

УДК 551.465

© P. N. Golovin*, M. S. Molchanov, 2023

© Translation from Russian: E.S. Kochetkova, 2023

FSBI “Arctic and Antarctic Research Institute”, 199397, Berings Str., 38, St Petersburg, Russia

*golovin@aari.ru

STUDY OF THE STRUCTURE AND INTENSITY OF DENSITY CURRENTS IN THE SHELF-SLOPE REGION IN THE ANTARCTIC

Received 20.04.2023, Revised 08.06.2023, Accepted 21.06.2023

Abstract

The research involves the examination of modeling outcomes regarding the density structure and baroclinic dynamics of Antarctic shelf waters (ASW) within the shelf-slope area, encompassing a wide range of extreme weather conditions. We used a small-scale non-hydrostatic *Fluidity-ICOM* model to understand the formation and persistence of quasi-stationary polynyas in the Antarctic, which play a role in enhancing the formation of ASW. The salt fluxes, or buoyancy, are calculated for different forms of ice formation, namely static ice formation in young ice-covered polynyas and dynamic intra-water ice formation, which is considered the most effective and occurs in open water polynyas. Based on the intensification of ASW formation and its spread, three distinct modes of propagation along the continental slope have been identified: non-wave or subcritical mode, vortex mode, and wave or supercritical mode, which is characterized by rapid flow. The classification into different modes is determined by the internal Froude number (Fr) estimates. At the moment when the most developed stage of near-bottom density currents are transformed on a slope, the spatial dimensions of meanders, eddies, or frontal waves were found to be similar in magnitude, as well as their thickness. This observation aligns with model calculations of the local baroclinic Rossby deformation radius (Rd_L) for these currents. These findings agree with comparable assessments of the baroclinic Rossby deformation radius (Rd_L) for the Antarctic Slope Front (ASF) in the Commonwealth Sea, which were based on field observations. Additionally, the calculated propagation velocities of density currents and the density gradients at their boundaries coincide with the data obtained from field measurements. By estimating the volumetric fluxes (q_v) and specific fluxes (q_l) of ASW along the continental slope near the Cape Darnley coastal polynya area in the Commonwealth Sea, we can determine the contribution of ASW cascading to the formation of bottom waters under different flux regimes. The precision and accuracy of the q_v and q_l estimates are ensured through small-scale calculations using the non-hydrostatic *Fluidity-ICOM* model. These calculations consider the occurrences of intensified ASW formation in open water polynyas. Numerical experiments have revealed that a four-fold increase in a spatial step X results in an underestimation of q_v by approximately 30%. As a consequence, in large-scale and even mesoscale hydrostatic models, such underestimation of q_v and q_l may be unsatisfactory (several times lower).

Keywords: Antarctic, sea ice formation in polynyas, dense water formation, non-hydrostatic small-scale model, dense water flow modeling, continental slope, density currents, flux estimation

© П. Н. Головин*, М. С. Молчанов, 2023

© Перевод с русского: Е. С. Кочеткова, 2023

Федеральное государственное бюджетное учреждение «Арктический и Антарктический научно-исследовательский институт», 199397, ул. Беринга, д. 38, г. Санкт-Петербург, Россия

*golovin@aari.ru

ИССЛЕДОВАНИЕ ИЗМЕНЧИВОСТИ СТРУКТУРЫ И ИНТЕНСИВНОСТИ ПЛОТНОСТНЫХ ТЕЧЕНИЙ В ОБЛАСТИ ШЕЛЬФ-СКЛОН В АНТАРКТИКЕ

Статья поступила в редакцию 20.04.2023, после доработки 08.06.2023, принята в печать 21.06.2023

Аннотация

Исследование заключается в анализе результатов моделирования развития плотностной структуры и бароклинной динамики антарктических шельфовых вод (АШВ) в области шельф-склон во всем геофизическом

Ссылка для цитирования: Головин П.Н., Молчанов М.С. Исследование изменчивости структуры и интенсивности плотностных течений в области шельф-склон в Антарктике // Фундаментальная и прикладная гидрофизика. 2023. Т. 16, № 2. С. 44–63. doi:10.59887/2073–6673.2023.16(2)–4

For citation: Golovin P.N., Molchanov M.S. Study of the Structure and Intensity of Density Currents in the Shelf-Slope Region in the Antarctic. *Fundamental and Applied Hydrophysics*. 2023, 16, 2, 44–63. doi:10.59887/2073–6673.2023.16(2)–4

диапазоне экстремальных метеоусловий образования и существования квазистационарных полыней в Антарктике, способствующих интенсификации формирования АШВ. Для этого используется мелкомасштабная негидростатическая модель *Fluidity-ICOM*. Получены оценки потоков соли (плавучести) для различных типов ледообразования: статического в полынях, покрытых молодым льдом, и внутриводного — динамического (наиболее эффективного), в полынях с открытой водной поверхностью. В зависимости от увеличения интенсивности формирования АШВ и увеличения скорости их распространения выявлены три режима стока по материковому склону: не волновой — или докритический; вихревой и волновой — или сверхкритические (быстрые). Разделение на режимы подтверждается оценками величин внутреннего числа Фруда Fr . При разбиении развитых придонных плотностных течений на склоне пространственные масштабы меандров, вихрей или фронтальных волн оказались близкими по величине (как и их толщина), что согласуется с модельными оценками локального бароклинного радиуса деформации Россби — Rd_L для этих течений. Они совпадают подобными оценками Rd_L , полученными на основе данных натурных измерений, для антарктического склонового фронта (АСФ) в море Содружества. Полученные оценки скоростей распространения плотностных течений и перепада плотностей на их границе также совпадают с данными натурных измерений. Получены оценки объемного q_v и удельного q_l потоков АШВ на материковом склоне вблизи района существования прибрежной полыни Дарнли в море Содружества, которые позволяют оценить возможный вклад каскадирования АШВ в образование донных вод при различных режимах стока. Точность и корректность оценок q_v и q_l обеспечивается мелкомасштабной дискретностью вычислений, с использованием негидростатической модели *Fluidity-ICOM* и учетом событий увеличения интенсивности образования АШВ в полынях с открытой водной поверхностью. При увеличении пространственного шага вычислений H в численных экспериментах в 4 раза недооценка q_v составляет ~30 %. Поэтому в крупномасштабных и даже в мезомасштабных гидростатических моделях недооценка q_v и q_l может быть неприемлемой (в несколько раз).

Ключевые слова. Антарктика, ледообразование в полынях, формирование плотных вод, негидростатическая мелкомасштабная модель, моделирование стока плотных вод, материковый склон, плотностные течения, оценки стока

1. Introduction

The shelf-slope regions across all oceans exhibit dynamic water movements, particularly in the polar waters of the Antarctic, where in certain areas along the sea shelves, quasi-stationary coastal, shore, or near-barrier polynyas are present during the cold season [1–6]. These regions experience vigorous formation of dense Antarctic shelf waters (ASW) due to intense local ice formation in winter [7–13]. As these ASWs extend beyond the polynyas, they cascade down the shelf and continental slope as near-bottom density currents [1–3, 5, 6].

The speed, composition, and stability of these currents are influenced by mesoscale and localized variations in the seafloor topography on the shelf and slope [6, 14–16]. A pronounced incline of the shelf and slope intensifies the flow of dense ASW, leading to an unstable cascading behavior [15–20]. Conversely, on a relatively smooth and gradual shelf and slope, the ASW density currents remain stable, demonstrating quasi-geostrophic characteristics. Furthermore, the presence of depressions on the shelf contributes to the accumulation of dense waters, even during the summer season [15–18]. However, in addition to the topographic features of the seafloor, the seasonal effectiveness of dense ASW formation in polynya areas plays a crucial role in shaping the structure and intensity of ASW density currents. The efficiency of ice formation relies on the specific type of ice formation occurring in the polynya, which determines the rate of salt introduction into the water and thus influences the intensity of external buoyancy fluxes on the polynya surface.

The most efficient ice formation occurs in open water polynya areas, which exhibits dynamic intra-water processes [12, 13, 21–24]. The rate of static-vertical ice formation on the lower surface of young ice in congealation polynyas is comparatively weaker, but it significantly surpasses the rate of ice growth on the lower surface of first-year drifting ice or fast ice that borders the polynya [23, 25–30]. The external salt fluxes (buoyancy) vary widely across different polynyas. Consequently, it is of interest to investigate the patterns of development and fluctuations in the intensity of density currents on the shelf and continental slope across the entire observed range of winter atmospheric forcing. This range encompasses the active formation of ASW in areas with the presence and persistence of various types of quasi-stationary polynyas, including coastal, near-shore (fast-ice), and near-barrier polynyas.

This investigation requires the utilization of numerical modeling within a non-hydrostatic framework, spanning various scales from small to mesoscale. To achieve this objective, the small-scale non-hydrostatic

Fluidity-ICOM model, previously validated in [31], is employed. The article provides a brief description of the model and outlines the upgraded configuration of graphical output for the presentation of computational results. An in-depth analysis of real atmospheric forcing is conducted, encompassing the entire spectrum of conditions leading to the formation and persistence of open water polynya areas and the presence of young ice cover. This study presents results of multiple three-dimensional numerical experiments investigating the presence of quasi-stationary polynyas in the Antarctic under various conditions. The experiments provide estimations of dense water movements along the upper continental slope. Additionally, the impact of enhancing the spatial resolution of calculations on these flow estimations is examined. To validate the simulations' accuracy, outputs are compared with contemporary field observations. A comparative analysis of the outputs with the laboratory investigations of the density currents' propagation along a seafloor slope is conducted.

2. Brief description of the model and numerical experiments design.

The *Fluidity ICOM* (the Imperial College Ocean Model), allows for the numerical simulation of dense water propagation along the shelf and slope using a three-dimensional adaptive unstructured grid (Fig. 1, *a*). The model incorporates automatic grid refinement to a specified scale and employs non-hydrostatic dynamics.

Shaded areas: blue represents a cross section across the shelf and slope; gray shows longitudinal sections along the polynya, along the shelf edge or the slope; brown marks bottom of the shelf and slope; blue lines are vertical distributions of hydrophysical parameters

The model utilized in this study is built upon a comprehensive set of ocean thermohydrodynamic equations, encompassing mass conservation equations, Navier-Stokes and Reynolds equations accounting for turbulence effects, as well as salinity and temperature conservation equations in three dimensions, and the

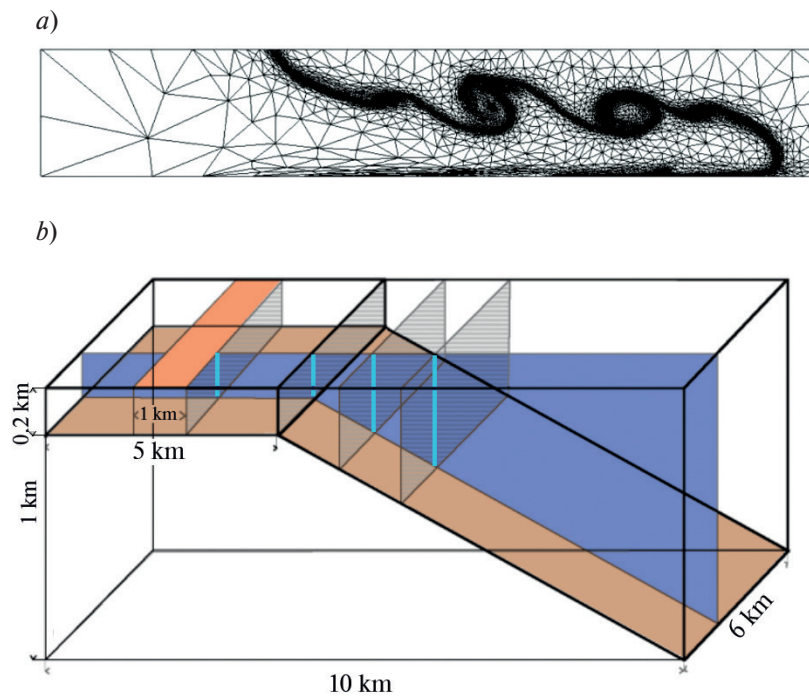


Fig. 1. *a* – an example of the adaptation grid refinement in the *Fluidity-ICOM* model when simulating a near-bottom gravity current propagation on a flat bottom [40]; *b* – computational domain representing a scheme of numerical experiments with a flux initial conditions method in the *Fluidity-ICOM* model. The salt flux (buoyancy) as a result of ice formation is set at the built-in polynya surface area 1 km wide (orange color)

equation of state of seawater [33]. To solve the Navier-Stokes and Reynolds equations on adaptive unstructured grids, the Galerkin finite element method with discontinuous basis functions (Discontinuous Galerkin (DG)) is implemented, ensuring solutions with high-order accuracy for modeling laminar and turbulent flows [36, 32, 34, 35]. In the numerical calculations, turbulent processes are parameterized using various methods. Throughout the computations, the viscosity is determined in accordance with the Smagorinsky formulation [37], which links it to the filter size (grid step) and the strain rate limitation of large eddies (i. e., velocity gradients of the computed current field). Friction against the bottom is accounted for using a friction coefficient formulation. For a more detailed understanding of the model formulation and equations employed, refer to [32, 38–40].

The *Fluidity-ICOM* model was used to simulate lock-exchange flows, highlighting its capability to adapt the grid (Fig. 1a) selectively to areas requiring high resolution [40, 41]. Furthermore, the model has been successfully employed in the modeling of currents and the pollutants transport across diverse marine environments such as seas, bays, estuaries, and other natural water bodies [42].

Initial and boundary conditions

The lateral boundaries of the simulated basin are configured to allow unrestricted flow, ensuring an open boundary condition. The free surface of the water body is treated as a dynamic boundary, where a kinematic boundary condition is applied to account for its movement. To establish the initial conditions, the flux method is employed, as illustrated in Figure 1b. The calculation of external salt fluxes, which play a crucial role in determining buoyancy, is thoroughly explained in section 3.

Upgraded visualization of the model output

The *Fluidity-ICOM* model generates output files containing simulation data that are managed using the *Visualization Toolkit* (VTK – <http://www.vtk.org/>). However, since unstructured adaptive grids are utilized, the default visualization package provided by the developer only allows for the construction of outer surfaces of the computational domain. These basic graphics are more illustrative in nature and may not fulfill the specific research objectives. In our application, it is necessary to access the numerical values of hydrophysical characteristics (such as salinity, temperature, density, and velocity projections) at any chosen point within the computational domain and at any desired computational step. The goal requires the capability to generate various cross-sectional views and vertical profiles at specific locations within the domain as well as to create distribution maps within predefined areas (refer to Fig. 1, b) while having the flexibility to adjust the scale of variability for any of the parameters.

Such a solution was achieved by software interpolation of computational data from an unstructured grid to a regular grid at any computational step of interest, which is a feature of the transformations' software package [31].

Experimental design for numerical simulations

The configuration for three-dimensional numerical experiments was established in [31] for small-scale water dynamics modeling on the shelf and slope within the mesoscale (regional) context which were possible with the *Fluidity-ICOM* model in conjunction with a high-performance computational cluster.

The computational domain used in this study is a three-dimensional rectangular area with dimensions of 1 km × 10 km × 6 km (total depth × shelf-slope width × shelf length). The shelf width is 5 km, and the shelf depth is 200 m (Fig. 1, b). The selection of these dimensions was based on the local baroclinic Rossby deformation radius, Rd_L , which is approximately 2–3 km in the ASF region, as determined from field observations [17, 19]. The chosen domain size is about 3–4 times larger than Rd_L . A polynya, measuring 1 km in width, was introduced on the surface at the midpoint of the shelf (Fig. 1, b). Thus, either an open-water or near-barrier polynya was geometrically modeled. The slope of the shelf, denoted as $s = 0.007$, was chosen to match observations in a specific area of the Commonwealth Sea. The continental slope was represented by a slope of $s = 0.16$, which is a basic representation without local details [15, 16, 18]. The choice of computational grid spacing was determined based on the resolution required to capture the Ekman near-bottom boundary layer in polar waters. A minimum refined grid vertical step was set as 5 m, a horizontal grid step was 50 m, and the time step Δt was set to 100s. The selected resolution is adequate for a detailed study of the propagation of dense currents along the continental slope, as confirmed by field observations [15–20]. At the initial moment of time, a uniform salinity value of $S = 34.4\text{psu}$ [18] and zero velocity was assigned throughout the domain.

An external salt flux (buoyancy) is imposed on the surface of the polynya. This allows for the simulation of gravity convection, which is the process of dense water formation on the shelf, for instance, along the shelf and slope due to the presence of a quasi-stationary wind-driven coastal (or near-barrier, or fast-ice) polynya. Initial conditions assume the absence of vertical stratification (or it is weak) which is actually observed in vast areas of the shelf, when salinity convection reaches the bottom at the end of winter.

3. Atmospheric forcing and external buoyancy fluxes

The focus of this study is to model the evolution of baroclinic water dynamics on the shelf and continental slope within the entire range of extreme weather conditions that are observed in the Antarctic and contribute to the formation and persistence of quasi-stationary polynyas. Based on sea-ice satellite observations, atmospheric reanalysis data, and instrumental meteorological observations [7–13], the range of atmospheric forcing that contributes to the most intense ice formation and salt injection into water in winter can be represented as follows. Firstly, there is a young ice-covered polynya with ice layer thickness ranging from 3 to 30 cm, known as a congelation polynya. The prevailing wind speed W in this case are approximately from 2 to 7 m/s, and the air temperature Ta ranges from $-20\text{ }^{\circ}\text{C}$ to $-35\text{ }^{\circ}\text{C}$. The ice in this polynya grows statically (vertically on its lower surface). The lifetime of such a polynya (with young ice 3–10 cm) is 3–4 days. Secondly, an open water polynya is formed and maintained in the event of off-shore winds $W \approx 12\text{--}16\text{ m/s}$ (which is the necessary condition) and air temperature $Ta \approx -15\text{--}20\text{ }^{\circ}\text{C}$. These conditions often occur when atmospheric fronts pass in cyclones during the winter [23]. The lifetime of such a polynya doesn't exceed 1–2 days. Thirdly, there are super-extreme conditions that can lead to the formation and relatively long-term sustenance of a quasi-stationary wind-driven open water polynya. These conditions involve significantly stronger winds, approximately from 16 to 30 m/s, and air temperatures ranging from $-20\text{ }^{\circ}\text{C}$ to $-30\text{ }^{\circ}\text{C}$. Such conditions are typically observed during winter in specific coastal or near-barrier regions of ice shelves in the Antarctic seas. They are caused by powerful and cold katabatic winds blowing from the Antarctic ice dome [12, 13, 24, 43, 44]. The Darnley and Mackenzie polynyas are located in the Commonwealth Sea and Prydz Bay in the Antarctica [11] are potentially subjected to such katabatic winds [24, 44, 45]. These polynyas exist 1–3 days. Lifetimes of polynyas with different types of ice formation served as a guideline for the numerical experiments' calculation times, when the external salt (buoyancy) fluxes can be considered almost quasi-constant (in order of magnitude).

All wind-driven polynyas are characterized by intense heat transfer to the atmosphere, especially when an open water surface exists [12, 24]. These conditions contribute to high ice productivity [46] and the vigorous salt release into the water [12]. Ice formation in the near-surface layer under the influence of wave-wind turbulence has a dynamic, intra-water regime [21–23, 29, 42]. A significant localized salinization of the upper-water polynya layer occurs, leading to the development of active salinity convection [12, 26, 27]. This convection process intensifies the formation of dense waters [6–9, 11] that subsequently spread along the shelf and flow down the continental slope (Fig. 2).

With a decrease in wind and waves, the polynya will be covered with young ice. In this case, static (vertical) growth of young ice will occur on its lower surface.

Assessment of heat loss from the open water polynya surface

The assessment of ice productivity and the associated salt fluxes into seawater in open water polynyas during winter is carried out using a methodology based on balance concepts [22, 26, 27, 29, 48]. This approach considers the crystallization heat flux, denoted as F_{cr} , which is released during the formation of intra-water ice within the turbulent upper polynya layer. The methodology assumes that this heat flux, F_{cr} , is equivalent to the total heat loss from the open water polynya surface $Q \approx F_{cr}$. The value of Q is determined using a balance model, as described in [22], which aligns with similar approaches utilized in [26, 27]. The calculations were conducted for sea water temperatures near the freezing point. On the surface of the polynya, a thermal balance is established at a temperature close to the freezing point, which is typical for this period [8, 24]. Consequently, the concept of winter salinity convection arises, which is solely driven by the salt fluxes into water. This happens during static ice formation on the lower surface of ice in a polynya covered with young ice or during intra-water dynamic ice formation in a near-surface turbulent layer in an open water polynya. Heat flux is not neglected, as there is no requirement to cool the water to the freezing point.

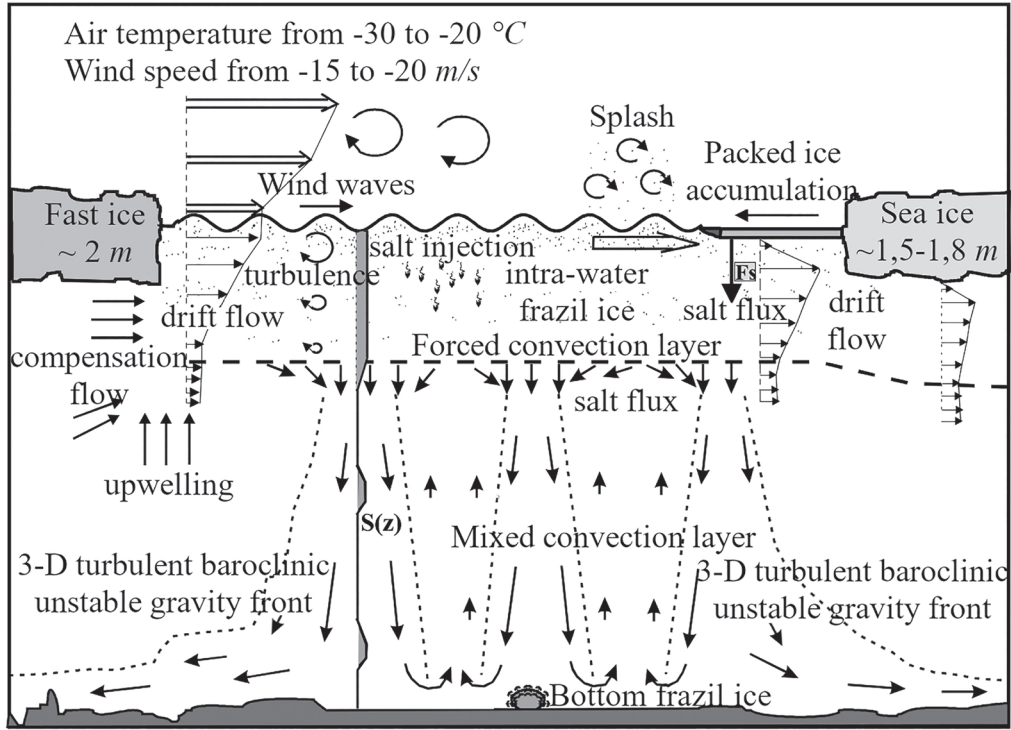


Fig. 2. Scheme of various circulations of different scales, convective and baroclinic dynamics in a winter open water polynya (coastal or near-barrier), which is periodically formed and **sustained** by a strong wind in shelf areas of the Antarctic seas. Formation scheme of dense ASW with intensive salt injection into water as a result of intra-water (dynamic) ice formation when the salinity convection is reached the bottom

The estimated values of Q , ranging from approximately 1000 to 4000 W/m^2 are in good agreement with similar findings derived from numerous field observations in both Arctic [26–29] and Antarctic polynyas [49–51]. Furthermore, recent observations in Antarctic polynyas have also verified these estimates [12, 24].

Estimation of the intra-water ice formation rate and salt flux in an open water polynya

By utilizing the condition $Q \approx F_{cr}$, we can determine the mass of pure (fresh) ice only. Consequently, the rate of intra-water formation, $dh/dt = F_{cr} / \rho_i \cdot L$, where dh/dt is measured in meters per second (m/s), h is the ice thickness, water density $\rho_i = 0.92 \cdot 10^3 \text{ kg/m}^3$ (fresh crystals of intra-water ice), $L = 3.34 \cdot 10^5 \text{ J/kg}$ – latent heat of phase transitions [26]. Additionally, the rate of ice formation can be described in terms of ice mass, M_i , representing the change in mass of ice formed per unit area over time, expressed as $dM_i/dt = (dh/dt) \cdot \rho_i \text{ kg/m}^2\text{s}$, or calculate dM_i/dt as $F_{cr} / L = Q/L$.

In this scenario, the salt flux into the water, known as external salt flux or buoyancy, occurs as a result of intra-water ice formation. It can be calculated using the formula $F_{s_{iw}} = \rho_i \cdot (dh/dt) \cdot (S_w - S_i)$ [26]. When $S_i \approx 0 \text{ psu}$ (representing fresh water ice crystals), then $F_{s_{iw}} = \rho_i \cdot (dh/dt) \cdot S_w \approx (F_{cr}/L) \cdot S_w \approx (Q/L) \cdot S_w$. Here, $F_{s_{iw}}$ is expressed in $\text{kg/m}^2\text{s}$ with S_w in kg/kg . The typical value of $S_w \approx 34.5 \text{ psu}$ or $34.5 \cdot 10^{-3} \text{ kg/kg}$, which corresponds to the measured salinity observed in locations such as the Darnley coastal polynya during winter [24]. Under the atmospheric conditions suitable for the formation and sustenance of an open water polynya when atmospheric fronts pass through, the $F_{s_{iw}} \approx 10^{-4} \text{ kg/m}^2\text{s}$. For super extreme conditions of opening and sustenance of an open water polynya driven by katabatic winds in the specific Antarctic areas, the $F_{s_{iw}} \approx 5 \cdot 10^{-4} \text{ kg/m}^2\text{s}$.

Estimation of the salt flux in a polynya covered with young ice

In order to determine the salt fluxes (F_s) into the water during the static growth of young ice in a polynya, several field experiments [52] were conducted in the Arctic Ocean in winter. These experiments, carried out at drifting stations, provided data on the variability of salinity profiles in the growing young ice. The findings from

these experiments are consistent with other similar field data [53–55] and offer more representative results compared to theoretical estimates or laboratory experiments. For the young ice thickness ~ 5 cm, the value of $F_s \approx 0.15 \cdot 10^{-4}$ [kg/m²s]. This field estimate of F_s agrees with the model estimate of $F_{s_{iw}}$ under the conditions of intra-water ice formation in the polynya, specifically in low-wind or calm weather ($W \approx 0–2$ m/s) which indicates the accuracy of the model estimate.

The obtained values of $F_{s_{iw}}$ and the adopted F_s are typical for various polynyas, which naturally exhibit variability throughout their typical lifespan. Nevertheless, these values are considered acceptable for idealized numerical experiments.

4. Numerical experiments results' analysis

The results of the presented numerical experiments with various atmospheric forcing and types of ice formation in polynyas allow us to analyze in detail the spatial structure at the most developed stage of density currents of the ASW in the shelf-slope region from the small scale to the mesoscale (Fig. 3).

The Fluidity-ICOM model accurately simulates the formation of convective circulations within the polynya, as well as the density currents propagation along the shelf and slope, exhibiting clear instability across a wide range of extreme external buoyancy fluxes. As the intensity of ASW formation increases within the polynya area, the occurrence of instability events at the upper boundary of near-bottom density currents due to baroclinic instability [17] becomes more frequent. These events propagate along the shelf, and their spacing decreases, particularly noticeable on the slope (refer to Figure 3).

The spatial structure of density currents in the bottom layer exhibits significant variability (see Figure 3). When relatively weak buoyancy fluxes occur in a polynya covered with young ice, a non-wave mode of density current propagation along the continental slope is observed at the most developed stage in 72h (see Fig. 3, *a*) as determined in classification from previous laboratory studies [56–58]. The flow cannot be characterized as laminar due to its structured nature and the presence of areas of instability. In contrast, in case of intense sea ice formation in open water polynya, density currents reach the most developed stage in 45h on the shelf-slope, the mode of propagation can be described as eddy-like. The formation of eddies can be clearly observed during the propagation of dense water meanders along the shelf edge and slope, see Fig. 3, *b*. This particular mode of propagation is extensively described in [31]. However, under super extreme conditions salt fluxes (buoyancy) in katabatic wind-driven open water polynyas, the near-bottom density flow mode change to a developed wave mode in 45h [56–58]. The density current manifests as a series of regular frontal waves, sequentially propagating downward and along the slope, as illustrated in Fig. 3, *c*.

The term “the most developed stage of near-bottom density currents” refers to the current state at the final moment of the calculated time in the experiments (45h) or (72h), which were selected based on the typical lifetime of different types of polynyas. In this study, it is not relevant to continue the calculation beyond this point due to the substantial changes in external buoyancy fluxes observed in natural conditions, often exceeding an order of magnitude. The cascading evolution is inherently non-stationary, making it impossible to determine the extent of density currents' development. The currents in the bottom layer should be referred to as “developing”, as a quasi-stationary state is unattainable within the realistic lifetimes of various types of polynyas.

The discovery of the wave mode in slope cascading was an unexpected outcome of the numerical simulation. In laboratory studies, this type of flow mode typically observed under specific conditions, involving the dense liquid flow or the density gradient between the stream and the environment is significant, and the bottom slope incline is significant. In fact, there is even a concept of a minimum critical bottom slope [57]. In the conducted numerical experiments, we set a representative external salt flux (buoyancy) in the polynya that is geophysically reasonable. Our focus was to investigate the density structure's development, specifically the evolution of density gradients (transformation of near-bottom density currents) on the shelf and slope. Additionally, within the computational domain (as shown in Fig. 1, *b*), we preset an incline of the bottom as steep as the continental slope observed in the Commonwealth Sea [16–18]. Based on the model results, it is reasonable to infer that in certain Antarctic areas, where steep slopes exist and there is super extreme atmospheric forcing during the formation and sustenance of a coastal or near-barrier open water polynya, a flow of dense ASW could potentially develop to a wave mode.

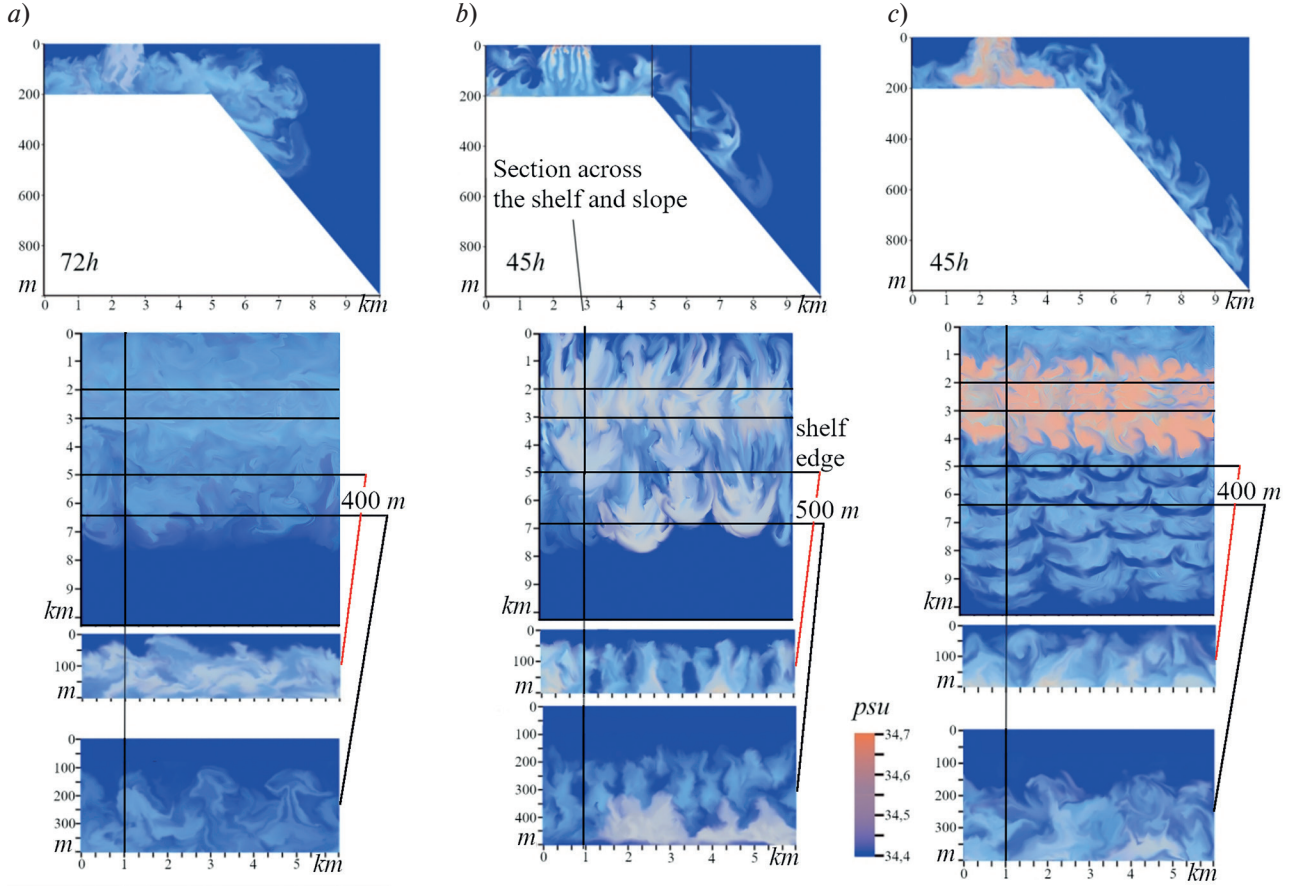


Fig. 3. Results of three small-scale experiments in mesoscale development in a non-hydrostatic setting *Fluidity-ICOM* model using the flux conditions method. Salt flux (buoyancy) is set for: *a* – a young ice covered polynya; *b* – a wind-driven open water polynya during typical (average) winter conditions; *c* – a katabatic wind driven open water polynya during extreme conditions. Presented are: sections of salinity (density) across the shelf and continental slope; salinity (density) map in the near-bottom layer; salinity (density) sections along the shelf edge and along the upper slope at the moments of the most developed stage of near-bottom density currents – at the estimated time is either 72h or 45h. Horizontal black lines show polynya boundaries and sections along the shelf edge and slope. Vertical lines – show a section across the shelf and slope, and points of the constructed vertical profiles of hydrophysical characteristics (Fig. 5)

A general consistent pattern emerges when analyzing the propagation at the most developed stage of near-bottom density currents on the slope in various flow ASW modes (Figure 3). The spatial scales of meanders observed along the shelf's edge and the upper slope (Fig. 3, *a*), as well as the eddies (Fig. 3, *b*) and frontal waves (Fig. 3, *c*), are consistently similar, ranging approximately from 1.5 to 2.5 kilometers. This observation is supported by an analysis of longitudinal sections depicting the horizontal current velocity components (U) across the shelf and slope, as well as the vertical current velocity components (W) in the upper slope (Fig. 4). Furthermore, the thicknesses of ASW density currents in the upper slope remain practically identical across all flow modes $H_{asw} \approx 150-170$ m (Fig. 3–5). Whereas, that in open water polynyas, the salt (buoyancy) fluxes resulting from intra-water ice formation (F_{siw}) exceed the salt fluxes in young ice-covered polynyas (F_s) by a factor of 7–10. Under super extreme conditions, the magnitude of F_{siw} can even surpass F_s by 25–30 times (as indicated earlier).

The observed spatial divisions of near-bottom density currents on the shelf edge and slope (Fig. 3 and 4) across different flow modes align with estimates of the local baroclinic radius of Rossby deformation $Rd_L \approx (g' \cdot H_{asw})^{0.5}/f$ for these currents in the upper slope as calculated from hydrophysical characteristics (Fig. 5).

Here, H_{asw} represents the local thickness of the density current, $g'x = g\Delta\rho_x/\rho$ describes to the buoyancy scale, $\Delta\rho_x$ is the local horizontal density drop, where g denotes the free fall acceleration, and $f \approx 1.4 \cdot 10^{-4} \text{ s}^{-1}$ signifies the Coriolis parameter. Notably, for the non-wave mode, $Rd_L \approx 1.5 \text{ km}$, for the eddy mode $Rd_L \approx 1.7 \text{ km}$, and for the wave mode, it reaches approximately $Rd_L \approx 1.9 \text{ km}$. These model-based Rd_L estimates are considered representative as they align precisely with numerous similar estimates of Rd_L derived from field measurements conducted in the Antarctic Slope Front (ASF) within the Commonwealth Sea [16–20].

The consistency of model estimates Rd_L , which determine the spatial scale of division at the most developed stage of density currents such as meanders, jets, eddies, or frontal waves on the shelf edge and slope, along with the similarity in thickness values H_{asw} , suggests their weak dependence on significantly different external buoyancy fluxes in various types of polynyas. Moreover, the variability range of horizontal density gradients in the upper slope at the boundary of density currents, as observed in numerical experiments, is relatively small, with $\Delta\rho_x$ ranging from approximately 0.03 to 0.05 kg/m^3 (Fig. 5). Notably, the calculated local values of $\Delta\rho_x$ match precisely with the values observed for the ASF based on numerous field observations [16–20]. This indicates that the *Fluidity-ICOM* model accurately captures the transformation of density currents during propagation.

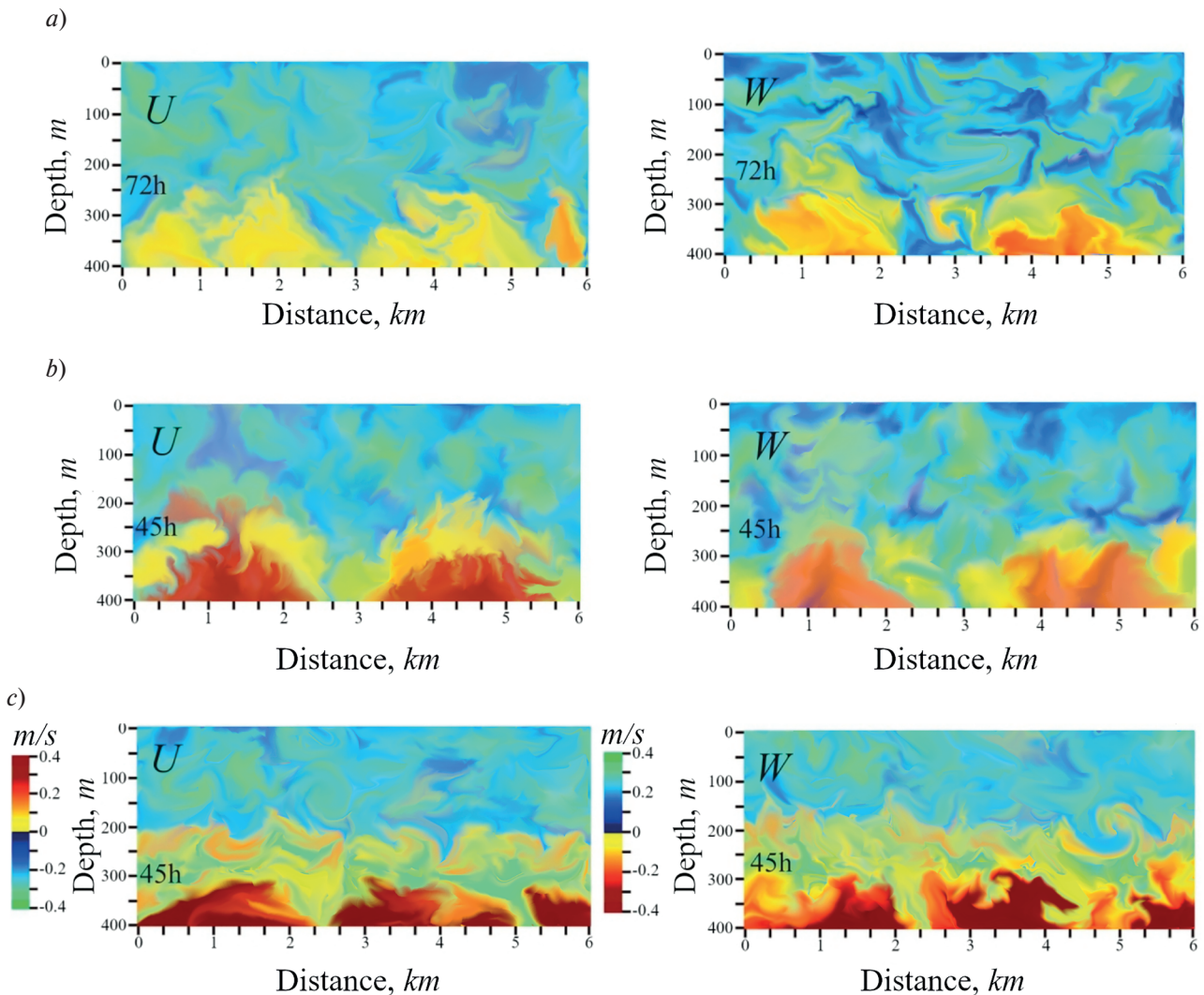


Fig. 4. The structure of the horizontal component U (directed across the shelf and slope) and the vertical component of the velocity W over sections across the upper part of the continental slope (400 m) at the most developed stage of near-bottom density currents, the estimated time is either 72h or 45h. In numerical experiments: *a* – young ice covered polynya; *b* – open water polynya under typical atmospheric conditions; *c* – katabatic wind-driven open water polynya under extreme conditions

The calculated horizontal velocity components of near-bottom density currents across the shelf and slope exhibit significant variability, ranging from $U \approx 0.12\text{--}0.4$ m/s. In the upper slope, these values differ by 2.5 to 3 times, while the vertical components of the velocity W , display even greater disparities, with values ranging from $W \approx 0.1\text{--}0.4$ m/s, differing by 3 to 4 times (Fig. 5). Consequently, when there is a substantial increase in ice formation intensity, resulting in augmented external salt fluxes (buoyancy), such as during the formation and sustaining of an open water polynya by strong forcing winds, the rate of propagation of dense ASW (Fig. 2) along the shelf beyond the polynya, as well as their propagation along the continental slope, experience a significant increase.

An increase in the speed of the ASW propagation determines the occurrence of a vortex or wave flow mode of density currents on a steep continental slope, which can also be referred to as supercritical or fast flow modes. This is supported by the estimates of the internal Froude number $Fr = V/(g' \cdot h)^{0.5}$ for the descending layer of dense waters [59] in the upper part of the slope, obtained by calculating values of the hydrophysical characteristics $Fr = V/(g' \cdot H_{\text{asw}})^{0.5}$ (Fig. 5). Here, $V = (U^2 + W^2)^{0.5}$ represents the velocity at which the density current propagates along the slope (Fig. 5), H_{asw} denotes the local thickness of the density current, $g'_x = g\Delta\rho_x/\rho$ represents the buoyancy scale, and $\Delta\rho_x$ represents the local horizontal density gradient at the boundary of the density flow (Fig. 5), and g represents the free fall acceleration. Thus, in the non-wave flow mode, $Fr \approx 0.8$ indicates a subcritical value. In the vortex mode, $Fr \approx 1.7$ already represents a supercritical value, surpassing the critical value $Fr = 1$. In the wave mode, as V increases even further (Fig. 5), the value of $Fr \approx 2.1$. The results obtained from numerical experiments align with the findings from laboratory studies on the propagation of density currents along the slope [56–57].

Moreover, it is important to highlight that the calculated values of $V = (U^2 + W^2)^{0.5} \approx 0.2\text{--}0.6$ m/s for different flow modes are highly realistic. These values closely align with the estimates of V derived from field observations conducted in the shelf-slope area of the Commonwealth Sea [17], and they perfectly match the observed velocities of dense water plumes in the continental slope of the Weddell Sea, where $V \approx 0.4\text{--}0.9$ m/s [5]. In the aforementioned study [5], the authors also emphasize the supercritical nature of these near-bottom density currents, suggesting the potential occurrence of periodic instability in the form of local hydraulic shocks.

5. Estimates of dense water flows on the slope

The computational capabilities of the *Fluidity-ICOM* model and improved graphical output allow for the direct and reliable estimation of dense currents in any location within the computational domain. This includes a specific section along the upper continental slope (see Fig. 4). By calculating the volumetric (q_v , m^3/s) and specific (q_l , m^2/s) values of dense water flows in the bottom layer of the continental slope (at the stage of the most developed density currents), we can assess the potential contribution of ASW cascading to the formation of bottom waters under different flow modes. The results of these calculations are presented in the Table. The accuracy and representativeness of the model's estimates for dense water flows on the slope are achieved through both the small-scale discretization, enabling a detailed analysis of the small-scale water dynamics within the mesoscale context and the initiation of numerical experiments with the most representative external salt fluxes (buoyancy).

The measured value of the specific flow q_l , which represents the flow of dense ASW along a slope in non-wave mode, closely matched the estimated q_l value based on field observations [18]. Similarly, this confirms the reliability of the model's q_l estimate, indicating its adequacy. However, in the presence of vortex flow mode, both q_l and q_v values increase by nearly 2 times, while in wave flow mode, they increase by nearly 3 times. In other words, under extreme weather conditions that promote the formation of ASW in young ice covered polynya areas (as indicated in the Table), the flow of dense ASW along the slope can increase by 2–3 times. Consequently, it is crucial to consider these events when assessing the volume of bottom water formation in specific Antarctic areas of the continental slope near quasi-stationary polynyas during the cold season. Neglecting these factors would lead to significant underestimations.

When examining the model's estimates of volumetric flow (q_v) for different flow ASW modes, a question arises: how significant or insignificant are these estimates? To gain insights, we can use sea-ice satellite observations, specifically focusing on the coastal Darnley polynya and the near-barrier Mackenzie polynya in the

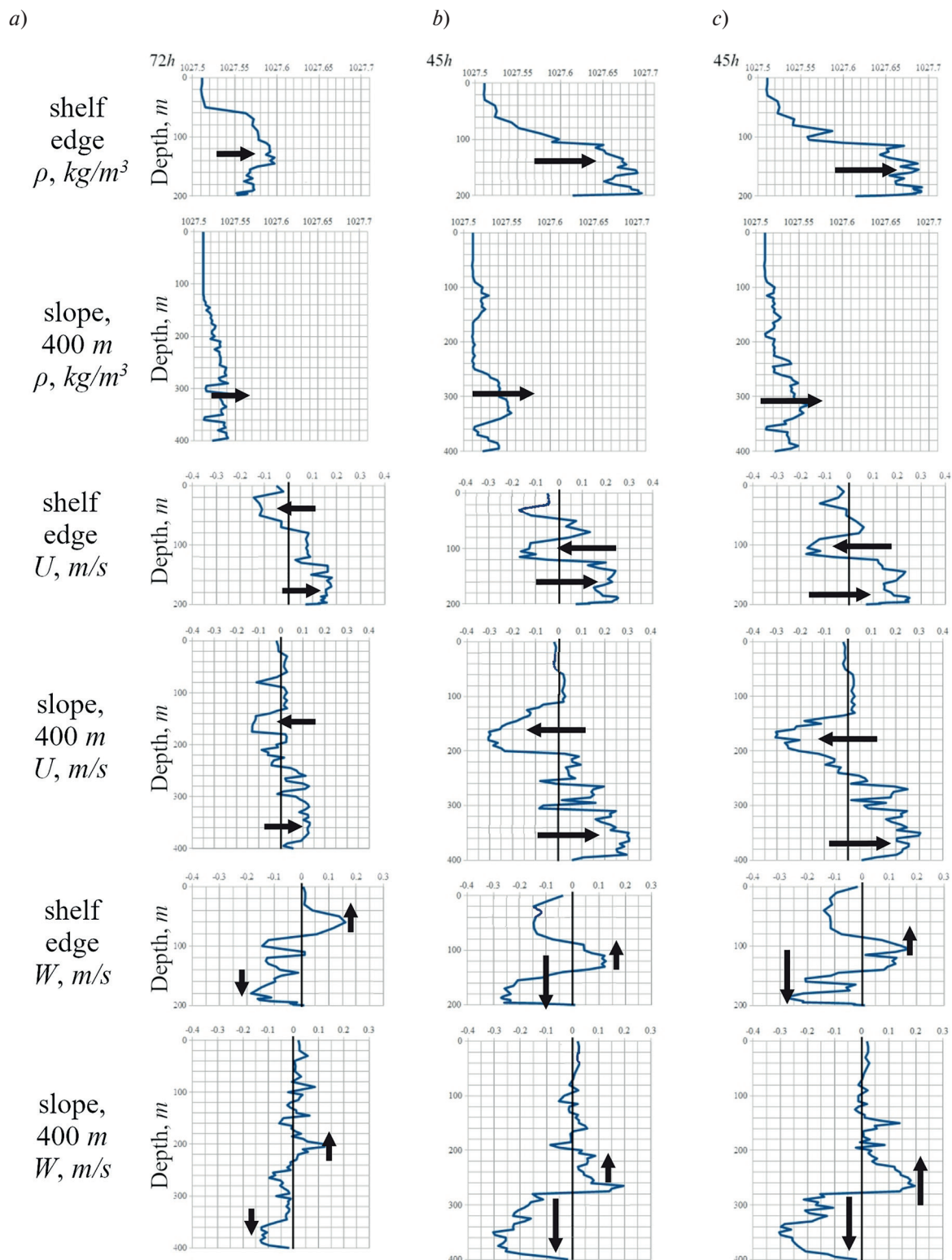


Fig. 5. Calculated at the moment of the most developed stage of near-bottom density currents on the shelf and continental slope (is either 72h or 45h) vertical density distributions, horizontal and vertical velocity components on the shelf edge and in the upper slope (400m). In numerical experiments: *a* – young ice covered polynya; *b* – open water polynya under typical atmospheric conditions; *c* – katabatic wind-driven open water polynya under extreme conditions. The arrows show the directions of water movement in the layers, down, up, to the right (in the direction of the slope and along the slope), to the left (in the direction of the shelf edge and along the shelf) (Fig. 3)

Commonwealth Sea (Prydz Bay) in Antarctica, during the winter season about late June 2015 (see Fig. 6). These observations were derived from publicly available sea-ice concentration data (representing the percentage of sea ice concentration) obtained from <https://seaice.uni-bremen.de>. The data was collected through the Advanced Microwave Scanning Radiometer 2 (AMSR2) instrument, which measures the brightness temperature, and processed using the *ARTIST Sea Ice (ASI)* algorithm.

According to Fig. 6, under winter conditions (June), the length of the Darnley coastal polynya (located near the shelf edge [Fig. 1, 16]) with open water surface (depicted in blue) can extend up to approximately 60 km. The total length of the polynya is approximately 135 km (Fig. 6). The calculated domain has a length of 6 km (Figure 1). Consequently, referring to the Table, it can be determined that when the polynya is completely covered with young ice, the volume dense ASW flow on the slope, which forms along the entire length of the Darnley polynya, can reach a significant value of $q_v \approx 1800000 \text{ m}^3/\text{s}$ or $q_v \approx 1.8 \text{ Sv}$. However, if polynya forms under strong winter winds and remains with an open water surface a few days (Fig. 6), the volume ASW flow along the slope can increase to $q_v > 2.4 \text{ Sv}$. In super extreme conditions, when polynyas can further expand in the event of katabatic winds [12, 13], the volume flow can exceed $q_v > 2.8 \text{ Sv}$.

The q_v values obtained in this study are significantly higher (several times) than previous estimates for the continental slope area near the Darnley polynya in the Commonwealth Sea, which were based on numerical modeling and field observation data, it where $q_v \approx 0.5\text{--}0.6 \text{ Sv}$ [60]. However, the previous study [60] used

Table

Estimates of the intensity of dense water flows in the upper part of the continental slope under various flow modes at the most developed stage of near-bottom density currents, based on the calculated values of the current velocity components (Fig. 4, 5)

Flow mode	Time moments when near-bottom density currents are at the most developed stage, [h]	Minimum vertical-horizontal resolution, [m]	Volume flow, q_v , [m^3/s]	Specific flow, q_p , [m^2/s]
Non-wave	72	5—50	83104	13.9
Vortex	45	5—50	143622	23.9
Vortex	45	20—200	103488	17.3
Wave	45	5—50	181950	30.3

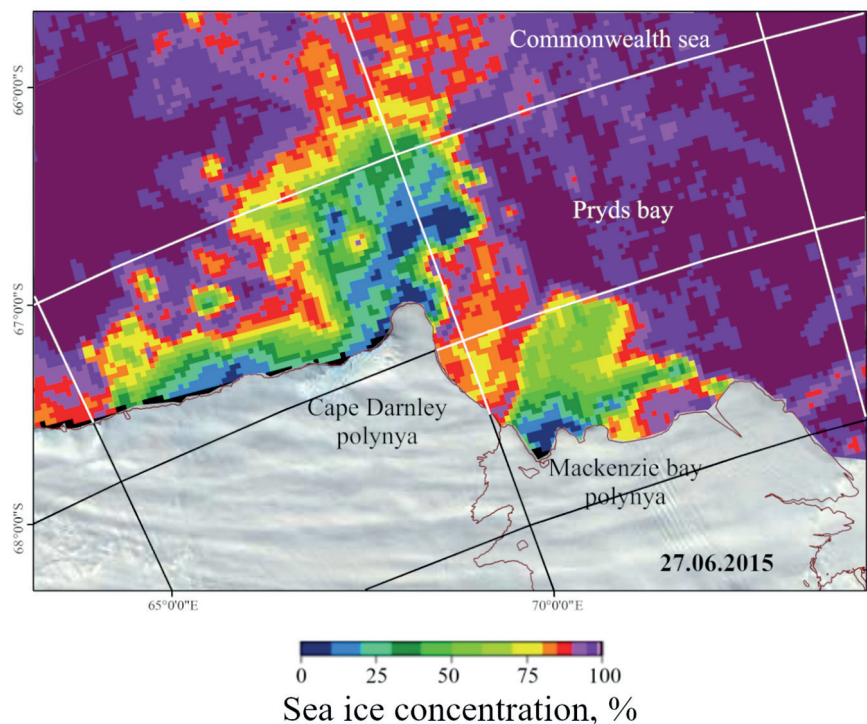


Fig. 6. AMSR-2 image of the open water area of the Darnley quasi-stationary coastal polynya and the Mackenzie barrier polynya in the Commonwealth Sea and Prydz Bay in Antarctica in winter (June) 2015

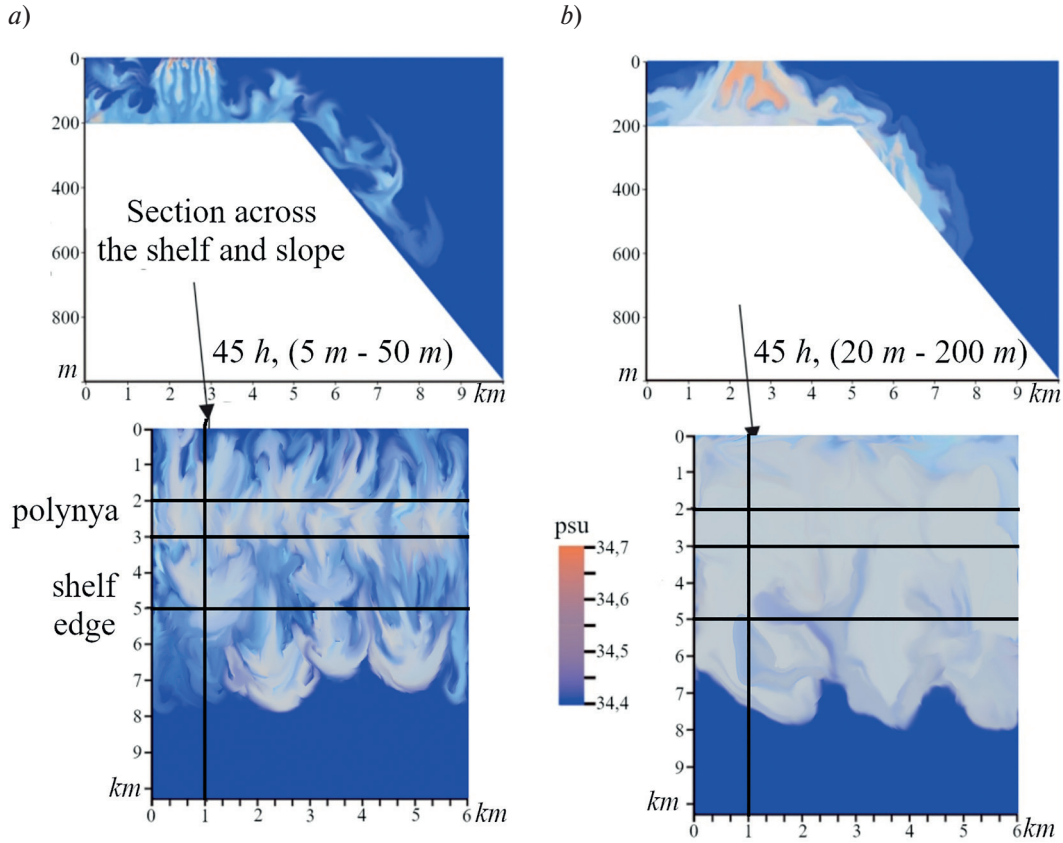


Fig. 7. Results of two small-scale numerical experiments in a non-hydrostatic setting the Fluidity-ICOM model. The salt flux (buoyancy) in a wind-driven open water polynya is specified under the typical winter conditions (Fig. 2): *a* — a minimum resolution of 5–50 m vertically and horizontally and *b* — 20–200 m. Presented are: sections of salinity (density) across the shelf and continental slope; salinity (density) map in the near-bottom layer at the moment of the most developed stage of near-bottom density currents in 45h. The black lines show the boundaries of the polynya and the shelf edge

a hydrostatic model with a computational grid spatial step of $X = 4$ km. Additionally, the study [60] only considered static ice formation on the lower surface of young ice. It also did not consider intra-water ice formation at the potential opening of the polynya. Moreover, in the research [60], the authors examined the impact of increasing X in numerical experiments on estimating the volume of dense water flow down a slope, specifically the estimation of q_v . They found that as X increased from 1–2 km to 4 km, the estimated q_v decreased by 20 %. Furthermore, when X was increased to 16 km (resolution in large-scale models), the estimate of q_v decreased by nearly half, resulting in a significant underestimation of dense water fluxes on continental slopes in Antarctica in large-scale and climate models [60]. The authors of [60] noted the need for model studies on computational grids with a smaller scale to better understand the extent of underestimation in q_v values.

In this study, we present such a study using non-hydrostatic *Fluidity-ICOM* model, which is considered the most suitable for simulating the dynamics of density currents on steep continental slopes [61], offering a small spatial resolution and accounting for salt fluxes resulting from intra-water ice formation in open water polynya, specifically the vortex mode (see Table for details). Our findings reveal that an increase in X by a factor of 4, from 50 m to 200 m, leads to a decrease of approximately 30% in the q_v estimate on the continental slope (see Table). This decline is likely attributed to the erosion of small-scale structure within the density currents on the slope (see Fig. 7). Now, let's consider what happens if we further increase X to 2 km, which corresponds to a 40-fold increase in X (not to mention 4 km or 16 km)? In that case, it is plausible that the obtained q_v estimates of approximately 1.8–2.4 Sv will decrease significantly and potentially match the q_v estimates from [60].

The analysis suggests that the most precise and accurate estimates of dense water flow on steep continental slopes can only be derived through numerical experiments employing small-scale non-hydrostatic models, which enable the resolution of the spatial structure of near-bottom density currents (refer to Fig. 3, 7, *a*). In large-scale or even mesoscale (regional) models with substantial spatial discretization in calculations the inadequate representation of such flows can be significantly problematic, potentially leading to considerable underestimation by several magnitudes. Moreover, this underestimation would be further magnified if the occurrence and presence of open water polynyas, where intensified ASW formation occurs, are neglected.

6. Conclusion

In order to accurately investigate the variations in structure and intensity of dense water flow in the shelf area and steep continental slope of Antarctica, the small-scale non-hydrostatic *Fluidity-ICOM* model is used. This model is capable of high-accuracy resolution by utilizing a 3-D adaptive unstructured grid with automatic refinement to a predetermined scale and flux condition setup. The model reproduces the dynamics of density currents at a small-scale within the mesoscale framework. Furthermore, recent upgrades to the graphical demonstration of results in the model allow for the assessment of dimensionless parameters that characterize the dynamics and intensity of these density currents.

The presented study aims to compare the results of modeling the density structure development and baroclinic dynamics of ASW in the shelf-slope area under a wide range of realistic extreme weather conditions, crucial for the formation and existence of quasi-stationary polynyas and intensifying the ASW formation.

To achieve this, the study obtains representative estimates of heat fluxes from an open water polynya surface driven by strong off-shore wind or extreme katabatic wind. By analyzing these heat fluxes, the study can estimate the ice formation rate within the intra-water (dynamic) processes in polynya and the salt fluxes (external buoyancy fluxes) caused by this ice formation. Furthermore, the study provides estimates of salt fluxes in young ice covered polynyas. These estimates indicate that the salt fluxes in congelation polynyas are 7–30 times lower compared to salt fluxes in open water polynyas.

In this study, we conducted three original 3-D numerical experiments in the shelf-slope area. These experiments focused on different scenarios: one with a built-in young ice covered polynya, second with an open water polynya, and a third with an extreme katabatic wind-driven open water polynya. In these experiments we simulated real salt (buoyancy) fluxes resulting from various ice formation types, including vertical (static) and intra-water (dynamic) processes, which reproduce the formation of a quasi-stationary wind-driven polynya (coastal, near-shore (fast-ice), or near-barrier) under the actual atmospheric conditions. These experiments replicate the winter gravity convection of salinization, a localized and intense process where dense waters form on the shelf and then propagate as density currents (cascading) along the shelf and continental slope. The bottom topography in our simulations set closely to the actual bottom topography in the Commonwealth Sea in Antarctica.

In each of the presented numerical simulations, the accurate modeling of near-bottom density currents, shows their increasingly pronounced instability on the shelf and slope as the intensity of dense ASWs formation in polynyas rises.

Based on the accelerated spread of ASW and the increased formation within various polynya types, three distinct modes of ASW propagation along the continental slope have been identified. These modes include the non-wave mode, also known as subcritical, where ASW cascades from beneath the congelation polynya. The vortex and wave modes, or supercritical regime, occurs when ASW cascades with varying intensity under open water polynya. The classification into these modes is supported by model calculations of the internal Froude number (Fr), which align with laboratory investigations of density current flow along the slope. The computed values of the propagation velocity (V) on the slope under different ASW regimes are very realistic, as they closely match V estimates derived from field observations and agree perfectly with instrumental measurements of dense water plume propagation rates on the continental slope.

A general consistent pattern emerges when analyzing the propagation of the most developed stage of near-bottom density currents on the slope in various flow ASW modes. The spatial scales of meanders, eddies, or frontal waves are found to be similar in magnitude, consistent with the estimated local baroclinic radius of Rossby deformation (Rd_L) for these currents. The model-derived estimates of Rd_L are reliable as they closely match numerous independent measurements conducted for the ASF in the Commonwealth Sea. Additionally,

the thickness of the density currents remains relatively uniform across different flow modes. Despite the considerable variation in external buoyancy fluxes within polynyas, the calculated horizontal density gradients ($\Delta\rho_x$) at the boundary of these currents on the slope exhibit minimal variability. The model's estimates of $\Delta\rho_x$ align perfectly with the observed values for the ASF, as determined through field observations. Thus, the *Fluidity-ICOM* model accurately captures the transformation of density currents as they propagate along the shelf and slope.

We obtained model estimates of the volume q_v and specific q_l of ASW fluxes on the continental slope near the region where the Darnley quasi-stationary coastal polynya exists in the Commonwealth Sea. These estimates are significantly higher (several times) than previous calculations. However, these estimates are currently the most accurate and reliable. This accuracy is achieved through small-scale discretization in calculations using the non-hydrostatic *Fluidity-ICOM* model and by incorporating representative external salt fluxes (buoyancy) while considering intra-water ice formation. The study of the spatial step X increase impact, on numerical experiments estimating q_v , revealed that increasing X by four times resulted in an underestimation of q_v by approximately 30%. Therefore, the most precise and accurate evaluations of q_v on steep continental slopes can only be derived from conducting numerical experiments utilizing small-scale non-hydrostatic models. In large-scale and even mesoscale (regional) hydrostatic models, where calculations are spatially discrete, the underestimation of such flows can be considered unacceptable, potentially by several times. Furthermore, this underestimation is further increased if we disregard the growth of intra-water ice in the formed and sustained open water polynyas, which allocate the most intensive ASW formation.

Funding

The presented study was supported by the Russian Science Foundation — grant No. 22-27-00013.

References

1. Foster T.D., Carmack E.C. Frontal zone mixing and Antarctic bottom water formation in the southern Weddell Sea. *Deep Sea Res.* 1976, 23, 301–317. doi:10.1016/0011-7471(76)90872-X
2. Foster, T.D., Foldvik A., Middleton J.H. Mixing and bottom water formation in the shelf break region of the southern Weddell Sea. *Deep Sea Res.* 1987, 34, 11, 1771–1794. doi:10.1016/0198-0149(87)90053-7
3. Fahrbach E., Rohardt G., Scheele N., et al. Formation and discharge of deep and bottom water in the northwestern Weddell Sea. *J. Mar. Res.* 1995, 53, 4, 515–538. doi:10.1357/0022240953213089
4. Foldvik A., Kvinge T., Torresen T. Bottom currents near the continental shelf break in the Weddell Sea. In: *Oceanology of the Antarctic Continental Shelf. Antarctic Research Series.* 1985, 43, 5–20. doi:10.1029/AR043p0021
5. Foldvik A., Gammelsrod T., Osterhus S., et al. Ice shelf water overflow and bottom water formation in the southern Weddell Sea. *J. Geophys. Res.* 2004, 109, C02015. doi:10.1029/2003JC002008
6. Baines P.G., Condie S.A. Observations and modelling of Antarctic downslope flows: a review. In: *Ocean, ice, and atmosphere: interactions at the Antarctic continental margin. Antarctic Research Series.* 1998, 75, 29–49. doi:10.1029/AR075p0029
7. Fuseo G., Budillon G., Sperie G. Surface heat fluxes and thermohaline variability in the Ross Sea and Terra Nova Bay polynya. *Cont. Shelf Res.* 2009, 29, 1887–1895. doi:10.1016/j.csr.2009.07.006
8. Ohshima K.I., Fukamachi Y., Williams G.D., Nihashi S. et al. Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. *Nat. Geosci.* 2013, 6(3), 235–240. doi:10.1038/ngeo1738
9. Snow K., Sloyan B.M., Rintoul S.R., Hogg A.M., Downes S.M. Controls on circulation, cross-shelf exchange, and dense water formation in an Antarctic polynya. *Geophys. Res. Lett.* 2016, 43, 7089–7096. doi:10.1002/2016GL069479
10. Snow K., Hogg A.M., Sloyan B.M., Downes S.M. Sensitivity of Antarctic bottom water to changes in surface buoyancy fluxes. *J. Clim.* 2016, 29, 313–330. doi:10.1175/JCLI-D-15-0467.1
11. Williams G.P., Herraiz-Borreguero L., Roquet F., Tamura T., et al. The suppression of Antarctic bottom water formation by melting ice shelves in Prydz Bay. *Nat. Commun.* 2016, 7, 12577. doi:10.1038/ncomms12577
12. Ackley S.F. et al. Sea-ice production and air/ice/ocean/ biogeochemistry interactions in the Ross Sea during the PIPERS2017 autumn field campaign. *Annals of Glaciology.* 2020, 61(82), 181–195. doi:10.1017/aog.2020.31
13. De Pace L. et al. Frazil ice growth and production during katabatic wind events in the Ross Sea, Antarctica. *The Cryosphere.* 2020, 14, 3329–3347. doi:10.5194/tc-14-3329-2020
14. Golovin P.N. Conditions of the formation and runoff of shelf waters in different water areas of the Arctic and Antarctic. *Russ. Meteorol. Hydrol.* 2012, 37, 752–761. doi:10.3103/S106837391211009X

15. Golovin P.N., Antipov N.N., Klepikov A.V. Peculiarities of Dense Water Cascading off the Deep Part of Antarctic Continental Slope (A Case Study for the Commonwealth Sea). *Russ. Meteorol. Hydrol.* 2018, 43, 852–861. doi:10.3103/S1068373918120063
16. Golovin P.N., Antipov N.N., Klepikov A.V. et al. Spatial Patterns of Dense Water Runoff on the Antarctic Shelf and Continental Slope. *Russ. Meteorol. Hydrol.* 2022, 47, 882–895. doi:10.3103/S1068373922110085
17. Golovin P.N., Antipov N.N., Klepikov A.V. Mechanisms of Deep and Bottom Water Ventilation over the Antarctic Continental Slope. *Russ. Meteorol. Hydrol.* 2019, 44, 404–415. doi:10.3103/S1068373919060050
18. Golovin P.N., Antipov N.N., Klepikov A.V. Downflow of the Antarctic shelf water at the shelf and continental slope of the Commonwealth Sea in the summer season and its effect on the bottom water formation in the Southern Ocean. *Oceanology.* 2011, 51, 370–384. doi:10.1134/S000143701103009X
19. Golovin P.N., Antipov N.N., Klepikov A.V. Studying the stability of the Antarctic slope front in the Commonwealth Sea. *Russ. Meteorol. Hydrol.* 2013, 38, 766–775. doi:10.3103/S106837391311006X
20. Golovin P.N., Antipov N.N., Klepikov A.V. Intrusive layering of the Antarctic slope front. *Oceanology.* 2016, 56, 470–482. doi:10.1134/S0001437016030085
21. Martin S. Frazil ice in rivers and oceans. *Ann. Rev. Fluid Mech.* 1981, 13, 379–397.
22. Monahov E.I. The conditions of the intra-water ice formation (P.h.D. monography). *Collections RFSI AARI*, 1989.
23. Golovin P.N. The role of quasi-stationary flaw polynya in formation of dense shelf waters in the wintertime and their subsequent slope cascading (the Laptev Sea case study). *Russ. Meteorol. Hydrol.* 2008, 33, 718–731. doi:10.3103/S106837390811006X
24. Ohshima K.I. Direct observations of coastal polynyas and glacier-ocean interaction in the East Antarctica. *Pre-sentation from the OASIIS Workshop*. 2017, Bremerhaven. Germany. 14–17th June. URL: https://soos.aq/images/soos/activities/cwg/oasiis/presentations2017/Wednesday/6_oasiis_kay_ohshima.pdf
25. Zakharov V.F. The role of the fast-ice polynya in the hydrological and ice regime of the Laptev Sea. *Oceanology.* 1966, 6, 1014–1022 (in Russian).
26. Martin S., Cavalieri D.J. Contributions of the Siberian shelf polynyas to the Arctic Ocean intermediate and deep water. *J. Geophys. Res.* 1989, 94, 12725–12738. doi:10.1029/JC094iC09p12725
27. Cavalieri D.J., Martin S. The contribution of Alaskan, Siberian, and Canadian coastal polynyas to cold halocline layer of the Arctic Ocean. *J. Geophys. Res.* 1994, 99, C9, 18343–18362. doi:10.1029/94JC01169
28. Schumacher J.D., Aagaard K., Pease C.H., Tripp R.B. Effects of a shelf polynya on flow and water properties in the northern Bering Sea. *J. Geophys. Res.* 1983, 88, 2723–2732. doi:10.1029/JC088iC05p02723
29. Smith S.D., R.D. Muench, Pease C.H. Polynyas and leads: An overview of physical processes and environment. *J. Geophys. Res.* 1990, 95, C6, 9461–9479. doi:10.1029/JC095iC06P09461
30. Smith S.D., Anderson R.J., G. et al. An investigation of a polynya in the Canadian archipelago, 2, Structure of turbulence and sensible heat flux. *J. Geophys. Res.* 1983, 88, 2900–2910. doi:10.1029/JC088iC05p02900
31. Golovin P.N., Molchanov M.S. Fine-scale modeling of water dynamics on the shelf and continental slope in the Antarctic. *Russ. Meteorol. Hydrol.* 2023, 6, 21–43. doi:10.52002/0130-2906-2023-6-21-43 (in Russian).
32. Piggott M.D., Gorman G.J. et al. A new computational framework for multi-scale ocean modelling based on adapting unstructured meshes. *Int. J. Numer. Meth. Fluids.* 2008, 56, 1003–1015. doi:10.1002/fld.1663
33. Chen C.T., Millero F.J. Effect of salt content on the temperature of maximum density and static stability in Lake Ontario. *Limnology and Oceanography.* 1977, 22, 1, 158–159.
34. Galerkin B.G. Rods and plates. Series in some questions of elastic equilibrium. *News magazine of engineers.* 1915, 19, 897–908 (in Russian).
35. Hiester H.R. The application of adaptive mesh techniques to numerical simulations of gravity current flows. *Thesis or dissertation*. 2011a. *Imperial College London*. doi:10.25560/9227
36. Wolkov A.V., Lyapunov S.V. Investigation of the efficiency of using high-order accuracy numerical schemes for solving the Navier–Stokes and Reynolds equations on unstructured adaptive grids. *Computational Mathematics and Mathematical Physics.* 2006, 46, 10, 1808–1820. doi:10.1134/S0965542506100162
37. Smagorinsky J. General circulation experiments with the primitive equations. I. The basic experiment. *Mon. Wea. Rev.* 1963, 91, 99–164. doi:10.1175/1520-0493(1963)091<0099: GCEWTP>2.3.CO;2
38. Davies D.R., Wilson C.R., Kramer S.C. Fluidity: A fully unstructured anisotropic adaptive mesh computational modelling framework for geodynamics. *Geochem. Geophys. Geosyst.* 2011, 12, Q06001. doi:10.1029/2011GC003551
39. Piggott M.D., Farrell P.E., Wilson C.R., Gorman G.J., Pain C.C. Anisotropic mesh adaptivity for multi-scale ocean modelling. *Philosophical Transactions of The Royal Society A: Mathematical, Physical and Engineering Sciences.* 2009, 367(1907), 4591–4611.
40. Hiester H.R., Piggott M.D., Allison P.A. The impact of mesh adaptivity on the gravity current front speed in a two-dimensional lock-exchange. *Ocean Modelling.* 2011b, 38, 1–2, 1–21. doi:10.1016/j.ocemod.2011.01.003

41. *Hiester H.R., Piggott M.D., Farrell P.E., Allison P.A.* Assessment of spurious mixing in adaptive mesh simulations of the two-dimensional lock-exchange. *Ocean Modelling*. 2014, 73, 30–44. doi:10.1016/j.ocemod.2013.10.003
42. *Jacobs C.T., Collins G.S., Piggott M.D., Kramer S.C., Wilson C.R.G.* Multiphase flow modelling of volcanic ash particle settling in water using adaptive unstructured meshes. *Geophys. J. Int.* 2013, 192, 2, 647–665. doi:10.1093/gji/ggs059
43. *Wendler G., Stearns C., Weidner G., Durgaund G., Parish T.R.* On the extraordinary katabatic winds of Adelie Land. *J. Geophys. Res.* 1997, 102, 4463–4474.
44. *Parish T.R., Walker R.* A re-examination of the winds of Adelie Land, Antarctica. *Aust. Met. Mag.* 2006, 55, 105–117.
45. *Parish T.R.* Surface winds over the Antarctic continent: A review. *Rev. Geophys.* 1988, 26, 1, 169–180. doi:10.1029/RG026i001p00169
46. *Tamura T., Ohshima K.I., Nihashi S.* Mapping of sea ice production for Antarctic coastal polynya. *Geophys. Res. Lett.* 2008, 35, L07606. doi:10.1029/2007GL032903
47. *Martin S., Kauffman P.* A field and laboratory study of wave damping by grease ice. *J. Glaciol.* 1981, 27, 281–314.
48. *Pease C.H.* The size of wind-driven coastal polynyas. *J. Geophys. Res.* 1987, 92, 7049–7059. doi:10.1029/JC092iC07p07049
49. *Winsor P., Bjork G.* Polynya activity in the Arctic Ocean from 1958 to 1997. *J. Geophys. Res.* 2000, 105, C4, 8789–8803. doi:10.1029/1999JC900305
50. *Danielson S., Aagaard K., Weingartner T., Martin S., Winsor P., Gawarkiewicz G., Quadfasel D.* The St. Lawrence polynya and the Bering shelf circulation: New observations and a model comparison. *J. Geophys. Res.* 2006, 111, C9, 1029–1057. doi:10.1029/2005JC003268
51. *Drucker R., Martin S.* Observation of ice thickness and frazil ice in the St. Lawrence Island polynya from satellite imagery, upward looking sonar, and salinity/temperature moorings. *J. Geophys. Res.* 2003, 108, C5, 3149–3167. doi:10.1029/2001JC001213
52. *Golovin P.N.* Convective Mass-transfer in the Sub-ice Layer of Winter Leads in the Arctic Basin. *Oceanology*. 1995, 35, 6, 854–863 (in Russian).
53. *Makstas A.P.* Thermal balance of Arctic ice in winter. *Leningrad, Gidrometeoizdat*, 1984. 67 p. (in Russian).
54. *Doronin Yu.P., Heisin D.E.* Sea ice. *Leningrad, Gidrometeoizdat*, 1980 (in Russian).
55. *Weeks W.F., Ackley S.* The growth, structure and properties of sea ice. Hanover (N.H.): U.S. Cold Region Research and Engineering Lab. Springfield. Va. available from N.T. I. S. 1982. 130 p.
56. *Zatsepin A.G., Kostianoy A.G., Semenov A.V.* Laboratory study of axisymmetric density flow on an inclined bottom in a rotating fluid. *Oceanology*. 1996, 36, 339–346 (in Russian).
57. *Zatsepin A.G., Grizenko V.A. et al.* Laboratory and Numerical Studies of the Propagation of Density Currents along the Bottom Slope. *Oceanology*. 2005, 45, 1, 5–15 (in Russian).
58. *Shapiro G.I., Zatsepin A.G.* Gravity current down a steeply inclined slope in rotating fluid. *Ann. Geophys.* 1997, 15, 366–374. doi:10.1007/s00585-997-0366-x
59. *Turner J.* Buoyancy Effects in Fluids (Cambridge Monographs on Mechanics). *Cambridge University Press*. doi:10.1017/CBO9780511608827
60. *Mensah V., Yoshihiro Nakayama Y., Fujii M., Nogi Y., Ohshima K.I.* Dense water downslope flow and AABW production in a numerical model: Sensitivity to horizontal and vertical resolution in the region off Cape Darnley polynya. *Ocean Modelling*. 2021, 165, 101843. doi:10.1016/j.ocemod.2021.101843
61. *Voltzinger N.E., Androsov A.A.* Modelling long-wave dynamics on the continental slope of the ocean and areas of sharp depth variation. *Fundamental and Applied Hydrophysics*. 2020, 13, 4, 16–26. doi:10.7868/S2073667320040024 (in Russian).

Литература

1. *Foster T.D., Carmack E.C.* Frontal zone mixing and Antarctic bottom water formation in the southern Weddell Sea // *Deep Sea Res.* 1976. Vol. 23. P. 301–317. doi:10.1016/0011-7471(76)90872-X
2. *Foster T.D., Foldvik A., Middleton J.H.* Mixing and bottom water formation in the shelf break region of the southern Weddell Sea // *Deep Sea Res.* 1987. Vol. 34, № 11. P. 1771–1794. doi:10.1016/0198-0149(87)90053-7
3. *Fahrbach E., Rohardt G., Scheele N., et al.* Formation and discharge of deep and bottom water in the northwestern Weddell Sea // *J. Mar. Res.* 1995. Vol. 53, N4 P. 515–538. doi:10.1357/0022240953213089
4. *Foldvik A., Kvinge T., Torresen T.* Bottom currents near the continental shelf break in the Weddell Sea. In: *Oceanology of the Antarctic Continental Shelf*. Antarctic Research Series. 1985. Vol. 43. P. 5–20. doi:10.1029/AR043p0021

5. Foldvik A., Gammelsrod T., Osterhus S., et al. Ice shelf water overflow and bottom water formation in the southern Weddell Sea // J. Geophys. Res. 2004. Vol. 109. C02015. doi:10.1029/2003JC002008
6. Baines P.G., Condie S.A. Observations and modelling of Antarctic downslope flows: a review. In: Ocean, ice, and atmosphere: interactions at the Antarctic continental margin. Antarctic Research Series. 1998. Vol. 75. P. 29–49. doi:10.1029/AR075p0029
7. Fuseo G., Budillon G., Sperie G. Surface heat fluxes and thermohaline variability in the Ross Sea and Terra Nova Bay polynya // Cont. Shelf Res. 2009. № 29. P. 1887–1895. doi:10.1016/j.csr.2009.07.006
8. Ohshima K.I., Fukamachi Y., Williams G.D., Nihashi S. et al. Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya // Nat. Geosci. 2013. № 6(3). P. 235–240. doi:10.1038/ngeo1738
9. Snow K., Sloyan B.M., Rintoul S.R., Hogg A.M., Downes S.M. Controls on circulation, cross-shelf exchange, and dense water formation in an Antarctic polynya // Geophys. Res. Lett. 2016. № 43. P. 7089–7096. doi:10.1029/2016GL069479
10. Snow K., Hogg A.M., Sloyan B.M., Downes S.M. Sensitivity of Antarctic bottom water to changes in surface buoyancy fluxes // J. Clim. 2016. № 29. P. 313–330. doi:10.1175/JCLI-D-15-0467.1
11. Williams G.P., Herraiz-Borreguero L., Roquet F., Tamura T., et al. The suppression of Antarctic bottom water formation by melting ice shelves in Prydz Bay // Nat. Commun. 2016. Vol. 7. P. 12577 doi:10.1038/ncomms12577
12. Ackley S.F. et al. Sea-ice production and air/ice/ocean/ biogeochemistry interactions in the Ross Sea during the PIPERS2017 autumn field campaign // Annals of Glaciology. 2020. Vol. 61(82). P. 181–195. doi:10.1017/aog.2020.31
13. De Pace L. et al. Frazil ice growth and production during katabatic wind events in the Ross Sea, Antarctica // The Cryosphere. 2020. Vol. 14. P. 3329–3347 doi:10.5194/tc-14-3329-2020
14. Головин П.Н. Условия формирования шельфовых вод и стока на разных акваториях Арктики и Антарктики // Метеорология и гидрология. 2012. № 12. С. 55–68.
15. Головин П.Н., Антипов Н.Н., Клепиков А.В. Особенности глубоководного каскадинга на антарктическом материковом склоне (на примере моря Содружества) // Метеорология и гидрология. 2018. № 12. С. 81–93.
16. Головин П.Н., Антипов Н.Н., Клепиков А.В., Молчанов М.С., Кашин С.В., Чистяков И.А. Пространственные закономерности стока плотных вод на антарктическом шельфе и материковом склоне // Метеорология и гидрология. 2022. № 11. С. 91–110.
17. Головин П.Н., Антипов Н.Н., Клепиков А.В. Механизмы вентиляции глубинных и донных вод над антарктическим материковым склоном // Метеорология и гидрология. 2019. № 6. С. 52–69.
18. Головин П.Н., Антипов Н.Н., Клепиков А.В. Сток антарктических шельфовых вод в летний период на шельфе и материковом склоне моря Содружества и их влияние на формирование донных вод Южного океана // Океанология. 2011. Т. 51, № 3. С. 393–408.
19. Головин П.Н., Антипов Н.Н., Клепиков А.В. Исследование устойчивости Антарктического склонового фронта в море Содружества // Метеорология и гидрология. 2013. № 11. С. 64–78.
20. Головин П.Н., Антипов Н.Н., Клепиков А.В. Интрузионное расслоение Антарктического склонового фронта // Океанология. 2016. Т. 56, № 4. С. 514–528. doi:10.7868/S0030157416030084
21. Martin S. Frazil ice in rivers and oceans // Ann. Rev. Fluid Mech. 1981/ № 13. P. 379–397. doi:10.1146/annurev.fl.13.010181.002115
22. Монахов Е.И. Условия формирования внутриводного льда — Дис. к.г.н. фонды ФБГУ «РФ ААНИИ». 1989. 171 с.
23. Головин П.Н. Роль квазистационарной заприпайной полыньи в формировании плотных шельфовых вод в зимний период и их последующем склоновом каскадинге (на примере моря Лаптевых) // Метеорология и гидрология. 2008. № 11. С. 57–75.
24. Ohshima K.I. Direct observations of coastal polynyas and glacier-ocean interaction in the East Antarctica // presentation from the OASIIS Workshop. 2017. Bremerhaven. Germany. 14–17th June. URL: https://soos.aq/images/soos/activities/cwg/oasiis/presentations2017/Wednesday/6_oasiis_kay_ohshima.pdf
25. Захаров В.Ф. Роль заприпайной полыньи в гидрологическом и ледовом режиме моря Лаптевых // Океанология. 1966. Т. VI. С. 1014–1022.
26. Martin S., and Cavalieri D.J. Contributions of the Siberian shelf polynyas to the Arctic Ocean intermediate and deep water // J. Geophys. Res. 1989. Vol. 94. P. 12725–12738. doi:10.1029/JC094iC09p12725
27. Cavalieri D.J., Martin S. The contribution of Alaskan, Siberian, and Canadian coastal polynyas to cold halocline layer of the Arctic Ocean // J. Geophys. Res. 1994. Vol. 99. P. 18343–18362. doi:10.1029/94JC01169
28. Schumacher J.D., K. Aagaard, C.H. Pease, Tripp R.B. Effects of a shelf polynya on flow and water properties in the northern Bering Sea // J. Geophys. Res. 1983. Vol. 88. P. 2723–2732. doi:10.1029/JC088iC05p02723

29. *Smith S.D., R.D. Muench, Pease C.H.* Polynyas and leads: An overview of physical processes and environment // *J. Geophys. Res.* 1990. Vol. 95, № C6. P. 9461–9479. doi:10.1029/JC095IC06P09461
30. *Smith S.D., R.J. Anderson, G. et al.* An investigation of a polynya in the Canadian archipelago, 2, Structure of turbulence and sensible heat flux // *J. Geophys. Res.* 1983. Vol. 88. P. 2900–2910. doi:10.1029/JC088iC05p02900
31. *Головин П.Н., Молчанов М.С.* Мелкомасштабное моделирование динамики вод на шельфе и континентальном склоне в Антарктике // *Метеорология и гидрология*. 2023. № 6. С. 21–43. doi:10.52002/0130-2906-2023-6-21-43
32. *Piggott M.D., Gorman G.J. et al.* A new computational framework for multi-scale ocean modelling based on adapting unstructured meshes // *Int. J. Numer. Meth. Fluids*. 2008. Vol. 56. P. 1003–1015. doi:10.1002/fld.1663
33. *Chen C.T., Millero F.J.* Effect of salt content on the temperature of maximum density and static stability in Lake Ontario // *Limnology and Oceanography*. 1977. Vol. 22, № 1. P. 158–159.
34. *Галеркин Б.Г.* Стержни и пластины. Ряды в некоторых вопросах упругого равновесия // *Вестник инженеров*. 1915. № 19. С. 897–908.
35. *Hiester H.R.* The application of adaptive mesh techniques to numerical simulations of gravity current flows // Thesis or dissertation. 2011a. Imperial College London. doi:10.25560/9227
36. *Волков А.В., Ляпунов С.В.* Исследование эффективности использования численных схем высокого порядка точности для решения уравнений Навье–Стокса и Рейнольдса на неструктурированных адаптивных сетках // *Журнал вычислительной математики и математической физики*. 2006. Т. 46, № 10. С. 1894–1907.
37. *Smagorinsky J.* General circulation experiments with the primitive equations. I. The basic experiment // *Mon. Wea. Rev.* 1963. Vol. 91. P. 99–164. doi:10.1175/1520-0493(1963)091<0099:GCEWTP>2.3.CO;2
38. *Davies D.R., Wilson C.R., Kramer S.C.* Fluidity: A fully unstructured anisotropic adaptive mesh computational modelling framework for geodynamics // *Geochem. Geophys. Geosyst.* 2011. Vol. 12. Q06001. doi:10.1029/2011GC003551
39. *Piggott M.D., Farrell P.E., Wilson C.R., Gorman G.J., Pain C.C.* Anisotropic mesh adaptivity for multi-scale ocean modelling // *Philosophical Transactions of The Royal Society A: Mathematical, Physical and Engineering Sciences*. 2009. Vol. 367 (1907). P. 4591–4611.
40. *Hiester H.R., Piggott M.D., P.A. Allison* The impact of mesh adaptivity on the gravity current front speed in a two-dimensional lock-exchange // *Ocean Modelling*. 2011b. Vol. 38. Issues 1–2. P. 1–21. doi:10.1016/j.ocemod.2011.01.003
41. *Hiester H.R., Piggott M.D., Farrell P.E., Allison P.A.* Assessment of spurious mixing in adaptive mesh simulations of the two-dimensional lock-exchange // *Ocean Modelling*. 2014. Vol. 73. P. 30–44. doi:10.1016/j.ocemod.2013.10.003
42. *Jacobs C.T., Collins G.S., Piggott M.D., Kramer S.C., Wilson C.R.G.* Multiphase flow modelling of volcanic ash particle settling in water using adaptive unstructured meshes // *Geophys. J. Int.* 2013. Vol. 192, № 2. P. 647–665. doi:10.1093/gji/ggs059
43. *Wendler G., Stearns C., Weidner G., Durgaund G., Parish T.R.* On the extraordinary katabatic winds of Adelie Land // *J. Geophys. Res.* 1997. Vol. 102. P. 4463–4474. doi:10.1029/96JD03438
44. *Parish T.R., Walker R.* A re-examination of the winds of Adelie Land, Antarctica // *Aust. Met. Mag.* 2006. Vol. 55. P. 105–117.
45. *Parish T.R.* Surface winds over the Antarctic continent: A review // *Rev. Geophys.* 1988. Vol. 26. № 1. P. 169–180. doi:10.1029/RG026i001p00169
46. *Tamura T., Ohshima K.I., Nihashi S.* Mapping of sea ice production for Antarctic coastal polynya // *Geophys. Res. Lett.* 2008. Vol. 35. L07606. doi:10.1029/2007GL032903
47. *Martin S., Kauffman P.* A field and laboratory study of wave damping by grease ice // *J. Glaciol.* 1981. № 27. P. 281–314.
48. *Pease C.H.* The size of wind-driven coastal polynyas // *J. Geophys. Res.* 1987. Vol. 92. P. 7049–7059. doi:10.1029/JC092iC07p07049
49. *Winsor P., Bjork G.* Polynya activity in the Arctic Ocean from 1958 to 1997 // *J. Geophys. Res.* 2000. Vol. 105, № C4. P. 8789–8803. doi:10.1029/1999JC900305
50. *Danielson S., Aagaard K., Weingartner T., Martin S., Winsor P., Gawarkiewicz G., Quadfasel D.* The St. Lawrence polynya and the Bering shelf circulation: New observations and a model comparison // *J. Geophys. Res.* 2006. Vol. 111, № C9. P. 1029–1057. doi:10.1029/2005JC003268
51. *Drucker R., Martin S.* Observation of ice thickness and frazil ice in the St. Lawrence Island polynya from satellite imagery, upward looking sonar, and salinity/temperature moorings // *J. Geophys. Res.* 2003. Vol. 108, № C5. P. 3149–3167. doi:10.1029/2001JC001213
52. *Головин П.Н.* Конвективный массоперенос в подледном слое зимнего разводя в Арктическом бассейне // *Океанология*. 1995. Т. 35, № 6. С. 854–863.
53. *Максимас А.П.* Тепловой баланс арктических льдов в зимний период. Л.: Гидрометеиздат, 1984. 67 с.

54. Доронин Ю.П., Хейсин Д.Е. Морской лед. Л.: Гидрометеиздат, 1980. 320 с.
55. Weeks W.F., Ackley S. The growth, structure and properties of sea ice. Hanover (N.H.): U.S. Cold Region Research and Engineering Lab. Springfield. Va. available from N.T. I. S. 1982. 130 p.
56. Зацепин А.Г., Костяной А.Г., Семенов А.В. Лабораторное исследование осесимметричного плотностного течения на наклонном дне во вращающейся жидкости // Океанология. 1996, Т. 36, № 3. С. 339–346.
57. Зацепин А.Г., Гриценко В.А., и др. Лабораторное и численное исследования процесса распространения плотностных течений по склону дна // Океанология. 2005. Т. 45, № 1. С. 5–15.
58. Shapiro G.I., Zatsepin A.G. Gravity current down a steeply inclined slope in rotating fluid // Ann. Geophys. 1997. Vol. 15. P. 366–374. doi:10.1007/s00585–997–0366-x
59. Тернер Дж. Эффекты плавучести в жидкости. М.: Мир, 1977. 431 с.
60. Mensah V., Yoshihiro Nakayama Y., Fujii M., Nogi Y., Ohshima K.I. Dense water downslope flow and AABW production in a numerical model: Sensitivity to horizontal and vertical resolution in the region off Cape Darnley polynya // Ocean Modelling. 2021. Vol. 165/ 101843. doi:10.1016/j.ocemod.2021.101843
61. Вольцингер Н.Е., Андросов А.А. Моделирование длинноволновой динамики на материковом склоне океана и регионах свала глубин // Фундаментальная и прикладная гидрофизика. 2020. Т. 13, № 4. С. 16–26. doi:10.7868/S2073667320040024

Об авторах

ГОЛОВИН Павел Николаевич, РИНЦ Author ID: 140551, Scopus Author ID: 6602132931, golovin@aari.ru
МОЛЧАНОВ Михаил Сергеевич, РИНЦ Author ID: 879684, Scopus Author ID: 5608261720, mms@aari.ru