Response letter to the referee #2

We sincerely thank the reviewer for the comments on our manuscript. Your suggestions are of great significance to improve the scientific rigor of our manuscript. All the comments and suggestions have been carefully considered. For the major revision comments, we have formulated specific revision plans; for some minor revision comments, we have made directly modifications in the revised manuscript. The detailed author responses are as follows.

This study presents a comparison of ice-ocean drag coefficient parameterization schemes in the Bohai Sea, a low-latitude thin-ice region. The research topic has clear regional application value, revealing the compositional characteristics of the ice-ocean drag coefficient in the thin-ice environment of the Bohai Sea and providing a reference for the optimization of parameterization in sea ice simulations of low-latitude shelf seas. However, the manuscript has significant issues in language expression, structural logic, results and its presentation, and figure design. In addition, there are deficiencies in the details of the model methodology, quantitative support for comparative analysis, and comparisons with observational data and previous studies. Specific comments are as follows:

Comment1:

The overall language lacks rigor and objectivity, and grammatical errors are present(e.g., the abstract). A professional scientific language polish is necessary. Numerous non-native English expressions are identified throughout the text, including awkward sentence structures, inappropriate preposition usage, subject-verb disagreement, and overuse of the passive voice. Inconsistent expressions are found for the same physical quantity (e.g., “marginal ice zone” is abbreviated as MIZ abruptly in subsequent sections without initial labeling, causing confusion for readers). Some technical terms are translated or expressed non-uniformly (e.g., “skin drag” is redundantly referred to as “surface skin drag” without a consistent nomenclature). A small number of colloquial expressions are used in this academic paper (e.g., phrases such as “it can be seen that” and “this behavior stems from” could be more concise and straightforward).

Reply:

We sincerely thank the reviewer’s comment and suggestion on our language and grammatical issues. We will polish the language of the entire text and correct the unprofessional terms in the revised manuscript. We will conduct a comprehensive examine and correction to the inconsistent expressions for the same physical quantity, including but not limited to the “skin drag” as pointed out by the reviewer. At the same time, we will revise the colloquial expressions in the text (change the phrases such as “it can be seen that” to “this behavior stems from”) to make it more professional and concise.

Regarding the “marginal ice zone” mentioned by the reviewer, we have already indicated the full name and the abbreviation in the original manuscript at the place where it first appeared, please refer to the lines 152-153 in the original manuscript: *“with significantly higher drag coefficients (approximately* $3.0-4.0\times10^{-3}$*) near* ***the marginal ice zone (abbreviated as MIZ)*** *compared to interior regions (*$1.0-2.5\times10^{-3}$*)”*

Comment2:

The C_{dw} parameterization scheme from TS2014 employed in this study was originally developed for Arctic conditions, and its applicability to the Bohai Sea, which is a low-latitude shelf sea with a water depth of approximately 30 m remains unvalidated. The applicability of the same constant parameters selected in schemes to the Bohai Sea has also not been verified. Furthermore, while the TS2014 parameterization scheme is adopted, the ridging geometric parameterization from this study is not used; instead, the parameterization from Steiner (1999) in Scheme 1 is applied for TS2014. In sea ice model, ridging parameterization serves as input data for the drag coefficient and exerts a critical influence on simulation results. This approach is inappropriate when compared the Scheme 1 and Scheme 2.

Reply:

We appreciate the reviewer's comment, and fully agree with your core judgment that ridging parameterization is a critical input for C_{dw} calculation, and the discussion of the regional applicability of parameterization scheme is necessary. We will make targeted revisions as follows:

Firstly, The TS2014 parameterization scheme originally developed for Arctic conditions needs to be verified for its applicability in the Bohai Sea. This parameterization scheme mainly calculates the ice-ocean drag coefficient C_{dw} based on several core variables: the grid-averaged spacing and height of the ice keel, ice thickness and ice concentration. Among them, the grid-averaged spacing and height of the ice keel are calculated through the energy balance equation (Equations A8-A13 in the appendix of the original manuscript) based on the deformation energy diagnosis. The ice thickness and ice concentration are the basic output variables of sea ice model. The aforementioned variables have already taken into account the specific environment of the Bohai Sea, not the variables that were pre-defined for the Arctic scale. Given that the core variables of this scheme are inherently parameters of marine environmental adaptability, we consider that it is feasible to introduce this scheme into the numerical simulation of sea ice in the Bohai Sea.

Furthermore, some empirical constants in the scheme also require attention to their adaptability to the sea ice in the Bohai Sea. According to the ice condition forecasts from the National Marine Forecasting Center, the predominant ice types in the main ice areas of the Bohai Sea are pancake ice, nilas and grey-white ice, with floe diameters ranging approximately from 0.3 to 3 m. Therefore, we will adjust the length of the ice floe from the Arctic size to the Bohai Sea size, setting the minimum ice floe length L_{min} from 8 (m) to 0.3 (m) and the maximum ice floe length L_{max} from 300 (m) to 3 (m).

The above discussion on the applicability of the TS2014 parameterization scheme to the sea ice in the Bohai Sea will be supplemented in the revised manuscript.

Secondly, regarding the issue "the TS2014 parameterization scheme is adopted, the ridging geometric parameterization from this study is not used; instead, the parameterization from Steiner (1999) in Scheme 1 is applied for TS2014" pointed out by the reviewer, we sincerely apologize for the incorrect citation of the article corresponding to Scheme1 in the original manuscript, which caused confusion for the reviewer.

Scheme1 (Large-scale roughness-based parameterization) was proposed by Steiner et al. (1999), it was wrongly labeled as Steiner et al. (1999) in the original manuscript. While, the calculation method of the grid-averaged height of ice keel $\boldsymbol{h_{km}}$ in Scheme2 (TS2014: Small-scale geometric roughness-based parameterization) was proposed by Steiner et al. (1999). In the article of Steiner et al. (1999), the grid-averaged height of ice keel $\boldsymbol{h_{km}}$ is derived inversely based on the proportional relationship between the potential energy of ice ridges and the deformation energy, which is exactly the method adopted by Tsamados et al. (2014).

Therefore, we did not actually transplant the ice ridge parameter (i.e., the grid-averaged height of ice keel $\boldsymbol{h_{km}}$) calculation method from Scheme1 to Scheme2. The corresponding incorrect statement has been revised in the revised manuscript to provide a clearer and more explicit description of the two parameterization schemes.

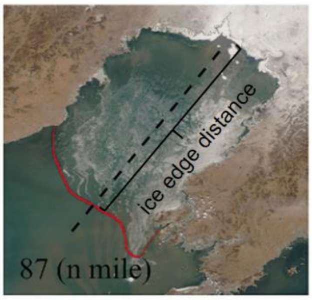
Comment3:

The study only uses data from a single freeze-melt ice season (2011.11–2012.5). A longer series of simulation results should be compared to enhance the generalizability of the findings. The result comparisons in the manuscript are also based on single-day results selected for different stages of this single ice season (e.g., Day 50, Day 70), which is unreasonable.

Reply:

We appreciate the reviewer's suggestion. Currently, the manuscript evaluates and compares the two ice–ocean drag coefficient parameterization schemes based on a single ice season (the 2011/2012 ice season). This ice season was selected because it represents the typical ice conditions for a normal ice year in the Bohai Sea, capturing the general characteristics of sea ice in this region. Moreover, the significant ice fluctuations driven by cold air fronts during this season provide a valuable case for evaluating the model's response under varying meteorological forcing conditions. Furthermore, from a practical perspective, the satellite remote sensing scatter data on sea ice extent in the Liaodong Bay during this ice season are sufficiently abundant to allow for a comparison with the simulated sea ice extent in the Liaodong Bay across the entire ice season (as shown in Figure 5). As the reviewer pointed out, including simulations from additional ice season is important for the robustness of the conclusions. Therefore, in the revised manuscript, we preliminary plan to add simulations for the 2015/2016 ice season with severe ice condition, in order to evaluate the performance of the two parameterization schemes more comprehensively. PS: Depending on the availability of observational data, the additional ice season may be subject to adjustment in the future.

For the 2011/2012 ice season, we strive to present the spatiotemporal variations of sea ice as comprehensively as possible. In the original manuscript, the time series over the entire ice season of the sea ice extent in the Liaodong Bay (Figure 5), as well as the ice-covered area-averaged ice thickness, ice concentration, and the ice-ocean thermodynamic variables in the Bohai Sea (Figures 10 and 11) were presented. And the spatial distributions of the drag coefficient, ice thickness, ice concentration, and ice drift velocity on typical ice days of the five ice stages were also presented. Following the reviewer's comment, we will include additional comparisons of simulation results in the revised manuscript. These will include the time series of the ice edge distance in Liaodong Bay (defined as the distance between the intersection of the Liaodong Bay central axis and the ice edge line, and the axis apex. Please refer to the picture below) over the entire ice season, as well as the ice-on date, ice-off date, and the ice season length. Model validation will also be conducted based on the observational data for these variables.



Comment4:

The logical of the manuscript needs to be polished. For example, in the Introduction section: the transition from the general discussion of Bohai Sea ice and sea ice dynamics directly to the ice-ocean drag coefficient is extremely abrupt, leaving readers unable to understand the specific role and position of the drag coefficient. Concise language should be added to clarify that where it is affected at ice-ocean interface, and how it indirectly affects the heat flux at the ice-ocean interface through momentum exchange. The manuscript also fails to combine the regional characteristics of the Bohai Sea to analyze the differences in drag coefficient parameterization between the Bohai Sea and Arctic/high-latitude sea ice regions, resulting in insufficient groundwork. Additionally, it only generally states that "related research is scarce" without sorting out the specific problems in the setting of drag coefficients in existing Bohai Sea ice simulations (e.g., which simulation results exhibit biases due to the use of a constant drag coefficient). In fact, studies comparing drag coefficient schemes do exist, such as Bernner et al. (2021).

Reply:

We thank the reviewer for the suggestion and the valuable reminder. Firstly, we will improve the Introduction section of the revised manuscript by adding the following transitional description between the general discussion of sea ice and ice dynamics in the Bohai Sea and the introduction of the ice–ocean drag coefficient:

The ice-ocean drag coefficient, which is responsible for regulating the momentum exchange at the ice-ocean interface, is a critical coefficient in the sea ice dynamics module. The ice-ocean drag coefficient depends on factors such as the size, shape,

roughness of ice floe, and the sea ice concentration, directly influencing the interfacial stress between sea ice and seawater and thus affecting the sea ice velocity; it also indirectly affects the heat flux at the ice-ocean interface by regulating the intensity of the ice-ocean turbulence.

Secondly, as the reviewer pointed out, it is necessary to analyze the differences in drag coefficient parameterization scheme between the Bohai Sea and the Arctic/high-latitude sea ice regions by taking into account the regional characteristics of the Bohai Sea. Therefore, we will adjust the region-dependent constants in Scheme2—the minimum ice floe length L_{min} and the maximum ice floe length L_{max}—to make them consistent with the typical floe sizes observed in the Bohai Sea.

Finally, we thank the reviewer for raising the issue regarding the review of the current research on the ice-ocean drag coefficient. We would like to clarify that a systematic comparative analysis of ice–ocean drag coefficients specifically for sea ice in the Bohai Sea is indeed lacking at present, and this constitutes the primary research objective of our paper—to introduce two ice-ocean drag coefficient parameterization schemes into the sea ice modeling of the Bohai Sea and to compare their simulation performance. Regarding systematic comparative analyses of ice–ocean drag coefficients in other sea areas, we will further review and supplement the Introduction section by fully referencing relevant studies such as Brenner et al. (2021).

Comment5:

The description of the development of drag coefficient parameterization in the Introduction is not accurate. In reality, Arya and Hanssen-Bauer & Gjessing (1988) proposed different drag partitioning methods based on distinct ice zone characteristics. Mai (1996) combined these methods. Steele et al. (1989) developed ice-ocean parameterization by referring to atmospheric boundary layer studies. This review section should be revised to be more accurate and comprehensive.

Reply:

We sincerely thank the reviewer for the correction. We will revise the description of the development of drag coefficient parameterization in the Introduction as suggested by the reviewer.

Comment6:

The second chapter contains excessive descriptive text about the model while lacking key information. Given that this study focuses on sea ice dynamic behavior, it should emphasize the governing equations and related processes of the sea ice dynamic module. The specific role and position of the drag coefficient are not clearly explained throughout the entire manuscript.

Reply:

We thank the reviewer for the suggestion and valuable reminder. In the revised manuscript, we will remove the redundant model description in Section 2 and add a new subsection after Section 2.1 to provide a detailed introduction to the sea ice dynamics equations, with a particular emphasis on the role and position of the ice–ocean drag coefficient.

The new subsection is as follows:

2.2 The dynamic equations related to the $\mathrm{C_{dw}}$

The dynamic processes of sea ice, including its drift and deformation, are simulated based on the momentum conservation and rheology. In the Cartesian coordinate system, sea ice drift velocity can be described by the differential equation of drift velocity:

$$\frac{D(m\boldsymbol{V_i})}{Dt} = \boldsymbol{\tau_a} + \boldsymbol{\tau_w} - mf\boldsymbol{k} \times \boldsymbol{V_i} - mg\nabla\eta - \nabla \cdot \boldsymbol{\sigma}, \qquad (1-5)$$

where the left-hand side term is the material derivative; $D/\mathrm{D t} = \partial/\partial \mathrm{t} + \boldsymbol{V} \cdot \nabla$, where $\boldsymbol{\tau_a}$ is the air-ice interfacial stress and $\boldsymbol{\tau_w}$ is the ice-ocean interfacial stress, f is the Coriolis parameter, g is the gravitational acceleration, η is the sea surface height, and $\boldsymbol{\sigma}$ is the sea ice stress tensor.

The ice-ocean interfacial stress $\boldsymbol{\tau_w}$ is commonly described using the quadratic bulk formula (Mcphee, 1979):

$$\boldsymbol{\tau_w} = \rho_w C_{dw} |\boldsymbol{V_w} - \boldsymbol{V_i}| \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} (\boldsymbol{V_w} - \boldsymbol{V_i}) \ , \qquad (1-6)$$

where ρ_w is the density of seawater, $\boldsymbol{V_w}$ is the ocean current velocity, $\boldsymbol{V_i}$ is the ice-drift velocity, θ is the rotation angle of ocean induced by the Coriolis force. The ice-ocean drag coefficient C_{dw} is a key parameter that describes the efficiency of horizontal momentum exchange between sea ice and the ocean. The equations of the two parameterization schemes of C_{dw} applied in this study, which utilize representations of sea ice roughness at different spatial scales, will be described in detail in Appendix A.

Comment7:

The results are confused, with extensive mechanistic analysis interspersed throughout, leading to logical discontinuities. The influence mechanism should be clearly elaborated upfront. The core function of the results section should be to systematically and objectively present simulation data comparisons with observational data. However, this issue is prevalent in Sections 3.1 to 3.3 of the manuscript. In particular, Section 3.3, along with Figures 9 and 12, contains extensive content on how C_{dw} influence on the sea ice thermodynamic processes. It makes readers confused.

Reply:

Thank you very much for this precise and constructive comment. We will restructure the manuscript by presenting the analysis of experimental results and the discussion of mechanisms as two separate sections. The specific revisions are as follows:

1. We will add a general introductory paragraph at the Introduction (Section1) and a new subsection after Section 2.1 to provide a detailed introduction to the sea ice dynamics equations (as mentioned in Reply6). The mechanism of how C_{dw} affect the sea ice dynamic-thermodynamic processes can be elaborated in the above content.

2. The content of the Conclusions (Section 3) is limited to the analysis and validation of the experimental results. Specifically including:1) the comparison and quantitative

analysis of the ice variables (ice extent, ice edge distance, ice-on date, ice-off date, ice season length) between the simulated results by two schemes and observational data; 2) the subsequent discrepancy analysis of the existed simulated ice variables (drag coefficients, ice concentration, ice thickness, ice-drift velocity) between the two schemes.

3. All the mechanism analysis will be placed separately in the Discussion (Section 4). The influence of C_{dw} on the ice processes at the ice-ocean interface and the air-ice interface will be presented in this section.The content of the Discussion (Section 4):

Section 4.1: Impact on ice-ocean interface variables

Section 4.2: Impact on air-ice interface variables

Comment8:

Transitions between sections are lacking, and the research thread is unclear. For instance, there are no transitional sentences between Section 3.1 (drag coefficient distribution) and Section 3.2 (sea ice variables), and between Section 3.3 (ice-ocean interface variables) to explain how differences in the drag coefficient affect subsequent sea ice variables. This prevents readers from establishing the logical link of "parameterization scheme → drag coefficient → sea ice variables".

Reply:

We thank the reviewer for the suggestion and valuable reminder. In the revised manuscript, we will add transitional explanations between sections to more clearly present the logical chain of "parameterization scheme → drag coefficient → sea ice variables" throughout the manuscript.

Comment9:

The comparative is confused, and observational references are lacking. Few of the core figures include observational data, only presenting comparisons between Scheme 1, Scheme 2, and their differences: Figures 3 (drag coefficient), 6 (ice concentration), and 7 (ice thickness) only show the distributions of the two schemes and their differences, without overlaying the spatial distribution of observational data, making it impossible for readers to judge which scheme is more consistent with real-world conditions. Also Figure 8. A large number of difference plots (Scheme 1 – Scheme 2) are used in the manuscript, but the physical meaning of the differences (e.g., positive values indicate Scheme 1 is greater than Scheme 2) is not clearly defined in the figure captions. Difference plots should only serve as supplementary materials, the core comparative plots should be "Scheme 1 vs. observations" and "Scheme 2 vs. observations".

In fact, directly comparing the C_{dw} results and their component proportions of Scheme 1 and Scheme 2 is scientifically meaningless, as there is no direct observational data to verify and indicate which is more realistic or deviated. Instead, meaningful comparisons should be made by contrasting sea ice physical variables (e.g., ice extent, thickness) and related thermodynamic coefficients influenced by different parameterization schemes with validated observational data.

Reply:

We thank the reviewer for the suggestion and valuable reminder. We are currently conducting broader data collection of observational sea ice data in the Bohai Sea for specific ice seasons. Because global sea ice datasets lack sufficient accuracy in the Bohai Sea region, we had to obtain observational information on Bohai sea ice solely from official forecasting platforms (e.g., the National Marine Environmental Forecasting Center) and relevant articles. This leads to certain spatiotemporal discontinuities in the collected observational data, with relatively continuous satellite-retrieved data available only for the sea ice extent and the ice edge distance of the Liaodong Bay.

At present, the available and validated sea ice observational data in the Bohai Sea are mainly macro-scale statistical products, including the time series of sea ice extent, the ice edge distance in Liaodong Bay, and visible satellite images of sea ice spatial coverage. However, there is no long-term, grid-by-grid observational product of sea ice concentration and ice thickness that covers the entire Bohai Sea and matches the spatial resolution of our model. The in-situ observation of sea ice in the Bohai Sea is mainly limited to a few shore-based fixed stations and sporadic ship-based surveys, which cannot form full-coverage grid-based observational data matching the model grid.

Nevertheless, we will collect as much observational data as possible to supplement the validation of simulations from both schemes. In addition to the satellite-retrieved time series of sea ice extent in the Liaodong Bay already presented, we will supplement the revised manuscript with observational data including the time series of the ice edge distance in the Liaodong Bay, ice-on date, ice-off date, ice season length, and scattered point data on ice thickness. Furthermore, additional quantitative metrics—such as root mean square error (RMSE), correlation coefficient (R), and mean relative deviation (MRD)—will be employed to evaluate the simulation performance of the two parameterization schemes.

Regarding the differential analysis of the two schemes, we will add a note in the figure captions clarifying the meaning of the difference value (i.e., Positive values denote Scheme1 > Scheme2, and negative values denote Scheme1 < Scheme2.).

Comment10:

Discussion and Conclusions sections: mechanistic analysis is overly qualitative, comparisons with previous studies are insufficient, and the analysis of study limitations is incomplete.

Reply:

We thank the reviewer for the suggestion and valuable reminder. Additional quantitative metrics will be introduced in the results analysis section of the revised manuscript, including root mean square error (RMSE), correlation coefficient (R), and mean relative deviation (MRD). In addition, comparisons with previous studies which using the constant drag coefficient setting in Bohai Sea ice simulations, as well as the analysis of study limitations will be supplemented in the Discussion section.

Comment11:

Other minor details require careful checking, such as problems with formula labeling and numbering, the units of parameters, and the format of references.

Reply: We thank reviewer for the kind reminder. We will thoroughly check all details of the manuscript, including equation labeling and numbering, parameter units, and reference formatting.

Comment12:

Appendix B is overly verbose and logically disorganized. These results are from TS2014 not authers, and the manuscript should directly specify the general formula of C_{dw}, its three components, and the determination of input parameters and data for each component. The descriptions in the appendix are repetitive. Otherwise, Figure A1 is not a “we proposed a simplified model⋯.”, but a simplified sea ice model designed for deriving the parameterization scheme in the TS2014 study. The description should be objective and realistic.

Reply:

We appreciate the reviewer’s suggestion. We have simplified and reorganized the Appendix, removed the redundant content, directly specified the general formula of C_{dw}, its three components, and the determination of input parameters and data for each component. We also describe the modifications made to the constant parameters of the TS2014 parameterization scheme in response to the specific ice conditions of the Bohai Sea, namely the region-specific adjustments of the minimum and maximum ice floe lengths.

The revised Appendix A is as follows:

Appendix A

1 Scheme1: Large-scale roughness-based parameterization

In the original ice-ocean drag coefficient parameterization scheme of the model (i.e., the scheme1), the magnitude of the ice-ocean drag coefficient is mainly determined by the bottom surface roughness of sea ice. This parameterization scheme using deformation energy R to characterize large-scale sea ice roughness was first proposed by Steiner et al. (1999). Here, the deformation energy R reflects the accumulation of deformation of sea-ice by internal forces. In this scheme, the ice-ocean drag coefficient C_{dw} is parameterized as a function of the deformation energy R and the ice concentration A_i:

$$C_{dw} = m_w R + b_w - 4d_w \left(A_i - \frac{1}{2}\right)^2 + d_w \ , \tag{A1}$$

where b_w is the ice-ocean interfacial skin drag constant, which represents the skin drag portion. Except for b_w, all the terms on the right side of the equal sign collectively represent the form drag portion. $\mathrm{m_w}$ and $\mathrm{d_w}$ are the form drag constants. The deformation energy R is introduced as a scalar ice property variable governed by dynamic and thermodynamic processes. For a detailed derivation, please refer to Steiner et al. (1999). Here, A_i represents ice concentration. The setting values of the constant parameters in Scheme1 are shown in Table A1.

Table A1. The constant parameter settings of Scheme1.

	Parameterization Scheme1
m_w	4.0×10^{-8}
b_w	1.2×10^{-3}
d_w	2.6×10^{-3}

2 Scheme2: Small-scale geometric roughness-based parameterization

Different to the original scheme of the model (Scheme1), Scheme2 involves the geometric elements generated by the deformation of sea ice within the grid to calculate the ice-ocean drag coefficient. Here, the small-scale geometric roughness elements refer to the geometric elements for ice pressure ridges, which includes the ice sails (the above-water portions) and ice keels (the submerged portions). Based on existing descriptions of ice pressure ridge profiles (Davis and Wadhams, 1995; Steiner et al., 1999; Kovacs, 1970; Tsamados et al., 2014), a simplified idealized ice floe model can be established (see Fig. A1). Assuming a grid with a transverse length of L_x, longitudinal length of L_y, and the total area of the grid (S_T) contains an idealized ice floe model with N ridges distributed linearly along the longitudinal direction. Each ice ridge has a length of L_y, with an average ice floe length (x-direction) of L ($L \ll L_x$) and an average ice floe spacing of D_f. The true ice thickness is defined as $D_{ice} = H_i / A_i$, where H_i is the ice thickness and A_i is the ice concentration. Here, the freeboard height and draft depth are denoted as h_f and h_d, respectively. The overall height of the ice ridge is the sum of h_{sm} for sail and h_{km} for keel, with grid-averaged spacings of between adjacent sails D_{sm} and between adjacent keels D_{km}. Unlike multiyear ice, which typically exhibits a Gaussian-shaped cross-section, first-year ice ridges tend to have triangular profiles at both the sail and keel tops.

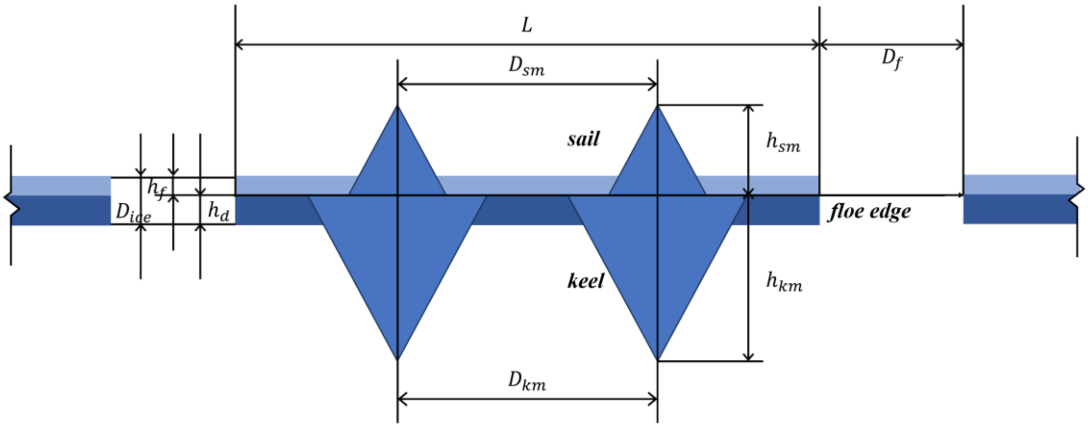


Figure A1: The idealized ice floe model features an ice floe with a length of L and a spacing of D_f. The above-water portions of the ice ridges, referred to as sails, have a grid-averaged spacing of D_{sm} and a grid-averaged height of h_{sm}. Correspondingly, the submerged portions, known as keels, exhibit a grid-averaged spacing of D_{km} and a grid-averaged height of h_{km}. The true ice thickness D_{ice} includes the freeboard height h_f and the draft depth h_d.

2.1 Total ice-ocean drag coefficient

According to the drag partitioning theory of Arya (1975), the total ice-ocean drag coefficient C_{dw} can be decomposed into form drag induced by obstacles (e.g., ice ridges or floes) and skin drag arising from tangential shear in the intervening areas:

$$C_{dw} = C_{dw}^{r} + C_{dw}^{s} + C_{dw}^{f} \ , \qquad \text{(A2)}$$

where C_{dw}^{r} is the form drag coefficient related to ice keels, C_{dw}^{s} is the skin drag coefficient, and C_{dw}^{f} is the form drag coefficient related to ice floe edge.

2.2 General form of the form drag coefficient

In this parameterization scheme, the general form of the form drag coefficient was derived by Tsamados et al. (2014):

$$C_{dw} = \frac{NcS_c^2 gL_yH}{2S_T}\left[\frac{\ln(H/z_0)}{\ln(10/z_0)}\right]^2 \ , \qquad \text{(A3)}$$

where N represents the number of obstacles (e.g., ice ridges or floes) with longitudinal length L_y within a grid of area S_T, c is the drag constant which account for drag on individual elements. H is the obstacle height, and z_0 is the roughness length. g denotes a geometric factor dependent on obstacle shape. For uniformly distributed linear obstacles, the geometric factor g can be obtained through directional averaging of the angle θ between the obstacle normal and flow direction, expressed as $g = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{1}{\pi} cos\theta d\theta$. Here, S_c is the sheltering function. The sheltering effect has significant physical implications as it describes how upstream obstacles modify water flow by creating drag and subsequent turbulent wakes. This wake effect reduces the current velocity experienced by downstream obstacles, thereby effectively decreasing downstream drag (Arya, 1975; Steele et al., 1989). In MIZ where ice ridges and floes exhibit irregular geometries, the sheltering effect becomes particularly pronounced (Tsamados et al., 2014). For modelling purposes, Tsamados et al. (2014) employed a sheltering function S_c:

$$S_c = \left[1 - \exp\left(-s_l \frac{D}{H}\right)\right]^{1/2}, \qquad \text{(A4)}$$

Here, s_l is the attenuation parameter, employing the value $s_l = 0.18$ proposed by Hanssen-Bauer and Gjessing (1988). D represents the distance between obstacles, and H denotes obstacle height.

2.3 Form drag coefficient related to ice keels C_{dw}^{r}

Building upon the ice ridge parameterization scheme of Tsamados et al. (2014), the total ridge length per unit ice area $\frac{NL_y}{A_i S_T}$ in Eq. (A3) is given by $\frac{NL_y}{A_i S_T} = \frac{\pi\mu}{2}$, where $\mu = \frac{1}{D}$ represents the number of ridges per unit track length, with D being the ridge spacing. By incorporating the small-scale geometric roughness elements (grid-averaged height of ice keel h_{km} and grid-averaged spacing of ice keel D_{km}), the expression for C_{dw}^{r} can be obtained as:

$$C_{dw}^{r} = \frac{1}{2} c_{kw} S_c^2 \frac{h_{km}}{D_{km}} A_i \left[\frac{\ln(h_{km}/Z_{0i})}{\ln(10/Z_{0i})}\right] , \qquad \text{(A5)}$$

where A_i is the sea ice concentration, $c_{kw} = 0.2$ denotes the local form drag constant, and z_{0i} represents the roughness length of level ice. Here, the calculation methods of h_{km} and $\mathrm{D_{km}}$ adopted in this scheme was originally proposed by Steiner et al. (1999), in which h_{km} is derived from examining the transfer of deformation energy into potential energy within ridges during ice ridging, and $\mathrm{D_{km}}$ is characterized as the reciprocal of the ridge frequency. The detailed calculation formulas please refer to Steiner et al. (1999).

2.4 Form drag coefficient related to ice floe edge C_{dw}^{f}

Considering the geometric features of the edge of the ice floe, the obstacle height H corresponds to the submerged draft depth h_d. The ice concentration A_i can be expressed as $A_i = \frac{N c_{sf} L^2}{S_T}$, where L is the average ice floe length (x-direction), and c_{sf} is a geometric parameter. The total ice floe edge length per unit area then simplifies to $\frac{NL}{S_T} = \frac{A_i}{c_{sf} L}$. Then, the form drag coefficient related to ice floe edge can be derived as:

$$C_{dw}^{f} = \frac{1}{2} \frac{c_{fw}}{c_{sf}} S_c^2 \frac{h_d}{L} A_i \left(\frac{\ln(h_d/z_{0w})}{\ln(10/z_{0w})}\right)^2 , \qquad \text{(A6)}$$

where c_{fw} is a constant of local form drag coefficient, submerged draft depth is simplified as $h_d = 0.9 D_{ice}$, and z_{0w} denotes the seawater upstream roughness length of floe. The ice floe length L can be parameterized as Lüpkes et al. (2012):

$$L = L_{\min} \left(\frac{A_{i_\star}}{A_{i_\star} - Ai}\right)^{\beta} , \qquad \text{(A7)}$$

In this equation, $A_{i_\star} = 1/\left[1 - (L_{\min}/L_{\max})^{1/\beta}\right]$ serves as a regularization parameter to eliminate the singularity at $A_i = 1$. β is a constant power. L_{min} and L_{max} are the minimum and maximum ice floe lengths, respectively, with values of 3 m and 300 m for the sea ice in the Arctic region applied by Tsamados et al. (2014). According to the ice condition forecasts from the National Marine Forecasting Center, the predominant ice types in the main ice areas of the Bohai Sea are pancake ice, nilas and grey-white ice, with floe diameters ranging approximately from 0.3 to 3 m. Considering the applicability of the parameterization scheme to the Bohai Sea, we set the minimum ice floe length $\mathrm{L_{min}}$ and maximum ice floe length $\mathrm{L_{max}}$ to 0.3 m and 3 m, respectively.

2.5 Skin drag coefficient C_{dw}^s

Based on the parameterization scheme of Arya (1975), the ice-ocean interfacial skin drag coefficient can be expressed as:

$$C_{dw}^s = A_i\left(1 - m_{wk}\frac{h_{km}}{D_{km}}\right)c_{sw}, \quad \text{if } \frac{h_{km}}{D_{km}} \le \frac{1}{m_{wk}} , \qquad \text{(A8)}$$

where m_{wk} is a proportional parameter related to keel height but typically assumed constant (here $m_{wk} = 10$), and c_{sw} represents the unobstructed skin drag coefficient, which is attained in the absence of keels and under complete ice cover ($A_i = 1$). We adopt the default value $c_{sw} = 0.002$.

The setting values of the constant parameters in Scheme2 are shown in Table A2.

Table A2. The constant parameter settings of Scheme2.

Parameterization Scheme2		
z_{0i}	5.0×10^{-4}	Roughness length of level ice
z_{0w}	3.27×10^{-4}	Roughness length of water upstream of the ice floe
s_l	0.18	Attenuation parameter
c_{kw}	0.2	Local form drag coefficient of oceanic form drag
c_{fw}	0.2	local form drag coefficient of ice floe edge

		form drag
c_{sw}	0.002	unobstructed skin drag coefficient
c_{sf}	1	geometrical parameter
m_{wk}	10	Proportional parameter
L_{min}	0.3 (m)	Minimum ice floe length
L_{max}	3 (m)	Maximum ice floe length
β	0.75	Constant power