EFFECT OF SALINITY ON SEA ICE MOTION

by

Bing-Ru LI[a]***, Min-Min WANG***[b]***, Xiu-Yang LU***[b]***,***
Zhan-Hong WAN[b,c]*** *, and Song HE***[d]

[a] School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou, China
[b] Ocean College, Zhejiang University, Zhoushan, China
[c] State Key Laboratory of Satellite Ocean Environment Dynamics, Hangzhou, China
[d] University of Science and Technology Liaoning, Anshan, China

Original scientific paper
https://doi.org/10.2298/TSCI1804563L

We combined large eddy simulation (LES) with a thermodynamic slab ice model to simulate and study the sea ice motion and frazil ice dynamics in the ocean mixed layer in the Arctic winter. To show the accurate representation of leads in models, fluxes distributed laterally beneath leads and sea ice need to be parameterized. The 3-D LES model, which is developed from a 2-D turbulence model, is used to model the convection of beneath leads and sea ice. The experiments were then achived by combining the LES model with the ice model. The concentration of frazil ice was modeled using the Omstedt and Svensson model. The ice crystal radius and growth rates were assumed to be constant and the temperature and salinity changes with depth were taken into account. Salinity distribution and frazil ice concentration were influenced by ice motion, and variations in ocean salinity during freezing and thawing were also investigated. Entrained flow caused by the movement of sea ice has a significant influence on the eddy. Sea ice roughness is also important in the formation of the eddy current, and the values of the ice crystal rise velocity and the ice concentration source term coefficient influence frazil ice dynamics. The effects of sea ice thermodynamic dissipation on the sea is more remarkable, affecting the heat transfer to the atmosphere. The brine rejected during ice crystal formation and dilution of seawater are other important mechanisms of marine cyclical shocks.

Key words: *large-eddy simulation, sea ice motion, frazil ice, salinity, temperature*

Introduction

During the many decades, various studies of the sea ice have demonstrated the significant role of frazil ice. The primary sea ice forming process in the Weddell Sea and Antarctic is the transformation of frazil ice to pancake ice by wave-ice interaction on the ocean surface [1]. In the Arctic, new ice often forms on the shallow shelves through frazil ice formation [2]. The so-called Odden ice tongue in the Greenland Sea presents the dominant type exhibition of the pancake ice. Most of the old ice is driven south by the wind, exposing a cold open water surface on which new ice forms as frazil and becomes pancake ice in the rough seas. The salt rejected in ice formation dissolves back into the ocean which causes the surface water to become much denser and thus sink, even to great depts, helping to drive the entire worldwide system of surface and deep currents known as the thermohaline circulation. Frazil ice

---

* Corresponding author, e-mail: wanzhanhong@zju.edu.cn

formation in the polar ocean occurs in at least four different situations: (1) in regions of open water called leads and polynyas, (2) at the interface of two fluid layers of diiierent salinity, each at their freezing point, (3) adjacent to ice shelves and icebergs, and (4) when cold, dense brine from sea ice drains into the underlying water [3]. In Polynyas, leads and ice edges frazil ice play an important role in ice formation process [4].

Bombosch and Jenkins [5] and Jenkins and Bombosch [6] have achieved the modeling of frazil ice beneath ice shelves, but it can not further dealt with the present study. We only pay attention to frazil ice formation in the upper ocean layer and the development of modeling this phenomenon which is the subject of the various studies. Bauer and Martin [7] considered the ice formation in leads, and then Pease [8] studied the polynayas driven by wind. They pointed out the effect of the Siberian shelf polynyas in generating dense water by considering the frazil ice formation. However, there were no models about the frazil ice dynamics until a frazil ice model for the upper layers of ocean was proposed by Omstedt and Svensson [9]. The large-eddy simulation (LES) ice model in this paper is based on the frazil ice model proposed by Svensson and Omstedt [10] for the upper layers of ocean, and the crystal number continuity equation is solved for a well-mixed jar in the model.

The LES-ice model

In 1975, Cox and Weeks [11] developed a finite-difference model to predict brine expulsion in a growing saline sea-ice sheet. However, as it is inconvenient to use a model in this form, we formulate an analytical expression for brine expulsion which is a development of the work presented by Cox [12] and Cox and Weeks [11] on the relationships between temperature change and the brine and air volumes in sea-ice samples [13]. Afterwards, a frazil ice model for the upper layers of the ocean was proposed by Omstedt and Svensson [9]. Jenkins and Bombosch [6] extended this work and development a model for frazil ice beneath ice shelves. The model we describe in this paper is a combination of the models previously mentioned.

The coupling between the sea ice model and the LES model is achieved by adding sea-ice related items to the LES model, which is frequently used in simulations of particle motion [14, 15]. The equation for this combination, which includes a sea ice motion term and frazil ice term, is:

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[K_m\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\epsilon_{ijk}f_j u_k-\delta_{i3}\mathrm{g}\left(\frac{\rho'}{\rho_0}+C\frac{\rho_0-\rho_i}{\rho_0}\right) \tag{1}$$

where K_m is the sub-grid scale eddy viscosity, f – the Coriolis term; ρ' and ρ_0 – the density perturbation from the initial state, and the initial state domain averaged density, respectively, witch defined by the state equation given in Sidney [16] and modified by Jackett and McDougall [17], g is the gravity acceleration, p – the pressure, C – the concentration of frazil ice, which represents the influence of buoyancy in the process of sea ice freezing, δ_{i3} – the Kronecker delta, ϵ_{ijk} – the Levi-Civita symbol, and u_i – the velocity.

Frazil ice consists of randomly-oriented needle-shaped loose ice crystal. It is defined as the first stage during sea ice formation. In the high-latitudes, frazil ice plays an important role in the process ice growth, and in some areas of the Weddell, 80-90% of the ice is composed of frazil ice [18]. In polynyas, wind or currents periodically sweep away or break open the ice cover, which is quickly replaced by frazil ice. The rapid ice growth always accompanied by an oceanic salt flux will generate a dense outflow along the bottom of the ocean. Further, frazil ice also plays a geological and biological role in the ocean: the ice frazil can serve a sediment transfer agent to form a fine sediment layer, the frazil ice also strongly interact with the biological communities in the upper layers of the ocean [19] when frazil production is high, such as in wintertime polynyas, the brine rejected during formation may alter the regional circulation [20]. We assume that the radius of ice crystals is constant. The frazil ice concentration equation of Omstedt and Svensson model is:

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x_i}(u_i C)=\frac{\partial}{\partial x_i}\left(K_h\frac{\partial C}{\partial x_i}\right)-\frac{\partial}{\partial x_3}(w_\mathrm{r}C)+\frac{2Cq}{\rho_i R_i L} \tag{2}$$

where R_i is the disc radius q – the source term for melting and freezing, d – the ice disc thickness, w_r – the ice crystal rise velocity, which depends on the volume of the disc-shaped frazil crystal [21] as well as disc orientation and turbulence. In this paper we assume the forms of frazil ice ranging from hexagonal star to flat discs with a constant radius, which is related to the Reynolds number. Based on the model of Morse and Richard [22], w_r is approximately evaluated for frazil discs:

$$w_\mathrm{r}=\sqrt{\frac{4(\rho_0-\rho_i)\mathrm{g}\varepsilon R_i}{\rho_0 C_d}} \tag{3}$$

where ε is the aspect ratio of the frazil disc.

Freezing and melting of frazil ice affect the temperature and salinity of the water through:

$$G=\begin{cases} G_T=-\dfrac{2Cq}{\rho_0 R_i C_P} \\ G_S=-\dfrac{2SCq}{\rho_0 R_i L} \end{cases} \tag{4}$$

$$q=\mathrm{Nu}\,K_w\frac{T_\mathrm{f}-T}{d} \tag{5}$$

where where G_T and G_S are the source/sink terms in the equations for temperature and salinity, T_f – the local freezing temperature of the seawater ($= -0.054S - 7.53\cdot10^{-4}Z$), T – the local seawater temperature, Nu – the Nusselt number, and S – the salinity. Initial potential temperature and salinity profiles represent conditions observed during the Arctic leads experiment in spring 1992.

Experimental and results

Most previous ice models have been concered with the prediction of ice behavior in the context of global climate simulations, in which the timescales are very longterm compared with LES. The combined LES-ice model described in this paper includes ice features from the models of Cox and Weeks [23] and Maykut [24], parameterizes the ice-water interfaces [16], and incorporates the frazil ice production models of Svensson and Omstedt [10] and Jenkins and Bombosch [6]. We aim to accurately model salt flux between ice and ocean during the freezing or thawing of ice crystals by adding ice-related flux terms the LES equations.

The coupling of LES-ice is focused on the impact of sea ice motion and salt precipitation in the ocean mixed layer. When building the sea-ice model we assume ice crystals have uniform size, shape, growth rate, and rise velocity. The model was performed by using a domain size of 190 × 190 m in the horizontal and 50 m in the vertical with a grid spacing of

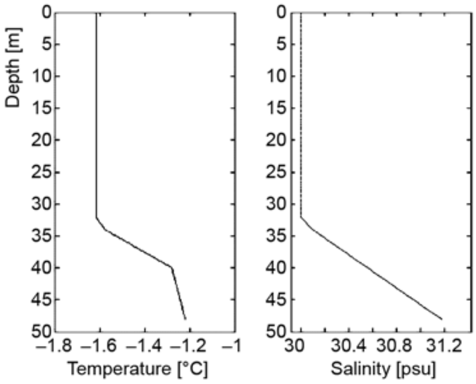

Figure 1. Initial temperature and salinity profiles representing conditions observed during the Arctic leads experiment in spring 1992

1.5 m. The initial temperature and salinity were determined by LEADEX (fig. 1). The simulation used a subgrid scale model. The boundary conditions are periodic in the lateral directions and wall at the bottom. The influence of gravity and the Earth's rotation was taken into consideration. The Simulation was run for 12 hours to allow for turbulence to develop. The effect of ice motion on the ocean mixed boundary-layer is presented by the comparison of different ice velocites given by the comparison.

Ice thickness, salinity and porosity will affect the strength of the ice. Salt plays an important role in ocean circulation. In cold, polar regions, changes in salinity affect ocean density more than changes in temperature. When salt ejected into the ocean during sea ice formation, the salinity in the water increases eventually. The upper part of the ice formed has low salinity, and the bottom has higher salinity. Thus the boundary-layer under the sea ice has the intensive salinity. The brine sinks because of increasing heavier density. To some extent, the exchange of salt between sea ice and the ocean influences ocean circulation across hundreds of kilometers.

Latitude, seasonal variation, and ocean depth also affects salinity. In the Arctic Ocean surface, salinity change is mainly due to the dilution effect of salinity precipitation and melting process on the ocean surface in the freezing process of seawater. The temperature of deep sea water is above its freezing point all year, and deep sea water flow relatively moderates salinity changes. The horizontal distribution of salinity is influenced by sea ice motion, such as frazil ice, as shown in fig. 2. Analysis of the simulation results shows that variation in salinity has important effects on the thermohaline circulation, salt transported into the deep sea promote the formation of the deep water group, which affects the thermohaline circulation.

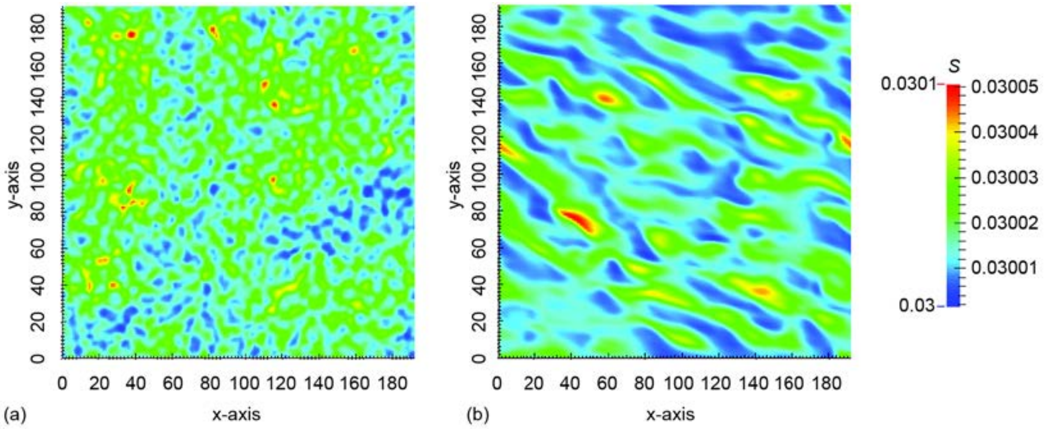

Figure 2. Salinity at a depth of 6 m after 6 hours for ice velocities of (a) 0 m/s and (b) 0.12 m/s
(*for color image see journal website*)

The effects of increased temperature and the disappearance of sea ice from the oceans are more significant. Thermal isolation by ice, diluted saline precipitation and ice melt have more significant effects on ocean stratification. Many scientists used coupled sea ice model to study the role of sea ice in the thermohaline circulation stability and its status in the process. The combination tested by Zhang *et al.* [25] showed that the heat isolation due to ice is the primary driver periodic decadal oscillation and that salt precipitation is secondary. In addition to oceanic temperature change, salt flux is also an important parameter describing the intensity of vortex. Although the upper ocean fluxes of salinity without leads are relatively small, such as ice ridges and thick ice area. In winter, most Arctic waters are covered by sea ice, so salt flux under the is an important component of the Arctic salinity budget. One measure of the vertical penetration of eddies produced at the ice-water interface is the magnitude of the horizontally averaged eddy salt, which represents the role convection may have in controlling salt flux at the base of Arctic Ocean boundary-layer. The formula of salinity is:

$$\frac{\partial \overline{S}}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{wS} - K_{\mathrm{h}}\frac{\partial \overline{S}}{\partial z}\right) + \overline{G_s} \tag{6}$$

In fig. 3 we find that the layered distribution of salinity is affected by vortex, and to a certain extent, will be destroyed. Compared to salinity distribution under the initial conditions, the salinity close to the ice surface increases significantly, but will not accumulate on the surface. The main reason for this phenomenon is that the precipitation of salts in seawater freezing process leads to the increase of upper water density which then causes a vertical convective flow that moves the denser seawater towards the ocean bottom. At the same time, from fig. 4, we find that even after sufficient time, salinity distribution in the vertical direction is basically the same, but the sea ice motions have a significant impact on salinity in the specific depth. When the sea ice is still, the vertical change in salinity from the ocean surface is smooth; when the sea ice is in motion, change in salinity fluctuates in the vertical column and salinity deposits to the bottom.

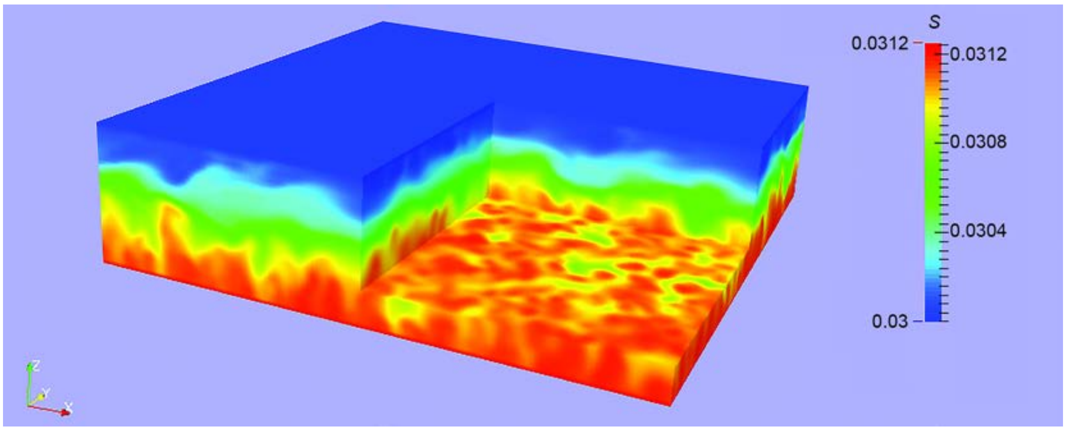

Figure 3. The 3-D cutaway view of salinity after 12 h for ice velocities of 0.12 m/s
(*for color image see journal website*)

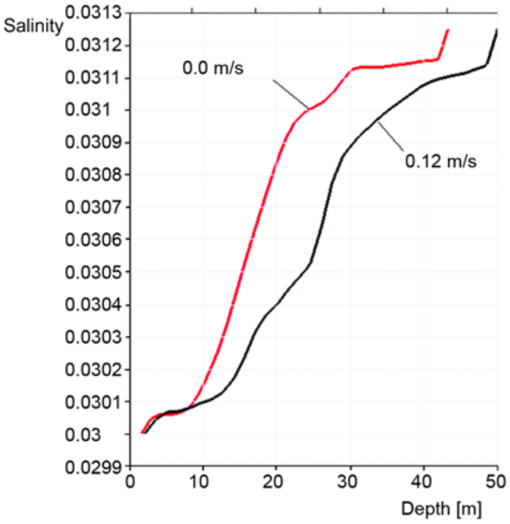

Figure 4. Salinity changed with depth after 12 hours for ice velocities of 0.0 and 0.12 m/s

Conclusions

Most studies of oceanic hydrodynamics have been concerned with boundary-layer processes. We pay attention to the influence of turbulent process under sea ice and leads. Because the ocean surface loses the fluxes of heat and salinity, a turbulent diffusion coefficient makes a strong effect on the resulting distribution of temperature. Considering the effect of brine rejection during the formation of frazil ice, the salinity profile depended on the magnitude and distribution of the turbulent diffusion coefficient. However, the distribution of temperature and salinity, in turn, also affect turbulence,which means that it is a coupling circulatory system. In this paper we have put focused on the effect of salinity change of turbulence under leads and sea ice at different ice velocites. The simulation results of LES-Ice model show the cmplexity of dynamic process in the upper ocean boundary-layer in the Arctic.

Features of ice causes a turbulent boundary-layer, which is determined by the ocean current velocities and the motion of sea ice. Ice motion is primarily driven by ocean currents and to a lesser extent by wind. When the motion of sea ice on the ocean boundary-layer is small, the convection due to brine rejection during freezing processes, creates the turbulence under leads. Furthermore, the convection will make contribution to coherent circulations associated with lead geometry and freezing rates, and will transport water into the mixed layer over some limited regions. In leads, the sea surface gains momentum from the wind and differential momentum flux may strengthen the mixing on the upper ocean sufficiently. But for the larger leads, mixing is primarily caused by Langmuir circulation due to wave-current leads [4]. Heat flux and salinity flux beneath pack ice are much less than the corresponding fluxes under leads because of the reduced surface heat flux and corresponding ice bottom freezing rate and do not typically influence turbulence as much as the bottom roughness.

Since sea ice isolates the ocean from the atmosphere, the water is no longer affected by the wind, which will not produce large wave fluctuations. Sea ice motion affects the distribution of the salinity in the turbulence model. Salinity is distributed in a cellular pattern when the ocean is covered by sea ice, but the distribution is altered by currents by ice motion. As the velocity of sea ice increases, stripes can be seen in the salinity distribution.

The change of salinity is the key variables of sea ice simulation. The isolating effect of sea ice prevents heat diffusion from the ocean into the atmosphere. Sea ice motion influences the change of saline flux and heat flux, and the fluxes decreases when sea ice velocity is lower on the ocean boundary-layer, otherwise the fluxes increase. In the Arctic Ocean, temperature and salinity gradient distribution is apparent, and the thermohaline circulation is intensive. The thermohaline circulation as an important part of the global climate system plays an important role in the global heat transfer.

Acknowledgments

The Support by the National Key Research & Development Plan of China (No. 2017YFC1403306), and National Natural Science Foundation of China (No. 11572283, 10902097), and the Open Fund of State Key Laboratory of Satellite Ocean Environment Dynamics (No. SOED0901) are gratefully acknowledged.

References

[1] Wadhams, P., *et al.*, The Ice Thickness Distribution Across the Atlantic Sector of the Antarctic Ocean in Midwinter, *Journal of Geophysical Research: Oceans, 92* (1987), C13, pp. 14535-14552
[2] Svensson, U., Anders, O., Numerical Simulations of Frazil Ice Dynamics in the Upper Layers of the Ocean, *Cold Regions Science and Technology, 28* (1998), 1, pp. 29-44
[3] Morison, J. H., *et al.*, The Oceanography of Winter Leads, *Journal of Geophysical Research: Oceans, 97* (1992), C7, pp. 11199-11218
[4] McPhee, M. G., Turbulent Heat Flux in the Upper Ocean under Sea Ice, *Journal of Geophysical Research: Oceans, 97* (1992), C4, pp. 5365-5379
[5] Bombosch, A., Jenkins, A., Modeling the Formation and Deposition of Frazil Ice Beneath Filchner-Ronne Ice Shelf, *Journal of Geophysical Research: Oceans, 100* (1995), C4, pp. 6983-6992
[6] Jenkins, A., Bombosch, A., Modeling the Effects of Frazil ice Crystals on the Dynamics and Thermodynamics of Ice Shelf Water Plumes, *Journal of Geophysical Research: Oceans, 100* (1995), C4, pp. 6967-6981
[7] Bauer, J., Martin, S., A Model of Grease Ice Growth in Small Leads, *Journal of Geophysical Research: Oceans, 88* (1983), C5, pp. 2917-2925
[8] Pease, C. H., The Size of Wind-Driven Coastal Polynyas, *Journal of Geophysical Research: Oceans, 92* (1987), C7, pp. 7049-7059
[9] Omstedt, A., Svensson, U., Modeling Supercooling and Ice Formation in a Turbulent Ekman Layer, *Journal of Geophysical Research: Oceans, 89* (1984), C1, pp. 735-744
[10] Svensson, U., Omstedt, A., Simulation of Supercooling and Size Distribution in Frazil Ice Dynamics, *Cold Regions Science and Technology, 22* (1994), 3, pp. 221-233
[11] Cox, G. F. N., Weeks, W. F., Equations for Determining the Gas and Brine Volumes in Sea-Ice Samples, *Journal of Glaciology, 29* (1983), 102, pp. 306-316
[12] Cox, G. F. N., Thermal Expansion of Saline Ice, *Journal of Glaciology, 29* (1983), 103, pp. 425-432
[13] McPhee, M. G., *et al.*, Dynamics and Thermodynamics of the Ice/Upper Ocean System in the Marginal Ice Zone of the Greenland Sea, *Journal of Geophysical Research: Oceans, 92* (1987), C7, pp. 7017-7031
[14] Wan, Z. H., *et al.*, An Integrated Turbulent Simulation and Parameter Modeling Study on Sea-Spray Dynamics and Fluxes, *Ocean Eng., 130* (2017), Jan, pp. 64-67
[15] Zhu, J. B., *et al.*, Modeling of Sea Spray Droplets in the Ocean, *Thermal Science, 18* (2014), 5, pp. 1577-1582
[16] Sidney, B. C., Tenth Report of the Joint Panel on Oceanographic Tables and Standards, UNESCO Technical Papers in Marine Science, 1981, 36, pp. 24-24
[17] Jackett, D. R., McDougall, T. J., Minimal Adjustment of Hydrographic Profiles to Achieve Static Stability, *Journal of Atmospheric and Oceanic Technology, 12* (1995), 2, pp. 381-389
[18] Lange, M. A., *et al.*, Development of Sea Ice in the Weddell Sea, *Annals of Glaciology, 12* (1989), 1, pp. 92-96
[19] Ackley, S. F., Sullivan, C. W., Physical Controls on the Development and Characteristics of Antarctic Sea Ice Biological Communities – A Review and Synthesis, *Deep Sea Research Part I: Oceanographic Research Papers, 41* (1994), 10, pp. 1583-1604
[20] Schumacher, J. D., *et al.*, Effects of a Shelf Polynya on Flow and Water Properties in the Northern Bering Sea, *Journal of Geophysical Research: Oceans, 88* (1983), C5, pp. 2723-2732
[21] Gosink, J. P., Osterkamp, T. E., Measurements and Analyses of Velocity Profiles and Frazil Ice-Crystal Rise Velocities during Periods of Frazil-Ice Formation in Rivers, *Annals of Glaciology, 4* (1983), 1, pp. 79-84
[22] Morse, B., Richard, M., A Field Study of Suspended Frazil Ice Particles, *Cold Regions Science and Technology, 55* (2009), 1, pp. 86-102

[23] Cox, G. F., Weeks, W. F., Changes in the Salinity and Porosity of Sea-Ice Samples during Shipping and Storage, *Journal of Glaciology, 32* (1986), 112, pp. 371-375
[24] Maykut, G. A., Energy Exchange over Young Sea Ice in the Central Arctic, *Journal of Geophysical Research: Oceans, 83* (1978), C7, pp. 3646-3658
[25] Zhang, S., *et al.*, A Decadal Oscillation Due to the Coupling between an Ocean Circulation Model and a Thermodynamic Sea-Ice Model, *Journal of Marine Research, 53* (1995), 1, pp. 79-106

Paper submitted: December 13, 2016
Paper revised: January 4, 2017
Paper accepted: February 2, 2017

© 2018 Society of Thermal Engineers of Serbia.
Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.
This is an open access article distributed under the CC BY-NC-ND 4.0 terms and conditions.