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Sensivity study of the warm Atlantic layer to diffusion parametrization in the Arctic modeling*

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Abstract. In this paper, we study the sensivity of the numerical model of the Arctic–North Atlantic Ocean to the way of the diffusion parametrization: standard horizontal/vertical diffusion (HOR), isopycnal mixing scheme, with the Cox approach (ISO); and the Gent–McWilliams parametrization (GM). As a result of numerical experiments we have obtained more intensive and distinct flows observed in the picture of the Arctic circulation in the ISO model release. It is also shown that the replacement of the standard horizontal/vertical diffusion by the isopycnal diffusion gives rise to a larger heat inflow to the Arctic Ocean through the Fram Strait.

1. Introduction

The energy of mesoscale motion, such as baroclinic eddies, internal waves, and their interaction with the topography, have a significant impact on the ocean circulation. In the most part of the ocean, the length scale of these motions typically lies between 10 and 100 km. Even high-resolution numerical models are often unable to resolve these motions, which may affect the global transport. When simulating, it is important that these mesoscale effects be included in a large-scale flow. It is appropriate to apply different parameterizations: semi-empirical formulas reflecting the cumulative subgrid-scale effect on the large-scale processes. Such parameterizations are especially important to operate properly when applied to the Arctic, as the explicit modeling of mesoscale eddies requires high spatial resolution, the Rossby radius in this region does not exceed 5 km.

Measurements of temperature, salinity and velocity carried out within one year at the intersection of the Lomonosov Ridge with the shelf indicate that the flow circulates cyclonically as a weak mean flow (1–5 cm/s) with strong isolated eddies (up to 40 cm/s) [1], which cannot be described with a given grid resolution.

Thus, currently the parametrization of subgrid-scale motions has become widespread, which takes into account the fact that fluid properties are transported more efficiently along isopycnal surfaces than across the isopycnal surfaces. This is the so-called isopycnal diffusion (ISO) [2–4]. Usually,

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in combination with it the Gent McWilliams eddie stirring (GM) [5], also called the layer thickness diffusion, is used.

Various models reveal different effects from the use of these parameterizations. In general, they indicate to differences and improvements when the ISO is compared with the parametrization of horizontal/vertical (HOR) diffusion and when the model results with the GM parametrization are compared with the results of another version of the model without GM. Some of these models reveal the elimination of The Veronis Effect [6, 7] while using ISO. The horizontal diffusion produces a false upwelling that would not occur if diffusion was along the isopycnal surfaces [8]. The Veronis effect reduces the North Atlantic Meridional Overturning Circulation and the associated northward heat transport.

In [9], there were revealed such advancements as a sharper main thermocline, a cooler abyssal ocean, elimination of the Deacon cell as a tracer transport agent, the meridional heat transport in a better agreement with observations.

In [10], the authors mark that the reduced diapycnal mixing in the ISO version of the model leads to abrupt transitions between water masses, reflecting the fact that the mixing mechanism that depletes density gradients has been reduced in strength, particularly, in the regions of strongly sloping isopycnals. As a result, a stronger and deeper circulation of the Atlantic overturning was obtained. There is also a mentioning that in large parts of the ocean, the isopycnal surfaces are approximately horizontal, and the isopycnal/diapycnal diffusivities in the ISO have essentially the same effect as the horizontal/vertical diffusivities in the HOR.

Still more changes were noticed in the models while using the GM. Conservative properties of parametrization are well-maintained on a Cartesian grid and the GM works much better than the HOR in maintaining the amount of water with a given density [11]. The parameterized eddy ocean heat transport has the same order of magnitude and a correct distribution with latitude estimated from observations and regional eddy-resolving models [11]. The GM also brings about a dramatic reduction in the convective adjustment in the model as compared to the results obtained with horizontal mixing; as a result, at high latitudes the simulated tracer distributions are improved.

In [7, 9, 12, 13], there is noted a decrease in temperature in the bottom layer while using the GM. Hirst and Cai [14] made the same conclusion when using isopycnal diffusion without thickness diffusion. Robitaille and Weaver [15] found that their simulated temperature in the lowest model layer is colder by about 1.5 °C with the GM parametrization, and by about half that much with the ISO parametrization.

The GM tends to flatten the isopycnals and hence to reduce the meridional density gradients. The consequences pointed out in [10] include a drastic decrease in the convective adjustment activity, a significant weakening of the large-scale circulation, and a much greater tendency for the major changes or reorganization of the circulation. According to [9], the GM version appears to give the most realistic results among the three formulations considered. The tendency of the GM to flatten isopycnals reduces the development of static instabilities in large parts of the ocean, while the vertical heat and salt fluxes continue maintaining by the isopycnal mixing.

The reduction of convective activity was also noticed in [7,9,12,14], which demonstrated that when isopycnal mixing is used in the OGCMs, convection is largely replaced by along-isopycnal mixing at or near a maximum allowable slope for density surfaces. In [16], it is reported that a dramatic reduction in the number of statically unstable points in a model that used the Cox isopycnal formulation as compared to a similar constructed model that used the standard horizontal/vertical mixing. As the model was becoming increasingly isopycnal (a steep allowable isopycnal slope, a low background horizontal diffusivity), the number of statically unstable points dropped near to zero. The incorporation of the GM mixing tends to reduce the overall Southern Ocean deep ventilation rate by damping or removing the spurious open ocean convection observed in the earlier obtained solutions.

Not much research has been conducted with Arctic models, which is sensitive to model parameters. Our main task was to investigate the influence of the considered types of parametrization on the thermohaline circulation in this region.

2. Isopycnal diffusion and skew-diffusion

The ocean tracer mixing can be mostly parameterized as downgradient diffusion. The diffusion part in the equations of the tracer represents but not to a minor extent the molecular diffusion but, primarily, unresolved subgrid movements, eddies. These movements primarily occur in the horizontal direction. Therefore, conventionally, such movements have been parameterized as horizontal and vertical diffusion. In this case, the vertical coefficient is taken much smaller than the horizontal one. However, a closer look reveals that the mixing processes in the ocean occur primarily along isopycnal surfaces (i.e., surfaces of constant density). The diapycnal mixing (across these surfaces) proceeds much slower. These surfaces are not horizontal in most parts of the ocean. This process has been described by Iselin and Montgomery [17,18]. Given this fact, the use of HOR in the model, leads to large diapycnal diffusive fluxes in the regions of steep sloping and, accordingly, appears to be unphysical. To eliminate these unrealistic fluxes, the new parameterization was proposed [2,3]. It represents the diffusion along isopycnal surfaces. In [2], diffusion fluxes are rotated and directed along isopycnal surfaces. In the 2D form, the diffusion equation is as follows:

$$\frac{\partial T}{\partial t} = K_H \frac{\partial^2 T}{\partial x^2} + 2\alpha K_H \frac{\partial^2 T}{\partial x \partial z} + (\alpha^2 k_H + K_V)\frac{\partial^2 T}{\partial z^2}.$$

Here T is the tracer, K_H and K_V are coefficients of horisontal and vertical diffusion, α is the slope of the isopycnal surface.

Redi [3] rotated the coordinate system. In the isopycnal coordinate system, the diffusion tensor is diagonal. While the transition to the geopotential coordinate system occur off-diagonal elements emerge. The diffusion tensor becomes

$$K^g = \frac{K_H}{\rho_x^2 + \rho_y^2 + \rho_z^2} \begin{pmatrix} \rho_z^2 + \rho_y^2 + \epsilon \rho_x^2 & (\epsilon - 1)\rho_x \rho_y & (\epsilon - 1)\rho_x \rho_z \\ (\epsilon - 1)\rho_x \rho_y & \rho_z^2 + \rho_x^2 + \epsilon \rho_y^2 & (\epsilon - 1)\rho_y \rho_z \\ (\epsilon - 1)\rho_x \rho_z & (\epsilon - 1)\rho_y \rho_z & \rho_x^2 + \rho_y^2 + \epsilon \rho_z^2 \end{pmatrix},$$

$\epsilon = \dfrac{K_V}{K_H} \simeq 10^{-7}$. The tensor can be simplified provided that that the term $\epsilon \dfrac{\rho_z^2}{\rho_x^2 + \rho_y^2}$ is negligible.

Cox [4] implemented a diffusion scheme version of the ocean model, with an attempt to numerically realize Redi's isoneutral diffusion. However the Cox scheme contains a numerical instability, and in long climate runs it requires a background lateral diffusion to be present to conserve the integrity of the model fields.

When using the isopycnal diffusion parametrization there arises a problem of very large vertical diffusive fluxes in the regions of steep slopes. To avoid them, the slopes of isopycnal surfaces are restricted. If the size of a slope exceeds a specified maximum value, it is simply set to the maximum one. The value of that limiter has been ranging between 10^{-3} [11] and 10^{-2} [9, 14]. However, it is important to choose the limit sufficiently large, because its clipping can lead to cross isopycnal diffusion in regions of steeply sloping isopycnals and, consequently, adversely influence the model solution.

A significant improvement in parametrization of the eddies mixing was proposed by Gent and McWilliams [5]. Their theory is based on a quasi-adiabatic stirring mechanism that redistributes the water mass within a layer bounded by two isopycnal surfaces, yet reduces the isopycnal slopes and so acts as a sink for available potential energy. This mechanism (the so-called mixing of the isopycnal layer thickness) can be represented as advection with an additional eddy-induced transport velocity (bolus velocity)

$$\frac{\partial T}{\partial t} + (u + u^*) \cdot \nabla T = \nabla_\rho \cdot (\kappa \nabla_\rho T).$$

Here

$$u^* = \left[-\frac{\partial (K_G s_x)}{\partial z}, -\frac{\partial (K_G s_y)}{\partial z}, \frac{\partial (K_G s_x)}{\partial x} + \frac{\partial (K_G s_y)}{\partial y} \right],$$

where

$$s_x = -\frac{\rho_x}{\rho_z}, \qquad s_y = -\frac{\rho_y}{\rho_z}.$$

The bolus velocities involve multiple spatial derivatives, which can consequently give rise to numerical noise. Griffies et al. [19] point out that the Gent McWilliams bolus fluxes can be identically written as a skew flux which involves fewer differential operators. He has developed skew-symmetric tensor bringing together the two processes — isopycnal diffusion and GM stirring:

$$\begin{pmatrix} K_I & 0 & (K_I - K_G)s_x \\ 0 & K_I & (K_I - K_G)s_y \\ (K_I + K_G)s_x & (K_I + K_G)s_y & K_I(s_x^2 + s_y^2) \end{pmatrix}.$$

Gent and McWilliams', Griffies' isopycnal layer thickness in conjunction with the Redi isopycnal diffusion is reasonably a good technique as of today for the parametrization of the ocean tracer mixing.

3. Numerical problems

In the process of implementation of the isopycnical diffusion and the GM stirrling as applied to the numerical model, there arises some problems and issues. One of them is emergence of numerical instabilities which require the background horizontal diffusion to suppress them. This fact is indicated in a number of studies. Griffies et al. [19] show how this problem appears in the Cox classical discretization. In [4], there is emphasized that the Cox scheme does not satisfy the two properties: downgradient orientation of the diffusive fluxes along the neutral directions and zero isoneutral diffusive flux of locally referenced potential density. This explains the necessity to add a non-trivial background horizontal diffusion to this scheme. It is also shown how such problem can be solved by using different averaging techniques.

Mathieu and Deleersnijder [20] investigated the non-monotonic behavior of the Cox isopycnal mixing formulation. The authors have shown why the discretization of the cross derivative terms is responsible for the occurrence of min-max violations in the tracer field. They equated the importance of preserving monotonicity of the isopycnal mixing formulation to the search for sophisticated advection schemes.

Gough [21] declared that a small background horizontal diffusivity was found to be necessary to suppress the gridpoint noise, although this leads to the cross isopycnal diffusion. He proposed a way to mitigate this problem by the local reduction of the isopycnal diffusivity in the regions of steep isopycnals. This reduces the isopycnal mixing but eliminates the undesirable cross isopycnal mixing. Beckers [22] considers that the standard diffusion along the coordinate surfaces is commonly retained as applied to the shallow seas in order to take into account the impact of the topography on the subgrid-scale motions.

The major problems for large-scale applications were the non-cancellation of density flux contributions of temperature and salinity on isopycnal surfaces [19].

4. The ocean circulation model

The modeling domain. To simulate the processes of interaction between the Arctic Basin and the North Atlantic we have considered the region of the Arctic Ocean and the North part of the Atlantic Ocean, starting with 20° S. The numerical grid is a combination of $1° \times 1°$ grid in the spherical coordinate system for the North Atlantic and the reprojected grid with a more detailed resolution of the Arctic. A maximum resolution in the polar regions is equal to 35 km. On average, the nodes of the numerical grid in the area of the Arctic Ocean are at a distance of about 50 km. The vertical discretization consists of 38 horizontal levels with concentration at the surface, where the resolution is 10 m.

The numerical model. The numerical model used for investigation, is a coupled regional ocean-ice model, which includes the ocean numerical model developed at the ICMMG SB RAS and the ice model CICE-3.14 (http://oceans11.lanl.gov/drupal/CICE). The history of the ocean part of model originates in [23, 24] on the large-scale model of the ocean. The description of the recent version of the model was presented in [25, 26]. In the system of the orthogonal curvilinear coordinates, the full nonlinear hydrothermodynamic equations of the ocean are considered using the standard approximations: Boussinesq, hydrostatics and "rigid lid".

The system includes the equation for the horizontal velocity components

$$\begin{aligned}\frac{\partial u}{\partial t} + L(u) - Kuv - fv &= -\frac{1}{\rho_0 h_x}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z} + F(u,\mu),\\ \frac{\partial v}{\delta t} + L(v) - Ku^2 + fu &= -\frac{1}{\rho_0 h_y}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\nu\frac{\partial v}{\partial z} + F(v,\mu),\end{aligned} \tag{1}$$

where

$$L(\xi) = \frac{1}{h_x h_y}\left[\frac{\partial}{\partial x}(h_y u\xi) + \frac{\partial}{\partial y}(h_x v\xi)\right] + \frac{\partial}{\partial z}(w\xi),$$
$$F(\xi,\mu) = \frac{1}{h_x h_y}\left[\frac{\partial}{\partial x}\Big(\mu\frac{h_y}{h_x}\frac{\partial \xi}{\partial x}\Big) + \frac{\partial}{\partial y}\Big(\mu\frac{h_y}{h_x}\frac{\partial \xi}{\partial x}\Big)\right];$$

the continuity equation

$$\frac{1}{h_x h_y}\left[\frac{\partial}{\partial x}(h_y u) + \frac{\partial}{\partial y}(h_x v)\right] + \frac{\partial w}{\partial z} = 0; \tag{2}$$

the hydrostatic equation

$$\frac{\partial \rho}{\partial z} = -\rho g; \tag{3}$$

the equation of state

$$\rho = \rho(T, S, p); \tag{4}$$

and the transport-diffusion equation for heat and salt

$$\frac{\partial T}{\partial t} + L(T) = D_T, \qquad \frac{\partial S}{\partial t} + L(S) = D_S. \tag{5}$$

Here we use the following notations: z is the vertical coordinate with the downgradient direction taken as positive, u, v are the horizontal velocity components, T is the potential temperature (°C), S is salinity (‰), ρ is the density of water, $\rho_0 = \text{const}$ is a standard density, p is pressure, $f = 2\Omega \sin\varphi$ is the Coriolis parameter, φ is the latitude, μ and ν and are the horizontal and vertical viscosity coefficients, D_T, D_S are the diffusion terms, h_x and h_y are metric coefficients.

The dynamic equations are solved by separating barotropic and baroclinic modes. The barotropic part represents the stream function equation. The second order operator is used to parameterize the diffusion in equations (1)–(5). The advective part is solved using the numerical scheme of the third order QUICKEST [25]. The convective mixing parametrization is based on the use of additional models of the upper mixed layer of the ocean [24].

The boundary conditions for the original system are the following:
at the surface $z = 0$:

$$w = 0, \quad \nu\frac{\partial \boldsymbol{U}}{\partial z} = -\frac{\tau}{\rho_0}, \quad \frac{\partial(T,S)}{\partial z} = (Q_T, Q_S),$$

at the bottom $z = H$:

$$w = \boldsymbol{U}\cdot\nabla H, \quad \nu\frac{\partial \boldsymbol{U}}{\partial z} = -R\overline{\boldsymbol{U}}\boldsymbol{U}, \quad \overline{\boldsymbol{U}} = (u^2+v^2)^{1/2}, \quad \frac{\partial(T,S)}{\partial z} = 0,$$

at the lateral boundaries Γ_0:

$$\frac{\partial \boldsymbol{U}\cdot l}{\partial n} = 0, \quad \boldsymbol{U}\cdot n = 0, \quad \frac{\partial(T,S)}{\partial n} = 0.$$

Here τ is the vector of the wind shear stress, $\boldsymbol{U} = (u, v)$ is the vector of the horizontal velocity components along the corresponding horizontal coordinates, R is the bottom friction coefficient, l and n are the tangential and the normal unit vectors to the contour of the boundary Γ, respectively, Q_T and Q_S are surface fluxes of heat and salt.

The model used for the sea ice, known as the elastic viscous-plastic model, is a modification of the standard viscous-plastic model of the ice dynamics [27]. This model is well documented in [28]. The ice thickness is calculated based on the thermodynamic model [29] for each category of ice. The horizontal transfer of ice is performed using the semi–lagrangian advection scheme [30].

Diffusion parametrization in the numerical model. The temperature diffusion in the numerical model is represented by the equation

$$\frac{\partial T}{\partial t} = D_T, \tag{6}$$

where in the case of the horizontal/vertical diffusion

$$D_T = \frac{1}{h_x h_y}\left[\frac{\partial}{\partial \xi_1}\left(\frac{h_y}{h_x} K_H \frac{\partial T}{\partial \xi_1}\right) + \frac{\partial}{\partial \xi_2}\left(\frac{h_x}{h_y} K_H \frac{\partial T}{\partial \xi_2}\right)\right] + \frac{\partial}{\partial z}\left[K_V \frac{\partial T}{\partial z}\right].$$

Here K_H and K_V are the horizontal and vertical diffusion coefficients, respectively.

When the isopycnal diffusion is introduced, the diffusion tensor

$$\begin{pmatrix} K_H & 0 & 0 \\ 0 & K_H & 0 \\ 0 & 0 & K_V \end{pmatrix}$$

is replaced by the isopycnal diffusion tensor [3]. So D_T in equation (6) changes to

$$D_T = \frac{1}{h_x h_y}\begin{pmatrix} h_y & 0 & 0 \\ 0 & h_x & 0 \\ 0 & 0 & h_x h_y \end{pmatrix} \times$$
$$\begin{pmatrix} K_I & 0 & (K_I - K_G)s_x \\ 0 & K_I & (K_I - K_G)s_y \\ (K_I + K_G)s_x & (K_I + K_G)s_y & K_I(s_x^2 + s_y^2) \end{pmatrix} \begin{pmatrix} \frac{1}{h_x}\frac{\partial T}{\partial \xi_1} \\ \frac{1}{h_y}\frac{\partial T}{\partial \xi_2} \\ \frac{\partial T}{\partial z} \end{pmatrix}$$

The isopycnal diffusion equation now is written down as follows:

$$\begin{aligned} \frac{\partial T}{\partial t} = {} & \frac{1}{h_x h_y}\frac{\partial}{\partial \xi_1}\left(\frac{h_y}{h_x} K_I \frac{\partial T}{\partial \xi_1} + h_y (K_I - K_G) s_x \frac{\partial T}{\partial z}\right) + \\ & \frac{1}{h_x h_y}\frac{\partial}{\partial \xi_2}\left(\frac{h_x}{h_y} K_I \frac{\partial T}{\partial \xi_2} + h_x (K_I - K_G) s_y \frac{\partial T}{\partial z}\right) + \\ & \frac{\partial}{\partial z}\left[\frac{(K_I + K_G)s_x}{h_x}\frac{\partial T}{\partial \xi_1} + \frac{(K_I + K_G)s_y}{h_y}\frac{\partial T}{\partial \xi_2} + K_I(s_x^2 + s_y^2)\frac{\partial T}{\partial z}\right]. \end{aligned}$$

It is resolved by using the splitting method.

Three different parameterizations of mixing in the ocean are investigated: the standard horizontal/vertical diffusion HOR, the isopycnal mixing scheme, where we use the Cox approach ISO [4]; and the Gent–McWilliams parametrization GM.

Combining all the above, the diffusion tensor can be written as

$$\begin{pmatrix} K_H + K_I & 0 & (K_I - K_G)s_x \\ 0 & K_H + K_I & (K_I - K_G)s_y \\ (K_I + K_G)s_x & (K_I + K_G)s_y & K_V + K_I(s_x^2 + s_y^2). \end{pmatrix}$$

Various combinations of coefficients give different parameterizations. Numerical experiments were conducted with the horizontal/vertical diffusion coefficients $K_H = 5 \cdot 10^5$ cm^2/s, $K_V = 0.1$ cm^2/s, the isopycnal diffusion coefficients $K_I = 5 \cdot 10^5$ cm^2/s. We keep the diffusion coefficients values as low as possible, since our advective scheme QUICKEST already includes the numerical diffusion. And as there is no clear understanding of what value the coefficient K_G should be, we took it equal to K_I. The uncertainty in the coefficient selection was also pointed out in [31]. The coefficient K_H was set to be zero, in the ISO and the GM runs, K_I was set to zero in the HOR run, and K_G was set to zero in the HOR and the ISO runs.

5. The numerical experiments

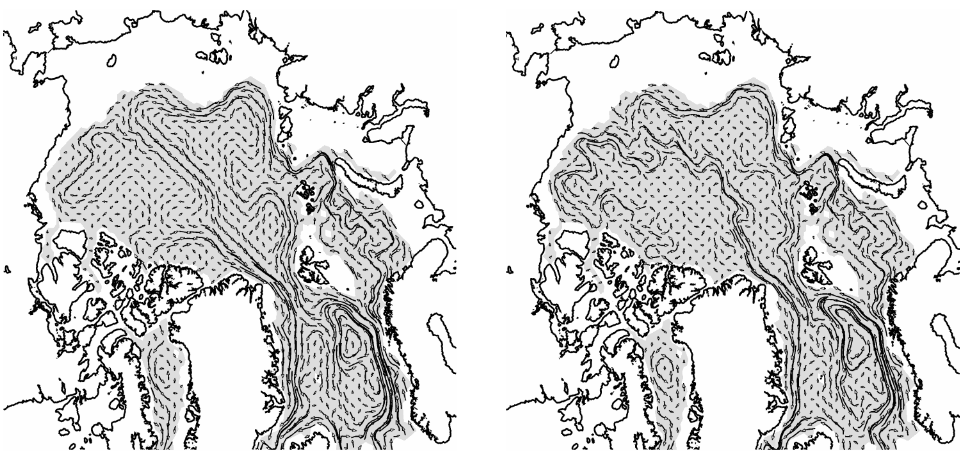
In order to evaluate the sensitivity of the Arctic ocean water state in the numerical model to the diffusion parametrization, we have carried out a series of numerical experiments. As the atmosphere forcing, we took characteristics of the atmosphere from the reanalysis data CIAF (http://data1.gfdl.noaa.gov/nomads/forms/mom4/COREv2.html). As the initial data for temperature and salinity an array of climatic Data PHC [32] was used. The period from 1948 to 2012 was taken for the simulation.

The thermohaline structure in the Arctic Ocean is forced by the atmospheric conditions and the state of water entering from the Atlantic and the Pacific Oceans. Despite numerous observational data collected during the last decades, the information is still insufficient even for restoring the Arctic Ocean circulation. The information about the temperature and salinity structure is also incomplete. Also, there is a wide variation in the simulated data during the model runs. All this indicates to the fact that relative roles of different mechanisms of formation and variability of the thermohaline structure of the Arctic Ocean are not clear. The primary source of heat in the Arctic is the warm intermediate Atlantic water.

Two branches of the Atlantic water inflow into the Arctic basin through the Norwegian Sea. Being mixed with the Arctic surface waters, the Atlantic waters generate the so-called Atlantic layer of positive temperature at depths ranging from 150 to 1,000 m. The eastern branch passes through the Barents Sea, where the Atlantic water loses most of its heat due to the mixing with shelf waters and through an intensive sea surface exchange. The second branch of the Atlantic water enters the Arctic basin through the Fram Strait.

Mixing with the cold Arctic water, it sinks to the level of intermediate waters and moves along the continental slope as a boundary current. This branch of the Atlantic water is considered to be the main source of heat in the Arctic basin, the processes of warming and cooling in the Arctic Ocean being often associated with its variability.

Therefore, when analyzing the results of the experiment we have paid a special attention to the influence of diffusion mechanisms on the circulation and state of the Atlantic water layer. The use of isopycnical and Gent McWilliams' parameterizations in the ocean numerical model has revealed several notable features. The numerical experiment comparison of three versions of the model has shown that more intensive and distinct flows were obtained in the ISO and the GM versions of the model in comparison with the results of the HOR version (Figure 1). The increase of flow intensity can be observed through the vertical section in the primary current in the Arctic (Figure 2). The results indicate that the use of diffusion along isopycnals increases the velocity in the cyclonic circulation from 2 to 6 cm/s along the Lomonosov Ridge and from 4 to 5 cm/s along the Eurasian continental slope. Moreover, the stream has become more narrow and sharper. These changes are of a local nature and appear in the upper layer only, predominantly along the continental slope. The cause of this intensification in flows is the strengthening of horizontal gradients in temperature and salinity, which leads to a difference in pressure. When horizontal diffusion runs it smoothes these gradients, and suppresses the acceleration, the diffusion along isopycnals maintains gradients of temperature, salinity, density and pressure and results in the increased flows.



a b

Figure 1. Averaged circulation in the Arctic Ocean on the depth 200 m in 1972 for model HOR (a) and ISO (b)

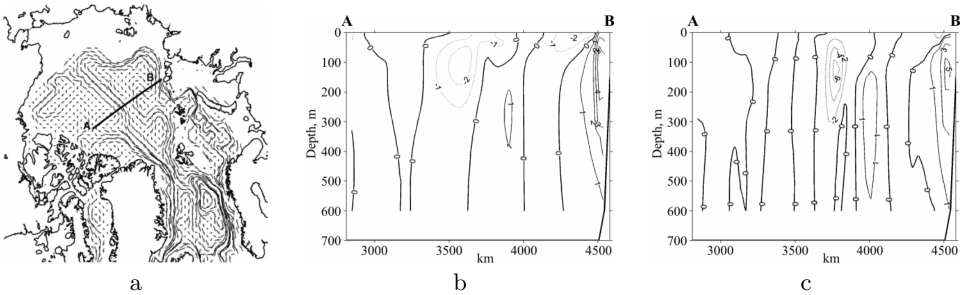


Figure 2. Location of considered section AB in the Arctic Ocean (a); velocity component in section AB (cm^2/s) in 1972 for model HOR (b) and ISO (c)

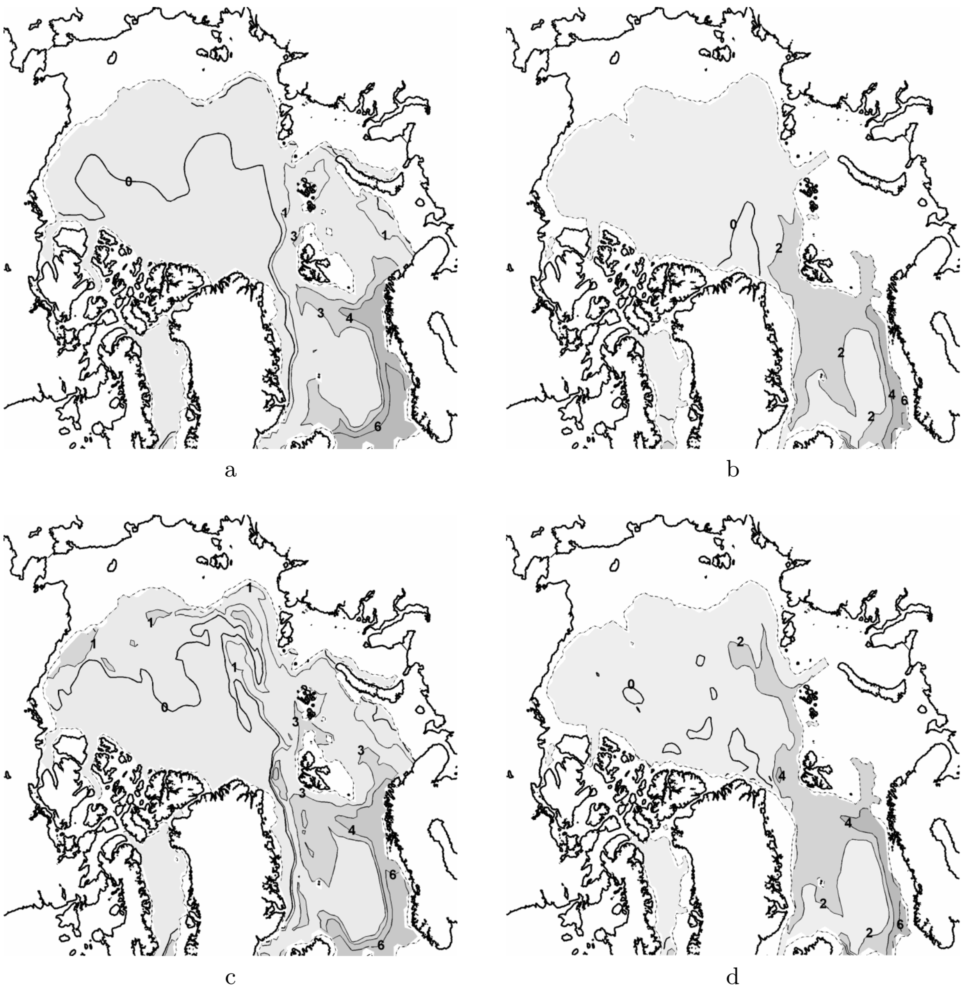


Figure 3. Temperature (°C) in 1982: HOR at the depth of 200 m (a) and 400 m (b), ISO at the depth 200 m (c) and 400 m (d)

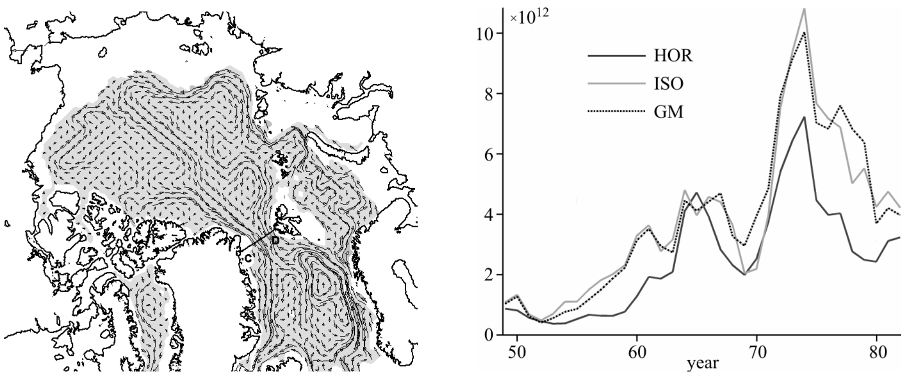


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Figure 4. Averaged heat flux (b) through the section CD (a) in the Fram Strait. Heat flux Q ($°\mathrm{C} \cdot \mathrm{cm}^3/\mathrm{s}$) is calculated as $Q = \int_{CD} T\boldsymbol{U}\, ds$, where T is the water temperature (°C), $\boldsymbol{U} = (u, v)$ is the vector of horizontal velocity components (cm/s)

Another notable result is the intensification of the heat inflow to the Arctic through the Fram Strait. Figure 3 shows the distribution of temperature at the 200 m depth and 400 m in 1982. It is seen that the ISO makes water inflow through the left branch warmer than that of in HOR. Increased heat input during the entire period of the model run is better seen in Figure 4 representing the calculated mean heat flow through the Fram Strait cross section. The use of the GM parameterizations does not result in appreciable impacts as compared to the ISO, neither in temperature and salinity fields nor in the circulation.

6. Conclusion

In the present study, we evaluate the sensitivity of the regional coupled ocean-ice circulation model to the parameterizations of subgrid scale motions. One of the results obtained is more intensive and distinct flows observed in the picture of the Arctic circulation in the ISO model release. It is also shown that the replacement of the standard horizontal/vertical diffusion by the isopycnal diffusion gives rise to a larger heat inflow to the Arctic Ocean through the Fram Strait.

The observational data record positive temperature in the Atlantic layer of less than 2 degrees [33, 34]. The temperature field reproduced by our model displays values reaching 3–4 degrees. Using the isopycnal diffusion makes the temperature in the Atlantic layer increase even stronger, and thereby, the results become less realistic. Apparently, the processes responsible for the heat transfer are not well described. In this regard, the use of this parametrization may not be always justified. As things stand now, using such parametrization can be seen as a mechanism increasing the heat inflow to the Arctic.

No significant changes were observed by the use of the GM parametrization as compared to the ISO. We have selected to add it to the isopycnal diffusion, because it is considered to be closer to the physical nature. And as there is no clear understanding of what value the coefficient of eddy stirring should be, we made it equal to K_I. Based on [35], we are expecting to obtain the appreciable impacts when investigating the variable coefficient K_G.

We have found no problems, arising in the above-mentioned papers [19–21], while using the Cox scheme, although we did not use the horizontal background diffusion. We consider that in our model, the numerical instability and negative values are smoothed by other techniques, mainly, by using the third order advection scheme QUICKEST [26]. A similar result was obtained by Weaver [36], who used the flux corrected transport algorithm as an advective scheme to eliminate numerical problems arising when applying parametrization of the isopycnal diffusion. Nevertheless, this issue is of great scientific interest and requires further study.

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