Analysis of ecologically relevant sea ice and ocean variables for the Southern Ocean using a high-resolution model to inform ecosystem studies

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Abstract

Southern Ocean organisms are uniquely adapted to the extreme environmental conditions that characterise this region, making them especially vulnerable to climate change. Alterations to the physical environment have already been linked to alterations in the structure and functioning of entire ecosystems, and ecological disruptions are expected to continue to occur. Although our understanding of the physical processes driving ecological change in the Southern Ocean has improved in recent years, significant knowledge gaps remain largely as a result of insufficient observational data being available.

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High resolution ocean models are an important tool that can help us overcome data scarcity. However, models generally contain biases that may affect their ability to accurately represent environmental conditions in the region of interest. Thus, their outputs must be evaluated before they can be used to answer questions about ecological impacts. Here, we examined the suitability of ACCESS-OM2-01, a high-resolution coupled ocean-sea ice model, for ecological applications. We provide a template for testing the suitability of model outputs for ecological applications, as well as quantitative estimates of changes in key environmental variables for the Southern Ocean over the recent past. Our results highlight the heterogeneous nature of the mean state of the environmental variables examined and their trends across the Southern Ocean. Our assessment shows that the ACCESS-OM2-01 model performance differs across variables, but overall, it does a reasonable job in reproducing the observed seasonal cycle and broad baseline climatological conditions of the mixed layer depth and sea ice variables for the Southern Ocean over the half century. Model performance also varies across space and time, which reflect gaps in our understanding of how different atmospheric and oceanographic mechanisms interact to drive change in the variables examined. These results emphasise the importance of understanding the capabilities and shortcomings of models within the boundaries of the area of interest prior to using model outputs in ecological applications.
Keywords: environmental status and trends, Southern Ocean, climate change, sea ice, ocean, Marine Ecosystem Assessment for the Southern Ocean

1. Introduction

Anthropogenic climate change has undeniably modified and continues to affect all parts of the global climate system, including the oceans (1). Organisms are closely associated with their physical setting, with major changes to environmental conditions inevitably leading to alterations in the structure and functioning of entire ecosystems. Climate impacts can be direct by influencing physiological processes and life history characteristics of organisms, or indirect by modifying community composition or disrupting important inter-species interactions. Examples of the former include the foraging and reproductive success of sea ice-dependent species of seals and penguins that are negatively impacted by a decline of total sea ice extent. An example of an indirect effect is the uncoupling of predator-prey life cycles that limits food availability and hinders the ability of species to reproduce and grow (2; 3; 4; 5). Rapidly changing environmental conditions pose a serious threat to biodiversity and will ultimately alter the quality and quantity of ecosystem services (i.e., benefits obtained by humans from normal ecosystem functioning) that these systems are able to provide (6).

Climate change is felt globally, however regional responses differ. The polar amplification encapsulates the critical importance of cryospheric processes in the system response to global warming (7). For example, parts of the Southern Ocean (SO) warm at a rate over four times faster than the global average (8; 9; 10). The SO is the smallest and southernmost ocean on the planet, extending from the Antarctic Convergence at about 45°S, to the coast of the Antarctic continent (11) and representing ∼10% of the global marine area (12). While it is small, it plays a crucial role in ocean circulation, biogeochemical cycles, and the climate system at global scales through linkages with physical, biogeochemical, and ecological processes in other ocean basins (13; 14). This strong influence is largely due to the eastward flowing Antarctic Circumpolar Current (ACC), which allows for exchange between surface and deep waters of the Atlantic, Pacific and Indian Oceans (15; 13). In flowing unimpeded from west to east, the ACC effectively isolates the cold waters of the SO from the warmer subtropical waters north of the Antarctic Convergence by reducing north to south water exchange (13; 10). The physical conditions in the SO are characterised by its extremes, with markedly different conditions across seasons and years, but also across space due to local topography and oceanographic features (e.g., location of fronts and eddies) (2; 9; 16). Its isolation, combined with the distinctive environmental conditions of the SO have been credited for the high levels of biodiversity and endemism reported in this region that supports large populations of top marine predators, including seabirds and marine mammals (17; 9; 12; 18). However, the exceptional adaptions that have allowed organisms to occupy and thrive in this region make them particularly vulnerable to the effects of climate change (19; 20).

Unprecedented environmental changes linked to anthropogenic climate change have been reported across the SO relative to the late 1950s (21; 1; 22). These changes include warming and freshening of the upper ocean (21; 2), ocean acidification (23), changes in stratification and mixed layer depth (24; 25), modifications to the extent, timing and total duration of sea ice cover (26; 27), enhanced melting and break up of ice shelves (9; 1), changes to precipitation patterns (9), increased eddy kinetic energy (28), and alterations to ocean circulation patterns, including changes in mixing and upwelling patterns (29; 1). Environmental change has not been uniform across the SO, instead regional impacts are highly variable. Opposing changes have been detected in adjacent regions, and the regional system response may lag due to differences in atmospheric or oceanic conditions (2; 27; 29; 10; 30; 23; 31). Further, environmental perturbations and extreme climatic events are expected to become more frequent and intense under a changing climate (32; 1; 33). Alterations to the physical environment have already negatively impacted the health, structure and functioning of SO marine ecosystems, and major ecological disruptions are predicted to occur in the future (2; 12; 14). Negative ecosystem responses are worse when the rate of environmental change surpasses the ability of organisms to adapt to the new conditions (34; 35; 33). Organisms with a narrow ecological niche, such as Antarctic notothenioids, Antarctic krill (*Euphasia superba*) and the emperor penguin (*Aptenodytes forsteri*) are expected to be among the worst affected (17; 2; 9; 12; 36; 18).

Our understanding of the physical processes driving the distribution and abundance of marine organisms and the structure and functioning of marine ecosystems in the SO has improved significantly in recent years (2; 12). However, significant gaps remain in our understanding of environmental change, its ecological implications at a circumpolar and regional scale, and in our knowledge regarding the ability of marine organisms to adapt to environmental change (37; 38; 4). These gaps are in large part due to insufficient long-term observational data being available for a variety of ecologically relevant variables because of the difficulty and high costs associated with data collection in the harsh environment of the SO (39; 40; 41). This limits our ability to assess the current state, to quantify the magnitude and rate of environmental change due to natural variability and climate change, and to determine the implications of these trends on ecological processes and ecosystem resilience (39; 40; 42). Ocean models may help us overcome the issue of data availability as their iterative development has yielded increasingly accurate and well-resolved simulations of environmental conditions. Furthermore, the spatio-temporal coverage of model outputs is not constrained by suitable environmental conditions regulating access to the study area; instead, they offer long-term continuous data at regular temporal and spatial intervals that are not currently available with observations (43). However, models generally contain biases so their ability to accurately replicate past and current environmental conditions of the region of interest must be evaluated before model outputs can be used to investigate the effects of environmental change on ecosystems (44; 4; 45).

In this study, we used outputs from ACCESS-OM2-01 (43), a high resolution (0.1° horizontal, 75 vertical levels) global ocean-sea ice coupled model forced with an atmospheric reanalysis product (Section 2.3.1) to assess the current status and past spatio-temporal trends of ecologically relevant variables: sea ice concentration, sea ice extent, marginal ice zone, sea ice seasonality (i.e., sea ice advance and retreat, total duration of sea ice season), and mixed layer depth (see Section 2.2). We used the Marine Ecosystem Assessment for the Southern Ocean (MEASO, Figure 1) to assess variability in environmental change and ecological responses at ecologically relevant scales that are useful for policy- and decision-makers (Section 2.1). Finally, we evaluated the ability of ACCESS-OM2-01 to reproduce past observations (Section 2.3.2) to determine whether the outputs of this model can accurately simulate past environmental conditions in the SO and ascertain if the model may be suitable to understand impacts of a changing climate on marine ecosystems. We achieved this by assessing the climatological means obtained from model outputs against calibrated observations. Through comparisons at a regional scale, we identified areas where the model has limitations for some environmental variables and where caution is needed for ecological applications.

2. Methods

2.1. Regions

We chose to use the MEASO regions (Figure 1) to evaluate and quantify the rate of change in the physical environmental of the Southern Ocean. These regions were designed to establish a standard spatial scale for reporting and assessing environmental and ecosystem change in the SO, and to facilitate comparisons across studies and throughout time (45). MEASO includes five meridional sectors roughly based on the ocean basins they occupy: Central and East Indian, East and West Pacific, and Atlantic. Each sector is subdivided into three latitudinal zones: Antarctic, Subantarctic and Northern (Figure 1). From north to south, zone boundaries are defined by the location of the Subtropical Front, Subantarctic Front, and the southern boundary of the Antarctic Circumpolar Current (46). MEASO region boundaries used in this study were obtained from the measoshape package (47) for the R programming language.

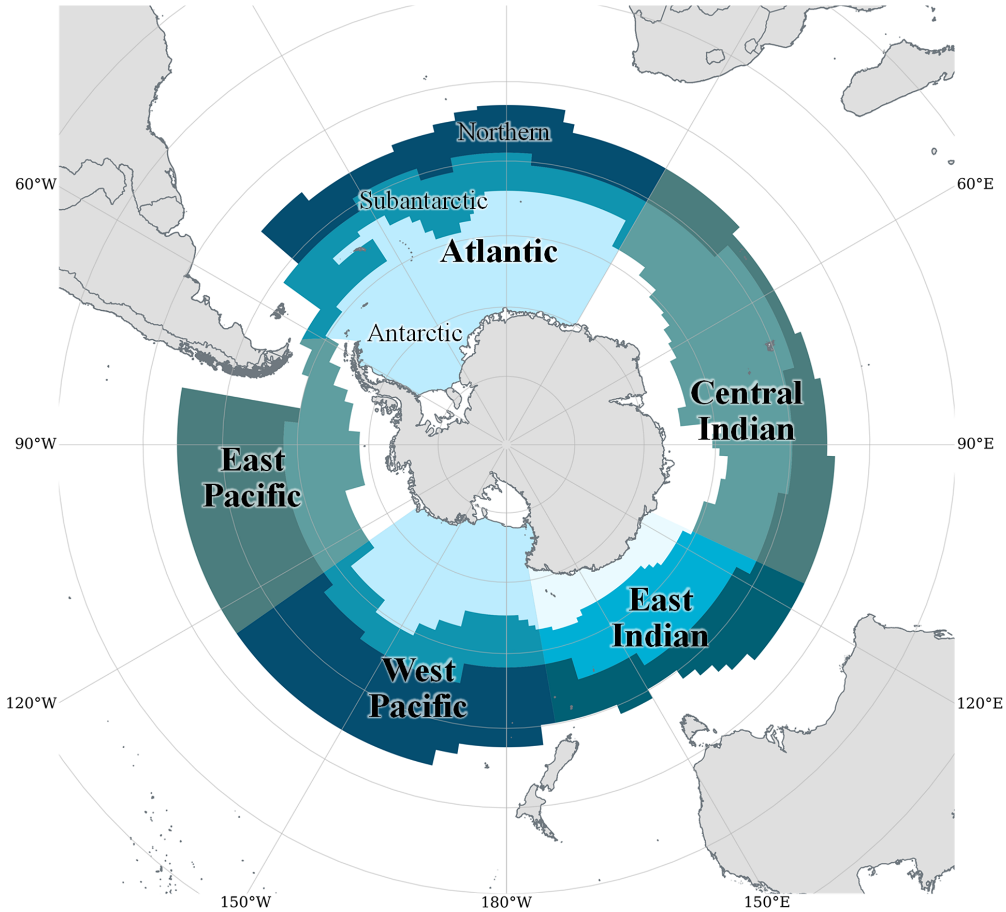

Figure 1: Marine Ecosystem Assessment for the Southern Ocean (MEASO) regions used in this study to assess environmental change over time. MEASO regions include five meridional sectors: Central and East Indian, East and West Pacific, and Atlantic. Each sector is subdivided in three latitudinal zones: Antarctic, Subantarctic and Northern.

2.2. *Environmental variables*

There are a number of sea ice, ocean, and biogeochemical variables that are available in the ACCESS-OM2-01 model that could be used to describe spatio-temporal changes in the physical environment of the Southern Ocean. We conducted a comprehensive review of current literature (Table 1), and selected a subset of these variables based on a combination of expert knowledge and the number of papers identifying a variable as ecologically relevant. We also prioritised variables about the physical environment that are available in ACCESS-OM2-01, and for which observational data are available for comparison.

The selected variables that we examine in this study are sea ice concentration (SIC), sea ice extent (SIE), marginal ice zone (MIZ) extent, sea ice seasonality and the mixed layer depth (MLD). There are multiple methods to estimate MLD (29), but here we define MLD as the depth at which the potential density is 0.03 $kg\, m^{-3}$ denser than at a reference depth of 1.1m in ACCESS-OM2-01 (43), or 10 m in the observations (25).

Table 1: Ecologically-relevant sea ice, ocean, and biogeochemical variables affected as a result of climate change in the Southern Ocean. Temporal and spatial trends were only examined for variables highlighted in **bold**. The column **Ecosystems** refers to effects at an ecosystem-wide scale.

	Primary producers	**Zooplankton (inc. krill)**	**Benthic invertebrates**	**Calcifying organisms**	**Aragonitic organisms**	**Fish**	**Sea birds**	**Marine mammals**	**Ecosystems**
Ocean variables									
Water temperature	(48; 49; 50; 51)	(52; 53; 54; 30; 5; 50; 51)	(55)				(56; 57; 18)	(56; 57; 18)	(2; 39; 40; 10; 49; 33)
Mixed layer depth	(2; 58; 24; 59; 10; 23)						(18)	(18)	(60; 39; 29)
Fronts position	(61)	(52; 53)					(18)	(18)	(2; 39; 10)
Water transport (eddies, upwelling)		(10; 53)				(10)	(18)	(18)	(2; 39; 40)
Eddy kinetic energy							(18)	(18)	

Table 1 continued from previous page

	Primary producers	**Zooplankton (inc. krill)**	**Benthic invertebrates**	**Calcifying organisms**	**Aragonitic organisms**	**Fish**	**Sea birds**	**Marine mammals**	**Ecosystems**
Salinity	(2; 59; 10; 48; 49)	(2; 10)							(40; 49)
Sea ice variables									
Snow depth on ice	(2)						(56; 2; 57; 18)		(39; 10)
Fast ice extent							(57; 18)	(57; 18)	(2)
Pack ice extent							(10; 18)	(10; 18)	
Sea ice extent	(61; 24; 59; 23; 51)	(52; 53; 59; 51)					(56; 57; 18)	(56; 57; 18)	(2; 39; 40; 10)
Sea ice thickness	(2)						(18)	(18)	(39)
Polynyas	(61)	(2; 10)				(57)	(57; 18)	(57; 18)	
Sea ice seasonality	(59)	(52)					(18)	(18)	(26; 2; 30)

Table 1 continued from previous page

	Primary producers	**Zooplankton (inc. krill)**	**Benthic invertebrates**	**Calcifying organisms**	**Aragonitic organisms**	**Fish**	**Sea birds**	**Marine mammals**	**Ecosystems**
Marginal ice zone									(2)
Biogeochemistry									
Photosynthetic active radiation (PAR) in ocean	(2; 10; 59; 23; 48)	(2)							(39)
PAR under ice	(2; 10; 59; 48)	(2)							(39)
Iron (Fe)	(61; 2; 10; 23)								
Nitrate (NO_3)	(2; 10; 48)								(39; 40)
Alkalinity / acidity (pCO_2)	(50; 2)	(2)		(10)					

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	Primary producers	Zooplankton (inc. krill)	Benthic invertebrates	Calcifying organisms	Aragonitic organisms	Fish	Sea birds	Marine mammals	Ecosystems
Dissolved inorganic carbon (DIC)	(2; 59)								(40)
Dissolved oxygen (O_2)						(2; 10)			(39; 40)
Chlorophyll-a		(52; 53; 39; 59; 30; 5)				(39)	(39)	(39)	(2; 40)
Aragonite concentration					(59)				
pH									(39)
Calcium carbonate ($CaCO_3$)				(2; 10)					

2.3. Data sources

2.3.1. Ocean-sea ice coupled model

The Australian Community Climate and Earth System Simulator Ocean Model version 2 (ACCESS-OM2) is a coupled ocean-sea ice model with global coverage, extending from the North Pole to the Antarctic ice shelf edge (80°S) using a tripolar grid (43). ACCESS-OM2 uses the Modular Ocean Model (MOM, (62)) version 5.1 developed by the Geophysical Fluid Dynamics Laboratory as its ocean component, and CICE version 5.1.2 (63) from Los Alamos National Laboratories as its sea ice component. ACCESS-OM2 is not a data-assimilating model, but the ocean and sea ice components are forced by repeated 61-year cycles of 1958-2018 atmospheric conditions from the Japanese Reanalysis for driving oceans (JRA55-do, (64)) version 1.4.0. However, it is worth noting that neither the ocean or sea ice models do not use data assimilation in ACCESS-OM2, therefore the model is only expected to match observations in detail for features that are dominated by atmospheric forcing rather than intrinsic model dynamics (43).

We use the 0.1° version of ACCESS-OM2 known as ACCESS-OM2-01, which represents many Southern Ocean and Antarctic shelf processes with remarkable fidelity (65; 66; 67; 68). This model configuration has a nominal horizontal resolution of 0.1° with 75 vertical ocean levels with a resolution of 1.1 m at the surface that coarsens to 198.4 m at 5,808.7 m depth. This is an updated version of the configuration described in (43). It was initialised from World Ocean Atlas 2013 v2 (69; 70) and run for several 61-year cycles of JRA55-do forcing. We analysed the monthly output of the second cycle to have the benefit of a 61-year spin-up while still being close to the climatological initial condition.

2.3.2. Observational data

We compared ACCESS-OM2-01 outputs against observation-based SIC and MLD datasets. The daily sea ice concentrations were obtained from the NASA Goddard-merged Near Real Time NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, version 3 (71; 72), with a spatial resolution of 25 km x 25 km. Observations are available from October 1978 until present, with daily outputs available from July 1987, and every other day before then. The ice edge is defined using a 10% sea ice concentration threshold (71).

Global climatological monthly mean MLDs and their trends for 1970-2018 were obtained from (73). This 0.5° x 0.5° gridded dataset was created using vertical conductivity-temperature-depth (CTD) profiles obtained from ships, the NOAA World Ocean Database, the PANGEA database, Argo float data, and profiles from marine mammal-borne sensors (29).

2.4. Data analysis

We examined a subset of the variables identified as ecologically relevant in the literature (Table 1) to develop a workflow for ecologists to apply when assessing the suitability of model outputs for ecosystem applications.

2.4.1. Trend analysis

Linear least squares regression analysis was used to estimate trends. The standard error of the estimated slope was used to determine the significance of the trend following (25). We considered trends to be significant only if their absolute value was larger than their estimated standard error.

2.4.2. Sea ice calculations

We defined sea ice concentration (SIC) as the percentage of ocean area that is covered by sea ice in a pixel/grid cell (27). We applied the same 10% threshold used to define the ice edge from satellite observations (71) to the modelled data for intercomparability. Sea ice extent (SIE) is defined as the total area with SIC of 15% or above (27). The marginal ice zone (MIZ) is defined as a transition area between consolidated pack ice and the open ocean (74). There are several methods to estimate the MIZ (e.g., wave penetration, floe size, etc.), but here, we define the MIZ as the region with SIC between 15% and 80% to be congruent to previous ecological studies (75; 74). Finally, sea ice seasonality includes the timing of annual sea ice advance and retreat, and the total duration of the sea ice season, within each year (starts on February 15 and ends on February 14 of the following year in the Southern Hemisphere (26)). Sea ice advance was defined to begin on the day when sea ice concentration stayed above 15% for five days or more. The sea ice retreat was set to have begun the day when sea ice concentration remained below 15% until the end of the sea ice season. The sea ice season duration is the time between the day of advance and retreat (26). Annual sea ice seasonality metrics were calculated per pixel using sea ice concentration data from the ACCESS-OM2-01 model following (26).

2.4.3. Evaluation of model-based estimates

Prior to performing comparisons, data were spatially aligned, which allowed us to perform pixel by pixel comparisons. Model outputs were then regridded using a bilinear interpolation to match the resolution of observational data.

3. Results

3.1. Sea ice

3.1.1. Mean climatological patterns

ACCESS-OM2-01 replicated well the distinct seasonal SIC cycle in the Southern Ocean (Figure 2) in the 39 years (1979-2018) covered by the observational dataset. The median SIC values peaked during austral winter (JJA) across all sectors, except in the Atlantic and West Pacific, where sea ice was found in similar concentrations from austral autumn (MAM, Table 2). These two regions showed the lowest spatio-temporal variability in autumn SIC values, with high SIC concentrated within the Weddell Sea (Atlantic sector) and Ross Sea (West Pacific), and rapidly declining SIC values north of 70°S.

Seasonal SIE patterns for the SO were also well represented in ACCESS-OM2-01 (Figure 2, Supplementary Figure Appendix A.1). The warmer waters north of the ACC prevent sea ice formation, acting as a boundary for SIE at a circumpolar level (26). All sectors reached their lowest extent in February. Mean SIE peaked in August in the East Indian and East Pacific sectors and September in the other sectors (Supplementary Figure Appendix A.1), although these differences are insignificant given the standard deviation. In terms of the relative sector area covered by sea ice, the largest proportions were found in the West Pacific sector, where just over half of its total surface area was covered by sea ice in winter and spring. The Atlantic sector stands out with the largest seasonal and inter-annual SIE variabilities when compared to the rest of the SO, particularly during summer and autumn. The substantial decadal SIE variability in ACCESS-OM2-01 is consistent with

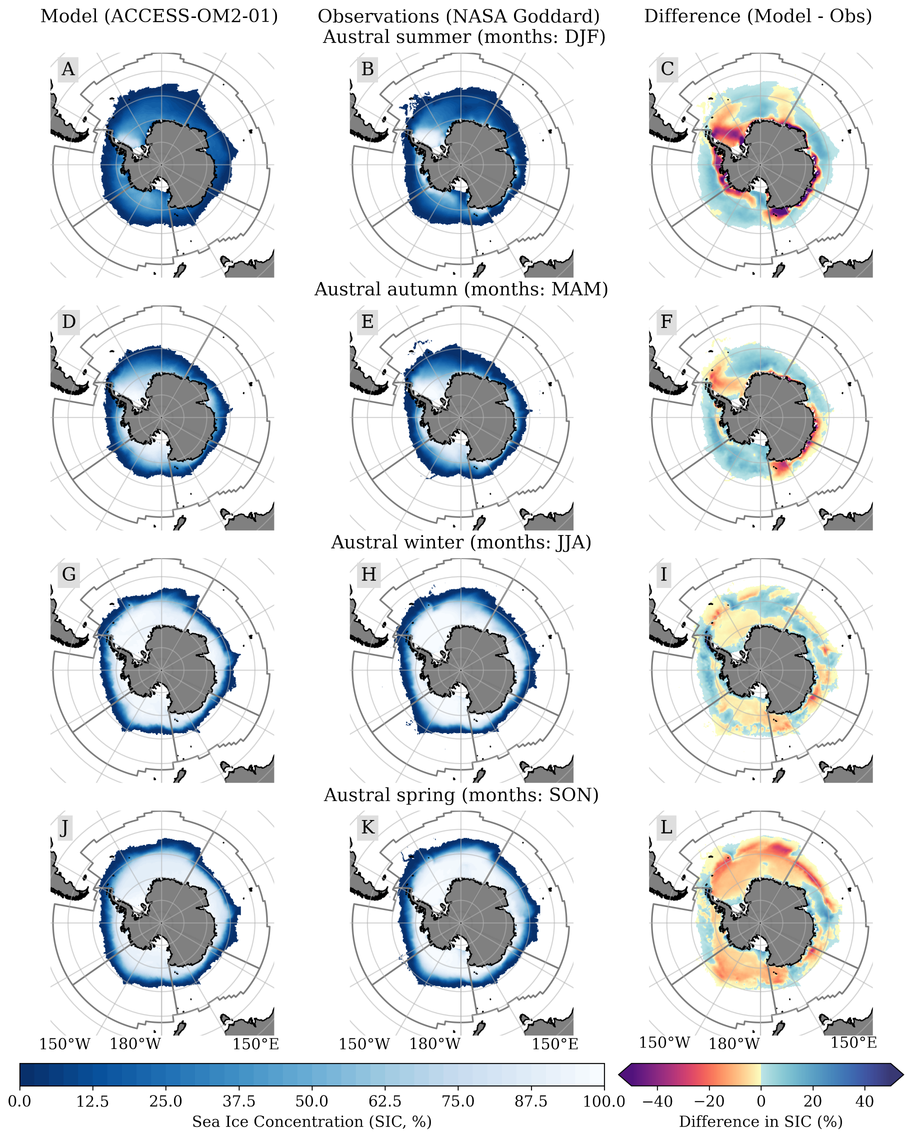

Figure 2: Climatological mean of sea ice concentration (SIC) in the Southern Ocean (1979-2018). (Left) Sea ice concentration estimates from ACCESS-OM2-01. SIC values under 10% were removed from plots to match observations. (Center) SIC estimates obtained from satellite data (71). (Right) Difference between modelled and observed sea ice concentration (model - observations). Grey lines denote MEASO sectors.

observations (76) and also seen in other high resolution models (77).

In the model, the marginal ice zone (MIZ) encircled the Antarctic continent in its entirety during winter and spring. However, during summer and autumn SIC fell under the 15% threshold at the northern end of the Antarctic Peninsula, therefore the MIZ was not present in this region, in agreement with observations (Figure 2 left and centre columns). The model showed the same situation during summer in the eastern side of the Central Indian sector and much of the East Indian sector, where the SIC does not surpass 15%, but this opposes the patterns seen in observations (Figure 2 A and B). The MIZ showed a highly asymmetrical seasonal pattern of advance and retreat across all sectors, except the East Pacific, with some differences in the timing and magnitude of change across sectors (Figure 2, Table 2), supporting previously published work (74). The MIZ minimum area occurred in February across all sectors, with increases in MIZ area occurring over a period of 9-10 months across all sectors, except the West and East Pacific. In the West Pacific sector, it took two months for the MIZ to reach its peak and a further two months to its lowest extent, with the MIZ persisting almost unchanged for the remaining eight months (not shown). Overall, the timing of maximum and minimum MIZ area derived from the model output and observations coincided across all sectors (not shown), except in the Central Indian where the maximum was predicted to occurred a month later than observed (December instead of November), and in the West Pacific where the minimum areas occurred three months apart (May instead of February). MIZ seasonal patterns are distinct from those in overall SIE. For example, the smallest median MIZ values between 1979 and 2018 in the Atlantic sector

Table 2: Summary statistics (median, with lower and upper quartiles in parentheses) per season and for each MEASO sector of ACCESS-OM2-01 1979-2019 climatological sea ice concentration, sea ice extent and marginal ice zone area. Median and quartiles were calculated by pooling all non-zero values within a sector boundary, thus they represent the spatio-temporal variability within each sector.

Sea Ice Concentration (%)				
	Summer	**Autumn**	**Winter**	**Spring**
Atlantic	59 (31-81)	95 (62-99)	95 (92-98)	90 (85-94)
Central Indian	39 (22-57)	71 (36-92)	91 (75-95)	88 (75-93)
East Indian	35 (19-57)	78 (40-93)	89 (69-94)	82 (58-89)
East Pacific	45 (24-70)	84 (45-97)	93 (74-97)	89 (68-95)
West Pacific	55 (30-76)	95 (70-98)	94 (91-97)	91 (86-94)
Sea Ice Extent (10^6 km^2)				
	Summer	**Autumn**	**Winter**	**Spring**
Atlantic	2.1 (1.0-4.9)	3.0 (1.8-4.4)	6.6 (6.1-7.1)	6.8 (6.4-7.3)
Central Indian	0.2 (0.02-2.1)	1.0 (0.2-1.7)	3.1 (2.7-3.4)	3.6 (3.4-3.7)
East Indian	0.2 (0.03-0.6)	0.7 (0.2-0.9)	1.5 (1.4-1.7)	1.5 (1.4-1.7)
East Pacific	0.8 (0.4-1.3)	1.1 (0.7-1.4)	2.1 (1.9-2.4)	2.1 (1.8-2.3)
West Pacific	1.9 (1.1-2.7)	2.5 (1.9-2.9)	3.7 (3.5-3.9)	3.8 (3.5-4.0)
Marginal Ice Zone area (10^6 km^2)				
	Summer	**Autumn**	**Winter**	**Spring**
Atlantic	1.8 (0.7-3.5)	1.1 (0.9-1.3)	1.0 (0.9-1.1)	1.3 (1.1-1.6)
Central Indian	0.2 (0.02-2.0)	0.7 (0.2-0.8)	1.0 (0.9-1.0)	1.1 (1.0-1.4)
East Indian	0.1 (0.03-0.6)	0.4 (0.2-0.4)	0.5 (0.4-0.6)	0.7 (0.6-0.8)
East Pacific	0.7 (0.4-1.1)	0.5 (0.4-0.6)	0.7 (0.6-0.7)	0.7 (0.6-0.8)
West Pacific	1.7 (1.1-2.0)	0.6 (0.5-0.9)	0.6 (0.6-0.7)	0.7 (0.7-0.8)

were recorded in winter and the maximum during summer, in contrast with the SIE patterns in the same sector. These opposing trends could be interpreted as the sea ice transforming from consolidated pack ice (i.e., areas with SIC $> 80\%$) into the MIZ range over a large area as the melting season began (74). The largest differences between MIZ maxima and minima occurred in the East Pacific sector, with variation of over 30% between the advance and retreat (Table 2). The MIZ covered a small percentage of the area within the Atlantic sector, from $\sim 7\%$ during autumn and winter, to just under 15% during summer. MIZ was the dominant sea ice area in summer across all sectors with a minimum of three quarters of sea ice classified as MIZ. The proportion of the sea ice classified as MIZ heavily declined in winter, with less than a third of sea ice considered as MIZ across any sectors.

The climatological mean of sea ice advance, retreat and total duration between 1979/80 and 2017/18 highlight the seasonal nature of sea ice in the Southern Ocean, with different patterns seen across different sectors (Figure 4). Sea ice advance occurred at a faster rate in areas such as the Atlantic sector, where sea ice extended about 10° of latitude along 30°W during the first month of the sea ice season. However, this process was much slower in the Central and East Indian sectors, where at its lowest point, sea ice advanced less than 2° of latitude along 120°E during the same time (May contour in Figure 4 A). Throughout spring, the rate of sea ice advance was almost the same throughout all areas of the SO where maximum yearly SIE was not yet reached. Overall, sea ice advance occurred over seven to eights months (Figure 4 A, Figure Appendix A.1). Sea ice retreat generally started in late spring and early summer and lasted about three to four months, which is

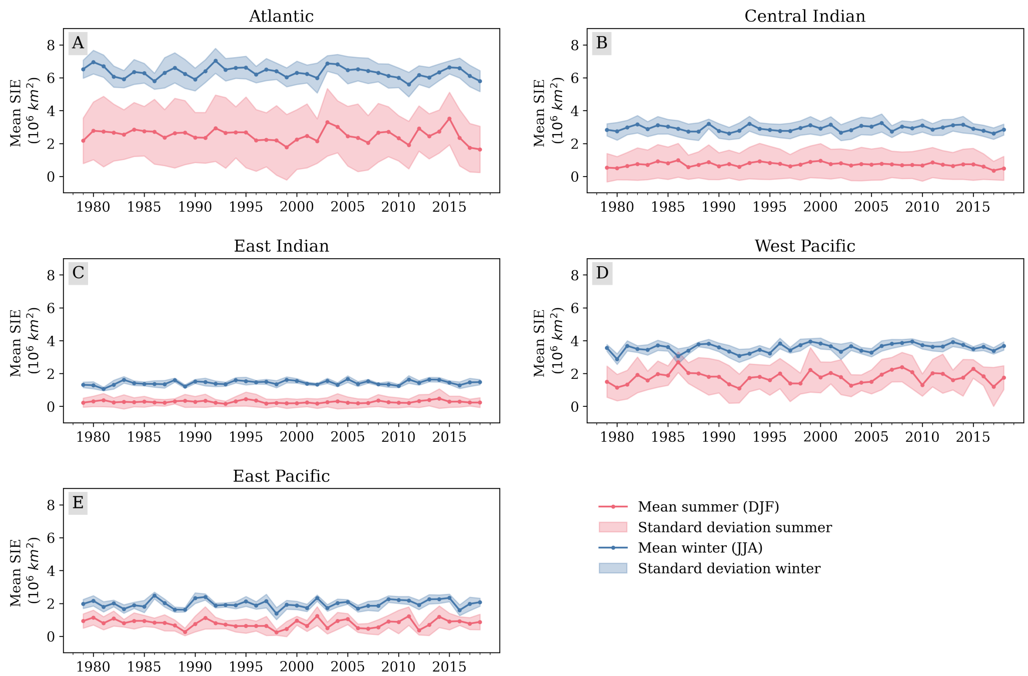

Figure 3: Yearly mean (dots) and standard deviation (shaded area) of sea ice extent (SIE) for summer (red) and winter (blue) for each MEASO sector. SIE was calculated from daily ACCESS-OM2-01 sea ice concentration data (December 1979 to November 2018).

about half of the total duration of the sea ice advance (Figure Appendix A.1). Sea ice retreated faster within the Atlantic sector than anywhere else in the SO, with sea ice receding about 11° of latitude along 0° between November and January. The slowest rate was found in the East Indian sector, where the sea ice retreat was about 3° of latitude at 120°E for the same period. In sectors where mean sea ice extent was largest and where sea ice advance occurred relatively fast, such as in the Atlantic and West Pacific sectors, only a small portion of sea ice persisted for 90 days or less (Figure 4 G).

The largest differences in sea ice advance between model and observations were found within the East and West Pacific sectors (from the Western Antarctic Peninsula to $\sim 150°W$), with differences of about 30 days over much of this area. The model was biased negative (i.e., earlier advance) mostly, with just a small area within the Amundsen and Bellingshausen Seas showing a later sea ice in the model (Figure 4 C). Sea ice retreat in the model showed the largest deviation from observations along the coast of the Central and East Indian sectors, where sea ice was predicted to retreat over 50 days earlier than observed (Figure 4 I). Interestingly, most of the areas where the sea ice advance was predicted to start later in the model showed an earlier start for the retreat. These differences in turn affected the total length of the sea season estimated from the model, with coastal areas largely predicted to have a shorter sea ice season than observed, while duration is largely overestimated in offshore areas.

3.1.2. Temporal trends

The magnitude and direction of SIC trends in the SO between 1979 and 2018 were not uniform across space and time, as both positive and negative

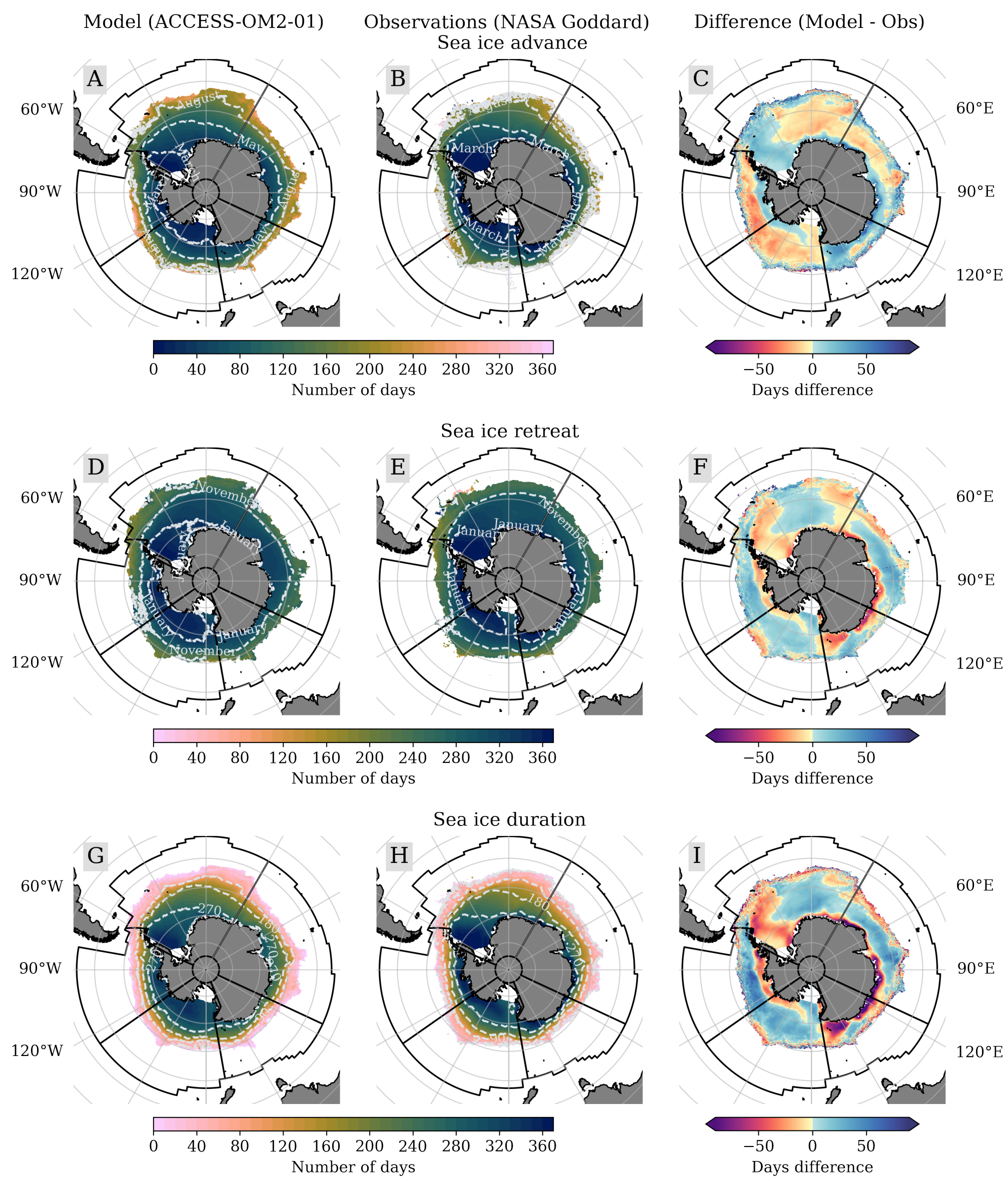

Figure 4: Climatological mean of sea advance, retreat and total duration in the Southern Ocean (1979/80-2017/18). Mean start day of sea ice advance (A-B) and sea ice retreat (D-E), and mean sea ice season duration (G-H) for model-based estimates (A, D, G), observations-based estimates (71) (B, E, H) and differences between model- and observation-based estimates (model-observations; C, F, I). Contours show months for sea ice advance (A-B) and retreat (D-E), and total number of days for duration (G-H). Black lines represent MEASO boundaries.

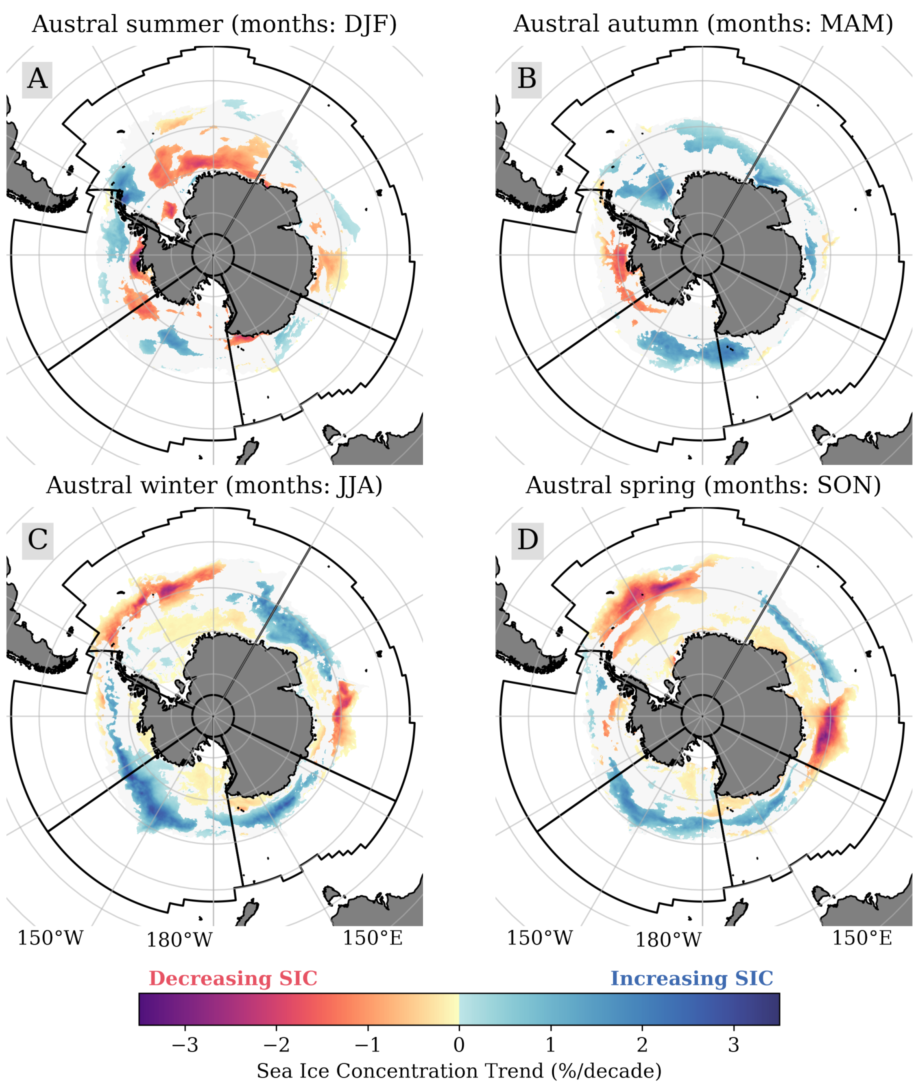

Figure 5: Decadal trends in seasonal mean sea ice concentrations for 1979-2018 calculated from ACCESS-OM2-01 outputs. Areas with no significant trend are blanked out. Black lines represent MEASO boundaries.

significant trends were found across all sectors (Figure 5). The largest negative trends during winter and spring were found in areas near the ice edge in the Atlantic sector (from $\sim 60°$W to 0°) and the eastern part of the Central Indian sector. Significant gains in SIC during spring were mostly confined towards the ice edge in the western half of the Central Indian sector (from $\sim 30°$E to 80°E), and along a continuous arc from 100°E to 110°W, which includes the entire ice edge in the East Indian and West Pacific sectors, and a small part of the East Pacific sector. The largest significant losses in SIC during summer and autumn occurred within the East Pacific sector, more specifically on the shelf areas of the Amundsen-Bellingshausen seas. The spatial patterns and direction of trends from the model data are similar to observations (27), but we found the rate of change in SIC was several times smaller (see Section 4 for a discussion of potential causes of this difference) . Trends for the SIE (not shown) were mostly statistically insignificant and an order of magnitude smaller than observed by (76).

As seen for other sea ice related variables, the trends in modelled sea ice advance, retreat and season duration were not consistent across the SO. Sea ice advance started about a week earlier every decade in most sectors, but was delayed in the East Pacific sector (not shown) by about five days per decade from the Antarctic coast up to 70°S, and 10 days or longer further north. Significant sea ice retreat trends were also mostly negative, but not as widespread as for the sea ice advance, being mostly concentrated in the Atlantic sector and towards the eastern edge of the Central Indian sector. Significant delays in the start of the sea ice retreat were also detected across all sectors, but they were very localised (not shown). The largest decrease in the season duration was in the East Pacific sector, which is largely driven by a later start of the sea ice advance. The areas where sea ice duration has significantly extended are also linked to changes in the advance of sea ice, in this case to an earlier start. Area-averaged trends in sea ice advance, retreat, and duration are statistically insignificant in all sectors except the Central Indian, where earlier advance causes a 2.5day/decade increase in duration (Supplementary Figure Appendix A.6).

3.2. Mixed Layer Depth

3.2.1. Mean climatological patterns

We analysed mixed layer depth changes in the model between 1970-2018 to compare with available observations. The model qualitatively captures the strong seasonality of the Southern Ocean MLD, increasing from tens of metres in summer to hundreds of metres in winter due to wind-induced mixing and vertical entrainment due to sea ice formation (Figure 6). The broad spatial patterns are qualitatively consistent with observations and previous findings (60; 78; 29). Quantitative agreement with observations was closest in summer and autumn (Figure 6 C, F). During summer, the shallowest mixed layer estimates overlapped with areas where sea ice was present and melting. Mean MLD estimates under the ice did not exceed 25 m across any MEASO sectors. On the other hand, the deepest mixed layer estimates in summer were found within the ACC, especially in the Central Indian Subantarctic (170 m) and Atlantic Subantarctic (100 m) sectors, which coincided with areas where surface waters subduct to form intermediate and mode waters (15). During autumn, the mixed layer was shallowest under sea ice covered areas, but deepened in certain areas along the coastline in all sectors except the East Pacific.

In winter and spring, there is a strong spatial variability in MLD estimates (Figure 6 G, J, Supplementary Table A.3). The model showed a narrow band along the continental shelf for all sectors except the East Pacific where the mixed layer reached several hundred meters during these two seasons. The mixed layer shoaled north of the continental shelf in areas covered by sea ice, with maximum MLD of 170 m in winter and 140 m in spring recorded in these ice-covered areas (Figure 6 G, J). These areas were generally predicted to be shallower in the model than in observations. These differences in depth were generally 50 meters or less, with limited areas (e.g., northern eastern Antarctic Peninsula in the Atlantic sector) showing a shallow bias of 100 m or more (Figure 6 I). In ice-free areas, the model showed a positive bias across most of the Southern Ocean (Figure 6 I, L) and generally the differences compared to observations were larger during winter and spring. The largest departures from observations occurred in the Weddell Sea (Atlantic sector) and within the ACC. Here, the model predicted the mixed layer to be over a thousand meters deeper than observation. Additionally, the deep mixed layer within the ACC was predicted to be wider, and it continued to deepen over a longer period than seen in observations.

3.2.2. Temporal trends

Trend analysis from model-based MLD estimates for summer and autumn show statistically significant deepening of the mixed layer across most of the SO over the 1970-2018 period, except in the Northern Central Indian sector (Figure 7 A, B). Deepening has occurred at a median rate of 0.2 m/decade to 1.4 m/decade in summer, and between 0.3 m/decade and 1.4 m/decade

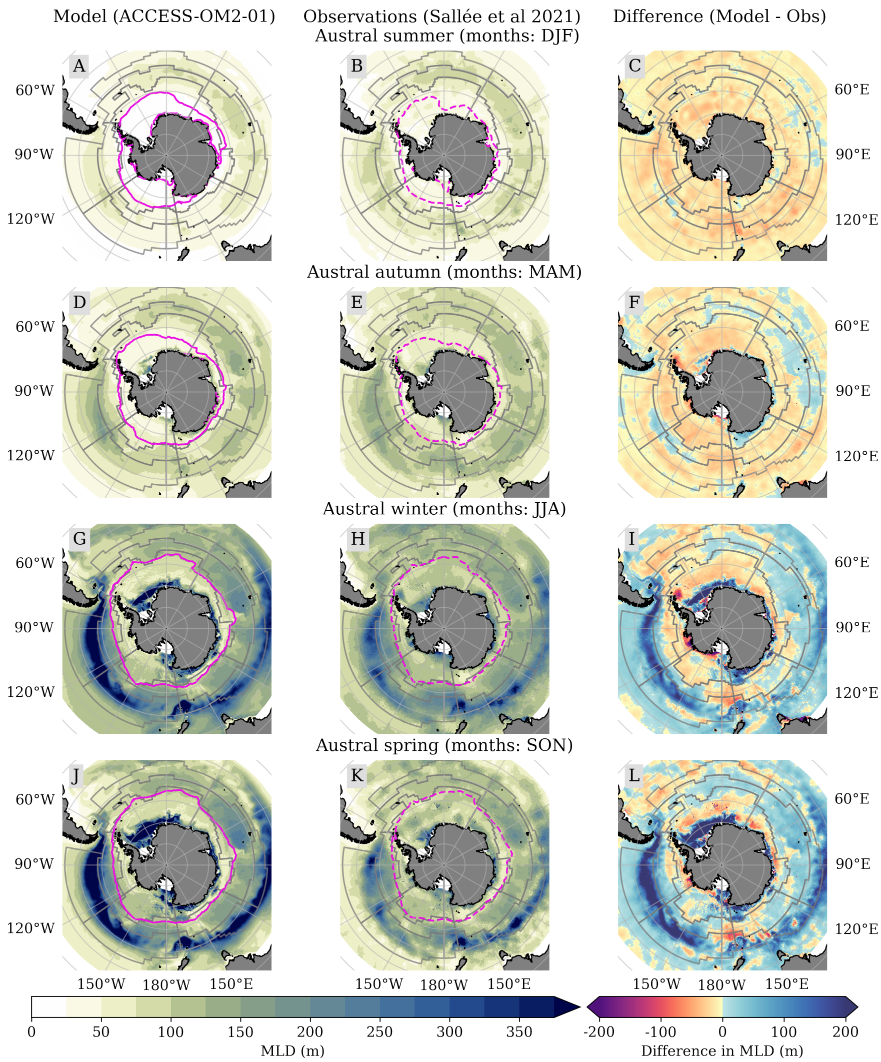

Figure 6: 1970-2018 seasonal mean mixed layer depth in ACCESS-OM2-01 (left) and the observation-based estimates of (73) (center). The solid pink line shows the 1970-2018 mean ice edge, and the dotted pink line is the 1979-2018 ice edge estimated from satellite data by (71). Right: Mixed layer depth difference (model - observations). Grey lines represent MEASO boundaries.

in autumn. This is about one order of magnitude less than trends calculated from observation-based MLD estimates (25). The Northern Central Indian is the only sector where MLD is shoaling (median rate of 0.6 m/decade in summer and 0.7 m/decade in autumn). Additionally, statistically significant shallowing MLD trends can be seen in parts of the Antarctic and Subantarctic East Pacific (near the Western Pacific Peninsula), and the western boundary of the Antarctic East Indian sector in autumn.

MLD trends showed greater spatial variability in winter and spring. About two thirds of MEASO sectors show deepening of the mixed layer (Figure 7 C, D). The fastest deepening of MLD was found within the Antartic Atlantic zone, which concentrated around Maud Rise in winter ($\sim 0°$) and extended further west into the northern Weddell Sea during spring. It is not immediately obvious what may be driving this trend. A significant shoaling MLD trend can be seen almost circumpolarly within the Antarctic MEASO zones (excluding the eastern Antarctic Peninsula) in these seasons, with the largest change occurring in the Antarctic East Indian sector. In this sector during winter, shoaling occurred at a median rate of 6.5 m/decade (almost 50% greater than the largest annual deepening trend). Additionally, the MLD was significantly shoaling across most of the Northern zone of the Central Indian, West Pacific sectors, which coincides with observations (25) and CMIP5 models (78).

4. Discussion

Ocean models are a key resource that can be used by ecologists to inform studies of the effects of climate change on ecosystems, and to improve pro-

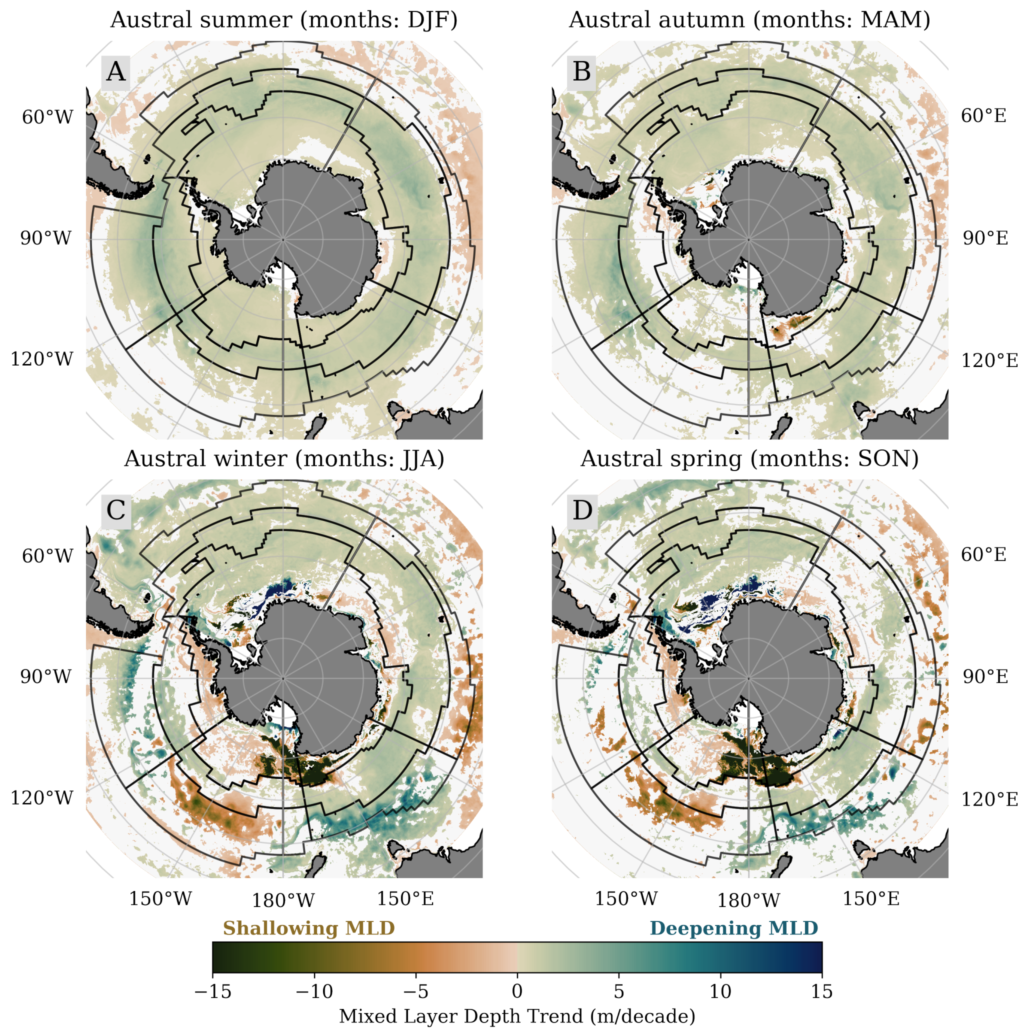

Figure 7: Decadal trends in ACCESS-OM2-01 seasonal mean mixed layer depth between 1970 and 2018. Insignificant trends (i.e., smaller magnitude than the standard error) are blank. Black lines represent MEASO boundaries.

jections of likely ecological responses to a changing environment. However, evaluation of model outputs is a necessary first step prior to incorporating this output in ecological research as uncertainties and biases in the model outputs directly impact the reliability of projected ecological responses (79; 4). Our analysis provides a template for testing the suitability of model outputs for ecological applications, and quantitative estimates of changes in key environmental variables for the Southern Ocean over the past 50 years. Such information is key to inform management of Antarctic marine resources and the design and implementation of marine protected areas aimed at conserving and building resilience of SO ecosystems to climate change (37; 4). It is worth noting that ACCESS-OM2-01 is a free running model and it does not use observational data (with the exception of JRA55-do, a reanalysis product used as atmospheric forcing) to improve model outputs, therefore our assessment focused on testing its statistical behaviour rather than on its ability to reproduce specific events.

Our assessment shows that the coupled ocean-sea ice model ACCESS-OM2-01 does a reasonable job in reproducing the observed seasonal cycle and baseline climatological conditions of the mixed layer depth, and sea ice variables (i.e., SIC, SIE, MIZ, seasonality) for the Southern Ocean for the periods between 1970-2018, and 1979-2018 respectively. Our results highlight the heterogeneous nature of the mean state of the environment and trends across the Southern Ocean. This heterogeneity reflects differences in local environmental processes (29; 10; 74) and in turn dictates the ecological responses to environmental variability (2; 12). This result supports the use of regions to assess long-term environmental change, and despite large heterogeneity in responses within sectors, the MEASO regions (45) allow us to carry out assessment at scales that are relevant to ecological processes and to policy-makers. Overall, ACCESS-OM2-01 provides a good representation of the ecologically relevant variables examined and we expect these and other variables included in the model will be suitable for examining the effects of climate change on SO ecosystems. The high resolution of ACCESS-OM2-01 allows future regional level ecological assessments to incorporate mesoscale environmental features that are key drivers of ecological processes. However, it is worth noting that there is some subjectivity in defining what makes a good model. Various criteria have been designed for this purpose and researchers are strongly advised to carefully consider their specific needs and develop metrics that capture the model performance across all variables of interest (79).

Sea ice is a critical element regulating the structure and dynamics of SO ecosystems as it provides key foraging, breeding and refuge habitats to a variety of marine organisms (80; 81; 2; 82; 83; 84). There is evidence already linking changes in sea ice (e.g., seasonal and interannual variability in SIE, SIC, MIZ, as well as advance and retreat patterns) to alterations in environmental conditions leading to shifts in the abundance and distribution of species at different levels of the trophic food web, from phytoplankton to top predators (84; 10). Our model results showed that at a circumpolar level, the largest SIC trends are negative across all seasons, but trends are much weaker than observations, which suggests we do not completely understand the mechanisms driving changes in sea ice. Despite these limitations, the model provides a generally realistic representation of the sea ice seasonal cycle, albeit with a widespread bias towards low SIC in summer. It is also worth highlighting that evolution of the MIZ within a yearly cycle showed large differences across sectors and it was markedly different than the overall SIE trends. The mechanisms driving changes in the distribution and extent of the MIZ and the more consolidated pack ice type is not fully understood yet (74), but changes to the MIZ area have ecological implications. This is because the MIZ is characterised by increased ocean stratification and reduced mixing due to freshening of surface waters by enhanced ice melting, and higher light availability due to reduced ice cover (82; 25). The combination of these conditions will likely result in an increase in primary productivity, particularly when nutrients trapped in the sea ice are released during melting (2; 50). The distribution and composition of phytoplankton communities are also affected by environmental change (2; 50), which in turn affects secondary producers, such as krill, because they may no longer have access to their preferred phytoplankton prey group (85; 54). Changes in the prevalence of MIZ, particularly during winter, also have a more direct effect on secondary consumers, such as Antarctic krill, by providing high deformed sea ice regions with relatively high levels of food availability that krill larvae use as refuge to survive the winter (86). Increases in SIE and the lengthening of the sea ice season, such as we have observed in the Central Indian sector, have already resulted in an exclusion of breeding southern elephant seals (*Mirounga leonina*) from highly productive shelf waters (10). Thus, we highlight the need to improve our understanding of mechanisms controlling changes to the timing and spatial variability of sea ice as a whole and in the MIZ.

Sea ice is notoriously difficult to simulate in climate models, largely because there are still some gaps in our understanding of how different atmospheric and oceanographic mechanisms interact to drive change in sea ice conditions (4; 87; 74). However, we found that ACCESS-OM2-01 replicated mean sea ice conditions with reasonable accuracy, particularly during winter months, and the high spatio-temporal variability at a regional scale. The SIE and MIZ thresholds in SIC were well represented in the model, with substantial overlap in the model- and observation-based monthly means. These results are encouraging as accurate representation of sea ice conditions at a regional level is required to assess the impacts of a changing climate at a scale that is relevant to study ecosystem impacts, and to provide support for decision makers (2; 12). Larger deviations from observations were found in the mean climatology for SIC, particularly during the summer months (Figure 2 C). This is not unique to the ACCESS-OM2-01 model; in fact the latest generation of climate models are known to have a very limited ability to reproduce past SIC conditions, with multiple models unable to replicate the strong sea ice decline observed between 2016 and 2018 (10). Although the model replicated well the spatial patterns in SIC trends, we found that they were several times smaller than those calculated from observations (27). We hypothesise the differences in the magnitude of the trend are due to the model keeping larger sections of sea ice with higher volume than reality due to sea ice being advected towards the Antarctic continent by wind stress. In reality, sea ice forms smaller masses that are more likely to melt. Differences in the total duration of the sea ice season were also found to be substantial between the model and observations, particularly along coastal areas which provide key habitat to sea ice dependent species, such as the emperor penguins (88). The distribution of positive and negative biases in sea ice outputs from ACCESS-OM2-01 varied across seasons and sectors, with their cause not immediately clear and beyond the scope of this publication. Less accurate estimates should be considered more carefully prior to their use in ecological research, since there is evidence showing that differences of one month in the start of the sea ice retreat can lead to significant changes to local environmental conditions that directly regulate the timing and magnitude of phytoplankton blooms and the productivity of the entire food web (4). Further, we found that ACCESS-OM2-01 replicates some, but not all, of the significant gains in SIE identified in observations (27). This may hinder our ability to identify the local processes driving temporal sea ice trends (74).

The mixed layer depth has been identified as another essential environmental variable driving ecosystem change in the SO as it regulates the size and distribution of the nutrient pool that is available within the photic zone of the water column, which is fundamental for primary productivity (60; 39; 29). Our results show that ACCESS-OM2-01 is able to capture the seasonal cycle of the MLD and broad spatial patterns in the climatological mean. Spatial MLD patterns were similar across all seasons and appeared to be influenced by the presence of sea ice (Figure 6, left column) through the regulation of salinity and density in the water column via freshwater input from ice melting, saltier water through brine rejection during sea ice formation and the amount of solar radiation that reaches the upper water column (29). The location of the ACC (between 50°S and 60°S) also appeared to influence MLD, as surface waters subduct in these areas to form Subantarctic Mode Water

(SAMW) and Antarctic Intermediate Water (AAIW) (15; 29). The model consistently had a mixed layer too deep in open water areas during winter and spring, and too shallow during summer, autumn and in ice-covered ocean areas during winter and spring. Some of the largest deviations from observations occurred during winter and spring within the ACC (Figure 6), mirroring the spatial distribution of biases in CMIP6 models (1) and a small subset of CMIP5 models (78). It has been suggested that these differences were the result of larger amounts of subtropical mode waters being subducted in models compared to reality (78). The Weddell Sea (Atlantic sector) was another area with large biases during winter and spring in ACCESS-OM2-01, however this area was not misrepresented to the same magnitude in CMIP6 models, and only two CMIP5 showed similar patterns in the location and magnitude of MLD biases in this area (78). The mechanisms responsible for biases in this area have not yet been identified, but the choice of method to estimate MLD could be a potential source of the mismatch (43; 58; 78).

MLD trends calculated from ACCESS-OM2-01 are an order of magnitude smaller than those derived from observational data (25). These differences may be the result of model drift from the initial ocean state, which occurs as the model reaches equilibrium, and makes trends harder to detect. Although the representation of MLD in ocean models has improved over time, particularly in high resolution models that are able to capture mesoscale features, these biases suggest gaps remain in our understanding of the mechanisms and mixing parameterisations driving changes in MLD at a regional level (29; 25). Additionally, we must keep in mind the quality and quantity of available observations, especially early in the data collection record. This paucity of observations may impact the observational trend seen by (25), especially during the winter season when observations are sparse. Indeed, spatio-temporal biases in observational data, which are largely collected during summer in ice-free waters north of the ACC (29; 25), hinder our ability to develop an in-depth understanding of the processes driving fluctuations in MLD at a regional level and across different seasons (29). Considering the strong correlation between surface solar irradiance and primary productivity in the SO (89; 90; 24), we argue that MLD model biases are an outstanding issue that must be resolved due to their ecological relevance. We emphasise that the effect of MLD goes beyond primary producers, as it indirectly affects the fitness of higher trophic levels, including top predators, via changes to prey availability (91; 92). Consistent biases or other errors in MLD in ACCESS-OM2-01 will impact the use of ACCESS-OM2-01 for ecosystem assessments. Despite these limitations this model provides a realistic seasonal cycle for MLD that matches observations in most regions.

5. Conclusions

We have focused on exploring the spatio-temporal trends of a small subset of variables related to the physical marine environment that are known to influence Southern Ocean ecosystems. Our model assessment shows that the coupled ocean-sea ice model ACCESS-OM2-01 reproduces baseline seasonal, climatological means in the SO with reasonable accuracy. Differences in model performance were seen across variables, but this is expected because computational resources currently available do not allow for a single model to capture the complexity of the climate system and represents all environmental variables equally well (4). We need reliable representations of past environmental conditions to better understand the ecological impact of past environmental change and to predict future ecological impacts (4). As such, these results emphasise the importance of understanding the capabilities and shortcomings of models within the boundaries of the area of interest prior to using model outputs in ecological applications. For variables, such as sea ice, that have complex effects on the structure and functioning marine ecosystems (80; 81; 2; 24; 82; 83; 84), the effect of small deviations in model output from observations can become amplified by the complexity of ecological interactions (4). Therefore we should be cautious when using sea ice seasonality outputs but also remind the reader of paucity of accurate frequent (in the order of days) high-resolution sea-ice measurements especially over Antarctic sea ice. It is ultimately up to end-users to decide if the difference between model outputs and observations make the model suitable to address their ecological questions. There are no set guidelines to define what a good model is, but thresholds of $\pm 20\%$ difference between observations and model estimates have been used in the past for sea ice data (4).

We must also highlight that the impact of climate change on the SO goes beyond its physical environment. Climate change affects biogeochemical cycles for example through ocean acidification due to enhanced carbon absorption, and oxygen depletion due to ocean warming (50). Changes to the chemical properties of the ocean in turn affect the ability of marine organisms to grow, reproduce and survive (2; 50). Future work will examine representations of biogeochemical variables in ACCESS-OM2-01. We should also consider that changes in sea ice conditions do not occur in isolation and in fact, they can result in alterations to other environmental variables, such as mixed layer depth (24; 82; 84). This means that ecosystems are affected by multiple stressors at once and the combined effects act in a cumulative way, which in turn compromises the ability of the SO to provide the same number and quality of ecosystem services that are important to humans, including fisheries support, carbon storage and sequestration, and tourism (93). Further, the cumulative nature of environmental impacts makes it difficult to project the ecosystem response to a changing climate. It is therefore important that future work takes this into account to improve predictions of ecological responses and better inform their management (4). Our analysis is highly adaptable to the needs of researchers and policy makers and can be extended to any environmental variable, time period and areas of interest. Scripts are publicly available in an effort to make this work accessible and reproducible.

Code and data availability

All scripts developed for this publication are available through the CLEX Code Collection available via Zenodo: (DOI TBA). The ACCESS-OM2-01 model outputs used in this publication are available via the National Computational Infrastructure (NCI) Data Catalogue and can be accessed from `http://dx.doi.org/10.4225/41/5a2dc8543105a`.

Declaration of competing interest

No conflicts of interest are declared by the authors.

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Appendix A. Supplementary Material

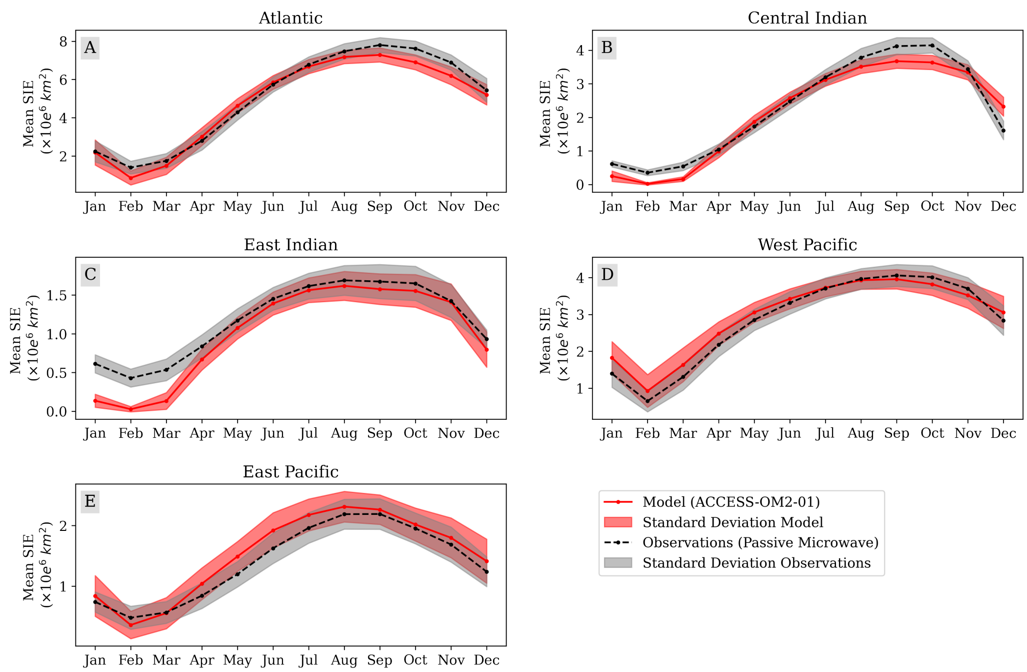

Figure Appendix A.1: 1979-2018 monthly mean (dots) and standard deviation (shaded area) of ACCESS-OM2-01 (red) and (71) observational (black) estimates of sea ice extent per sector. Axis scales differ.

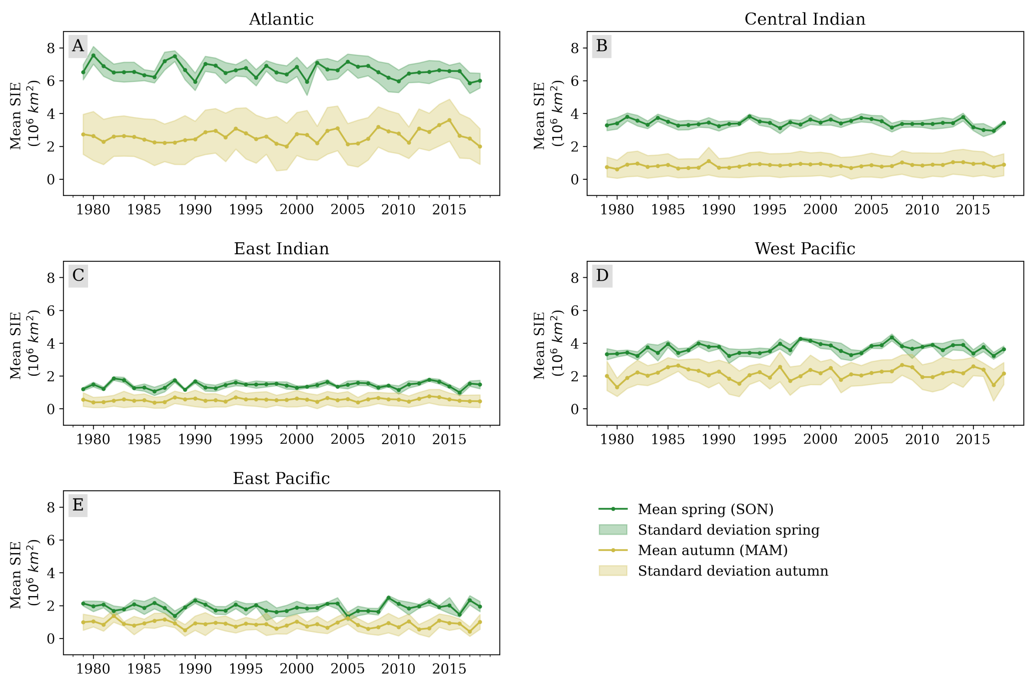

Figure Appendix A.2: Yearly mean (dots) and standard deviation (shaded area) of sea ice extent for spring (green) and autumn (yellow) per sector (MEASO). SIE was calculated from daily ACCESS-OM2-01 sea ice concentration data between 1979 and 2018.

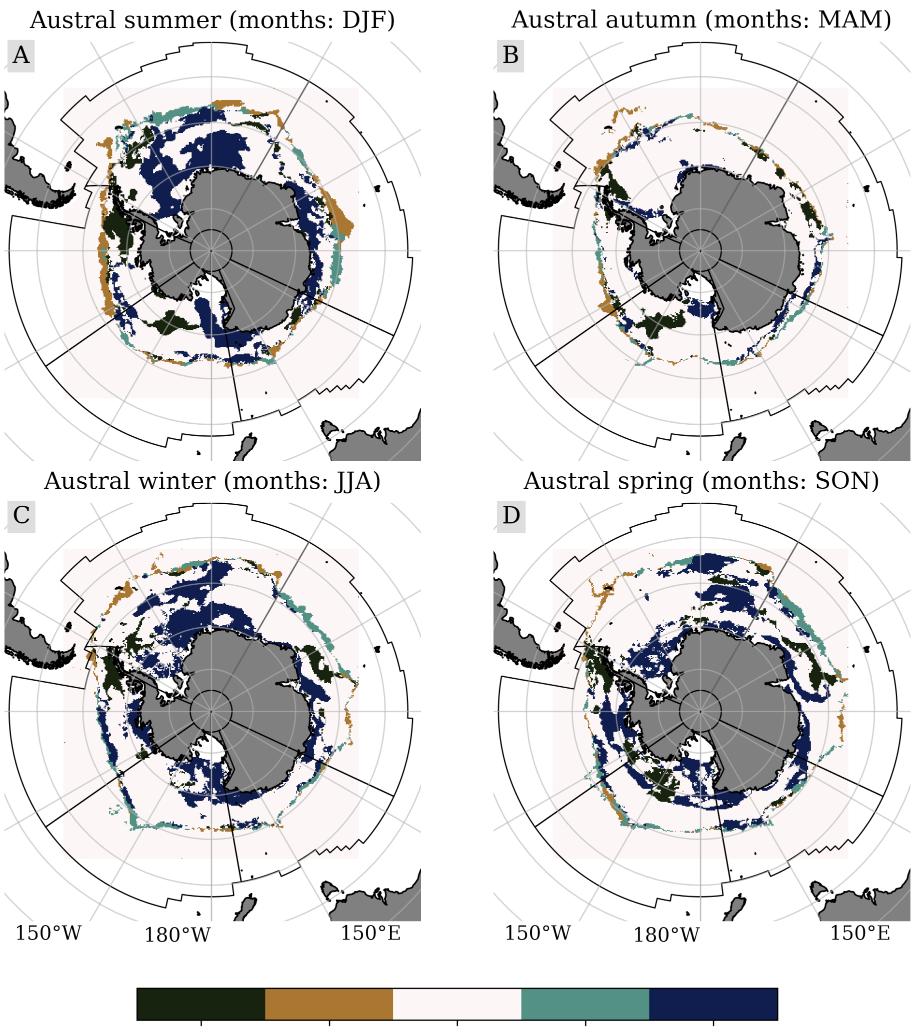

Figure Appendix A.3: Differences in trend direction for summer (A), autumn (B), winter (C), and spring (D) calculated from ACCESS-OM2-01 outputs and observations (71) between 1979 and 2018. Zero values shown in white indicate trends in the model and observations agree. Negative values indicate that observations had a negative trend while the model had either a positive trend (-2) or no trend was detected (-1). Positive values indicate positive trends in observations with either no trend detected in the model (+1), or a negative trend in the model (+2). Black lines denote MEASO sectors.

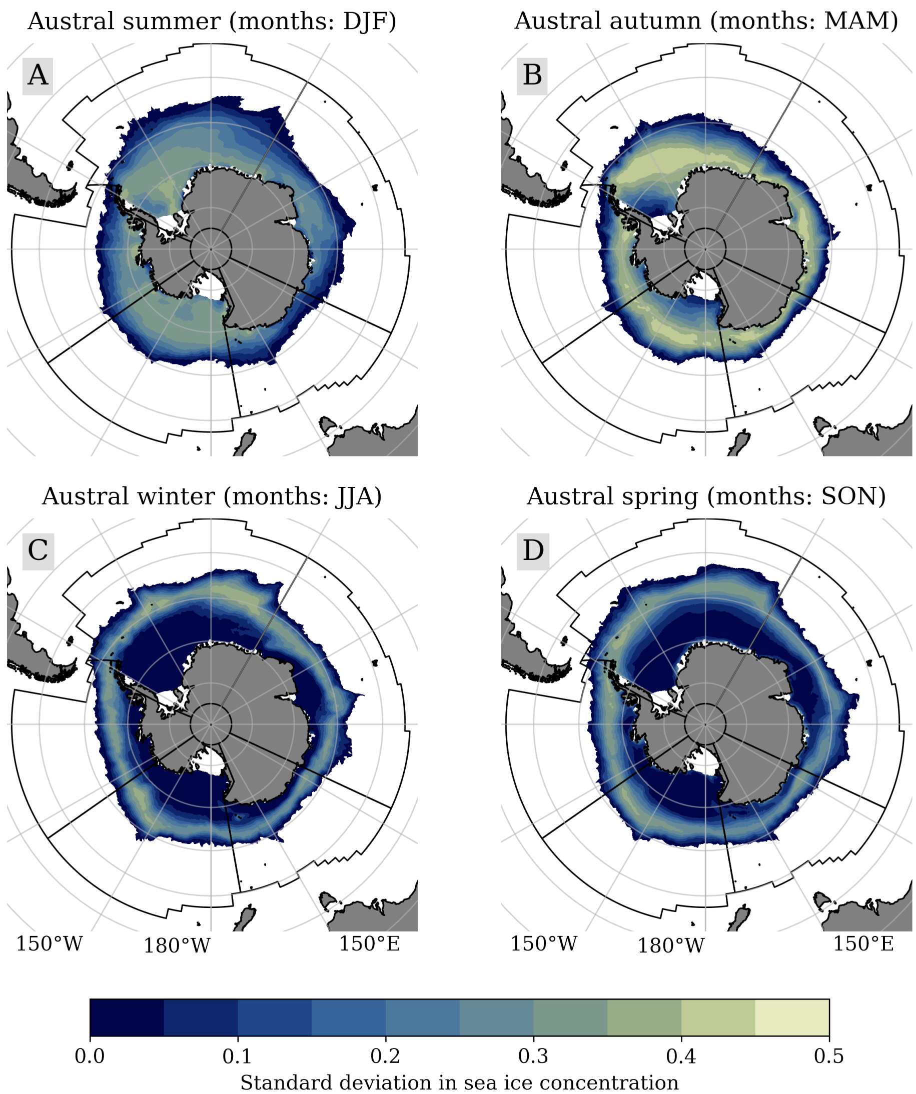

Figure Appendix A.4: Standard deviation in sea ice concentration estimated from ACCESS-OM2-01 outputs between 1979 and 2018. Black lines denote MEASO sectors.

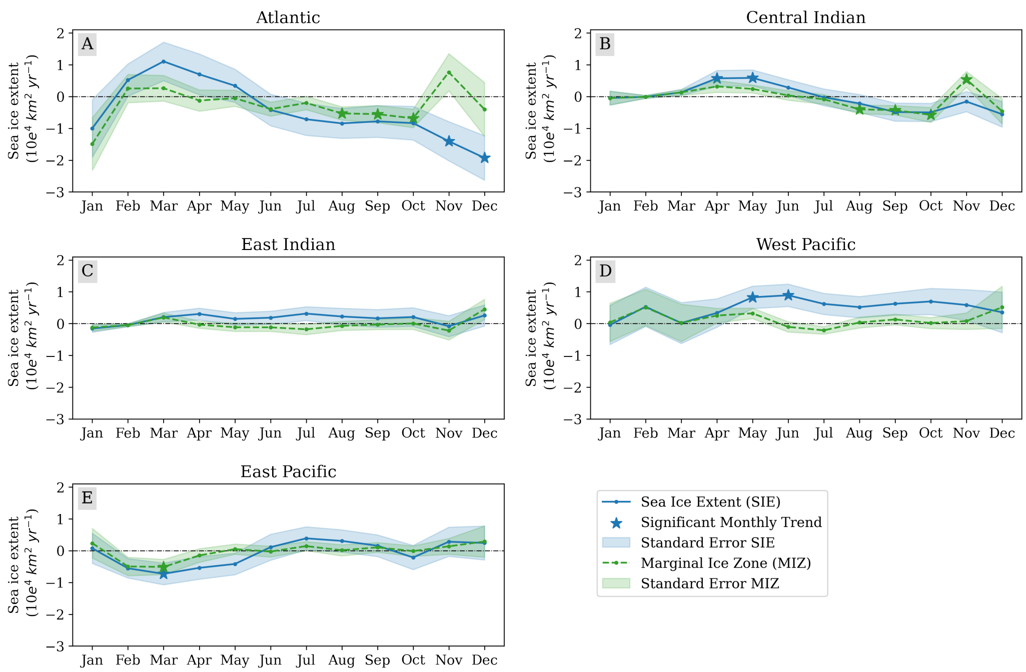

Figure Appendix A.5: Sea ice extent (SIE, blue dots) and marginal ice zone area (MIZ, green dots) trends per month and MEASO sector in ACCESS-OM2-01 model outputs for 1979-2018. Shading shows the standard error of trends. Stars highlight significant trends.

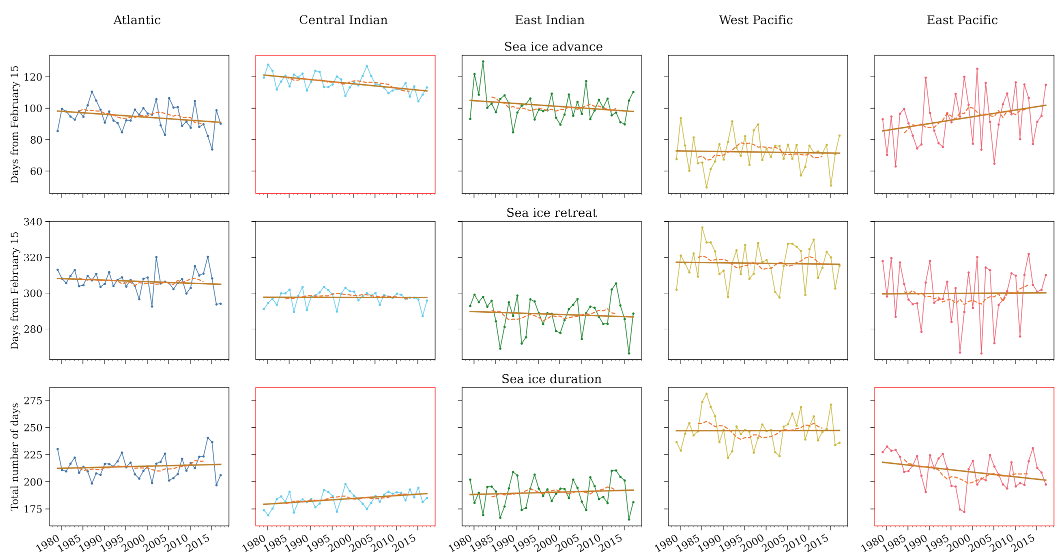

Figure Appendix A.6: Mean yearly start of sea ice advance (top row), sea ice retreat (middle row) and total duration (bottom row) for each MEASO sector calculated from ACCESS-OM2-01 model outputs from 1979 to 2018. Red borders highlight significant trends ($p \leq 0.05$).

Table A.3: Descriptive statistics for mixed layer depth (MLD) climatological estimates (1970-2018) obtained from the ACCESS-OM2-01 model across all seasons and MEASO sectors: Median values and 1st and 3rd quartiles in brackets (m). Quartiles were calculated by pooling all non-zero values within a sector boundary, thus they represent the spatio-temporal variability within each sector.

	Summer			**Autumn**		
	Antarctic	**Subantarctic**	**Northern**	**Antarctic**	**Subantarctic**	**Northern**
Atlantic	17 (14-29)	55 (36-67)	35 (28-43)	46 (36-68)	76 (58-92)	62 (51-69)
Central Indian	24 (20-30)	61 (49-73)	45 (35-54)	56 (46-76)	95 (81-110)	80 (68-91)
East Indian	24 (21-27)	42 (36-50)	41 (34-50)	64 (51-88)	83 (72-95)	88 (76-99)
West Pacific	22 (18-30)	47 (43-53)	31 (24-41)	54 (47-66)	92 (87-96)	68 (55-88)
East Pacific	15 (12-20)	43 (31-55)	41 (29-57)	38 (35-43)	84 (60-106)	78 (60-107)
	Winter			**Spring**		
	Antarctic	**Subantarctic**	**Northern**	**Antarctic**	**Subantarctic**	**Northern**
Atlantic	94 (77-163)	119 (99-134)	120 (97-130)	102 (83-259)	113 (91-131)	94 (73-109)
Central Indian	97 (76-142)	150 (131-174)	228 (147-296)	91 (73-136)	148 (123-177)	233 (131-340)
East Indian	164 (90-236)	143 (112-160)	260 (204-315)	141 (81-235)	138 (100-158)	280 (192-365)
West Pacific	106 (95-130)	170 (145-199)	182 (122-261)	117 (105-156)	166 (137-196)	141 (80-247)
East Pacific	78 (67-90)	179 (121-250)	157 (116-374)	81 (67-100)	192 (130-255)	134 (80-390)

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