

Turbulence-Driven Nutrient Supply Sustains ~~Algal~~Ice-Algal Growth in the Arctic: A Modeling Approach with CICE 6.1 coupled to Icepack 1.2, and with SIMBA 2.0.

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Abstract. Fluxes of nutrients at the ice-ocean interface are affected by the smooth or turbulent nature of the flow under the ice. The nature of the flow depends on the friction velocity, which determines the thickness of the ~~laminar~~molecular sublayer, and the roughness of the ice ~~surface~~bottom. Based on in situ boundary layer studies, the range of variability of the thickness of the ~~laminar~~molecular sublayer and that of ~~surface~~bottom roughness suggest that the flow under sea ice may easily shift from smooth to turbulent. This transition enhances nutrient exchanges at the ice-ocean interface. Despite the importance of such turbulent nutrient exchanges for sea ice algae, no current biogeochemical model accounts for the dependence of fluxes on the nature of the flow, while different approaches were previously implemented to compensate for the perceived overestimation of ~~the nutrient limitation of~~nutrient limitation on ice algae growth. In the present study, we implement and test a Reynolds number-based parameterization that accounts for shifts between smooth and turbulent flow, weighing the contributions of viscosity and turbulence, in two sea-ice biogeochemical models. The results of three different case studies show that with increasing roughness, the turbulent nature of the flow contributes to larger fluxes of nutrients from the ocean to the ice. Nutrients accumulate during the winter, up to concentrations comparable to surface waters of the ocean. ~~However, when~~When light levels are sufficient to initiate algal growth, enhanced fluxes can support higher total production over a longer period, resulting in biomass accumulation more than twice that achieved under smooth flow conditions. In nutrient-rich waters, turbulence can supply sufficient nutrients to bring model outputs closer to observations. ~~However, other processes, such as brine drainage in the vertically resolved model, appear to limit agreement between the two models.~~ Our parameterization provides a more realistic representation of nutrient exchange at the sea ice–ocean interface, avoiding the need to “overtune” other model processes to reproduce observations. However, other processes -particularly the representation of light limitation- play a critical role in determining the timing of algal growth onset and significantly affect agreement with observations.

1 Introduction

Sea ice in polar regions provides a unique habitat for marine algae (Tedesco et al., 2025). These ice-associated (sympagic) algae, together with phytoplankton, represent the foundation of the marine ecosystem of polar oceans that provide organic

carbon to the greater foodweb. Algal phenology is constrained by the life-time of sea ice (time of ice formation and melt) and is driven by the interplay of light and nutrients as major limiting factors. The growth of ice-associated algae begins in spring with the relief of light limitation, and in the Arctic, is predominantly concentrated in the bottom most centimeters of the sea ice. The availability of light to ice algae is regulated by factors such as latitude, time of year, and by ice and snow attenuation (Light et al., 2008; Castellani et al., 2022). After the onset of an algal bloom, the accumulation of algal biomass is mainly limited by the amount of nutrients available since the demand of nutrients increases to support sustained growth. Thus, ultimately the availability of nutrients limits the magnitude of algal growth (Smith et al., 1997; Leu et al., 2015; Dalman et al., 2019). Nutrient supply to bottom-ice algae is largely sustained by interactions with the ocean beneath the ice. These processes are linked to brine dynamics and can be categorized as follows (Duarte et al., 2022; Castellani et al., 2025): 1) entrapment during sea ice growth (and release during ice melt); 2) flushing from the surface, active only during summer surface melting and rain events; 3) brine gravity drainage, driven by density instability of the brine; 4) molecular diffusion; and 5) turbulent diffusion, driven by friction velocity at the ice-ocean interface (e.g., Cota and Horne, 1989; Cota and Sullivan, 1990; Duarte et al., 2017; Mortenson et al., 2017). The ability of biogeochemical models to properly represent algal phenology thus relies to a great extent on their capacity to simulate both light transmission through snow-covered sea ice, and the exchange of nutrients at the ice-ocean interface.

Existing sea-ice biogeochemical models apply different approaches to compute nutrient fluxes between the ocean and the ice bottom (Castellani et al., 2025). Most models treat such exchanges as a diffusive process (Arrigo et al., 1993, 1997; Jin et al., 2006, 2012; Nishi and Tabeta, 2005; Deal et al., 2011; Pogson et al., 2011; Elliott et al., 2012; Mortenson et al., 2017, 2018; Hayashida et al., 2019). Only few models account for the entrapment/release during ice growth/melt (Vancoppenolle et al., 2010; Tedesco et al., 2010; Tedesco and Vichi, 2014; Watanabe et al., 2015) and even fewer models account for the contribution of turbulence (Sibert et al., 2010; Haddon et al., 2024). Recently, driven by the perception that nutrient limitation may be overestimated in some models, Duarte et al. (2022) included turbulence-driven nutrient exchanges in the Jeffery et al. (2011) model. Their results indicate that, when light limitation is relieved simulated algal growth increases substantially due to the alleviation of nutrient limitation under turbulent conditions. These findings support our argument that the characteristics of under-ice flow should be explicitly considered when describing fluxes at the ice–ocean interface.

The physical representation of flow beneath sea ice is grounded in the ocean boundary layer studies of McPhee (1979, 1982, 1983). Based on under-ice measurements, Shirasawa and Grant Ingram (1991) showed that the flow can be hydraulically smooth (so of viscous nature), or hydraulically rough (of turbulent nature), or in transition between the two regimes. Eddy-covariance studies (Long et al., 2012) confirmed that the under-ice environment may be dominated by viscosity or turbulence. The shift between viscosity- and turbulence-dominated regimes under sea ice results from an interplay between current velocity and sea ice bottom roughness (Shirasawa and Ingram, 1991). The roughness Reynolds number (Re^*), which measures the ratio between inertial and viscous forces, may thus be used to evaluate the type of regime dominating the flow (Olsen et al., 2019, and references therein).

The main goal of this study was to implement and test a formulation to compute nutrient exchanges at the ice-ocean interface that weighs the contribution of viscosity and that of turbulence based on shear velocity and sea ice roughness. The formulation

is applied to two sea-ice biogeochemical models: the Los Alamos sea ice model CICE + Icepack (Hunke et al., 2015) and the Sea Ice Model for Bottom ~~algae~~ Algae SIMBA (Castellani et al., 2017). This provides experimental evidence to the conclusions presented in Duarte et al. (2022) by evaluating the effect of this parameterization in three case studies covering diverse sea-ice regimes: The Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, the Norwegian young sea ICE cruise (N-ICE2015), and observations from Resolute Passage in the Canadian Arctic Archipelago. Section 2 presents the parameterization developed and the models used. Section 3 outlines the main results that are then discussed in Section 4. Finally, a summary and conclusion are provided in Section 5.

65 2 Methodology

2.1 Parameterizing the role of turbulence on nutrients exchange

The oceanic boundary layer under sea ice is conceptually divided into a thin molecular ~~or viscous~~ sublayer in which viscous effects dominate, a transition region influenced by both viscous and turbulent flow, and a fully turbulent region in which the ocean current is well represented by a logarithmic law known as the "law of the wall" (Shirasawa and Ingram, 1991). The thickness and structure of these different layers is affected by the velocity profile and by the roughness of the surface, as was shown by previous studies for the case of general surfaces (e.g., Kadivar et al., 2021) and for the particular case of sea ice (McPhee, 2008). Surface roughness increases flow instability near the wall, which can lead to increased localized turbulence disrupting the viscous sublayer. This concept was described in Nikuradse (1933) where the author experimentally quantified how roughness determines a shift from the smooth flow regime to the turbulent one. In the smooth regime, the ~~viscous~~ molecular sublayer is still intact and the exchange processes at the ice-ocean interface can be well described by molecular diffusion in a scheme similar to that of Lavoie et al. (2005):

$$F_{\text{Mol}} = -K_D \frac{C_w - C_i}{\delta Z}, \quad (1)$$

where K_D is the molecular diffusion coefficient taken as in Mann and Lazier (2005) equal to $10^{-9} \text{ m}^2 \text{ s}^{-1}$, $C_{w,i}$ are the nutrient concentrations in the ocean and at the ice-ocean interface, respectively, and δZ is the thickness of the molecular sublayer. In the turbulent regime, however, the molecular sublayer may be destroyed by the interaction between the flow and the roughness elements, and thus the exchange process can be described by turbulent exchange as presented in Duarte et al. (2022), following (McPhee, 2008):

$$F_{\text{Turb}} = -\alpha_s \cdot u^* (C_w - C_i), \quad (2)$$

where u is the friction velocity (m s^{-1}), and α_s is an interface salt–nutrient exchange coefficient (dimensionless) ~~set at 0.6×10^{-3} in CICE + Icepack (McPhee, 2008). In SIMBA v2.0 we had to lower the value of α_s due to possible instabilities so we set the value to 0.6 that ranges between 8.6×10^{-4} , $^{-5}$ and 0.006 (McPhee, 2008).~~ For computing the friction velocities we

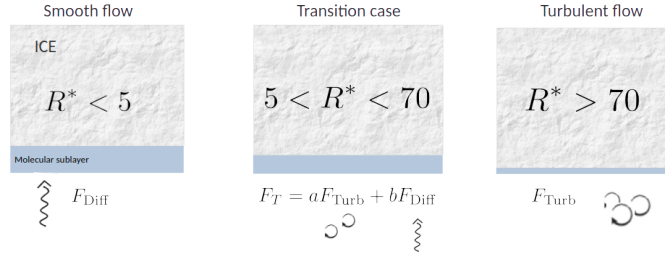


Figure 1. ~~Sonepetual~~ Conceptual representation ~~fo~~ of the parameterization developed which accounts for the nature of the flow under the ice (smooth vs turbulent) by weighting the contribution of molecular diffusivity or turbulent exchange ~~through the Reynolds number R^* in computing the fluxes at the ocean-ice interface~~ transition case (for $5 < Re^* < 70$). The two weights a and b vary linearly between 0 and 1 as a function of the Reynolds number (equations 5-6)

use a drag coefficient of ~~$C_d^w = 0.536 \times 10^{-3}$~~ $C_d^w = 5.36 \times 10^{-3}$ in both models following the standard approach of CICE + Icepack (Hunke et al., 2015)

We developed a conceptual model that takes into account the different flow regimes i.e., smooth or turbulent, that can occur
 90 ~~at in~~ at the bottom of the ice, as well as the transition between the two (Figure 1). The total flux F_T is then a weighted contribution of the two regimes:

$$F_T = aF_{Diff} + bF_{Turb}. \quad (3)$$

The two weights a and b are defined so that $a = 1$ and $b = 0$ in the full smooth regimes, and vice versa in the full turbulent regime. Between these two regimes, a and b decrease/increase linearly between 0 and 1. In order to define a and b , we use the
 95 roughness Reynolds number (Shirasawa and Ingram, 1991) Re^* :

$$Re^* = \frac{h_s u^*}{\nu}, \quad (4)$$

where h_s is the mean height of the surface protrusions and ν is the kinematic viscosity ($\nu = 2.1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$). ~~Note that h_s relates to the surface roughness parameter z_0 through the relation $h_s = 30z_0$.~~ Previous studies (Nikuradse, 1933; Shirasawa and Ingram, 1991) showed that the flow is hydraulically smooth for $Re^* < 5$ and hydraulically rough for $Re^* > 70$. In the case
 100 $5 < Re^* < 70$ the flow is in transition and is influenced by both viscosity and turbulence ~~and, thus~~ and, thus the total flux of nutrients is given by equation (3) ~~with the two weights assuming the form (see also the supplementary material):~~

$$a = \max \left(\min \left(1 - \frac{1}{65} \cdot (Re^* - 5), 1 \right), 0 \right) \quad (5)$$

$$b = \max \left(\min \left(\frac{1}{65} \cdot (Re^* - 5), 1 \right), 0 \right). \quad (6)$$

The mean height of the ~~surface-ice~~ bottom protrusions h_s needs to be prescribed. The literature values vary between less
105 than a mm to a few centimeters. Here, based on measurements by McPhee (2002) and McPhee (2008) we used values between
a minimum of $h_s = 0.6 \times 10^{-3}$ m in the case of very smooth ice ~~surface~~bottom, and a maximum of $h_s = 0.18$ m, for a rough
bottom~~surface~~. As described in Section 3 such values encompass the different flow regimes from fully smooth to fully turbulent.

2.2 Model description

We implemented and tested the Reynolds number parameterization in the Los Alamos (CICE + Icepack) ([https://bb.cgd.ucar.
110 edu/cesm/forums/cice-consortium.146/](https://bb.cgd.ucar.edu/cesm/forums/cice-consortium.146/), last access: ~~23-January-2025~~26 May 2026) (e.g. Hunke et al., 2015; Jeffery et al., 2016) and in the new version of the SIMBA (Castellani et al., 2017) sea ice models. The former includes a vertically resolved biogeochemical setup, whereas the latter is based on bottom ice biogeochemistry.

2.2.1 CICE + Icepack

The Los Alamos Sea Ice Model includes two independent packages: CICE, for computing ice dynamic processes, and Icepack,
115 that computes ice column physics and biogeochemistry. The model set-up used in the present study is described in Duarte (2025a) and Duarte (2025b) and available at the git repositories (<https://github.com/pduarte8/CICE>, last access: ~~28-October-2025~~27 May 2026, and <https://github.com/pduarte8/Icepack>, last access: 18 October 2025). As explained in Duarte et al. (2022), both CICE + Icepack are used together by defining a 1D vertically resolved model with 1 snow layer and 15 ice layers and 5 x 5 horizontal cells. Therefore, ice column physics and biogeochemistry are calculated by Icepack, but CICE is the model
120 driver. The input file is the same as the one used in Duarte et al. (2022) and we refer to their Tables S1 and S2 for a list of the initial parameters used. The methodology for tuning the model parameters to better align with observational data is outlined in Section 2.5 and expanded in the Supplementary Material.

We implemented equations (2) - ~~(4)~~(6) in Icepack file icepack_brine.F90, in the subroutine compute_microS_mushy. This implied adding ~~a parameter~~(the parameters h_{iceruf} ~~;~~(h_s in equation (4)) and α_s (α_s in equation (2)) to the file icepack_ parameters.F90.
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2.2.2 SIMBA

We use a new version of the SIMBA model ~~(Sea-Ice-Model-for-Bottom-Algae)~~ that was further developed from its first application in Castellani et al. (2017) and has a Git repository ([https://github.com/EyringMLClimateGroup/Castellani2025_ GMD_SIMBA2](https://github.com/EyringMLClimateGroup/Castellani2025_GMD_SIMBA2), last access: 21 October ~~2024~~2025) under Castellani (2025). Version 2 of SIMBA includes two more limiting
130 nutrients: ~~silicate~~silic acid and phosphate, besides the original nitrate. Another ~~further~~ development is the transition from a fixed cell stoichiometry to a variable Chl_a:C ratio as a function of nutrients concentration and light availability. This choice is particularly relevant for sea ice, where algae experience wide fluctuations of irradiance, in order to enhance the realism of the model (Ayata et al., 2013). In SIMBAv2.0, nutrients are exchanged at the sea-ice–ocean interface during ice growth and melt, ~~flushing~~, through molecular diffusion, turbulence, and by the combination of processes described in equation 3. In the way

135 it is coded, SIMBAv2.0 allows high flexibility; indeed, through several flags, it is possible to switch on and off the different terms for the resupply of nutrients. Similarly, the use of flags allows to select the limiting nutrient(s). The model equations and parameters used are presented in Appendix A.

SIMBAv2.0 is only a biogeochemical module so it needs the physics to be prescribed as forcing. In this study, we use the results for ice thickness from CICE + Icepack as input for SIMBAv2.0 for all three case studies. For snow thickness, we use observations taken at the coring site for the MOSAiC case study, whereas for the N-ICE2015 and Resolute case we use the CICE + Icepack output. Moreover, SIMBAv2.0 resolves only biogeochemical processes ~~at in~~ the bottom of the ice. The thickness of the bottom layer can be chosen according to the resolution of the data used for comparison - in the present study, we set it to 10 cm for MOSAiC and N-ICE2015, and to 3 cm for Resolute (see also Section 2.4). The initial choice of parameters reflects what is used in CICE + Icepack, further tuning is explained in Section 2.5 and in the Supplementary Material.

2.3 Forcing data

We apply the new parameterization of nutrient exchanges at the ice–ocean interface to both models and test them in three ~~contrasting case studies~~ case studies (Figure 2) — two from the Nansen Basin (Arctic Ocean), based on forcing data and ice floes monitored during the N-ICE2015 (Granskog et al., 2019), and the MOSAiC (Nicolaus et al., 2012; Shupe et al., 2022; Rabe et al., 2022) expeditions, and one from Resolute Bay in the Canadian Arctic (Mortenson et al., 2017). Data from the N-ICE2015 expedition and from Resolute Bay were detailed in previous modeling studies (Duarte et al., 2017, 2022; Mortenson et al., 2017). Therefore, here we briefly detail only the MOSAiC data.

~~The Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC)~~

The MOSAiC expedition took place from October 2019 to July 2020 with the aim of measuring a multitude of variables at a variety of spatial scales in the coupled atmosphere-ice-ocean system along the transpolar drift throughout a whole annual cycle. Expedition and data sampling are largely described in Shupe et al. (2022), Nicolaus et al. (2022), Rabe et al. (2022), and Fong et al. (2024), so we defer the reader to those references for a detailed description. The observational data collected during MOSAiC and used in this study to force the models are described in detail in Gu et al. (2024), here we will only provide a summary (see also Figure 3). The atmospheric variables include: 6-hourly surface downward shortwave and longwave radiation, daily 2 m air temperature and specific humidity, ~~and~~ 10 m wind speed, and precipitation. The oceanic data consist of daily 10 m sea temperature and salinity averaged from 8 CTD buoys, and 3 m sea temperature, salinity, and current velocity averaged from 4 autonomous ocean flux buoys. ~~Following Gu et al. (2024) we prescribe snow depth. Observations of snow depth and ice thickness were obtained from the snow and ice mass balance buoy array, particularly the T63 buoy (Lei et al., 2022) that was located on a second-year ice (SYI) floe.~~ We force the biogeochemistry module of CICE + Icepack and SIMBAv2.0 with observed nutrient concentrations of surface water (Torres-Valdés et al., 2024a, b, and figure 3e). Initial conditions for sea ice physical and biogeochemical variables are from ice coring data collected on November 25th, 2019 (Oggier et al., 2024a, b). Observations of sea ice draft and snow height from ice cores are shown in Figure 3c, however from the data we omitted a

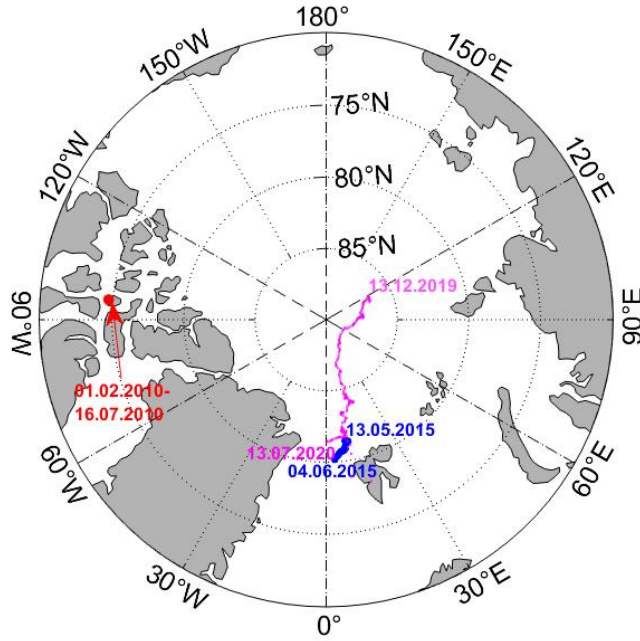


Figure 2. Map showing locations and time period of the three data sets used for model comparison: MOSAiC - purple line, N-ICE2015 - blue line, and Resolute - Red dot.

measurement taken at the end of March right after a rafting event (Angelopoulos et al., 2022), since with CICE + Icepack in the configuration used in the present study we can only simulate thermodynamic growth.

170 2.4 Model simulations

We compare the results of the runs performed with the new parameterization in which we vary the height of the ~~surface~~ bottom roughness protrusions h_s . The minimum value used is $h_s = 0.6 \cdot 10^{-3}$ m, which corresponds to a fully molecular regime, and ~~a maximum of the maximum used is~~ $h_s = 0.18$ m, which corresponds to a fully turbulent regime (Section 3). The values in between are 0.0025, 0.005, and 0.01 m. In the MOSAiC case we perform simulations for ~~both the~~ first-year ice (FYI) ~~and~~ second-year ice (SYI), ~~but we present and discuss results for only FYI, except when specified otherwise.~~ Table 1 ~~list~~ lists the simulations performed and the main characteristics for each case study.

175 2.5 Tuning

The CICE + Icepack configuration from Duarte et al. (2022) was originally tuned to represent the N-ICE2015 refrozen lead case. We used that set of parameters as initial control version of the model. The initial set of parameters for SIMBAv2.0 was the same of the tuned set of SIMBA from Tedesco et al. (2026). When simulating the MOSAiC case, however, CICE +

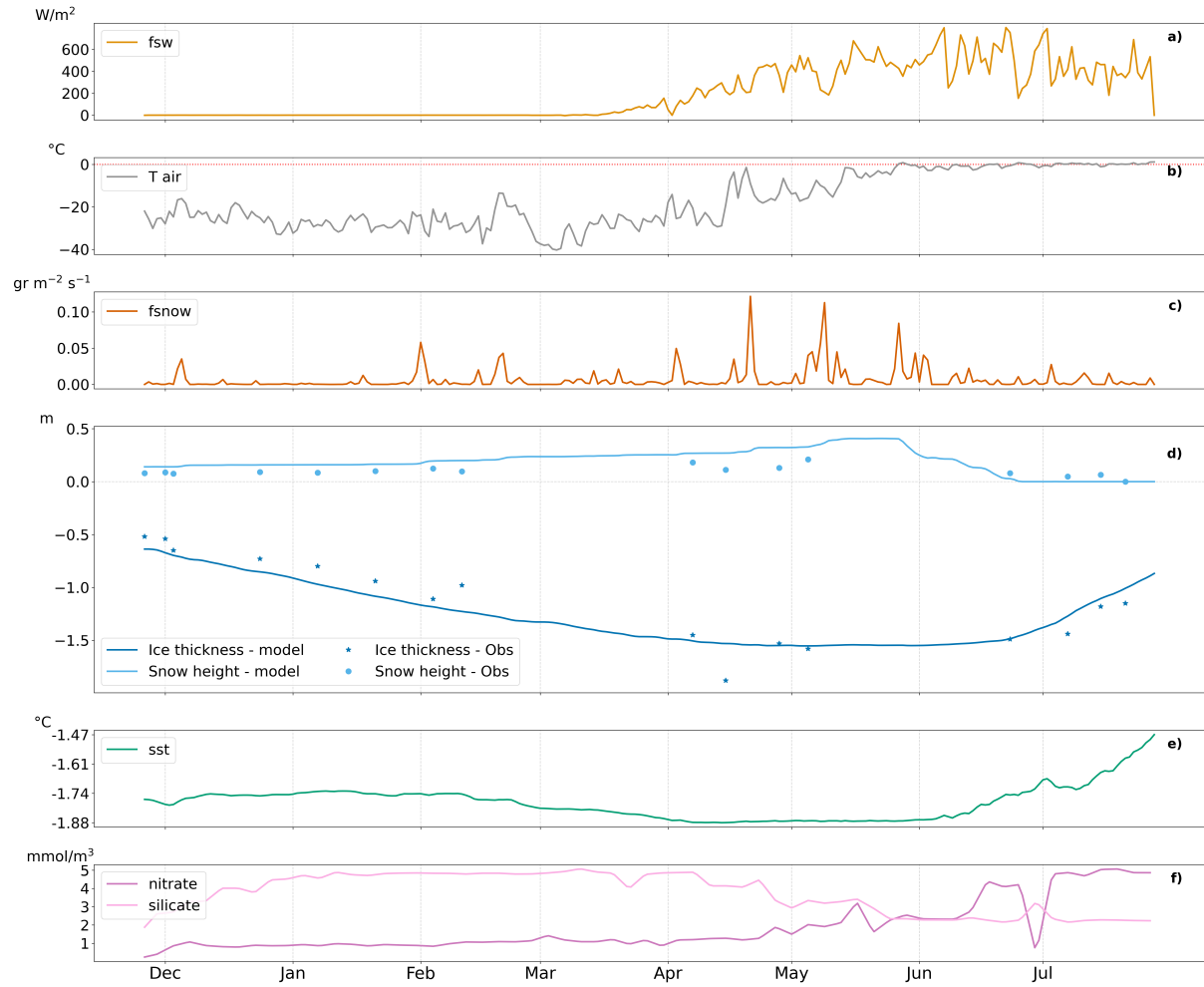


Figure 3. Overview of the forcing for the MOSAiC study case. Atmospheric forcing: a) downward shortwave radiation (fsw), and b) 2 m atmospheric temperature T_{air} ; oceanic forcing: d) sea surface temperature, and e) precipitation (fsnow) nutrients concentration in the water. Panel ed) shows snow depth that is prescribed in both CICE + Icepack height and ice thickness as simulated by CICE + Icepack and used to force SIMBA v2.0. Starts in panel b (line) represents together with observations collected during the coring events at the FYI site (dots/stars). Oceanic forcing: e) sea surface temperature (sst), and f) nutrients concentration in the water.

Table 1. Summary of simulations for the different case studies.

case study	ice type	location	start	end	h_s values used (m)
MOSAiC	FYI	Nansen Basin	24 November 2019	26 July 2020	$0.6 \times 10^{-3}, 0.0025, 0.005, 0.01, 0.18$
MOSAiC SYI " " " " N-ICE2015	refrozen lead	"	24 April 2015	6 June 2015	"
Resolute	landfast FYI	Canadian Arctic	1 February 2010	18 June 2010	"

Table 2. Values of tuned parameters for CICE+Icepak and SIMBAv2.0. α_s is the exchange coefficient in equation (2), adimensional; α (m^2/W) and op_{min} (adimensional) are parameters used to calculate light limitation in Icepack (Jeffery et al., 2016); k_{sil} (mmol m^{-3}) is the half saturation constant for silicate; λ_{mor} is the mortality rate (d^{-1}); μ_M is the maximum growth rate (d^{-1}). Note that SIMBAv2.0 calculates light limitation differently so it does not use the same α and op_{min} as Icepack.

Parameter	CICE+Icepak			SIMBAv2.0		
	MOSAiC	N-ICE2015	Resolute	MOSAiC	N-ICE2015	Resolute
α_s	8.6×10^{-5}	8.6×10^{-5}	0.006	8.6×10^{-5}	0.006	1.2×10^{-4}
α_s (melting)	1.2×10^{-6}	1.2×10^{-6}	8.6×10^{-5}	1.2×10^{-6}	8.6×10^{-5}	1.2×1.4^{-5}
α	3.78	0.3	2.0	~	~	~
op_{min}	0.0001	0.03	0.01	~	~	~
k_{sil}	3.9	2.2	2.2	3.9	2.2	3.9
λ_{mor}	0.01	0.007	0.007	0.01	0.01	0.01
μ_M	0.7	0.81	0.81	0.86	0.86	0.86

Icepak model failed to represent the onset of algal growth. The reason lies in the fact that simulated snow height is larger than observations at the coring site (Figure 3d) and algae remain light limited until the end of May (onset of surface melt). We thus tuned the light limitation parameter α of the CICE + Icepack model to match observations. Details of the tuning are presented in the Supplementary Material, the tuned parameters are presented in Table 2. We aimed at keeping the values of parameters the same in both SIMBAv2.0 and CICE + Icepack, however this has not been possible due to intrinsic differences between the models. For example, to better reproduce the N-ICE2015 case with SIMBAv2.0 we had to increase the exchange coefficient α_s (see Table 2) and we had to allow algae to stick to the ice bottom (i.e., to not be released during melting). This tuning approach has already been discussed for the same case study with different models in Tedesco et al. (2026). In the Resolute case, for both SIMBAv2.0 and CICE + Icepack we used a larger value of the exchange coefficient α_s compared to the MOSAiC case to allow accumulation of biomass to the levels observed. For all case studies, we kept the exchange coefficient constant during the simulation period, but we accounted for stratification by lowering its values by ~ 1 order of magnitude in the case of bottom melt following McPhee (2008). It has to be noted that the aim of this study is to test the sensitivity of the models in reproducing algal phenology to the parameterization of fluxes at the ocean-ice interface, so an in-depth tuning of the models to represent the different case studies is beyond the scope of this manuscript.

3 Results

3.1 MOSAiC case study

The friction velocity u^* ranged between nearly zero and 0.02 m s^{-1} (Figure 4a). Although the Reynolds number Re^* correlated with u^* , its magnitude was largely dependent on h_s (Figure 4b). With $0.0025 \leq h_s \leq 0.01 \text{ m}$, Re^* remained between 5 and 70,

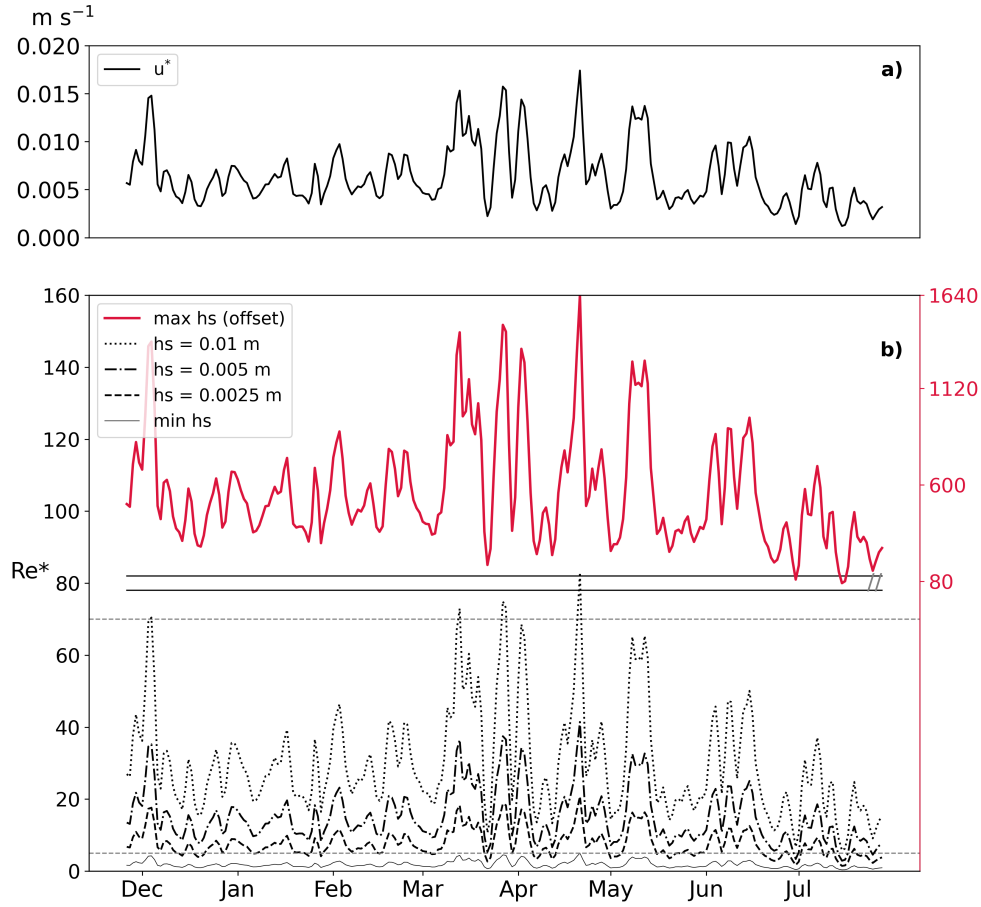


Figure 4. MOSAiC case study: a) Friction velocity; b) roughness Reynolds number Re^* for the all the different size-sizes of roughness elements tested. The horizontal dashed lines at $Re^* = 5$ and $Re^* = 70$ depict the upper limit for a smooth flow and the lower limit for a rough turbulent flow, respectively. Note that the values of Re^* for the maximum roughness (red colour) are represented on a different scale (y-axis on the right side).

implying that the flow regime was in transition between smooth (viscosity-dominated) and turbulent. Therefore, both molecular diffusion and turbulence contributed to the nutrient fluxes. In the case of the lowest h_s ($= 0.6 \times 10^{-3}$ m), Re^* was always < 5 , implying that the flow was smooth and nutrient exchanges were driven only by molecular diffusion. For the largest h_s values ($= 0.18$ m), the Reynolds number was always above 70, so the fluxes were entirely driven by turbulence (e.f. Section 2.1).

Our analysis will focus on nitrate, the primary nitrogen source for the spring bloom (~~see below~~), and silicic acid (reported in the Supplementary Material) to compare nutrient concentrations and fluxes across different simulations. The fluxes of nitrate at the ice-ocean interface were predominantly negative (from the ocean to the ice) and of the same order of magnitude using either CICE + Icepack or SIMBAv2.0 (Figures 5a, 6a respectively). However, their ~~magnitude was value was slightly~~ larger in the former model. The larger negative values occurred in spring-summer, precisely in ~~June~~ April (in the case of CICE + Icepack) and May (SIMBAv2.0). The variability of fluxes preceding the spring period (before ~~May~~ April) was relatively low. Fluxes increased with increasing h_s in both models, ~~but more notably in CICE + Icepack. Here. For very smooth ice,~~ fluxes were ~~very close to zero in the case of very smooth ice, but increased to nearly zero, but rose to approx.~~ $-1.25 \times 10^{-6} \text{ mmol m}^{-2} \text{ s}^{-1}$ in CICE + Icepack (and to approx. $-0.75 \times 10^{-1} \text{ mmol m}^{-2} \text{ d}^{-1}$ in SIMBAv2.0) when the roughness increased to the maximum value tested. At the beginning of the simulation period (Nov-Dec) the ~~large~~ gradient of nitrate between the sea ice bottom and the ocean caused ~~fluxes in SIMBAv2.0 as large as $3.5 \times 10^{-7} \text{ mmol m}^{-2} \text{ s}^{-1}$. Silica fluxes larger fluxes than during the rest of the winter.~~ Fluxes of silicic acid are presented in the supplementary material (Figure S1).

Both models showed an initial increase in bulk nitrate concentration at the ice bottom (Figures 5b and 6b). We note here that ~~CICE-Icepack~~ CICE + Icepack resolves biogeochemistry in 15 layers within the ice column. Thus, in order to select the bottom 10 cm we apply a weighted average of the number and portion of layers that are included in this depth range. In CICE + Icepack, concentrations stabilize around 0.5 mmol m^{-3} and show no trend during winter. ~~A maximum is reached in mid-June, right after the maximum of ocean-ice fluxes.~~ In SIMBAv2.0 the concentration of nitrate stabilizes at values ~~between 0.1 (minimum h_s) and around~~ 1.0 mmol m^{-3} ($h_s \geq 0.05$) ~~depending on ice roughness,~~ and show no or very little increase ~~until mid-February. Similarly to CICE + Icepack, the maximum concentration is reached after the maximum in ocean-ice fluxes, but earlier in the season (mid-May) during winter.~~ In both models, the bottom of the ice becomes depleted in nitrate ~~right after reaching a maximum concentration in April-May.~~ The depletion of nitrate corresponds with the co-occurring ice algal blooms (Figures 5c and 6c). Compared with observations, CICE + Icepack exhibits bottom nutrient values lower than those measured (Figure 5b), whereas SIMBAv2.0 shows larger values (Figure 6b). Both models fail to capture the full variability observed, which may partly reflect spatial heterogeneity in the ice core data. Ice algal biomass is presented as chlorophyll *a* (chl *a*) concentration. In CICE + Icepack biomass is calculated in nitrate units, so we ~~follow Duarte et al. (2017) and apply followed Duarte et al. (2017) and applied~~ a conversion factor of $2.1 \text{ mg chl } a \text{ mmol N}^{-1}$ (Smith et al., 1993). Differently, SIMBAv2.0 has a variable Chl_a:C, and thus Chl_a:N, ratios so chl *a* content ~~is was~~ computed at each time step. The time series of Chl_a:C is shown in the supplementary material. Chl *a* remains close to zero until spring and reaches its maximum in June in both models. ~~While predicted nitrate concentrations at the ice bottom were comparable for both models, SIMBAv2.0~~ However, differences in algal phenology can be seen between the different values of the roughness parameters: Algal biomass reaches a plateau in both models that remains approximately stable in May in all simulations, except the one with the fully turbulent case ($h_s = 0.18 \text{ m}$) where algae keep growing until a maximum. CICE + Icepack predicted larger ice algal biomass with a maximum about twice that in CICE + Icepack. Compared with observations, three times that in SIMBAv2.0. This is due to the tuning of the photophysiology parameter in CICE + Icepack exhibits bottom nutrient values lower than those measured (Figure 5b), whereas SIMBAv2.0 shows larger values (Figure 6b). Both models, however, fail to capture the full variability observed, which

MOSAiC (FYI) - ICEPACK

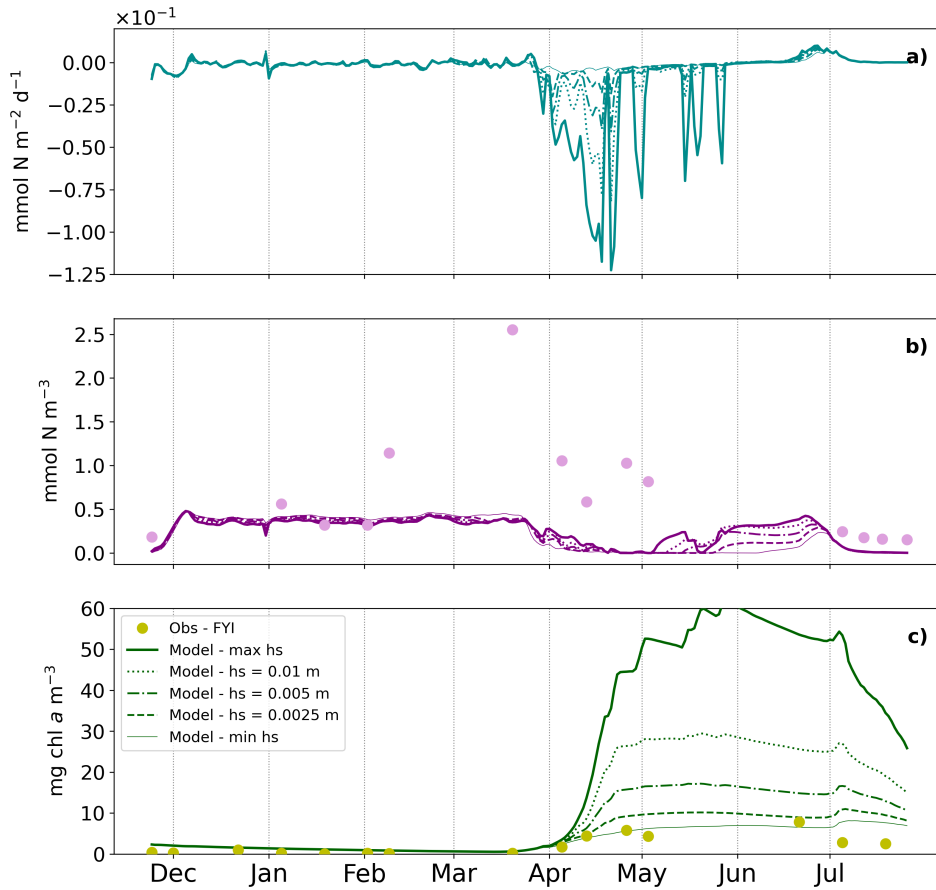


Figure 5. MOSAIC case study: CICE + Icepack results for all tested sea ice roughness values: a) Nitrate fluxes at the ice-ocean interface; b), c) Nitrate and chl *a* concentration at the sea ice bottom 10 cm, respectively. Dots represent observations from ice cores collected on FYI.

may partly reflect spatial heterogeneity in the ice core data: a larger light limitation factor α pushes algal bloom earlier in the season to match observations, but it also leads to larger biomass accumulation. It has to be noted that observational data for chl *a* are unavailable from early May to late June —coinciding with the development of the spring algal bloom— making direct comparison between model and observations difficult. However, the model correctly simulates the onset of growth and captures the maximum in June, indicating the potential for a robust representation of algal phenology. The case that better matches the few observations available is the one with the lowest values of bottom roughness (when molecular exchanges dominate) for both models.

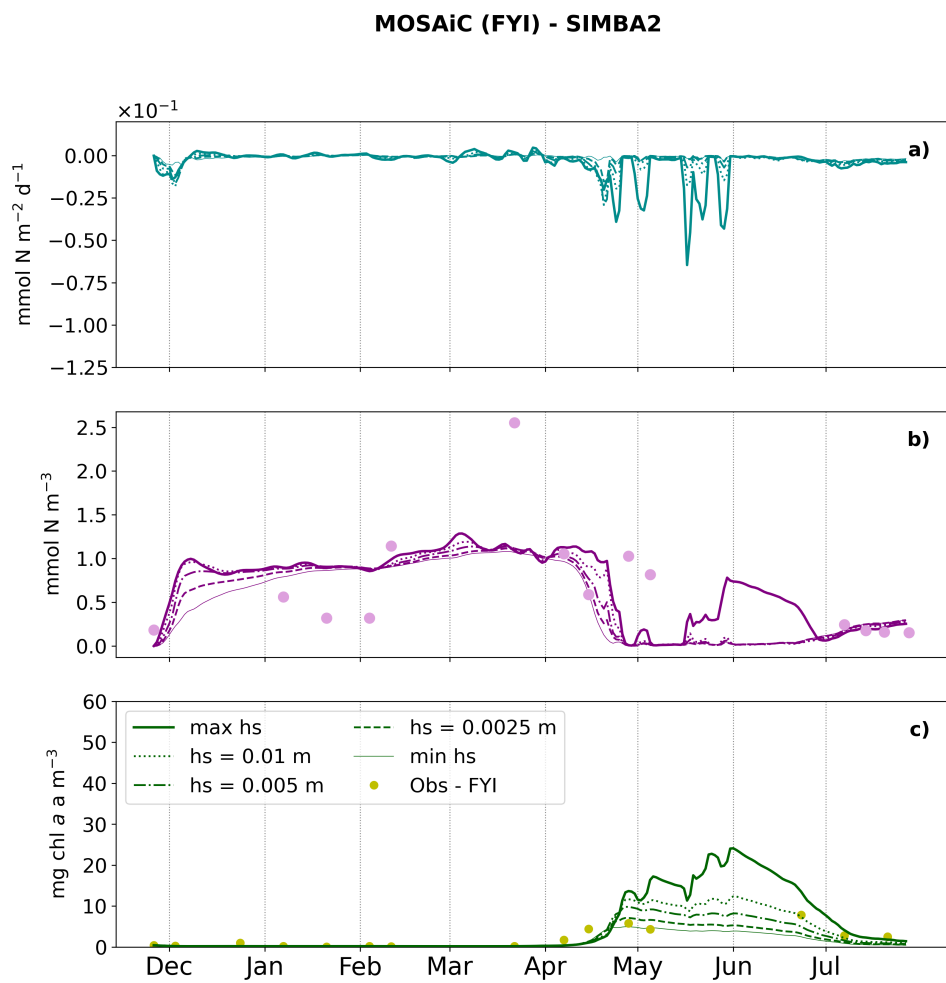


Figure 6. Same as Figure 5 but for SIMBAv2.0 results.

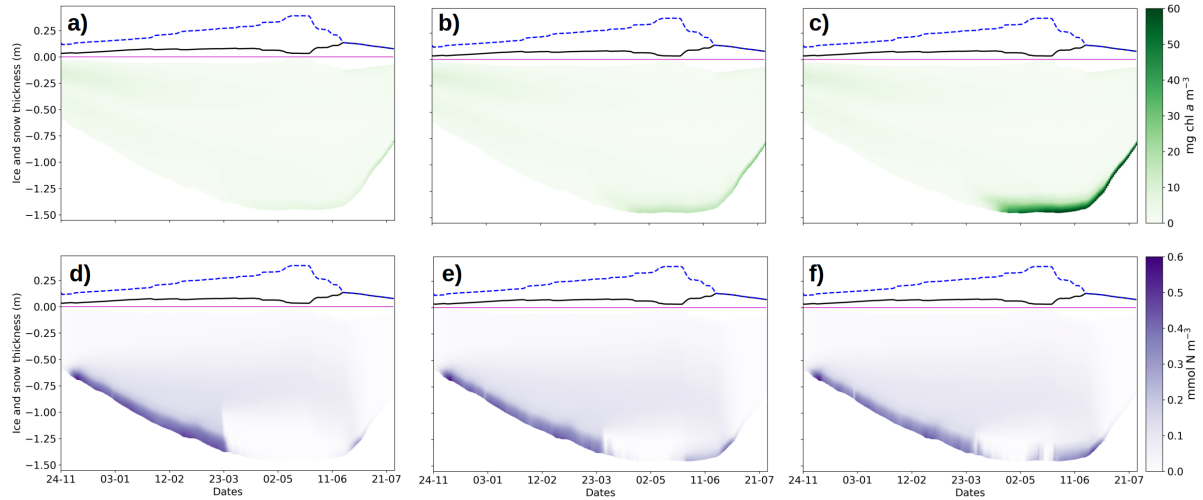


Figure 7. MOSAiC case study: Vertically resolved chl *a* and **bulk** nitrate concentration (top row and lower row, respectively) in CICE + Icepack in the case of a-d) minimum h_s ; b-e) $h_s = 0.005$ m; c-f) maximum h_s . The blue dashed and the black lines represent snow height and freeboard, relative to the sea level (magenta line) as simulated by the model.

245 ~~The patterns described above were the same for all tested h_s , except the smallest value, when exchanges were entirely dominated by molecular diffusion. In CICE + Icepack~~ In both models, when the ice is smooth (min h_s) nitrate concentration starts to decrease already in April, the nitrate concentration begins to decrease earlier, with the bottom of the ice becoming completely nitrate-depleted ~~at the end of May~~ earlier than in other cases, thus preventing ~~any significant further~~ algal growth. SIMBAv2.0 exhibits a similar pattern, with nitrate concentrations being lower under very smooth ice, strongly limiting algal growth. In all other cases of bottom roughness, nutrients are depleted by early May. When turbulence is included (i.e., for all values of h_s above minimum), nutrient concentrations begin to increase again after the peak of the algal bloom.

255 In ~~CICE-Icepack~~ CICE + Icepack the bulk concentration of nitrate is larger ~~at the bottom rather in the bottom~~ than in the ice interior (Figure 7, lower row) ~~, this is true~~ for all values of h_s . In the case of smooth ice, the decrease in nutrient concentration seen at the end of March and beginning of April in the sea ice bottom (Figure 5b) extends up to 50 cm in the ice column. For rougher ice, the ~~largest~~ concentration of nutrients ~~is visible~~ recovers to its pre-bloom values in mid June in the bottom 25 cm of ~~sea~~ the sea ice. At the end of the simulations, nutrients are depleted from the entire ice column in all cases, coinciding with flushing of melted snow through the ice, ~~mirroring what is seen already in the bottom 10 cm~~. Algae remain mostly concentrated at the ice bottom in all simulated cases.

3.2 N-ICE2015 case study

260 The results presented here are from a refrozen lead detailed in previous studies and reaching a maximum ice ~~and snow~~ thicknesses of ~~thickness and snow height of~~ ~ 30 cm and a few millimeters, respectively (Duarte et al., 2017, 2022). The

refrozen lead was monitored regularly between its formation on the 24th of April until the beginning of June 2015. Friction velocities were in the same range of the MOSAiC case ($0.0 - 0.02 \text{ m s}^{-1}$), but with fewer values exceeding 0.01 m s^{-1} (Figure 8a). Also in this case the flow was smooth under the smallest h_s , while for maximum roughness the flow was fully turbulent. For the values in between, the flow was in transition (Figure 8b). Algal biomass followed the same pattern observed in the MOSAiC case for both models: greater sea-ice roughness led to increased algal growth (Figure 9). ~~Also in the N-ICE2015 case, SIMBAv2.0 accumulates more algal biomass than CICE + Icepack. Both models~~ The two models accumulated a comparable algal biomass and showed improved agreement with observations compared to the earlier case. It should be noted, however, that CICE + Icepack was previously tuned using this dataset (Duarte et al., 2017) ~~on this data set, and SIMBAv2.0 uses the same parameters as CICE + Icepack to ensure comparability; when only molecular diffusivity was implemented,~~ therefore, it is not surprising that ~~SIMBAv2.0 also reproduces~~ they reproduce observations more accurately in the N-ICE2015 case. The former version of SIMBAv2.0 was also tuned on this data set (Tedesco et al., 2026), but in its new model configuration SIMBAv2.0 is able to reproduce observations only when turbulence is considered.

3.3 Resolute case study

Friction velocity remained always below 0.01 m s^{-1} during the Resolute time series (Figure 10a). For most of the roughness values above the minimum, however, the flow ~~remains~~ remained in transition between smooth and turbulent, despite the low Reynolds numbers ($Re^* < 40$). For the maximum roughness, the Reynolds number was ~~still~~ above the limit for turbulent flow (Figure 10b). For consistency with the depth range of the observations ~~here~~ (Mortenson et al., 2017) we present average chl a concentrations for the bottom 3 cm (Figure 11). Observed values ~~at the sea-ice in the sea-ice~~ bottom were two orders of magnitude larger than those of the previous case studies. Both models ~~predict~~ predicted chl a concentrations proportional to h_s ~~but CICE + Icepack has an order of magnitude negative bias, even under the highest h_s , whereas SIMBAv2.0 may predict even larger values than the observed maximum~~ and were able to reach observed values only when turbulence was considered. Irrespective of the h_s chosen, the CICE + Icepack model predicted strong nitrate depletion (Figure 12) ~~At the start of the ice algal bloom, around mid-April, the depletion was confined to a narrow band just above the bottom layer, later on it expanded throughout the ice column (Figure 12)~~ that extends through the entire ice column. For roughness values above the minimum, the ice bottom was replenished with nutrients during algal growth, but the ice interior remained depleted, apart for a small amount of nutrients at the surface when snow melted around June 20th.

4 Discussion

4.1 Parameterization of Ocean Fluxes

The physics governing the fluxes of nutrients at the ice-ocean interface happen at small scales that are not resolved by current ~~sea-ice~~ sea-ice models. The mixing and exchange processes ~~thus~~ therefore need to be parameterized. Based on boundary layer and eddy-covariance studies, the flow at the ice-ocean interface that determines such exchanges can be smooth or turbulent,

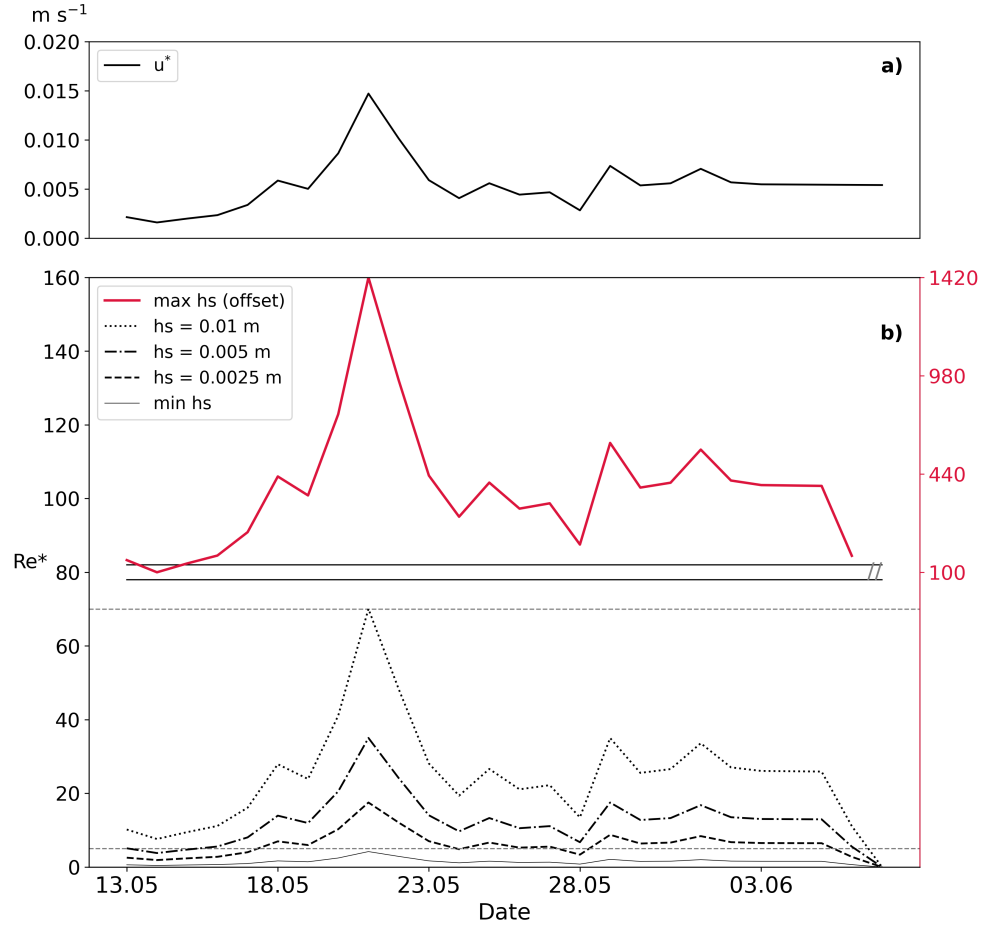


Figure 8. N-ICE2015 case study: a) Friction velocity; b) roughness Reynolds number Re^* for ~~the~~ all the different size of roughness elements tested. The horizontal dashed lines at $Re^*= 5$ and $Re^*= 70$ depict the upper limit for a smooth flow and the lower limit for a rough turbulent flow, respectively. Note that the values of Re^* for the maximum roughness (red colour) are represented on a different scale (y-axis on the right side).

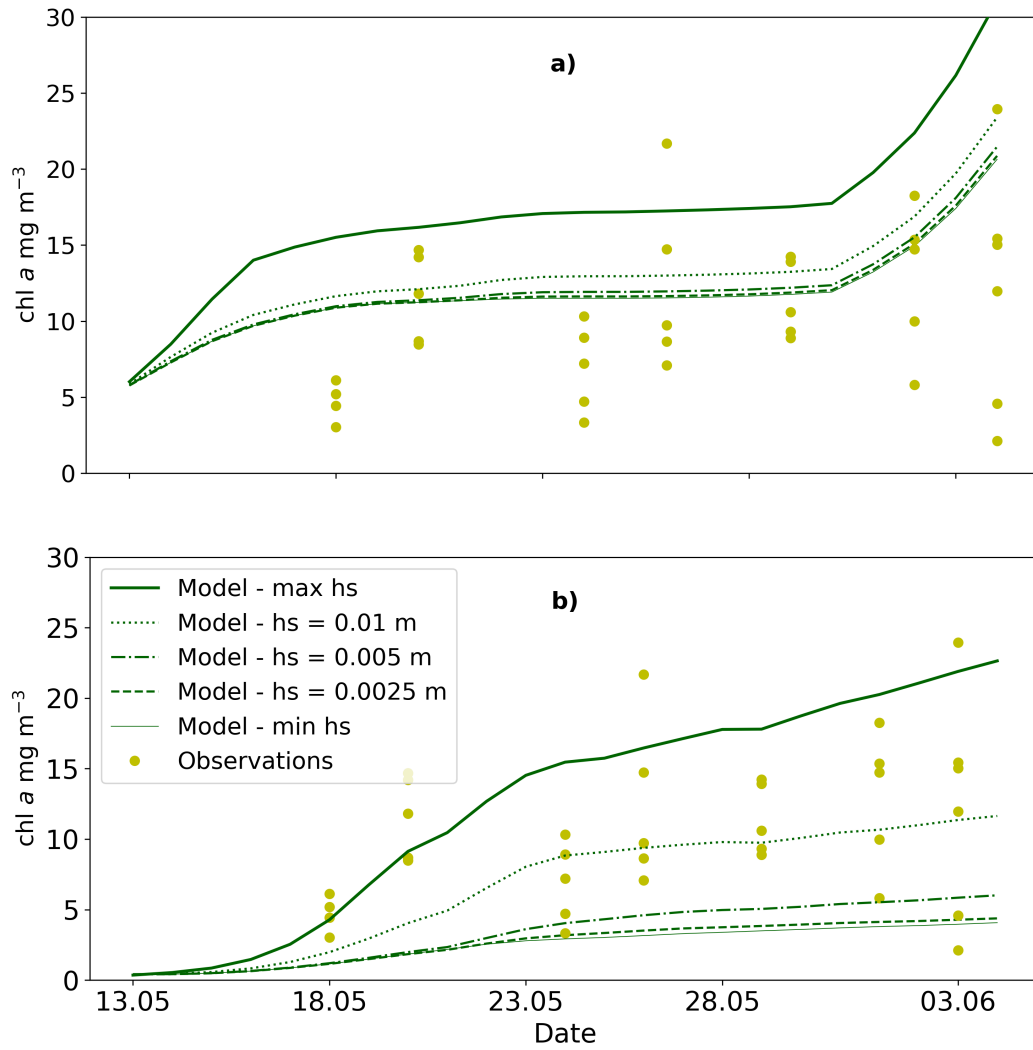


Figure 9. N-ICE2015 case study: Chl *a* concentrations at in the sea-ice sea-ice bottom 10 cm in a) CICE + Icepack, and b) SIMBAv2.0.

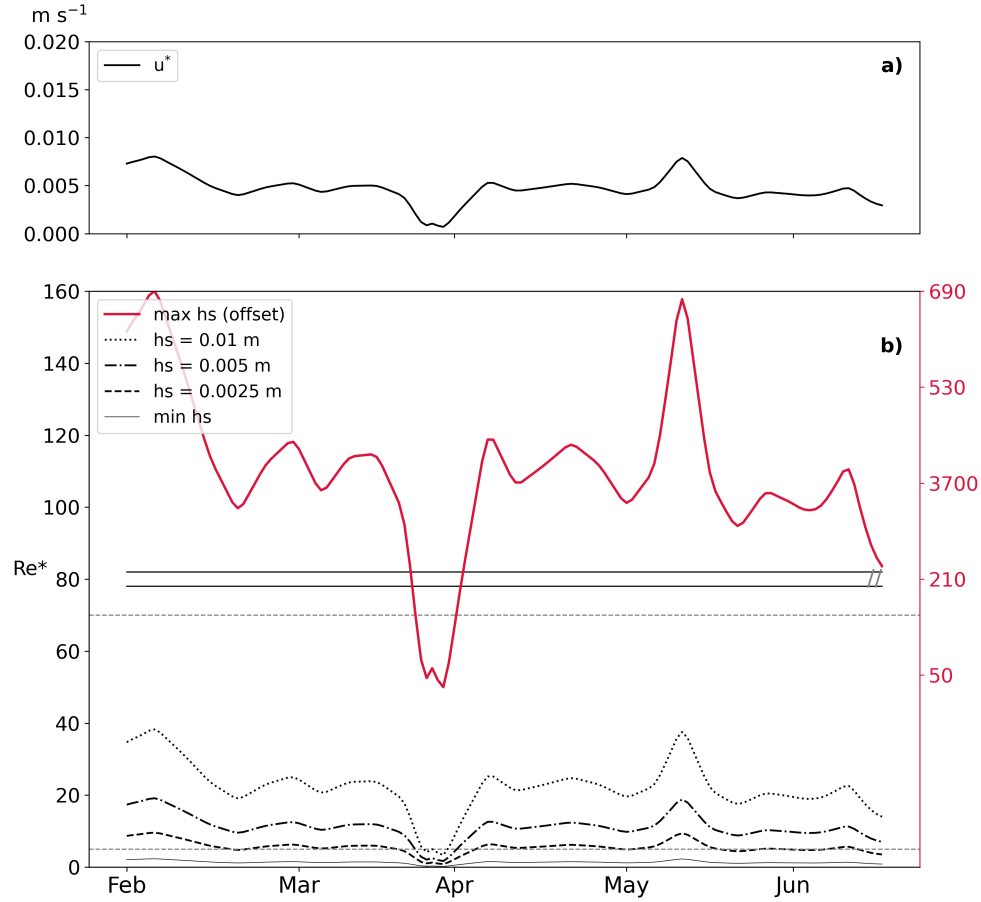


Figure 10. Resolute case study: a) Friction velocity; b) roughness Reynolds number Re^* for ~~the~~ all the different ~~size~~ size-sizes of roughness elements tested. The horizontal dashed lines at $Re^* = 5$ and $Re^* = 70$ depict the upper limit for a smooth flow and the lower limit for a rough turbulent flow, respectively. Note that the values of Re^* for the maximum roughness (red colour) are represented on a different scale (y-axis on the right side).

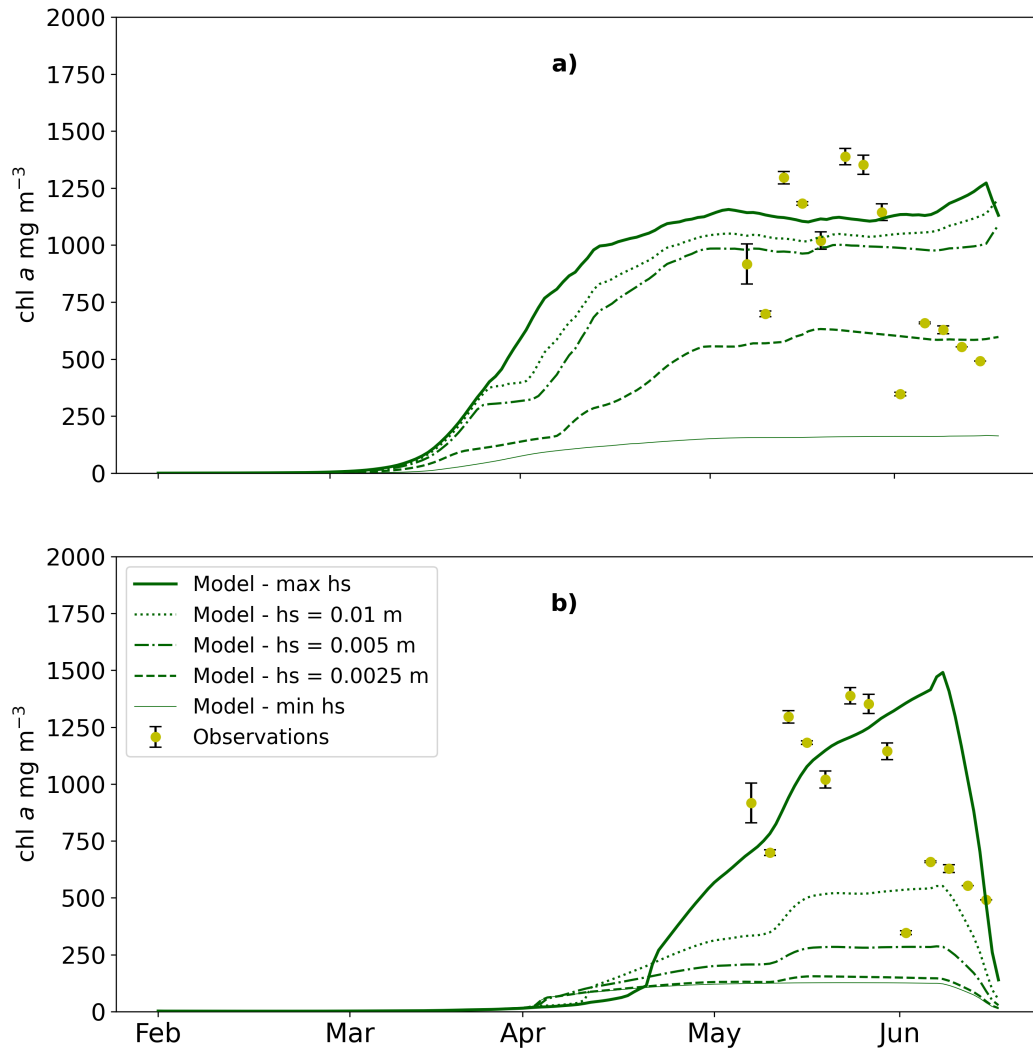


Figure 11. Resolute case study: Chl *a* concentrations at-in the sea-ice-sea-ice bottom 3 cm in a) CICE + Icepack, and b) SIMBAv2.0.

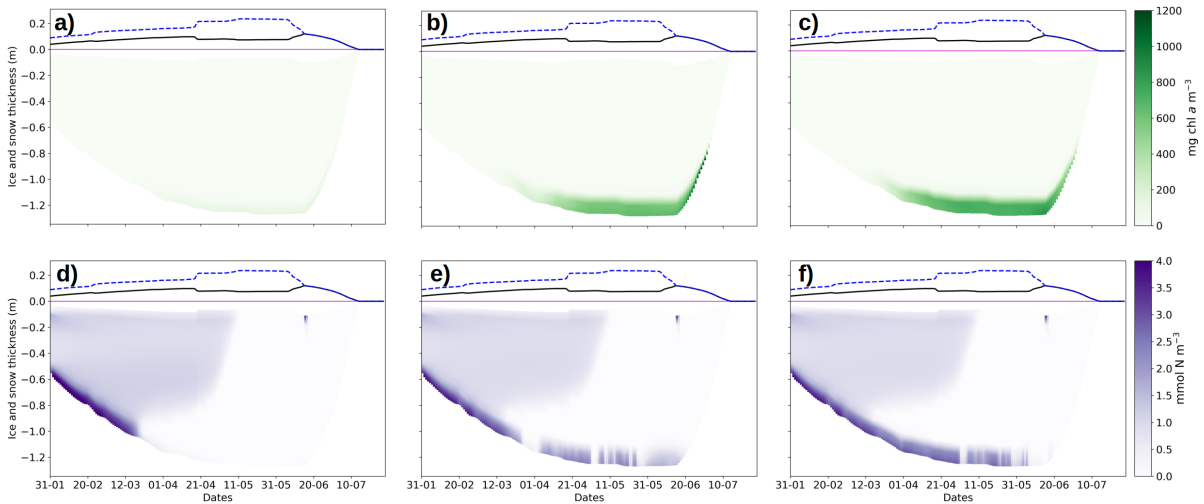


Figure 12. Resolute case study: Vertically resolved chl *a* and nitrate concentration (top row and lower rows, respectively) in CICE + Icepack in the case of a-d) minimum h_s ; b-e) $h_s = 0.005$ m; c-f) maximum h_s . The blue dashed and the black lines represent snow height and freeboard, relative to the sea level (magenta line).

leading to molecular diffusion or turbulent driven exchanges, respectively (e.g., McPhee, 2008; Long et al., 2012). Many sea-ice biogeochemical models include one of these exchange types, with a preference for the former. However, the fluxes due to molecular diffusion (~~viscosity-dominated~~ dominated by viscosity) are often too small to provide enough nutrients to explain the biomass accumulation observed in the field (Dalman et al., 2019; Van der Linden et al., 2020; Roukaerts et al., 2021). This may be the reason why Lavoie et al. (2005) used a formulation based on molecular diffusion where the thickness of the boundary layer is calculated as a function of friction velocity. Similarly, Jin et al. (2006) used a diffusion coefficient 4 orders of magnitude higher than the molecular diffusivity, and ~~Watanabe et al. (2019)~~ Watanabe et al. (2015) assumed that ice algae may uptake nutrients directly from seawater, based on a study by Boetius et al. (2013). However, this last study was focused on *Melosira arctica*, which forms aggregates or macroscopic strand colonies at the bottom-ice interface, whereas our focus is on the more common occurrence of ice algae living within the brine network and skeletal layer. Very few models ~~parametrize~~ parameterize the exchange fluxes as turbulent (e.g. Haddon et al., 2024), and none include the contribution of both viscosity and turbulence dominated regimes. In the present study, we developed and implemented a new parameterization that accounts for the contribution of the two regimes, allowing the flow to be in a transitional stage between smooth and turbulent. The fluxes are thus the result of a weighted contribution of both processes.

In our three case studies, we found that the friction velocity was in the range of previous observations (~~McPhee, 2008, e.g.~~ e.g. McPhee, 2008). Furthermore, we found that the friction velocity was generally high enough to keep the flow in a transition between smooth and turbulent. With low current velocity, ~~and thus and, thus,~~ low friction velocity, viscous forces gain importance and the thickness of the molecular sublayer ~~is such to limit~~ limits the exchange fluxes. This was shown

by ~~(Long et al., 2012)~~ Long et al. (2012) during an eddy-covariance study in a southwest Greenland fjord, where stratification and low current velocities prevented the determination of oxygen fluxes during more than half of the instrument deployment time. ~~Besides velocity,~~ In addition to velocity, the flow regime is ~~determined also by under-ice roughness~~ also determined by the roughness of the ice bottom. It is indeed the ratio between the thickness of the molecular sublayer (function of u^*) and
315 the height of the roughness elements h_s that determines the nature of the flow (Nikuradse, 1933; Shirasawa and Ingram, 1991; Shirasawa and Grant Ingram, 1991; Kadivar et al., 2021); when roughness elements at the ice-ocean interface are larger than the thickness of the molecular sublayer the flow may shift from smooth to rough (see Supplementary material of Olsen et al., 2019, and references therein). This thickness of the molecular sublayer δz ~~may can~~ be estimated with (Lavoie et al., 2005, and references therein):

$$320 \quad \delta z = \frac{\nu}{u^*} . \quad (7)$$

For friction velocities in the range of the MOSAiC case study, the thickness of the molecular sublayer ranges between a maximum of 2 mm and a minimum of 0.1 mm. In Lavoie et al. (2005) the thickness of this sublayer was < 1 mm. The ~~undersurface~~ bottom roughness in multiyear ice during the SHEBA experiment was 0.0048-0.007 m, i.e. around 6 mm (McPhee, 2002) and larger than our estimates of δz . We do not have information on the small scale roughness of the ice bottom in our three case
325 studies, thus we tested different values covering the literature range. The range of variability of the thickness of the ~~laminar~~ molecular sublayer and that of the ~~surface-bottom~~ roughness suggests that the flow under the sea ice may easily shift from smooth to turbulent, since the latter is larger than the former. The dependence on sea-ice roughness is a limitation of the current parameterization, since roughness measurements are usually not conducted during sea-ice monitoring. Moreover, it should be noted that the Reynolds number depends on the value of the oceanic drag coefficient through the friction velocity. We could
330 have changed the value of the drag coefficient, which itself is a measure of ~~surface-bottom~~ roughness, rather than the roughness parameter directly. However, the drag coefficient in CICE + Icepack is also used in the momentum equation, thus we would have introduced other effects difficult to disentangle in our analysis. When considering large scale applications, a simple approach would be to rely on a fixed value of h_s in the middle range of those tested in the present study. Another approach could be based on the determination of the value of such parameter based on ice type/age. For those models that include deformation processes, values of bottom roughness could be based on the amount of deformation per grid cell (e.g., Castellani et al., 2018). However, the scale of deformation may not be relevant for the scale of the molecular sublayer and targeted observations are needed to better relate nutrient fluxes to ice deformation.

In the ~~MOSaIC~~ MOSAiC case, our parameterization led to a simulated increase in ~~ocean-to-ice~~ ocean-ice nutrients fluxes that was proportional to roughness. The concentration of nutrients in the ice bottom did not vary substantially for most of the
340 study, ~~rather it rapidly equilibrated with the ocean concentration,~~ but large changes occurred as soon as algal growth began, after release from light limitation. The two models showed different equilibrium concentrations ~~, which were higher in with~~ SIMBAv2.0 ~~. This may be due to the fact that showing higher concentration in the bottom ice. Differences between the two models can be explained by discetization and complexity, indeed~~ SIMBAv2.0 ~~nutrients remain at the bottom ice, whereas~~

in CICE + Icepack they diffuse vertically along the brine network, and thus the bottom brine concentration takes longer to equilibrate with the sea water and remains lower than in the former model. ~~does not compute brine fraction but it uses a fixed value for the skeletal layer, whereas Icepack calculates brine fraction in each layer based on thermodynamic processes. Differences in brine fraction between the models would lead to differences in bulk concentrations.~~ Both models, though, agree with observations (panel b in Figures 5 and 6), since the latter are scattered around 0.5 and 1.0 mmol N m⁻³, except for one large value at the end of March. This "outlier" may be attributed to a rafting event (Angelopoulos et al., 2022), and it is thus of a dynamic nature (unresolved by our models). In July, observed values are lower and simulations with both models agree well, except for the maximum value of surface roughness in SIMBAv2.0. In both models, ~~when only molecular diffusion is active, the ice bottom is rapidly depleted with nitrates after the bloom onset. This prevents any further algal growth~~ nutrients that are flushed into the ice are then transferred upwards. However, the two models are very different in nature (i.e., CICE + Icepack is vertically resolved and calculates brine convection, whereas SIMBAv2.0 has only bottom algae and the transport of nutrients upwards is only due to remapping during ice growth/melt). The trend in nutrients is visible in the vertically integrated time series for Icepack (shown in the Supplementary Material) and in the concentration of nutrients in the upper layer of the ice in SIMBAv2.0. It has to be noted that in SIMBAv2.0 the nutrients are simply stored in the above layer and are not used for any biological production.

4.2 Algal Phenology

In the MOSAiC case, modeled algal bloom started ~~at the end of May~~ in April. Algal growth led to an increase in ~~nutrients~~ nutrient fluxes, especially in CICE + Icepack case. This increase in nutrient fluxes does not lead to larger accumulation of nutrients in the ice bottom, but nutrients are rather utilized immediately by algae to sustain the growth. The higher the ~~surface~~ bottom roughness parameter (thus, the higher the turbulence), the more algae can grow, ~~and this holds for in~~ both models. ~~The In SIMBAv2.0 the~~ maximum biomass accumulated in the case of fully turbulent flux was almost four times larger than in the case of molecular diffusion, ~~nad its was even larger for CICE + Icepack.~~ Initiation of growth, as well as timing of maximum biomass were not affected by the nature of the exchanges. ~~Observations (Hoppe et al., 2024) show an initial increase in biomass at the beginning of April, which was not captured by either model. Between the beginning of May and mid-July, no observations are available (Fong et al., 2024), thus it is not possible to know what was the maximum biomass accumulated during that time. The lack of growth in April in both models is due to the thick snow cover still present, but rather by~~ light limitation. SIMBAv2.0 was forced with snow observations collected at the coring site and was able to represent the algal increase in April. In CICE + Icepack we had to tune the value of the light limitation factor to match observations (see Supplementary Material). The reason for such tuning is that the model predicts thicker snow cover on the order of 25 cm (e.g., Campbell et al., 2015, Figure 7). We note here that the forcing used to compute sea-ice thermodynamics and to compute light limitation for algae were collected with an IMB buoy located at distance from the FYI coring site (Lei et al., 2022). Unfortunately, none of the buoys located next to the coring site provided a time series long enough to simulate the ice growth during the entire drift period. As a result of this failure, as well as the inherent heterogeneity of the snow cover, the snow depths used to force the model may differ from those actually present at the FYI coring site. In both models algae start growing when

~~snow melts and enough light is available to initiate the bloom~~(Figure 7) at the time of the observed algal growth. It should also ~~however~~ be noted that this early growth in observations was unexpected (Hoppe et al., 2024) and probably due to very efficient
 380 light use from sea-ice algae, ~~thus~~. Thus it is no surprise that ~~models are not able a tuning of the light limitation parameter~~
~~was needed in the model~~ to represent such early growth. ~~Between the beginning of May and mid July, no observations are~~
~~available (Fong et al., 2024), thus it is not possible to know what was the maximum biomass accumulated during that time.~~
 Maximum biomass is reached at the same time for all different roughness values, ~~but in SIMBAv2.0 the maximum and in both~~
~~models it occurs at the end of June, whereas in CICE + Icepack, it occurs at the beginning of July~~May. Models represent better
 385 ~~observation in the case of molecular diffusivity only. The explanation could reside in two possible mechanisms: it is possible~~
~~that the ice bottom was so smooth to not develop any turbulent exchange. On the other hand, during MOSAiC a freshwater~~
~~layer was observed (Smith et al., 2022, 2025) that accumulated under the ice. Such layer was isolating the bottom of the ice~~
~~from the more nutrients-rich sea water, thus impeding nutrients resupply to the ocean-ice interface. This points to the large~~
~~complexity of both collecting measurements (nutrient concentrations in water should be measured close to the ice bottom) and~~
 390 ~~modeling sea-ice physical and biogeochemical processes to represent observations.~~

In the MOSAiC case, observations are sporadic so it is difficult to constrain model results. However, both in the N-ICE2015
 and Resolute cases observations are available at higher time resolution. In the N-ICE2015 case, both models agreed with ob-
 servations for at least 2-3 values of ~~surface-bottom~~ roughness considered. Both models simulated algal biomass accumulation,
 which was recorded in the refrozen lead. It has to be noted that CICE + Icepack was tuned (Duarte et al., 2017) to simulate
 395 the refrozen lead case before the parameterization was introduced, and when only molecular diffusion was considered (the
 default process in Icepack biogeochemistry). This explains why the case of minimum sea-ice roughness is able to capture the
 right accumulation of biomass. It should also be noted that the tuning carried out in Duarte et al. (2017) was independent of
 the flux parameterization. Specifically, Duarte et al. (2017) reduced the half-saturation constant for silicate uptake by ~~almost~~
 50%. While this adjustment affects ice-algal physiology and illustrates how tuning can be used to compensate for the absence
 400 of a more physically based representation of the system, such tuning may also reduce the model's realism by shifting physi-
 ological parameters away from observed or experimentally derived values. ~~In SIMBAv2.0 was not tuned on the N-ICE2015~~
~~data and the observed algal accumulation is properly simulated only when the contribution of turbulence is taken into account.~~
~~However, SIMBAv2.0 utilizes parameters values as close as possible to those of CICE + Icepack, which may explain the better~~
~~comparison with observations also for SIMBAv2.0 in the N-ICE2015 case.~~ Resolute is a particular case characterized by very
 405 large biomass accumulation (Mortenson et al., 2017). Here, both models accumulated larger biomass compared to the other
 two cases, mainly due to the larger ocean nutrient concentrations than in the previous case studies. ~~However, only SIMBAv2.0~~
~~was~~Both models were able to reproduce observations when the contribution of turbulence was taken into account, ~~even though~~
~~the maximum biomass was reached later (around June 7th) compared to observations.~~ This shows the potential importance of
 turbulence in sustaining growth and in representing algal accumulation without relying on tuning parameters that are not well
 410 constrained by observations. ~~For CICE + Icepack we also had to increase the light limitation parameter alpha (Table 2).~~ The 1D
 model intercomparison of ~~Tedesco et al. (2026)~~ showed that the parameters that are often tuned to match observations are the
 half saturation constants and the ~~chl-amax-specific~~ ~~maximum chl-specific~~ growth rate. Although such tuning strategies allow

better representation of observed phenology, they still fail in representing ~~nutrients concentration~~ nutrient concentrations in the ice. The model intercomparison of ~~?~~ Tedesco et al. (2026) was focusing on Arctic data, however recently Lim et al. (2019) tuned the half saturation constant for ~~silicate~~ silic acid in an order to match a 17-day time series of biogeochemical sea-ice observations from Davis in East Antarctica. ~~For CICE + Icepack, biomass values remained significantly lower compared to observations, even when the role of turbulence was included. One explanation could be that the redistribution of nutrients vertically does not happen fast enough for the bottom of the ice to be replenished by the amount of nutrients needed for algae to grow (Figure 12). Moreover, algae located higher in the ice have access to less nutrients and may grow slower, thus 'diluting' the overall growth. Finally, the vertical resolution of the model may not be appropriate to simulate the massive algal growth at its very bottom. In SIMBAv2.0 algae are forced to be located in the bottom 3 cm, whereas in CICE + Icepack the thickness of the bottom layer is the same as of the other layer of the biogrid and, possibly larger than 3 cm. Experiments not presented here showed that increasing vertical resolution (i.e. reducing the thickness of individual layers of the biogrid) leads to an overall increase in biomass concentration.~~

The response of the two models to the new parameterization was consistent: turbulence enhanced the nutrient fluxes at the ice-ocean interface. This led to a reduction in nutrient limitation and a significant increase in ~~ice algal net primary production and chl *a* biomass accumulation~~ in the ice, particularly in the bottom-ice. The parameterization performance was comparable in the two models presented in this study, so it may be used in models with different complexity. The fluxes have no influence on the onset of the bloom, which is determined by light availability, ~~and also in this case the response of both models is consistent, despite differences in calculating light limitation.~~ In the MOSAiC case, ~~ice algae started growing only after a decrease in snow depth since with thick snow light limitation is such to prevent any growth. This results points to two distinct limitation: on one hand the~~ we had to increase the light limitation parameter in CICE + Icepack to reproduce the observed algal growth, even though the model still indicated thick snow cover. This suggests a fundamental limitation in the current modeling framework: while the model simulates snow accumulation based on precipitation and standard thermodynamic physics, it may not accurately represent the true snow height or distribution –particularly in regions where local processes such as wind-driven snow redistribution, rafting, or ridging events significantly alter the snow cover. These sub-grid-scale processes, which are not captured in a one-dimensional (1D) model, can lead to localized thinning of snow and enhanced light availability, thereby enabling algal growth despite seemingly unfavorable conditions. Thus, the need to adjust the light limitation parameter may reflect a symptom of missing physical realism in the snow accumulation prescribed in the model and sued to force the physics

~~may not be exactly representing the snow on top of the ice sampled with ice cores for biogeochemical analysis ice-light coupling rather than a real need for biological tuning, thus underscoring the importance of incorporating higher-resolution or process-based representations of snow dynamics in future model developments.~~ On the other hand, algal physiology may be such that in reality algae can start growing at very low light levels (Hoppe et al., 2024) but the model is not able to represent such physiological trait. ~~In general, suggesting that a variable photosynthetic efficiency α could be more appropriate than one constant value. In contrast, SIMBAv2.0 accumulates more biomass than CICE + Icepack and it seems that the response of algae to enhanced nutrient fluxes is more sensitive. This appeared to be the case already with the previous version of SIMBA (Castellani et al., 2017) as it is shown in Tedesco et al., preprint offers a more practical alternative for process evaluation and~~

model–observation comparison, as it does not simulate the underlying physical processes (e.g., snow accumulation, ice growth, or brine dynamics) but instead relies on prescribed ice and snow thicknesses. This allows the model to be directly forced by observations, making it easier to isolate and evaluate biogeochemical responses. Despite the fact that SIMBAv2.0 is only a biogeochemical model, so it does not resolve physics, the main differences between the two models lie in the complexity of the biological processes. For example, CICE + Icepack includes ammonia; a temperature dependent description of mortality; a zooplankton term; a different parameterization of light limitation where light inhibition is also considered; and algal growth is also salinity and temperature dependent. ~~On the other hand, The simplified structure of SIMBAv2.0 presents a variable Chl:a:C ratio which results in a variable carbon to nitrogen ratio, whereas CICE + Icepack uses constant ratios. Finally, our results suggest that the vertical resolution plays an important role in the accumulation of biomass at the bottom of the ice and its reduced number of parameters make it more straightforward to tune and interpret, particularly when assessing the sensitivity of algal growth to environmental drivers.~~

5 Conclusions

We developed a parameterization that is well-grounded on the physics of the ocean-ice boundary layer, and accounts for the nature of the flow under sea ice, whether this is of smooth nature, of turbulent nature, or a combination of the two. The parameterization was implemented in two sea-ice biogeochemical models of different complexity to test its effects on the fluxes of nutrients at the ice-ocean interface. Our results show that when turbulence is taken into account, the fluxes of nutrients are much higher than those we could obtain with molecular diffusion alone. These enhanced fluxes can sustain larger accumulation of biomass for longer periods, consistently in both models. In two out of three case studies the models are able to reproduce observations only when turbulent fluxes are considered. This seems to fill the "nutrient deficit" that pushed ~~modellers~~ modelers to over-tune some physiological parameters in their models, or to accept that ice algae have direct access to ocean nutrients. ~~We argue~~ At the same time, tuning of parameters such as those representing light limitation may help enhancing realism by compensating a poor representation of the physics in the models. Our results show that turbulence should be considered when parameterizing ~~nutrients exchanges, and that the~~ nutrient exchanges. The implementation of the parameterization presented here can avoid the "cascading" changes that may incur when tuning a model, while at the same time adding realism to the simulations.

Code and data availability. The code for SIMBA can be downloaded at https://github.com/EyringMLClimateGroup/Castellani2025_GMD_SIMBA2 under DOI:10.5281/zenodo.17408325 (Castellani, 2025). CICE and Icepack are available, respectively, at <https://github.com/pduarte8/CICE> and <https://github.com/pduarte8/Icepack> under DOI:10.5281/zenodo.17383699 (Duarte, 2025a) and DOI:10.5281/zenodo.17394666 (Duarte, 2025b). Simulation results for both CICE + Icepack and SIMBA can be found at 10.21334/NPOLAR.2025.D8BD7FED.

Appendix A: SIMBAv2.0

The Sea Ice Model for Bottom ~~algae~~ Algae (SIMBA) in its version 2.0 consists of three to five state variables describing the rate of change of ice algae, detritus and, one to three nutrients according to how many nutrients are used (nitrate, ~~silicate~~ silicic acid, phosphate). The equation for sea-ice algae is:

$$\frac{\partial C_{Al}}{\partial t} = \mu C_{Al} - (\lambda_{Res} + \lambda_{Mor}) C_{Al} + \frac{\tilde{M}}{\delta z} C_{Al}, \quad (A1)$$

where C_{Al} is the concentration of ice algae (mmol N m^{-3}) in the bottom of the ice δz . The thickness of the ice bottom can be set according to the resolution of the available observations. The second term on the right hand side of equation (A1) represent the algal loss due to mortality (λ_{Mor}) and respiration (λ_{Res}), both taken as constant with value of 0.01 d^{-1} for mortality and
485 value of 0.005 d^{-1} for respiration. The last term accounts for algae lost due to basal melt with $\tilde{M}$ representing the basal melt rate (m s^{-1}), whereas the first term represents the rate of algal growth due to primary production, which depends on nutrients and Photosynthetic Active Radiation (PAR) :

$$\mu = \mu_M \min(L_{nit}, L_{sil}, L_{phos}, L_{PAR}), \quad (A2)$$

where μ_M represents the specific growth rate. The parameter μ_M is a tuning parameter and for the present study we use a
490 value of 0.86 d^{-1} ~~in the MOSAiC and Resolute case, and a value of 0.5 d^{-1} for the NICE case study (see discussion in ?)~~ (see Table 2). The nutrient limitation functions are based on the Monod formulation (Monod, 1949):

$$L_N = \frac{C_N}{k_N + C_N}, \quad (A3)$$

where C_N represents the concentrations of nitrate (mmol N m^{-3}), ~~silicate~~ silicic acid (mmol Si m^{-3}) or phosphate (mmol P m^{-3}). ~~k_{CN}~~ k_N is the half saturation constant for the nutrient chosen. Standard values in SIMBAv2.0 are $k_{nit} = 1.6$, $k_{sil} = 3.9$,
495 and $k_{phos} = 0.24$ (Castellani et al., 2025). The light limitation function (L_{PAR}) is taken as in Jassby and Platt (1976):

$$L_{PAR} = \tanh\left(\frac{\alpha PAR}{P_m}\right). \quad (A4)$$

In equation (A4) the photosynthetic efficiency α [$\text{gC (g Chl } a \text{ hr } \mu\text{E m}^{-2} \text{ s}^{-1})$] represents the increase of carbon assimilation per gram of chlorophyll for each unit increase in PAR. It indicates how quickly ice algae reach their light-saturated specific photosynthetic rate P_m [$\text{gC (g Chl } a \text{ hr}^{-1})$]. Various values are used in literature (see e.g., Lavoie et al., 2005), in the present
500 study we use a value of $\alpha = 0.055$. In SIMBAv2.0 we set only the value of α since we express P_m using Geider et al. (1998):

$$P_m = \mu_M \frac{L_N}{r_C^{Chl}}. \quad (A5)$$

We introduce in equation (A5) the Chl : C ratio r_C^{Chl} (g g^{-1}) which we compute following Sibert et al. (2010):

$$r_C^{\text{Chl}} = r_C^{\text{Chl}}|_{\text{max}} \left[0.25 + 0.75 \exp \left(-\frac{1}{2} \frac{\text{PAR}}{k_E} \right) L_N \right], \quad (\text{A6})$$

where the half saturation parameter k_E is taken as $10 \mu\text{E m}^2 \text{s}^{-1}$, and the maximum Chl : C ratio is taken as 0.1. The equations
505 for the nutrients and for the detritus are given by:

$$\frac{\partial C_{\text{nit}}}{\partial t} = -(\mu + \lambda_{\text{Res}}) C_{\text{Al}} + \lambda_{\text{rm}} C_{\text{Det}} + \beta + \gamma, \quad (\text{A7})$$

$$\frac{\partial C_{\text{sil}}}{\partial t} = -R_{\text{sn}} (\mu + \lambda_{\text{Res}}) C_{\text{Al}} + R_{\text{sn}} \lambda_{\text{rm}} C_{\text{Det}} + \beta + \gamma, \quad (\text{A8})$$

$$510 \quad \frac{\partial C_{\text{phos}}}{\partial t} = -R_{\text{pn}} (\mu + \lambda_{\text{Res}}) C_{\text{Al}} + R_{\text{pn}} \lambda_{\text{rm}} C_{\text{Det}} + \beta + \gamma, \quad (\text{A9})$$

$$\frac{\partial C_{\text{Det}}}{\partial t} = \lambda_{\text{Mor}} C_{\text{Al}} - \lambda_{\text{rm}} C_{\text{Det}}, \quad (\text{A10})$$

where β is the source/sink of nutrients given by the parameterization described in Section 2.1 [and \$\gamma\$ accounts for entrapment/release of nutrients during growth/melt](#). Silicate and phosphate are converted into nitrate units with the conversion factors $R_{\text{sn}} = 1.8$
515 for silicate to nitrate, and $R_{\text{pn}} = 0.07$ for phosphate to nitrate.

Author contributions. GC coded the model SIMBA2 and implemented the parameterizations in both models, conducted the simulations, analyzed the results, and drafted the manuscript. PD developed the study idea, contributed to implementing the parameterizations in CICE + Icepack and contributed to data analysis and manuscript drafting. KC and SB contributed to analysis of results and drafting of the manuscript.

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