Ice Algae Model Intercomparison Project phase 2 (IAMIP2)

Hakase Hayashida[1,2], Meibing Jin[3,4,5], Nadja S. Steiner[6,7], Neil C. Swart[7], Eiji Watanabe[8], Russell Fiedler[9], Andrew McC. Hogg[2,10], Andrew E. Kiss[2,10], Richard J. Matear[2,9], Peter G. Strutton[1,2]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia
5 [2]Australian Research Council Centre of Excellence for Climate Extremes, Australia
[3]School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing, China
[4]Southern Laboratory of Ocean Science and Engineering, Zhuhai, China
[5]International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA
[6]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, BC, Canada
10 [7]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC, Canada
[8]Japan Agency for Marine-Earth Science and Technology, Yokosuka, Kanagawa, Japan
[9]CSIRO Oceans and Atmosphere, Hobart, TAS, Australia
[10]Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

15 *Correspondence to*: Hakase Hayashida (hakase.hayashida@utas.edu.au)

Abstract. Ice algae play a fundamental role in shaping polar marine ecosystems and biogeochemistry. This role can be investigated by field observations, however the influence of ice algae at the regional and global scales remains unclear due to limited spatial and temporal coverage of observations, and because ice algae are typically not included in current Earth System Models. To address this knowledge gap, we introduce a new model intercomparison project (MIP), referred to here
20 as the Ice Algae Model Intercomparison Project phase 2 (IAMIP2). IAMIP2 is built upon the experience from its previous phase, and expands its scope to global coverage (both Arctic and Antarctic) and centennial timescales (spanning the mid-twentieth century to the end of the twenty-first century). Participating models are three-dimensional regional and global coupled sea ice–ocean models that incorporate sea-ice ecosystem components. These models are driven by the same initial conditions and atmospheric forcing datasets by incorporating and expanding the protocols of the Ocean Model
25 Intercomparison Project, an endorsed MIP of the Coupled Model Intercomparison Project phase 6 (CMIP6). Doing so provides more robust estimates of model bias and uncertainty, and consequently advances the science of polar marine ecosystems and biogeochemistry. A diagnostic protocol is designed to enhance the reusability of the model data products of IAMIP2. Lastly, the limitations and strengths of IAMIP2 are discussed in the context of prospective research outcomes.

1 Introduction

30 Microalgae that colonize sea ice, referred to here as ice algae, are the foundation of polar marine food webs. Understanding the susceptibility of ice algae to climate change is therefore essential to comprehending the climatic impacts on higher trophic levels, such as fish, seals, whales, penguins, polar bears, and humans (Cavan et al., 2019; Darnis et al., 2012). Vernal

blooms of ice algae also directly influence lower trophic levels, such as phytoplankton, zooplankton, and krill, by drawing down near-surface nutrients, reducing light transmission through sea ice, seeding subsequent pelagic blooms, and providing

35   a food source for pelagic and benthic grazers (Leu et al., 2015). Ice algae also regulate ocean biogeochemistry through the biological carbon pump (Mortenson et al., 2020; Watanabe et al., 2015) and polar climates via the production of the climate-active trace gas dimethyl sulfide (Levasseur, 2013) and via the modification of sea-ice albedo (Zeebe et al., 1996).

Field observations of ice algae abundance and distribution are scarce, mainly due to logistical and methodological challenges

40   in these remote and cold environments (Miller et al., 2015). Satellite observations are incapable of detecting algae in sea ice. Therefore, the role of ice algae in polar marine ecosystems and biogeochemistry at the regional and global scales remains unknown. One approach to address this knowledge gap is numerical modelling, which simulates ice algae abundance and distribution across the sea-ice domain by incorporating a numerical model of the sea-ice ecosystem into a regional or global three-dimensional coupled sea ice–ocean general circulation model (Vancoppenolle and Tedesco, 2016).

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An initial model intercomparison effort was made recently to understand the similarities and differences in simulated ice algae abundance and distribution among the existing three-dimensional models (Watanabe et al., 2019). This model intercomparison investigated the seasonal-to-decadal variability in ice-algal primary productivity in four regions across the Arctic during 1980-2009 simulated by five participating models. The conclusions were: (1) the decadal trend is unclear

50   despite the ongoing reduction of Arctic sea ice; (2) the vernal bloom shifts to an earlier onset and briefer duration over the period of the simulations; and (3) the choice of the maximum growth rate is a key source of the inter-model spread in the simulated ice-algal primary productivity.

Polar regions, especially the Arctic, are warming faster than the rest of the globe, which results in the reduction of both

55   Arctic and Antarctic sea ice (Smith et al., 2019). However, as demonstrated by the previous model intercomparison study (Watanabe et al., 2019), the transient response of ice algae to the anticipated loss of sea ice throughout the twenty-first century may not necessarily be linear. Using a one-dimensional sea-ice biogeochemistry model, Tedesco et al. (2019) found such a non-linear projected response of ice-algal primary productivity to global warming, that also has strong latitudinal dependence. Further investigation using three-dimensional models will provide a comprehensive view of the climate change

60   impacts on polar marine ecosystems and biogeochemistry at the regional-to-global scale, and determine whether ice algae exert any influence on global climate. This knowledge will help to clarify whether ice algae should be incorporated into the next generation of Earth System Models (ESMs), such as those participating in the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring et al., 2016).

65   This paper introduces a new model intercomparison effort for ice algae, referred to here as the Ice Algae Model Intercomparison Project phase 2 (IAMIP2). IAMIP2 improves on the previous effort (IAMIP1 hereafter; Watanabe et al.,

2019) in its experimental design, which is based on the experimental protocols of CMIP6. A consistent experimental design allows us to provide more robust estimates of model bias and uncertainty, and consequently advance the science of polar marine ecosystems and biogeochemistry. The scope of IAMIP2 is global, covering both the Arctic and Antarctic, and centennial timescales, spanning the mid-twentieth century to the end of the twenty-first century. IAMIP2 has five main objectives: (1) evaluation of systematic bias in the existing sea-ice ecosystem models; (2) mechanistic understanding of the past changes in ice algae abundance and distribution; (3) assessment of projected changes and their uncertainty in ice algae abundance and distribution; (4) regional-to-global impacts on marine ecosystems and biogeochemistry; and (5) open-access distribution of the model output for sea-ice research and education.

2 Participating models

To date, six three-dimensional coupled sea ice–ocean models have been committed to participating in IAMIP2 (Table 1). All of these models represent either a global or regional configuration of the sea-ice and ocean components of the ESMs or global coupled models (GCMs) participating in CMIP6. A key difference from these parent model components is that the IAMIP2 models include sea-ice ecosystem components that simulate the biological sources and sinks of ice algae biomass and nutrient concentrations in the bottom sea-ice skeletal layer (Fig. 1). In each model, the sea-ice ecosystem component is coupled to the sea-ice component to account for physical processes that regulate the budgets of ice algae biomass and nutrient concentrations, such as sea-ice growth and melt. The sea-ice ecosystem component is also coupled to ocean dynamics and ecosystem components to simulate the tracer exchange at the sea ice–ocean interface. Three of the IAMIP2 models are global configurations, while the other three are pan-Arctic regional configurations in which the tracer states in the ocean are prescribed at the lateral boundaries. The IAMIP2 models are driven by applying a common atmospheric forcing dataset at the surface boundary. We welcome participation of additional models.

2.1 ACCESS-OM2

ACCESS-OM2 refers to the sea ice–ocean model of the Australian Community Climate Earth System Simulator (ACCESS), and is described in detail in Kiss et al. (2020). In brief, ACCESS-OM2 consists of an ocean dynamics component based on the Modular Ocean Model (MOM) version 5.1 and a sea-ice dynamics component based on the Los Alamos sea ice model (CICE) version 5.1.2. Notably, these sea ice–ocean physical model components are identical to those adopted for ACCESS-CM2, the GCM of ACCESS contributing to CMIP6 (Bi et al., 2020).

For IAMIP2, ocean and sea-ice ecosystem components are added to ACCESS-OM2. The ocean ecosystem component is the Whole Ocean Model of Biogeochemistry and Trophic-dynamics (WOMBAT), which consists of nitrate, iron, phytoplankton, zooplankton, detritus, dissolved oxygen, dissolved inorganic carbon, total alkalinity, and calcium carbonate (Ziehn et al., 2020). The sea-ice ecosystem component is the Biogeochemistry of CICE (Jeffery et al., 2016), which is based on Jin et al.

(2006). For IAMIP2, ACCESS-OM2 simulates ice algae biomass and nitrate concentration in the bottom-ice skeletal layer, which are respectively coupled to phytoplankton biomass and nitrate concentration in the ocean surface layer. The horizontal

100   resolution of ACCESS-OM2 is nominally 1° (360×300) and the vertical resolution in the ocean surface layer is 2.3 m (Kiss et al., 2020).

2.2 CESM-IARC

CESM-IARC refers to the 1° global sea ice–ocean configuration of the Community Earth System Model (CESM) version 1 with a sub-grid-scale brine rejection parameterization that improves ocean mixing under sea ice (Jin et al., 2018). The ocean

105   dynamic component of CESM-IARC is the Parallel Ocean Program (POP) version 2 and the sea-ice dynamic component is CICE version 5.1.2. The vertical resolution of the ocean surface layer is 10 m. The ocean ecosystem component consists of multiple nutrients (nitrate, ammonium, iron, silicate, and phosphate), phytoplankton functional groups (diatoms, flagellates, and diazotrophs), a single zooplankton group, dissolved organic matter (nitrogen, carbon, iron, and phosphorus), dissolved oxygen, dissolved inorganic carbon, and total alkalinity (Moore et al., 2013). The sea-ice ecosystem component consists of

110   nitrate, ammonium, silicate, and ice algae (Jin et al., 2006).

2.3 RASM

RASM refers to the 1/12° sea ice–ocean configuration of the Regional Arctic System Model, and consists of the same physical and ecosystem model components as CESM-IARC. The spatial coverage of RASM is pan-Arctic with lateral boundaries located approximately along the 40 °N Atlantic sector and along the 30 °N Pacific sector (Jin et al., 2018). The

115   vertical resolution of the ocean surface layer is 5 m.

2.4 CanNEMO

CanNEMO is the ocean component of CanESM5 (Swart et al., 2019), which is modified from version 3.4.1 of the Nucleus for European Modelling of the Ocean (NEMO; Madec and the NEMO team, 2012), and includes the Louvain-la-Neuve sea Ice Model version 2 (LIM2; Bouillon et al., 2009; Fichefet and Maqueda, 1997). The modifications include the addition of a

120   lee wave mixing scheme based on Saenko et al. (2012) and an update to the mesoscale eddy mixing length-scale (Saenko et al., 2018), as well as various parameter settings, as described in Swart et al. (2019). CanNEMO is configured on the ORCA1 tripolar grid, with a nominal grid spacing of 1°, refining to 1/3° within 20° of the equator. There are 45 vertical levels, ranging from 6 m near the surface to 250 m in the abyss. In the version used here, ocean biogeochemistry is represented by the Canadian Ocean Ecosystem (CanOE) model. CanOE contains two classes of phytoplankton, zooplankton and detritus,

125   with variable elemental (C/N/Fe) ratios in phytoplankton and fixed ratios for zooplankton and detritus; as well as prognostic carbonate chemistry, and cycles of iron, calcium carbonate and parameterized nitrogen fixation and denitrification (Swart et al., 2019).

For IAMIP2, CanNEMO–CanOE is coupled to the Canadian Sea-Ice Biogeochemistry (CSIB) model, which consists of
130 nitrate, ammonium, and ice algae (Hayashida et al., 2019). Modelled ice algae have a higher sensitivity to low-light
conditions relative to modelled phytoplankton (Mortenson et al., 2017). When modelled ice algae are released from sea ice
into seawater, they contribute partly to the large detritus pool and the seeding of large phytoplankton.

2.5 NEMO-NAA

NEMO-NAA is a pan-Arctic regional sea ice–ocean model based on NEMO version 3.4 coupled to LIM2 (Hu and Myers,
135 2013). The version used here incorporates several modifications that improve the simulation of physical and biogeochemical
processes in the Arctic (Hayashida et al., 2019; in revision). Specifically, these modifications include light penetration
through snow and sea ice, the vertical resolution of the ocean model, river runoff of biogeochemical tracers, removal of iron
dependency of phytoplankton and zooplankton, and changes to sea-ice model parameters. The horizontal grid resolution is
1/4°, which ranges from 10 km near the North American coastline to 14.5 km along the northern Eurasian coastline. The
140 vertical resolution ranges from 1 m for the upper surface layer to 255 m in the deep ocean. Similar to CanNEMO, the
ecosystem component of NEMO-NAA is CSIB–CanOE.

2.6 COCO–Arctic NEMURO

COCO–Arctic NEMURO refers to a pan-Arctic regional sea ice–ocean model developed at the Japan Agency for Marine-
Earth Science and Technology (JAMSTEC; Watanabe et al., 2019). The physical model component is the Center for Climate
145 System Research Ocean Component Model (COCO) version 4.9 (Hasumi, 2006). The sea-ice component of COCO accounts
for seven-category distributions of sub-grid snow depth and ice thickness with a one-layer thermodynamic formulation (Bitz
and Lipscomb, 1999; Bitz et al., 2001; Lipscomb, 2001) and the elastic–viscous–plastic (EVP) rheology (Hunke and
Dukowicz, 1997). The model domain covers the entire Arctic Ocean with boundaries at the North Atlantic (45 °N) and at the
Bering Strait on the Pacific side. The Bering Strait throughflow across the Pacific model boundary is prescribed by idealized
150 seasonal cycles of temperature, salinity, and current velocity based on Woodgate et al. (2005). The model adopts the
spherical coordinate system rotated by 90°, which sets the singular points (the North and South Poles of the model grid) at
the equator. The horizontal resolution of COCO–Arctic NEMURO is 1/4°, and there are 28 vertical levels in the ocean with
variable resolutions from 2 m in the uppermost layer to 500 m below 1,000 m depth. The ecosystem model component is the
Arctic and North Pacific Ecosystem Model for Understanding Regional Oceanography (Arctic NEMURO; Watanabe et al.,
155 2015). The ocean ecosystem model component consists of 3 nutrients (nitrate, ammonium, and silicate), 5 plankton types
(diatoms, flagellates, microzooplankton, copepod, and predator zooplankton), dissolved organic nitrogen, particulate organic
nitrogen, and opal (Kishi et al., 2007). The sea-ice ecosystem model component consists of ice algae, ice-related fauna, and
particulate organic matter (Watanabe et al., 2015).

3 Experiments

160   The experimental design of IAMIP2 is developed based on the experience from IAMIP1 and the Ocean Model
Intercomparison Project (OMIP; Griffies et al., 2016; Orr et al., 2017), which is an endorsed Model Intercomparison Project
(MIP) of CMIP6. The OMIP protocol is useful because OMIP is based on sea ice–ocean models driven by common
atmospheric forcing fields at their surface boundaries. Applying common forcing eliminates uncertainties due to atmospheric
processes and feedbacks, and allows us to focus on differences in the sea-ice, ocean, and biogeochemistry components.

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Four numerical experiments are planned for IAMIP2: historical, projection, exclusion, and control as described in detail
below and shown in Fig. 2. The IAMIP2 models are expected to conduct all of these experiments.

3.1 Historical

The historical experiment is designed to simulate changes in ice algae abundance and distribution since the mid-twentieth
170   century, the period for which we have realistic surface-atmospheric conditions based on observations. This experiment spans
the 61 years from January 1, 1958, to December 31, 2018, and uses the Japanese 55-year atmospheric reanalysis for driving
sea ice–ocean models version 1.4.0, referred to here as JRA55-do (Tsujino et al., 2018). For reference, version 1.4.0 is also
used for the second phase of OMIP (Tsujino et al., 2020). JRA55-do is regarded as a successor of the Coordinated Ocean-ice
Reference Experiment version 2 forcing dataset (CORE2; Large & Yeager, 2009), and has finer spatial and temporal
175   resolutions than CORE2. The surface atmospheric variables of JRA55-do are air temperature at 10 m, specific humidity at 10
m, eastward wind at 10 m, northward wind at 10 m, sea level pressure, downward shortwave, downward longwave, rainfall
flux, snowfall flux, river runoff, and calving flux (Fig. 1). The original spatial and temporal resolutions of these variables are
respectively ~0.5° and 3 hourly except for river runoff and calving flux, which are provided at 0.25° and daily (Tsujino et al.,
2018). However, in reality, the daily calving flux is provided by linear interpolation of monthly data for Greenland and it is
180   temporally constant for Antarctica (Tsujino et al., 2018). Although JRA55-do provides calving flux, none of the IAMIP2
models have iceberg components, and therefore it is released into the ocean as meltwater, adopting the approach before
version 1.4.0 (Tsujino et al., 2018). JRA55-do is interpolated to the model grid either prior to or during the experiment.

All IAMIP2 models are initialized from rest (zero velocity and sea level) and with ocean temperature, salinity, dissolved
185   oxygen, and nutrients (nitrate, phosphate, and silicate) from the World Ocean Atlas version 2 (WOA13v2; Garcia et al.,
2013; Locarnini et al., 2013; Zweng et al., 2013). More specifically, these fields are the version of WOA13v2 provided for
OMIP (Griffies et al., 2016; Orr et al., 2017). There is no recommended protocol for the initialization of sea-ice and other
biogeochemical fields. As discussed in Section 2.3 of Griffies et al. (2016), the restoring of sea-surface salinity is necessary
to reduce drift in sea ice–ocean models over decadal timescales. However, there is no best practice for salinity restoring

190   because it depends on model details. Therefore, the restoring procedure is left to the discretion of the participating groups,
       although it is recommended to choose a weak restoring as much as possible to minimize the impact on variability.

       Three of the IAMIP2 models are based on pan-Arctic regional configurations that require lateral boundary conditions. How
       to prescribe these conditions is left to the discretion of the participating groups.
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       Although carbonate chemistry is not the primary focus of IAMIP2, we recommend that modelled total alkalinity and
       dissolved inorganic carbon should be initialized with the Global Ocean Data Analysis Project version 2 (GLODAPv2;
       Lauvset et al., 2016) and prescribe the monthly global-mean atmospheric carbon dioxide concentration for the air-sea carbon
       flux (Meinshausen et al., 2017). These procedures are consistent with OMIP (Orr et al., 2017), and allow us to expand the
200   use of the IAMIP2 product for future research.

3.2 Projection

       The projection experiment is designed to simulate the projected changes in ice algae abundance and distribution throughout
       the twenty-first century under the highest greenhouse gas emission scenario for CMIP6, known as the Shared Socioeconomic
       Pathway 5-8.5 (SSP5-8.5; O'Neill et al., 2016). This experiment spans 86 years from 2015 to 2100. The IAMIP2 models are
205   initialized from states at the end of 2014 in the historical experiment. The atmospheric carbon dioxide concentrations are set
       to their monthly global-mean values prescribed for SSP5-8.5 (Meinshausen et al., 2020).

3.2.1 Selection of the projected atmospheric forcing dataset

       The IAMIP2 models are driven by the atmospheric output of selected CMIP6 models that provide the atmospheric forcing
       fields at the temporal resolutions needed for simulating high-frequency variability. To date, there are three CMIP6 models
210   that satisfy this criterion: ACCESS-CM2, EC-Earth3, and MRI-ESM2-0. Specifically, these models provide the simulated
       atmospheric forcing variables over 2015-2100 under the SSP5-8.5 scenario at the temporal resolutions identical to those of
       JRA55-do except for sea level pressure, river runoff, and calving flux. Sea level pressure fields are provided 6 hourly, as
       opposed to 3 hourly in JRA55-do. River runoff fields are provided at monthly, as opposed to daily in JRA55-do. Calving
       flux fields are not provided at all under the SSP5-8.5 scenario. To partly overcome this limitation, we prescribe a monthly
215   climatology of the calving flux of JRA55-do over 1958-2018 for the projection experiment. This will provide interannually-
       invariant calving flux for Greenland, and constant calving flux for Antarctica as noted in Section 3.1.

       Among the three CMIP6 models, we choose the output of EC-Earth3 for the atmospheric forcing for the projection
       experiment because EC-Earth3 provides overall the most realistic atmospheric conditions (in best agreement with JRA55-
220   do). Specifically, we compare the global and polar surface air temperature and major climate modes derived from JRA55-do
       with those simulated by the following 24 CMIP6 models over 1958-2100 (Figures 3 and 4): ACCESS-CM2, ACCESS-

ESM1-5, AWI-CM-1-1-MR, BCC-CSM2-MR, CESM2-WACCM, CIESM, CanESM5, EC-Earth3, EC-Earth3-Veg, FGOALS-f3-L, FGOALS-g3, FIO-ESM-2-0, GFDL-ESM4, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, KACE-1-0-G, MIROC6, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NESM3, NorESM2-LM, and NorESM2-MM. Although the objective here is to compare among the three candidates for the projected atmospheric forcing, we include the remaining 19 CMIP6 models that have provided the output at monthly resolution as well as the multi-model mean product of the 24 models for reference. These model products belong to Variant Label *r1i1p1f1* of Experiment IDs *historical* and *ssp585*, and were downloaded from https://esgf-node.llnl.gov/ (accessed on July 1, 2020).

3.2.2 Comparison of surface air temperature

In terms of global averages, the three candidates simulate roughly 1 °C colder surface air temperature than JRA55-do prior to 2000 (Figure 3a). After 2000, EC-Earth3 simulates warmer surface air temperature that agrees well with JRA55-do. Compared with the multi-model averages, EC-Earth3 and ACCESS-CM2 project greater global warming throughout the 21st century, whereas MRI-ESM2-0 projects lesser warming in the late 21st century (Figure 3b).

In terms of Arctic averages, MRI-ESM2-0 simulates surface air temperature that is in closest agreement with JRA55-do, but EC-Earth3 again compares well later in the 2010s (Figure 3c). Polar amplification is evident in all models, but is more so in EC-Earth3 and ACCESS-CM2 (>10 °C warming by the end of the 21st century relative to their 1958-2014 averages; Figure 3d).

In the Antarctic, the average air temperature of EC-Earth3 agrees by far the best with JRA55-do compared to the rest of the candidates (Figure 3e). Besides EC-Earth3, only two other CMIP6 models simulate surface air temperature that is within 2 °C of JRA55-do. MRI-ESM2-0 exhibits greater and highly-variable Antarctic warming than ACCESS-CM2 and EC-Earth3 (Figure 3f).

3.2.3 Comparison of major climate modes of variability

Three major modes of climate variability considered here are the El Niño–Southern Oscillation (ENSO), the Northern Annular Mode (NAM), and the Southern Annular Mode (SAM). ENSO is the dominant mode of climate variability for the globe, which can be characterised by an index called the Equatorial Southern Oscillation Index (EQSOI; Bell and Halpert, 1998). EQSOI is the standardised sea level pressure difference between two regions over Indonesia (80 °W-130 °W, 5 °S-5 °N) and the eastern equatorial Pacific (90 °E-140 °E, 5 °S-5 °N). Because the CMIP6 models have their own ENSO variability, EQSOIs of these models are not expected to be in phase with that of JRA55-do (this is applicable also to other modes of climate variability, such as NAM and SAM discussed below). Instead, we compare the magnitude of the sea level

pressure difference, which determines the strength of the easterly winds along the equator (Figure 4a). Furthermore, we compare the power spectra of EQSOI over 1958-2014 (Figure 4b).

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ACCESS-CM2 simulates the sea level pressure difference for EQSOI that is in closer agreement with JRA55-do than EC-Earth3 and MRI-ESM2-0 (Figure 4a). These two models simulate about 100 Pa lower sea level pressure difference than JRA55-do. The three models agree with JRA55-do in simulating strong signals of EQSOI at periods between >2 and 6 years (Figure 4b). MRI-ESM2-0 shows a distinct maximum in the spectrum at period of about 4 years.

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NAM is the dominant mode of climate variability in the Northern Hemisphere, which can be characterised by the sea level pressure difference between the zonal means at 35 °N and 65 °N (Li and Wang, 2003). EC-Earth3 simulates closer sea level pressure difference to JRA55-do and the multi-model mean than ACCESS-CM2 and MRI-ESM2-0 (Figure 4c). The power spectra of NAM are spread more broadly than those of EQSOI (Figure 4d). JRA55-do shows peaks at about 0.5, 1, and 10

265 years, indicating the importance of seasonal, interannual, and interdecadal variability of NAM, respectively. The three models also exhibit peaks within this seasonal-to-interdecadal time scale, but differ in terms of the exact locations of these peaks. The power spectra of ACCESS-CM2 and EC-Earth3 are strongest at around 5 years, whereas the strongest signal of NAM in MRI-ESM2-0 is present at period of less than 1 year.

270 SAM is the dominant mode of climate variability in the Southern Hemisphere, which can be characterised by the sea level pressure difference between the zonal means at 40°S and 65 °S (Gong and Wang, 1999). The three candidates compare equally well with JRA55-do in simulating the sea level pressure difference for SAM, which is lower than the multi-model mean of the 24 CMIP6 models (Figure 4e). Similar to NAM, the power spectra of SAM are distributed across the broad time scales, but the peaks occur at periods of >1 year (Figure 4f). The only exception is EC-Earth3, in which the strongest signal

275 is present at period of slightly less than 1 year. ACCESS-CM2 and EC-Earth3 agree with JRA55-do in simulating strong SAM signals at periods of around 2 years, whereas such signals are lacking in MRI-ESM2-0. Consistent among the three models and JRA55-do, SAM exhibits appreciable variability also at lower frequencies, as indicated by the presence of local maxima at periods of 3-6 years and beyond 10 years. Notably, this low-frequency variability is the strongest signature of SAM simulated by MRI-ESM2-0.

280 **3.2.4 Recommendations for the projected atmospheric forcing dataset**

In summary, all three candidates for the projected atmospheric forcing dataset simulate reasonable historical atmospheric conditions compared to JRA55-do. The only exception is the substantially colder surface air temperature over the Antarctic region, for which EC-Earth3 is superior to the other two models. For this reason, we adopt the output of EC-Earth3 under the SSP5-8.5 scenario as the standard atmospheric forcing dataset for the projection experiment of IAMIP2. However,

285 depending on computational resources, additional projection experiments using the output of the other two candidates as

well as other CMIP6 models may be considered if they provide the output at high temporal resolution. Such additional experiments will allow assessment of the sensitivity of the IAMIP2 models to projected atmospheric conditions.

3.3 Exclusion

The exclusion experiment is designed to simulate ocean biogeochemistry in the absence of ice algae, which is the case for all
290 CMIP6 models. This experiment is done in the same set up as the projection experiment except that the sea-ice ecosystem component is excluded. Comparing the results of the projection and exclusion experiments allows us to quantify the impacts of ice algae on polar marine lower-trophic-level ecosystems and biological carbon pump under global warming. Doing so assesses the significance of incorporating sea-ice ecosystem components into the next-generation ESMs.

3.4 Control

295 The control experiment is designed to diagnose artificial model drifts and to distinguish anthropogenic effects from natural variability. This experiment spans 143 years by repeating the annual cycle of JRA55-do from May 1, 1990 to April 30, 1991, during which major climate modes were all in neutral phases (Stewart et al., 2020).

4 Diagnostics

The following guidelines are developed for IAMIP2 in order to implement the Findability, Accessibility, Interoperability,
300 and Reusability (FAIR) data principles (Wilkinson et al., 2016) and ensure that the IAMIP2 product reaches the end users (Objective 5). Specifically, we make the product discoverable from the website http://cosima.org.au/index.php/working-groups/iamip2 which provides a list of hyperlinks to the IAMIP2 product archived by individual modelling groups.

All model diagnostics are saved as daily averages in the NetCDF format, and where applicable, their names must follow the
305 CMIP6 naming conventions (Table 2). Daily temporal resolution is needed to quantify the bloom phenology (Watanabe et al., 2019) and to provide the ocean and sea-ice climate data for driving sea-ice biogeochemical models (Lavoie et al., 2010; Tedesco et al., 2019). To limit data storage needs, only two-dimensional fields are saved, and to preserve the spatial details in regional models, they are stored on the model's native grid. To perform interpolation for analysis, an additional file containing longitude, latitude, and grid-cell area needs to be provided for each model.

5 Discussion

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Although the experimental design of IAMIP2 advances from that of IAMIP1 (Watanabe et al., 2019) in many aspects, it has its own limitations which are discussed here to help the interpretation of results and for consideration of prospective end users. First, the vertical extent of the sea-ice ecosystem component of the currently committed selection of IAMIP2 models

is restricted to the bottom-ice skeletal layer, which likely underestimates depth-integrated ice algae biomass and primary
315   production because ice algae are present throughout the sea-ice column. Although simulating ice algae throughout the sea-
ice column is desirable and has been conducted under one-dimensional settings (Duarte et al., 2015; Pogson et al., 2011) as
well as in a recent study using an ESM (Jeffery et al., 2020), its implementation into high-resolution three-dimensional
models is computationally expensive. Nevertheless, we anticipate that this limitation has a negligible effect on the estimation
of depth-integrated biomass and primary production as demonstrated by field observations (Meiners et al., 2018).

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For projections of sea ice-ocean models, a few previous studies have prescribed a synthetic atmospheric forcing dataset
instead of applying the raw output of climate models in order to ensure that there is no undesirable step change in the
atmospheric conditions at the beginning of projections (Naughten et al., 2018) and that the high-frequency climate variability
is simulated realistically (Zhang et al., 2017). In contrast to the approach taken by these previous studies, the IAMIP2
325   models are driven by the raw output of CMIP6 model projections, which is made possible thanks to three CMIP6 models so
far that have provided their atmospheric output available at the temporal resolutions needed to simulate the high-frequency
climate variability. Our approach is advantageous over that of the previous studies in that the IAMIP2 model projections
account for projected changes in both the high- and low-frequency climate variability. As demonstrated in Section 3.2, EC-
Earth3 simulates the atmospheric conditions most comparable to JRA55-do especially in terms of Antarctic surface air
330   temperature, and therefore its projected atmospheric output is adopted as the default atmospheric forcing dataset for the
IAMIP2 projection experiment. However, it would be worthwhile investigating the uncertainty in the projected changes in
ice algae abundance and distribution due to the uncertainty in the projected atmospheric conditions among the CMIP6
models under the same climate change scenarios. Similarly, the implications of climate change scenarios for polar marine
ecosystems and biogeochemistry can be addressed by performing additional experiments based on other SSP scenarios
335   (O'Neill et al., 2016). Given the commitment to undertake the experiments outlined in Section 3, such experiments are not
the top priority of IAMIP2, but may be considered in the future, or alternatively can be investigated individually by the
participating modelling groups.

IAMIP2 is an ongoing international effort aiming primarily to understand the role of ice algae in polar marine ecosystems
340   and biogeochemistry at the regional and hemispheric scales. This paper describes the design of IAMIP2 which is built upon
the experience from IAMIP1 (Watanabe et al., 2019) and by keeping up to date with the CMIP6 protocols (Griffies et al.,
2016; O'Neill et al., 2016; Orr et al., 2017). Six three-dimensional regional and global coupled sea ice–ocean models are
currently committed to participating in IAMIP2. These models are driven by the same initial conditions and atmospheric
forcing dataset to assess systematic biases in these models in terms of simulating ice algae abundance and distribution. Two
345   numerical experiments are designed to understand the past changes since the mid-twentieth century by applying realistic
atmospheric forcing (JRA55-do) as well as the projected changes throughout the twenty-first century by applying the high-
temporal-resolution output of selected CMIP6 model projection under the SSP5-8.5 scenario. Two other experiments are

used to separate the anthropogenic effect from natural variability and quantify the large-scale impacts of incorporating ice algae into regional and global models on marine ecosystems and biogeochemistry. The model data products of IAMIP2 are

350 expected to meet the FAIR data principles and intended to be used for future research and as educational tools. In conclusion, IAMIP2 is expected to advance the science of polar marine ecosystems and biogeochemistry.

Data availability

The model output of IAMIP2 will be made available by individual modelling groups, which will be discoverable from the website http://cosima.org.au/index.php/working-groups/iamip2.

355 **Author contributions**

HH conceived IAMIP2 and developed the details with MJ, NSS, NCS, and EW. AH, AK, RM, and PS supervised the ACCESS-OM2 contribution to IAMIP2. RF and HH developed the model code for enabling sea ice-ocean coupling of biogeochemistry in ACCESS-OM2. HH prepared the projected atmospheric forcing datasets, performed the analysis, and wrote the paper with input from all co-authors.

360 **Competing interests**

All authors declare that they have no conflict of interest.

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365 Research Council Centre of Excellence for Climate Extremes (CE170100023). This study was undertaken with the assistance of resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Government. Analyses are performed using the Climate Data Operator (CDO) software (Schulzweida, 2019) and Python. Normalised power spectra are computed using SciPy (Virtanen et al., 2020). EW is supported by the Grant-in-Aid for Scientific Research of Japan Society for the Promotion of Science (JSPS) (KAKENHI 18H03368) and the Arctic

370 Challenge for Sustainability II (ArCS II) project (JPMXD1420318865) in Japan. NSS and NCS acknowledge funding through the Departments of Environment and Climate Change Canada and Fisheries and Oceans Canada. This work is a contribution to the Biogeochemical Exchange processes at Sea Ice Interfaces (BEPSII) network.

References

Bell, G.D., and Halpert, M.S. (1998). Climate Assessment for 1997. Bull. Am. Meteorol. Soc. *79*, S1–S50.

375 Bi, D., Dix, M., Marsland, S., O'Farrell, S., Sullivan, A., Bodman, R., Law, R., Harman, I., Srbinovsky, J., and Rashid, H. (2020). Configuration and spin-up of ACCESS-CM2, the new generation Australian Community Climate and Earth System Simulator Coupled Model. J. South. Hemisphere Earth Syst. Sci. Submitt.

Bitz, C.M., and Lipscomb, W.H. (1999). An energy-conserving thermodynamic model of sea ice. J. Geophys. Res. Oceans *104*, 15669–15677.

380 Bitz, C.M., Holland, M.M., Weaver, A.J., and Eby, M. (2001). Simulating the ice-thickness distribution in a coupled climate model. J. Geophys. Res. Oceans *106*, 2441–2463.

Bouillon, S., Maqueda, M.A.M., Legat, V., and Fichefet, T. (2009). An elastic–viscous–plastic sea ice model formulated on Arakawa B and C grids. Ocean Model. *27*, 174–184.

Cavan, E.L., Belcher, A., Atkinson, A., Hill, S.L., Kawaguchi, S., McCormack, S., Meyer, B., Nicol, S., Ratnarajah, L.,
385 Schmidt, K., et al. (2019). The importance of Antarctic krill in biogeochemical cycles. Nat. Commun. *10*, 4742.

Darnis, G., Robert, D., Pomerleau, C., Link, H., Archambault, P., Nelson, R.J., Geoffroy, M., Tremblay, J.-É., Lovejoy, C., Ferguson, S.H., et al. (2012). Current state and trends in Canadian Arctic marine ecosystems: II. Heterotrophic food web, pelagic-benthic coupling, and biodiversity. Clim. Change *115*, 179–205.

Duarte, P., Assmy, P., Hop, H., Spreen, G., Gerland, S., and Hudson, S.R. (2015). The importance of vertical resolution in
390 sea ice algae production models. J. Mar. Syst. *145*, 69–90.

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., and Taylor, K.E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. *9*, 1937–1958.

Fichefet, T., and Maqueda, M.A.M. (1997). Sensitivity of a global sea ice model to the treatment of ice thermodynamics and
395 dynamics. J. Geophys. Res. Oceans *102*, 12609–12646.

Garcia, H.E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., Baranova, O.K., Zweng, M.M., Reagan, J.R., Johnson, D.R., Mishonov, A.V., and Levitus, S. (2013). World ocean atlas 2013. Volume 4, Dissolved inorganic nutrients (phosphate, nitrate, silicate).

Gong, D., and Wang, S. (1999). Definition of Antarctic Oscillation index. Geophys. Res. Lett. *26*, 459–462.

400 Griffies, S.M., Danabasoglu, G., Durack, P.J., Adcroft, A.J., Balaji, V., Böning, C.W., Chassignet, E.P., Curchitser, E., Deshayes, J., Drange, H., et al. (2016). OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project. Geosci. Model Dev. *9*, 3231–3296.

Hasumi, H. (2006). CCSR Ocean Component Model (COCO) version 4.0 (University of Tokyo).

Hayashida, H., Christian, J.R., Holdsworth, A.M., Hu, X., Monahan, A.H., Mortenson, E., Myers, P.G., Riche, O.G.J., Sou,
405 T., and Steiner, N.S. (2019). CSIB v1 (Canadian Sea-ice Biogeochemistry): a sea-ice biogeochemical model for the NEMO community ocean modelling framework. Geosci. Model Dev. *12*, 1965–1990.

Hu, X., and Myers, P.G. (2013). A Lagrangian view of Pacific water inflow pathways in the Arctic Ocean during model spin-up. Ocean Model. *71*, 66–80.

Hunke, E.C., and Dukowicz, J.K. (1997). An elastic-viscous-plastic model for sea ice dynamics. J. Phys. Oceanogr. *27*, 410   1849–1867.

Jeffery, N., Elliott, S.M., Hunke, E.C., Lipscomb, W.H., and Turner, A.K. (2016). Biogeochemistry of Cice: The Los Alamos Sea Ice Model Documentation and Software User's Manual Zbgc_colpkg Modifications to Version 5 (Los Alamos National Lab. (LANL), Los Alamos, NM (United States)).

Jeffery, N., Maltrud, M.E., Hunke, E.C., Wang, S., Wolfe, J., Turner, A.K., Burrows, S.M., Shi, X., Lipscomb, W.H., 415   Maslowski, W., et al. (2020). Investigating controls on sea ice algal production using E3SMv1.1-BGC. Ann. Glaciol. 1–22.

Jin, M., Deal, C.J., Wang, J., Shin, K.-H., Tanaka, N., Whitledge, T.E., Lee, S.H., and Gradinger, R.R. (2006). Controls of the landfast ice–ocean ecosystem offshore Barrow, Alaska. Ann. Glaciol. *44*, 63–72.

Jin, M., Deal, C., Maslowski, W., Matrai, P., Roberts, A., Osinski, R., Lee, Y.J., Frants, M., Elliott, S., Jeffery, N., et al. (2018). Effects of Model Resolution and Ocean Mixing on Forced Ice-Ocean Physical and Biogeochemical Simulations 420   Using Global and Regional System Models. J. Geophys. Res. Oceans *123*, 358–377.

Kishi, M.J., Kashiwai, M., Ware, D.M., Megrey, B.A., Eslinger, D.L., Werner, F.E., Noguchi-Aita, M., Azumaya, T., Fujii, M., Hashimoto, S., et al. (2007). NEMURO—a lower trophic level model for the North Pacific marine ecosystem. Ecol. Model. *202*, 12–25.

Kiss, A.E., Hogg, A.M., Hannah, N., Boeira Dias, F., Brassington, G.B., Chamberlain, M.A., Chapman, C., Dobrohotoff, P., 425   Domingues, C.M., Duran, E.R., et al. (2020). ACCESS-OM2 v1.0: a global ocean–sea ice model at three resolutions. Geosci. Model Dev. *13*, 401–442.

Large, W.G., and Yeager, S.G. (2009). The global climatology of an interannually varying air–sea flux data set. Clim. Dyn. *33*, 341–364.

Lauvset, S.K., Key, R.M., Olsen, A., van Heuven, S., Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., 430   et al. (2016). A new global interior ocean mapped climatology: the 1-deg. by 1-deg. GLODAP version 2. Earth Syst. Sci. Data *8*, 325–340.

Lavoie, D., Denman, K.L., and Macdonald, R.W. (2010). Effects of future climate change on primary productivity and export fluxes in the Beaufort Sea. J. Geophys. Res. Oceans *115*, C04018.

Leu, E., Mundy, C.J., Assmy, P., Campbell, K., Gabrielsen, T.M., Gosselin, M., Juul-Pedersen, T., and Gradinger, R. (2015). 435   Arctic spring awakening – Steering principles behind the phenology of vernal ice algal blooms. Prog. Oceanogr. *139*, 151– 170.

Levasseur, M. (2013). Impact of Arctic meltdown on the microbial cycling of sulphur. Nat. Geosci. *6*, 691–700.

Li, J., and Wang, J.X.L. (2003). A modified zonal index and its physical sense. Geophys. Res. Lett. *30*.

Lipscomb, W.H. (2001). Remapping the thickness distribution in sea ice models. J. Geophys. Res. Oceans *106*, 13989– 440   14000.

Locarnini, R.A., Mishonov, A.V., Antonov, J.I., Boyer, T.P., Garcia, H.E., Baranova, O.K., Zweng, M.M., Paver, C.R., Reagan, J.R., and Johnson, D.R. (2013). World ocean atlas 2013. Volume 1, Temperature.

Madec, G., and the NEMO team (2012). NEMO ocean engine, version3.4 (Institut Pierre-Simon Laplace Note du Pole de Modélisation).

445 Meiners, K.M., Vancoppenolle, M., Carnat, G., Castellani, G., Delille, B., Delille, D., Dieckmann, G.S., Flores, H., Fripiat, F., Grotti, M., et al. (2018). Chlorophyll-a in Antarctic Landfast Sea Ice: A First Synthesis of Historical Ice Core Data. J. Geophys. Res. Oceans *123*, 8444–8459.

Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D.M., Fraser, P.J., Montzka, S.A., Rayner, P.J., Trudinger, C.M., et al. (2017). Historical greenhouse gas concentrations for climate modelling (CMIP6).
450 Geosci. Model Dev. *10*, 2057–2116.

Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci. Model Dev. *13*, 3571–3605.

Miller, L.A., Fripiat, F., Else, B.G.T., Bowman, J.S., Brown, K.A., Collins, R.E., Ewert, M., Fransson, A., Gosselin, M.,
455 Lannuzel, D., et al. (2015). Methods for biogeochemical studies of sea ice: The state of the art, caveats, and recommendations. Elem. Sci. Anthr. *3*.

Moore, J.K., Lindsay, K., Doney, S.C., Long, M.C., and Misumi, K. (2013). Marine Ecosystem Dynamics and Biogeochemical Cycling in the Community Earth System Model [CESM1(BGC)]: Comparison of the 1990s with the 2090s under the RCP4.5 and RCP8.5 Scenarios. J. Clim. *26*, 9291–9312.

460 Mortenson, E., Hayashida, H., Steiner, N., Monahan, A., Blais, M., Gale, M.A., Galindo, V., Gosselin, M., Hu, X., Lavoie, D., et al. (2017). A model-based analysis of physical and biological controls on ice algal and pelagic primary production in Resolute Passage. Elem Sci Anth *5*.

Mortenson, E., Steiner, N., Monahan, A.H., Hayashida, H., Sou, T., and Shao, A. (2020). Modeled Impacts of Sea Ice Exchange Processes on Arctic Ocean Carbon Uptake and Acidification (1980–2015). J. Geophys. Res. Oceans *125*,
465 e2019JC015782.

Naughten, K.A., Meissner, K.J., Galton-Fenzi, B.K., England, M.H., Timmermann, R., and Hellmer, H.H. (2018). Future Projections of Antarctic Ice Shelf Melting Based on CMIP5 Scenarios. J. Clim. *31*, 5243–5261.

O'Neill, B.C., Tebaldi, C., Vuuren, D.P. van, Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., et al. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci. Model Dev. *9*,
470 3461–3482.

Orr, J.C., Najjar, R.G., Aumont, O., Bopp, L., Bullister, J.L., Danabasoglu, G., Doney, S.C., Dunne, J.P., Dutay, J.-C., Graven, H., et al. (2017). Biogeochemical protocols and diagnostics for the CMIP6 Ocean Model Intercomparison Project (OMIP). Geosci. Model Dev. *10*, 2169–2199.

Pogson, L., Tremblay, B., Lavoie, D., Michel, C., and Vancoppenolle, M. (2011). Development and validation of a one-
475 dimensional snow-ice algae model against observations in Resolute Passage, Canadian Arctic Archipelago. J. Geophys. Res. *116*, C04010.

Saenko, O.A., Zhai, X., Merryfield, W.J., and Lee, W.G. (2012). The Combined Effect of Tidally and Eddy-Driven Diapycnal Mixing on the Large-Scale Ocean Circulation. J. Phys. Oceanogr. *42*, 526–538.

480 Saenko, O.A., Yang, D., and Gregory, J.M. (2018). Impact of Mesoscale Eddy Transfer on Heat Uptake in an Eddy-Parameterizing Ocean Model. J. Clim. *31*, 8589–8606.

Schulzweida, U. (2019). CDO User Guide.

Smith, D.M., Screen, J.A., Deser, C., Cohen, J., Fyfe, J.C., García-Serrano, J., Jung, T., Kattsov, V., Matei, D., Msadek, R., et al. (2019). The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: investigating the causes and consequences of polar amplification. Geosci. Model Dev. *12*, 1139–1164.

485 Stewart, K.D., Kim, W.M., Urakawa, S., Hogg, A.McC., Yeager, S., Tsujino, H., Nakano, H., Kiss, A.E., and Danabasoglu, G. (2020). JRA55-do-based repeat year forcing datasets for driving ocean–sea-ice models. Ocean Model. *147*, 101557.

Swart, N.C., Cole, J.N.S., Kharin, V.V., Lazare, M., Scinocca, J.F., Gillett, N.P., Anstey, J., Arora, V., Christian, J.R., Hanna, S., et al. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). Geosci. Model Dev. *12*, 4823–4873.

Tedesco, L., Vichi, M., and Scoccimarro, E. (2019). Sea-ice algal phenology in a warmer Arctic. Sci. Adv. *5*, eaav4830.

490 Tsujino, H., Urakawa, S., Nakano, H., Small, R.J., Kim, W.M., Yeager, S.G., Danabasoglu, G., Suzuki, T., Bamber, J.L., Bentsen, M., et al. (2018). JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do). Ocean Model. *130*, 79–139.

Tsujino, H., Urakawa, L.S., Griffies, S.M., Danabasoglu, G., Adcroft, A.J., Amaral, A.E., Arsouze, T., Bentsen, M., Bernardello, R., Böning, C.W., et al. (2020). Evaluation of global ocean–sea-ice model simulations based on the
495 experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2). Geosci. Model Dev. *13*, 3643–3708.

Vancoppenolle, M., and Tedesco, L. (2016). Numerical models of sea ice biogeochemistry. In Sea Ice, (Wiley-Blackwell), pp. 492–515.

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., et al. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. Nat. Methods
500 *17*, 261–272.

Watanabe, E., Onodera, J., Harada, N., Aita, M.N., Ishida, A., and Kishi, M.J. (2015). Wind-driven interannual variability of sea ice algal production in the western Arctic Chukchi Borderland. Biogeosciences *12*, 6147–6168.

Watanabe, E., Jin, M., Hayashida, H., Zhang, J., and Steiner, N. (2019). Multi-Model Intercomparison of the Pan-Arctic Ice-Algal Productivity on Seasonal, Interannual, and Decadal Timescales. J. Geophys. Res. Oceans *124*, 9053–9084.

505 Welch, P. (1967). The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Trans. Audio Electroacoustics *15*, 70–73.

Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data *3*, 1–9.

510 Woodgate, R.A., Aagaard, K., and Weingartner, T.J. (2005). Monthly temperature, salinity, and transport variability of the Bering Strait through flow. Geophys. Res. Lett. *32*.

Zeebe, R.E., Eicken, H., Robinson, D.H., Wolf-Gladrow, D., and Dieckmann, G.S. (1996). Modeling the heating and melting of sea ice through light absorption by microalgae. J. Geophys. Res. Oceans *101*, 1163–1181.

515 Zhang, X., Church, J.A., Monselesan, D., and McInnes, K.L. (2017). Sea level projections for the Australian region in the 21st century. Geophys. Res. Lett. *44*, 8481–8491.

Ziehn, T., Chamberlain, M.A., Law, R.M., Lenton, A., Bodman, R.W., Dix, M., Stevens, L., Wang, Y.-P., and Srbinovsky, J. (2020). The Australian Earth System Model: ACCESS-ESM1.5. J. South. Hemisphere Earth Syst. Sci.

Zweng, M.M., Reagan, J.R., Antonov, J.I., Locarnini, R.A., Mishonov, A.V., Boyer, T.P., Garcia, H.E., Baranova, O.K., Johnson, D.R., and Seidov, D. (2013). World ocean atlas 2013. Volume 2, Salinity.

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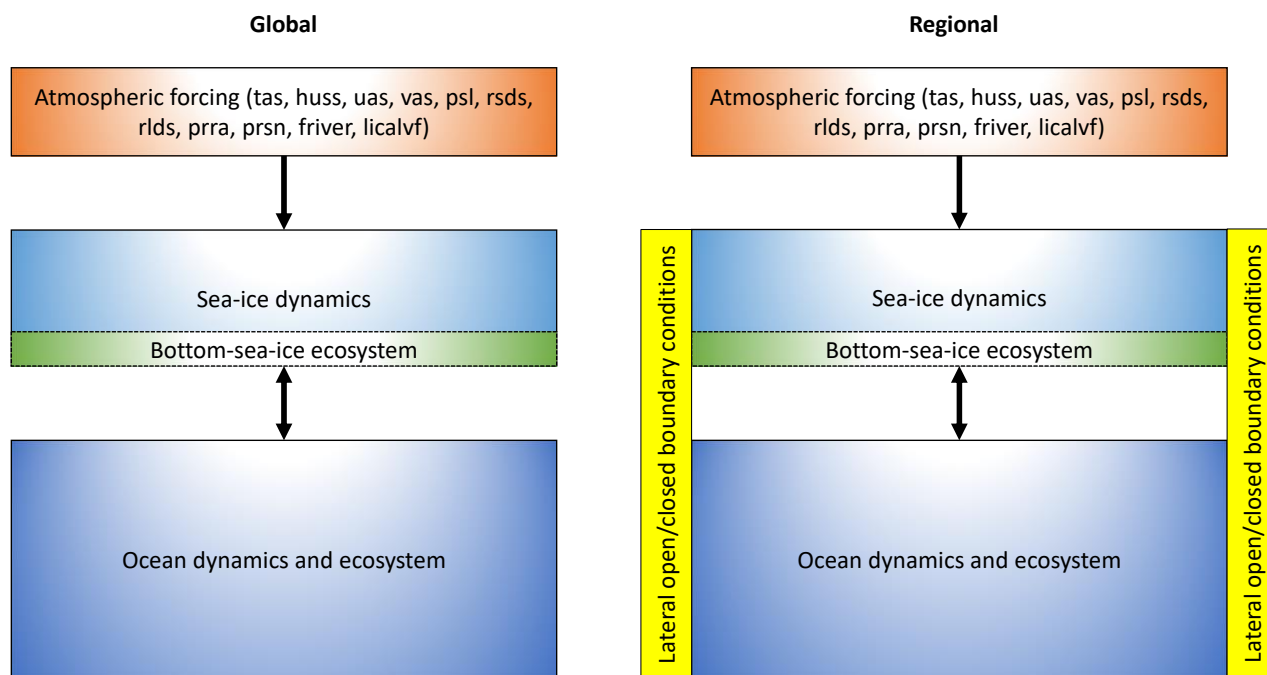
Figure 1: Global (left) and regional (right) configurations of the three-dimensional coupled sea ice–ocean physical–biogeochemical models participating in IAMIP2. The surface-atmospheric forcing dataset consists of air temperature at 10 m (tas), specific humidity at 10 m (huss), eastward wind at 10 m (uas), northward wind at 10 m (vas), sea level pressure (psl), downward shortwave (rsds), downward longwave (rlds), rainfall flux (prra), snowfall flux (prsn), river runoff (friver), and calving flux (licalvf).
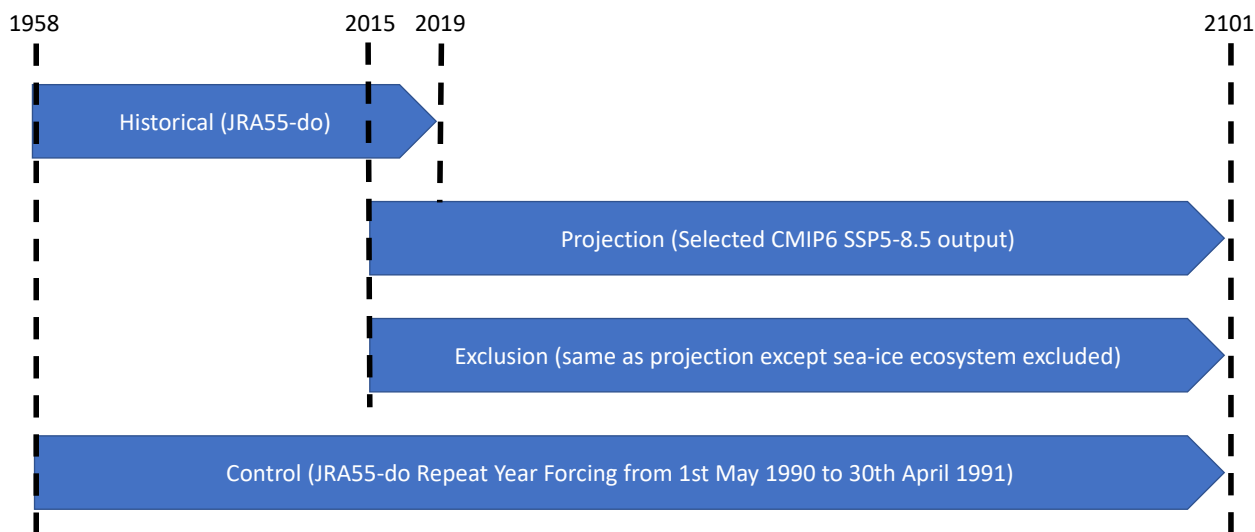
Figure 2: Timeline of the numerical experiments of IAMIP2. Years begin on January 1. Each experiment starts on January 1 and ends on December 31. For example, the historical experiment starts from January 1, 1958, and ends on December 31, 2018.

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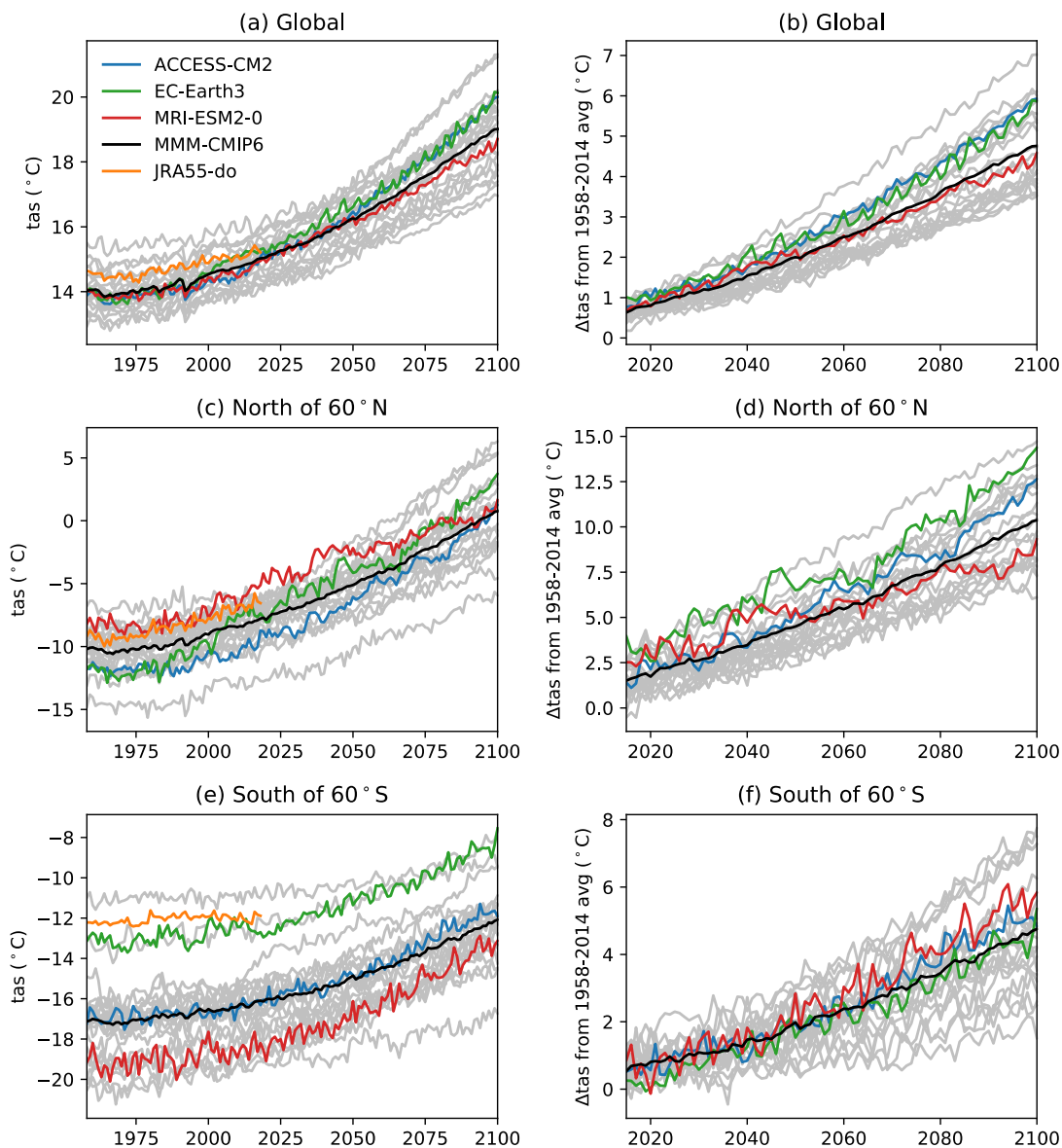
Figure 3: Comparisons of historical and projected global and polar warming simulated by 24 CMIP6 models over the historical period (1958-2014) and the projection period under the SSP5-8.5 scenario (2015-2100). Time series of annual mean surface air temperature averaged over (a) the globe, (c) the Northern Hemisphere north of 60 °N, and (e) the Southern Hemisphere south of 60 °S. Projected changes in annual mean surface air temperature averaged over (b) the globe, (d) the Northern Hemisphere north of 60 °N, and (f) the Southern Hemisphere south of 60 °S, relative to their averages during 1958-2014. Blue, green, and red denote 3 of the 24 models that provide the atmospheric output at the temporal resolutions needed for the projection experiment of IAMIP2. Gray denotes the remaining 19 models. Black denotes the multi-model mean of the 24 models. Orange denotes the JRA55-do dataset used for the atmospheric forcing for the historical experiment of IAMIP2.
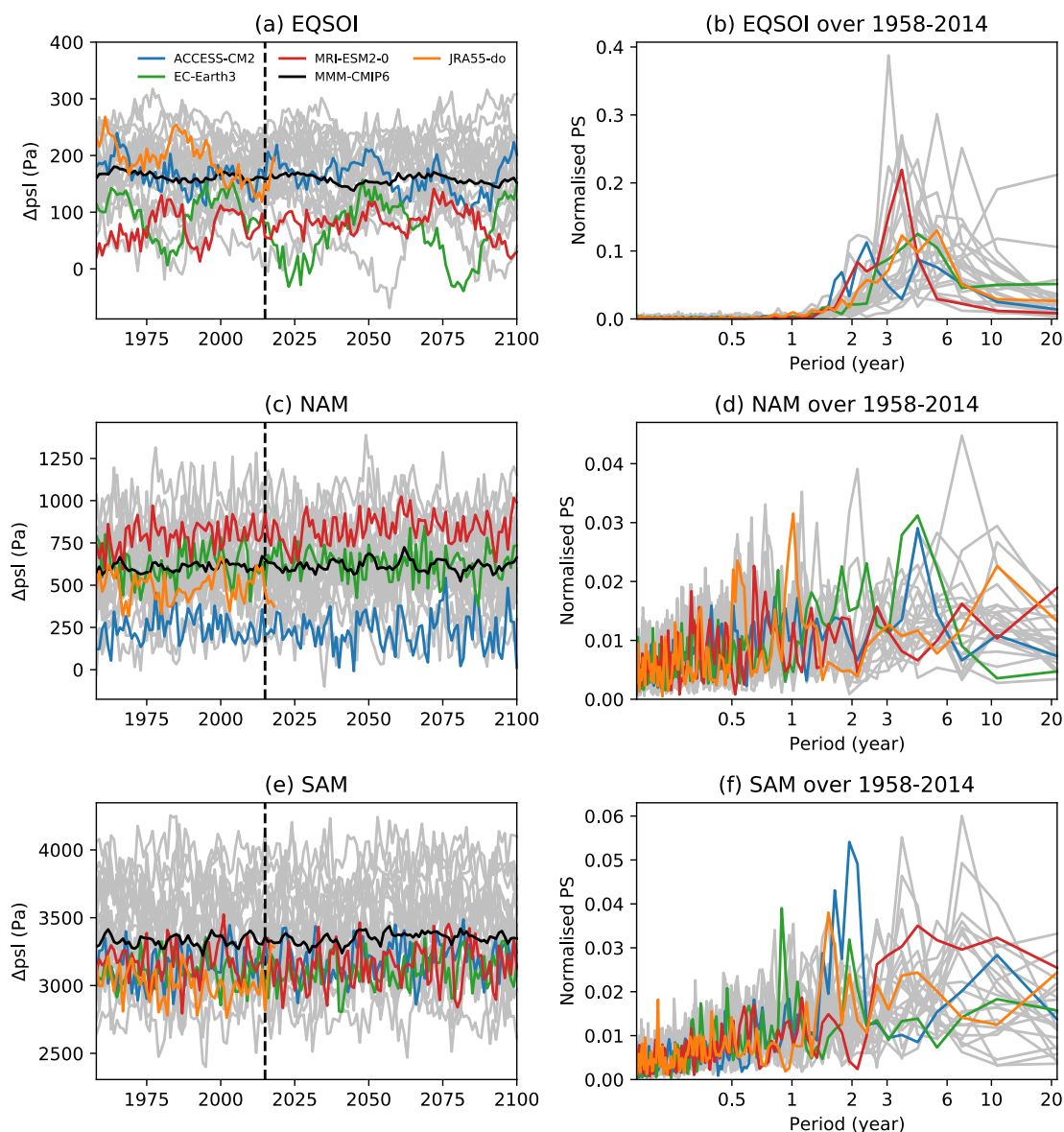
Figure 4: Comparisons of major climate modes simulated by 24 CMIP6 models over the historical period (1958-2014) and the projection period under the SSP5-8.5 scenario (2015-2100). Time series of annual mean sea level pressure difference between two regions representative of (a) EQSOI, (c) NAM, and (e) SAM. Normalised power spectra of (b) EQSOI, (d) NAM, and (f) SAM derived from time series of standardised monthly mean anomaly of sea level pressure difference over 1958-2014 based on Welch's method (Welch, 1967). Blue, green, and red denote 3 of the 24 models that provide the atmospheric output at the temporal resolutions needed for the projection experiment of IAMIP2. Gray denotes the remaining 19 models. Black denotes the multi-model mean of the 24 models. Orange denotes the JRA55-do dataset used for the atmospheric forcing for the historical experiment of IAMIP2.

Table 1: List of participating models for IAMIP2. For ocean and sea-ice ecosystem components, the letters denote nutrients (N), phytoplankton (P), zooplankton (Z), and detritus (D), which are followed by the numbers indicating the complexity. For example, N1

denotes one type of modelled nutrients (e.g., nitrate), whereas N2 indicates two types of modelled nutrients (e.g., nitrate and iron). The vertical resolution is rounded to the nearest integer.

Model	ACCESS-OM2	CESM-IARC	RASM	CanNEMO	NEMO-NAA	COCO-Arctic NEMURO
Relevant CMIP6 model	ACCESS-CM2, ACCESS-ESM1.5	CESM2	CESM2	CanESM5	CanESM5	MIROC6
Ocean dynamics	MOM5.1	POP2	POP2	OPA	OPA	COCO4.9
Sea-ice dynamics	CICE5.1.2	CICE5.1.2	CICE5.1.2	LIM2	LIM2	COCO4.9
Ocean ecosystem	N1P1Z1D1	N4P3Z1D1	N4P3Z1D1	N3P2Z2D2	N3P2Z2D2	N3P2Z3D2
Sea-ice ecosystem	N1P1	N4P1	N4P1	N2P1	N2P1	N3P1D1
Spatial domain	Global	Global	Pan-Arctic	Global	Pan-Arctic	Pan-Arctic
Horizontal resolution	1°	1°	1/12°	1°	1/4°	1/4°
Vertical resolution of the surface ocean layer	2 m	10 m	5 m	6 m	1 m	2 m
Bottom-ice ecosystem layer thickness	0.03 m	0.03 m	0.03 m	0.03 m	0.03 m	0.02 m
Reference	(Jeffery et al., 2016; Kiss et al., 2020; Ziehn et al., 2020)	(Jin et al., 2018)	(Jin et al., 2018)	(Hayashida et al., 2019; Swart et al., 2019)	(Hayashida et al., 2019; Hu and Myers, 2013)	(Watanabe et al., 2015)

555 **Table 2: List of model diagnostics for IAMIP2.** Where applicable, variable names and units follow the CMIP6 convention (https://earthsystemcog.org/projects/wip/CMIP6DataRequest). Tiers refer to mandatory (Tier 1) and optional (Tier 2).

Variable name	Long name	Units	Tier
siconc	Percentage of grid cell covered by sea ice	%	1
sithick	Actual sea ice thickness (sea-ice volume divided by sea-ice-covered area)	m	1
sisnthick	Actual snow thickness (snow volume divided by snow-covered area)	m	1
intppbi	Vertically integrated primary organic carbon production by bottom ice algae	mol m^{-2} s^{-1}	1
intpp	Vertically integrated primary organic carbon production by phytoplankton	mol m^{-2} s^{-1}	1
epc100	Downward flux of particulate organic carbon at 100 m	mol m^{-2} s^{-1}	2
phycbi	Bottom ice algae carbon concentration	mol m^{-3}	1
phycos	Sea surface phytoplankton carbon concentration	mol m^{-3}	1
no3bi	Bottom ice dissolved nitrate concentration	mol m^{-3}	1

no3os	Sea surface dissolved nitrate concentration	mol m^{-3}	1
parbi	Downwelling photosynthetic radiance flux at bottom ice	W m^{-2}	2
paros	Downwelling photosynthetic radiance flux at sea surface	W m^{-2}	2
sst	Sea surface temperature	°C	1
sss	Sea surface salinity	PSU	1
mlots2t	Ocean mixed layer thickness defined by sigma-t	m	2
dissicos	Sea surface dissolved inorganic carbon concentration	mol m^{-3}	2
talkos	Sea surface total alkalinity	mol m^{-3}	2
fgco2	Sea surface downward flux of carbon dioxide	kg m^{-2} s^{-1}	2