown that the drag coefficient of a surface covered with puddles, which is typical for most of the Arctic in summer, also depends on the shape of the surface - more precisely, on the rise of the edges of puddles above the water inside. Analysis of the SHEBA experiment data showed that resistance increases with an increase in the relative area of puddles and reaches a maximum at 50% concentration. For the marginal zones, the maximum resistance is also observed at ice concentration of 50–60%. That is, the concept of resistivity parameterization, originally derived for small marginal areas of sea ice, can be used for a much larger geographic region. At present, the most common approach for calculating drag coefficient is when the resistance of a smooth surface is considered separately, and the shape resistance caused by the edges of sea ice or puddles is considered separately [19, 21, 23]. the parameterization also takes into account stability, which strongly affects the surface drag in winter [23, 24].

To experimentally determine the dependence of the exchange coefficients on various factors, we used the data of experimental observations of the characteristics of energy exchange in the Arctic in the period from 2004 to 2018 within the framework of the international project NABOS (Nansen and Amundsen basin observation system) [25]. A continuous measurement of the components of the energy balance in the near-surface layer of the atmosphere, as well as an analysis of the energy exchange of the atmosphere and the underlying surface under various meteorological conditions and conditions of atmospheric stratification, using instrumental measurements of the heat and momentum fluxes and radiation exchange in the near-surface layer of the atmosphere was carried out. Basically, measurements were carried out in the central regions of the Arctic at the boundaries of the continental shelf in the summer-autumn period. Ice conditions during this period of the year are characterized by various types of ice: newly formed forms of ice, annual and perennial ice, ice covered with hummocks and puddles, ice with streaks. Atmospheric stratification is generally neutral or unstable. Stable boundary layers were also observed over the fields of multiyear ice on cold days.

Measurements show that with low and moderate winds, C_D over an icy snow-covered surface does not depend on wind speed. But with an increase in wind speed, a drift develops on the surface, noticeable at a height of 10 meters at a wind speed of 5-7 m/s. This phenomenon causes an increase in surface resistance and, accordingly, C_D . [26, 27]. The data on the behavior of C_D and z_0 during snowfalls according to the measurement data are contradictory due to the difficulty of making observations in such conditions. The data indicate a downward trend in C_D . [28]. The distribution of the values of the exchange coefficients obtained by us from direct measurements over ice is shown in Fig. 1 (a, b and c). Its variability lies in a wide range, which is associated not only with the heterogeneity of the underlying surface, but also with a number of other factors, for example, with the direction of the wind, and stratification of the surface layer, ice concentration [22, 29].

Figure 2 shows the measured dependence of the drag coefficient on the stability of the atmosphere with stable stratification over a weakly hummocked surface. As in the case of an open sea surface, a decrease in surface resistance is observed with an increase in stability. The prevalence of stable stratification over ice fields is also associated with the fact that the value of the roughness parameter in the Arctic is significantly less than that observed over the snow cover in the middle and even high latitudes of the Northern Hemisphere. Under such conditions, for the air flow, the uneven surface turns into a flat surface, since the depressions between the sastrugs and ridges of hummocks are filled with heavier air to the height of the irregularities, and the air flow moves at the level of the tops without flowing into the depths of the depressions [30].

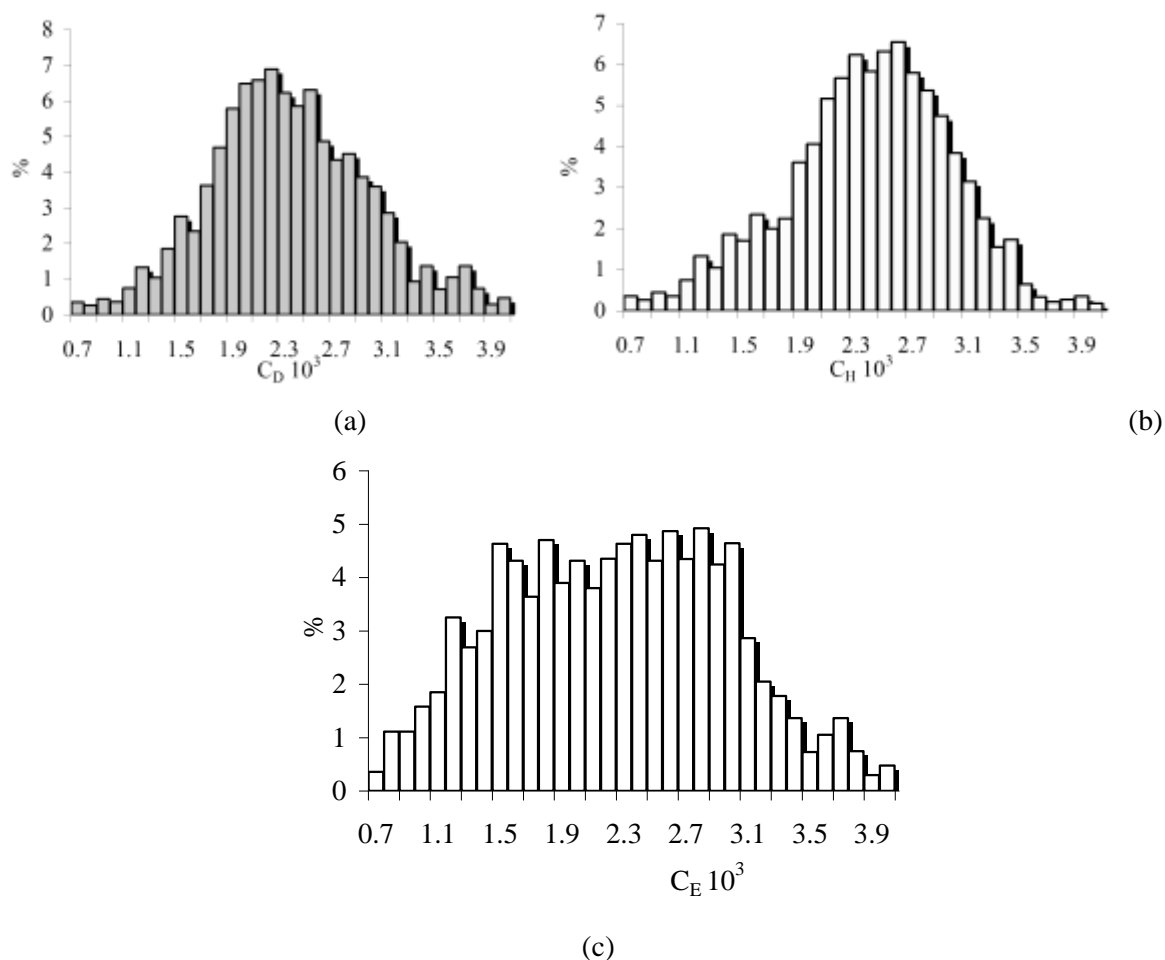


Figure 1. Distribution of the values of the exchange coefficients C_D (a), C_H (b) and C_E (c) obtained from direct measurements over ice.

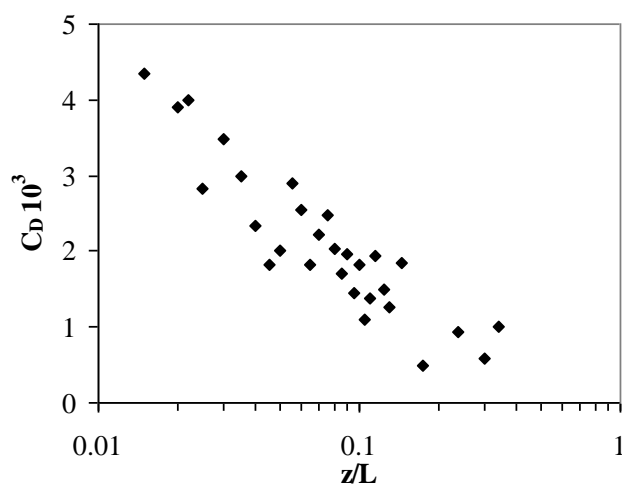


Figure 2. Dependence of the drag coefficient on the stability parameter over a weakly hummocked surface.

As for the exchange coefficients for sensible and latent heat fluxes, calculations show that C_H is always 2-3% less than C_E , both decrease monotonically with increasing wind speed when the surface becomes rough. Their values are between 10^{-3} and $1.5 \cdot 10^{-3}$. At the same time, our measurements did not show a significant dependence of C_H on wind speed.

The influence of hummocks and other irregularities on the air flow is very significant [31]. The form resistance arising from air flow around irregularities on the ice surface, as shown by laboratory and special field measurements, can be 5–7 times higher than the shear stress of a flat surface. In particular, this fact is illustrated by the measurements we obtained during our work in the polar regions. To study the transformation of the air flow over the ridge of hummocks, direct measurements of the pulse flux were carried out at different distances from the ridge of hummocks on the windward and leeward sides. The diameter of the hummock base was 2-3 meters, the height $h \sim 1.5$ m. Under the influence of interaction with hummocks, the structure of the turbulent flow changes significantly - large turbulent eddies break into smaller ones and the intensity of turbulence increases sharply. The average C_D value over such hummocks was: $3.1 \cdot 10^{-3}$. The value of z_0 changes by two orders of magnitude when passing from a flat surface to a hummocked one. A zone of increased turbulence intensity spreads along the stream behind the ridge of hummocks. The horizontal distance to which the influence of hummocks extends depends on the degree of development of this zone. Directly behind the ridge (from the underlying surface, to a height of the order of h), the flow retains for some time the properties that were formed in it when passing through the ridge of hummocks. The wind speed is weakened here, the turbulent friction stress increases with height, and, therefore, in this flow region, the basic similarity relations for the near-wall flow cannot be used.

The data of our measurements (1998-2018) over surfaces with an average height of irregularities of 0.5, 1 and 1.5 and 2 m gave the following dependence:

$$C_D \cdot 10^3 = 1.4 + 0.2 \ln E, \quad (4)$$

But, taking into account the measurement results presented above, this dependence is fulfilled only in the presence of sufficiently long ridges of hummocks and stable winds.

From a set of measurements above the leads of various widths, the dependence of the value of the Stanton number on the dimensionless width of the lead was obtained. This dependence is well parameterized by the relation:

$$C_H = 1.1 + 0.7 \exp[0.05(X/L)] \quad (5)$$

For small x/z (z is the height of measurements), this coefficient is $1.8 \cdot 10^{-3}$, for large - 10^{-3} , which corresponds to the value typical for the open ocean. This also agrees with the data of other measurements [1]. This dependence also confirms the fact that small divots a few meters wide provide more efficient turbulent heat transfer compared to those with a width of hundreds of meters. The exchange coefficient C_E for calculating the latent heat flux over the leads, on average, corresponds to the ratio $C_E = C_H$.

Experimentally obtained values of drag coefficients: $C_D = 1.49 \cdot 10^{-3}$. This is less than over ice covered with hummocks but more than in the open ocean. These coefficients do not depend on the wind speed at $U=1-10$ m/s and on x at $x=7-500$ m. At low and medium winds, the dependence of the coefficients on temperature stratification is also observed.

Measurements in the marginal zones and above the puddles confirmed the fact of the nonlinear dependence of the drag coefficient on the ice concentration (A) and the relative area of the puddles (B) (Fig.3 a, b). A large scatter with a small number of puddles is associated with the predominance of other inhomogeneities - hummocks, sastrugs, etc. The dependence of the drag coefficient on ice concentration can be parameterized by the relation:

$$10^3 C_D = 1.17 + 4.34A(1 - A^2) \quad (6)$$

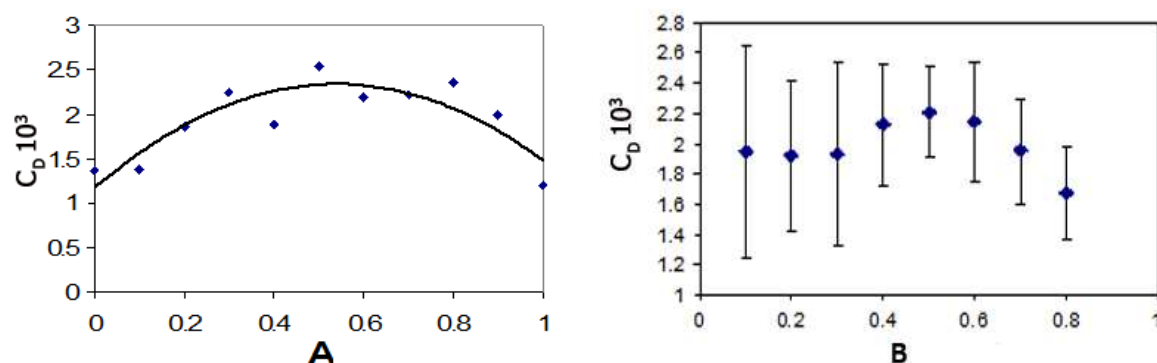


Figure 3. Experimental dependence of the drag coefficient on the concentration of sea ice (A) and the relative area of puddles on its surface (B).

Conclusion

The North Polar Region occupies a special place in the modern climate system as an indicator of ongoing changes due to the effect of polar enhancement. A significant manifestation of these changes is the sharp increase in the ice-free area in the Arctic Ocean in the early 2000s. The state of the ice cover largely determines the thermal interaction between the ocean and the atmosphere in the polar regions, and its decrease can increase the intensity of heat exchange between the atmosphere and the ocean.

Significant changes occur not only with the area and thickness of the ice, but also with its structure. The relative area of leads and puddles changes, hummocking intensifies. This article shows that structural inhomogeneities of the ice surface have a significant impact on its interaction with the atmosphere. A review of remote sensing methods for openings, puddles and irregularities in the height of the ice cover shows the importance of satellite observations. And especially such ice characteristics as aerodynamic roughness and drag coefficient. The article, based on the results of observations in the Arctic and literature data, shows a significant variability of these parameters depending on the morphometric properties of the ice-covered surface. The drag coefficient nonlinearly depends on the concentration of the ice cover, the relative area of puddles on the surface, on the width and configuration of the openings, on the spatial location and height of hummocks, as well as from the atmospheric stability. The parameterizations obtained from the measurement data can be used for calculating fluxes in regional and climate models.

Acknowledgments

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