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**Critical Literature Review  
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***Antarctic sea-ice extent in global coupled climate models***

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**ABSTRACT**

Antarctic sea ice plays a key role in the global climate system, moderating heat and moisture exchange in the Southern Ocean, reflecting solar radiation, and maintaining global thermohaline circulation. However, the trend of increasing Antarctic seasonal sea ice extent observed during the past few decades is not currently reproduced by the majority of climate models. A key question has emerged: Is this disparity due to problems within the physics of the models, or due to drivers of sea ice extent that are not yet incorporated in the models? Accurate representation of sea ice dynamics and processes is vital to inform regional and global climate predictions, and a large body of publications investigating this disparity has developed in the past decade. This paper summarises academic literature on modelling sea ice extent, concluding that while the models contain biases and poorly represent some climate processes, particularly in ocean components, substantial uncertainty remains as to the processes driving sea ice extent increases, which could limit the capacity for accurate representation in models. Further research into the processes driving the increase in sea ice extent is therefore highly recommended.

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## INTRODUCTION

The extent of seasonal Antarctic sea ice is a key feature of the global climate system. The ice reflects solar radiation through its high albedo and acts as an insulating 'blanket' for the surface ocean to moderate the transportation of heat, moisture and momentum between the ocean and atmosphere (Dieckmann & Hellmer, 2003). Rejection of salt during ice formation causes surface waters to increase in density and sink, resulting in convective overturning of the Southern Ocean, which plays a large role in maintaining the global ocean circulation (IPCC, 2013). Sea ice also plays a significant role in the viability of Antarctic marine ecosystems, influencing the life cycles of microorganisms, birds, and small and large animals (Lizotte, 2003; Schnack-Schiel, 2003; Ainley et al., 2003).

Understanding the drivers, processes and dynamics of sea ice extent is essential for accurate prediction of regional and global climates. Sea ice is a fundamental component of General Circulation Models (GCMs), due to its influence on feedbacks such as the ocean circulation feedback (transportation and exchange of heat within the oceans) and the ice-albedo feedback (loss of ice reveals a darker ocean surface which absorbs more heat and leads to greater ice loss) (Wadhams, 2000).

Modelling sea ice dynamics produces valuable information about changes to thickness, concentration, and extent. To do so requires consideration of interactions between the ocean, ice and atmosphere, namely *momentum balance* (the strength and scale of forces such as wind stress and water stress), *ice rheology* (the reaction of ice to these forces), *ice strength* (the extent to which the ice can withstand stress without fracturing or breaking into pieces), and *mass balance* (how the ice grows and decays) (Wadhams, 2000). The three general types of sea ice rheology are: viscous (ice as a fluid), plastic (static until a particular level of force is reached, at which the ice 'yields' or deforms), and granular (inelastic characteristics under collision) (see Lepparanta, 2011). Sea ice is modelled with both thermodynamic (heat energy transfer) processes, and dynamic processes which simulate physical deformation and transportation of the ice mass (Hunke et al., 2010). Due to high levels of interaction and feedback

between sea ice and the boundary layers of the ocean and atmosphere, these climate components are often combined in *coupled models*, which model two or three of these components together to represent their interactions and evolutions (NSIDC, 2014). Thermodynamic components are computed vertically, while dynamic processes are depicted on horizontally, forming the basic composition of a coupled sea-ice model (Hunke et al., 2010). Numerical models of sea ice use a computerised grid to represent the area in individual cells, which vary in size (e.g. 10km<sup>2</sup> or 100km<sup>2</sup>), with smaller cell sizes giving more detailed descriptions of the ice dynamics (NSIDC, 2014).

#### SEA ICE MODELLING – A BRIEF HISTORY

Sea ice modelling originated in Arctic research, and was then adapted for use in the Southern Ocean. In 1965, the first comprehensive sea-ice model was published, which presented the movement of sea ice as a highly-viscous fluid under stress from air, water, internal ice stress, the Coriolis force, and sea surface tilt (Campbell, 1965). Following this, in 1970, researchers of the Arctic Ice Dynamics Joint Experiment (AIDJEX) began planning a pilot study to obtain a year-long coordinated record of observation data from unmanned ‘drifting’ stations surrounding four manned stations. The experiment measured atmospheric conditions including atmospheric pressure and wind speed, meteorological conditions, ice conditions, and changes in the position of the drifting stations (AIDJEX, 1970). The first pilot study commenced in 1971 and the second in 1972, with the main experiment from 1975-76, after which the data underwent processing for submission to the National Snow and Ice Data Centre (NSIDC) (Untersteiner et al. 2007). The rapid development of sea-ice modelling utilising elastic-plastic rheology throughout the experiment resulted in more complete and simplified thermodynamic models as well as advancements in modelling plastic flow (Wadhams, 2000). Following the success of AIDJEX, a nonlinear viscous-plastic model was applied to the Arctic Ocean basin in an 8-year simulation that reasonably reproduced many circulation and thickness features (Hibler, 1979). Hunke and DuCowicz (1997) developed the efficient and flexible elastic-viscous-plastic rheology, prompting further development to improve efficiency in viscous plastic models as well (e.g. Zhang &

Hibler, 1997). Hibler and AIDJEX's legacies continue in current climate models, which utilise ice dynamics, plastic failure and thickness distributions that originated in the research results of these experiments, and both EVP and VP rheology are common in global sea ice models today (Untersteiner et al. 2007; Bitz & Marshall, 2012).

## MODELLING SEA ICE EXTENT

### TRENDS IN OBSERVATIONS

Several statistically significant trends in sea ice extent have been observed in the Antarctic Ocean since the 1970s, following the commencement of continuous satellite imaging of Antarctic waters. Parkinson and Cavalieri (2012) use satellite passive-microwave remote sensing data between 1979 and 2010 to calculate and analyse sea ice trends in the Antarctic region, dividing the surrounding waters into five sectors comprising the Ross Sea, Bellinghausen and Amundsen Seas, Indian Ocean, Weddell Sea, and Western Pacific Ocean. The study found positive trends in the Ross Sea, Indian Ocean, and Weddell Sea, a negative trend in the Bellinghausen and Amundsen Seas, and no significant trend in the Western Pacific Ocean region. The Weddell Sea trend is statistically significant at the 95% confidence level, and the trends in the Ross Sea, Bellinghausen and Amundsen Seas, and Indian Ocean are all statistically significant at the 99% confidence level. The trend in the Ross Sea trend has the highest magnitude  $13,700 \pm 1500 \text{ km}_2 \text{ yr}^{-1}$ , followed by the negative trend of  $-8200 \pm 1200 \text{ km}_2 \text{ yr}^{-1}$  in the Bellinghausen and Amundsen Seas (Parkinson & Cavalieri, 2012). The overall winter sea-ice trend for the region has been calculated as increasing at a rate of approximately 1.3-1.8% per decade from 1979-2012 (IPCC, 2013).

### REPRESENTATION IN CMIP5 SIMULATIONS

The 5<sup>th</sup> Coupled Model Intercomparison Project (CMIP5) is the fifth phase of a coordinated global climate model experiment, producing simulations that are heavily relied upon to address major research gaps and questions for the Intergovernmental Panel on Climate Change (IPCC) (Turner et al., 2012; Meehl et al., 2009). The majority of model simulations within the 5<sup>th</sup> Coupled Model

Intercomparison Project (CMIP5) have returned a decreasing trend in Antarctic sea ice, with minimal exceptions that are limited to a small number of ensemble runs (e.g. Uotila et al. 2013).

There are two likely possibilities to explain why the models do not accurately reproduce Antarctic sea ice extent. The first is that there are inaccuracies within the model physics; in fact, a number of biases have already been identified. For example, model drift in the ocean and atmosphere components of some CMIP5 models produces statistically significant biases, particularly in the deep ocean (Gupta et al., 2013). Similarly, Turner et al. (2013a) suggest that biases in ocean temperature data could be contributing to (though not solely responsible for) the large positive and negative biases of sea ice extent in several models.

The second possibility is that the drivers causing increased sea ice growth in the Southern Ocean are not yet properly understood, and therefore have not yet been correctly simulated.

## CURRENT LIMITATIONS AND FUTURE DIRECTIONS

### CLIMATE SIGNALS

The predictability of Antarctic sea ice extent is highly dependent on the timeline of interest. Research by Zunz et al. (2014) shows that predictions of interannual sea ice extent are limited by high levels of atmospheric variability that overwhelm signals from the ocean, reducing forecast timeframes to 3 years in advance, at best. Furthermore, the predictability of interannual trends is affected by seasonality, as freshwater stratification in the summer traps ocean heat anomalies by reducing vertical mixing. These anomalies resurface and impact on sea ice formation in winter when vertical mixing resumes, and increases predictability on short-term timescales. However, the same study highlights the potential for prediction on multi-decadal timescales, finding that long-term sea ice predictability relies heavily on the initialisation method for the ocean used in the model, and consequently focus on initialisation rather than parameterisation may yield more accurate results in global climate models (Zunz et al., 2014).

Climate signals can also be masked or exaggerated by issues within source data, or by the processing methods utilised. Screen (2011) cautions that discontinuity in remotely sensed observation data of sea ice concentration caused by switching between source datasets must be accounted for, as otherwise it can artificially inflate the positive trend in Antarctic sea ice area by a factor of 2 during the winter growth period; however, autumn sea-ice observations are thought to be less affected as they align more closely with local trends in temperature (Bintanja et al., 2013).

#### STRATOSPHERIC OZONE DEPLETION

Given the location of the ozone hole over Antarctica, the possibility that atmospheric or ocean conditions could be influenced by the depletion of stratospheric ozone was among the first theories suggested to explain the overall positive trend of Antarctic sea ice extent in recent years. Simulations by Turner et al. (2009) show that the ozone hole over Antarctica has contributed to changes in the Amundsen Sea Low, which causes higher wind speeds during the autumn that facilitate ice mass growth. It is similarly argued that the effect of ozone depletion may have led to cooling of sea surface temperatures in Antarctica, delaying the effects of ocean warming in the region in the past decades and permitting increasing sea ice growth (Marshall et al., 2014). However, several studies utilising model simulations of ozone and Antarctic sea ice found that the ozone hole was associated with decreasing sea ice trends, suggesting that the major drivers of increasing Antarctic sea ice extent lie elsewhere (Sigmond & Fyfe 2014; 2010; Zunz et al., 2013; Bitz & Polvani, 2012).

#### ALBEDO

Climate models vary in their parameterisation of Antarctic albedo, from a simplified four-value parameterisation encompassing cold or warm, melting or bare snow and ice, to more complex simulations that include thickness and absorptive characteristics (Hunke et al., 2010). Currently, under- or over-estimation of the sea ice albedo effect a significant factor impacting the accuracy of simulations in some CMIP5 models (Uotila et al., 2013), and more sophisticated modelling of dust, aerosols, biological matter, and their respective

contributions to radiation absorption need to be incorporated into climate models to capture their impacts on the strength and melt rates of Antarctic ice shelves (Hunke et al., 2010).

#### ATMOSPHERIC CIRCULATION

Changes to high latitude circulation are considered important drivers of climate change in the Southern Hemisphere (Thompson & Solomon, 2002). Analysis of Antarctic weather station data shows a decreasing trend in annual mean pressure and increasing mean wind speeds, both of which are consistent with changes to index of the Southern Annual Mode (SAM) (Turner et al., 2013b). Several studies have investigated climate model simulations to determine if the observed increase in the SAM index can reasonably explain the observed sea ice trends in Antarctica, and have found a strong association between increased SAM index and increasing sea ice extent (e.g. Goosse et al., 2009; Stammerjohn et al., 2008; Gupta & England, 2006), though additional study to verify the seasonal role of the SAM is required to address the uncertainty and lack of consensus in the simulations of CMIP5 models (Goosse et al., 2009).

Holland and Kwok (2012) produce model simulations to show that winds can substantially influence the forcing of the surface ocean, concluding that more accurate mapping and analysis of wind-driven ice drift and thermodynamics would result in more accurate depiction of several Antarctic climate components, such as freshwater budgets and brine release. Similarly, Mahlstein et al. (2013) suggest that the current CMIP5 models lack consensus in their simulation of the impacts of wind speed, zonal wind strength, and cloud cover on sea ice growth and decay. Zonal winds have significant influence on temperatures in the atmosphere and upper ocean and in turn can significantly impact the growth of sea ice extent and concentration (Raphael, 2007).

#### OCEAN

Interactions and heat exchange between the ocean and atmosphere system are a potential factor in explaining the discrepancy between observation and simulation of sea ice extent. Significant biases exist in the representation of the major water masses of the Southern Ocean in the CMIP5 models, and there is

significant disagreement between the models as to the transportation of the Antarctic Circumpolar Current, the formation of Bottom Water, and subpolar gyre dynamics, among other elements (Meijers, 2014). Close and Goosse (2013) suggest that the heat and salinity budgets of the ocean-ice-atmosphere system may be strongly influenced by heat from the atmosphere and from transportation changes (entrainment) at the base of the mixed layer of the ocean, and that model simulation of sea ice extent could be dependent on the strength of the relationship between these heat exchanges. Similarly, Zhang (2007) presents model findings showing that heat exchange between the ocean and atmosphere results in a more strongly stratified ocean column and less convective overturning, which then leads to reduced heat transport from the deeper ocean layers and hence less melting of ice. This then provides the opportunity for ice mass growth in the surface ocean. However, this is only one potential explanation for the observed growth, and Zhang (2007) maintains that other mechanisms could also be responsible.

It is also possible that the input of freshwater into the ocean surrounding Antarctica has not been accurately accounted for in the CMIP5 models. The models do not realistically simulate either mass loss from the Antarctic ice sheet or basal melting of ice shelves, inhibiting representation of ocean-ice dynamics (Bintanja et al., 2013; Swart & Fyfe, 2014). Simulations show that increased freshwater melt from the Antarctic ice sheet as well as from basal melting of ice shelves results in a cold, fresh surface ocean layer with lower density than the warmer, saltier waters beneath, and weakens convective overturning (Hellmer, 2004; Price et al., 2008). This results in stronger stratification of the ocean waters adjacent to the Antarctic coast (Swingedouw et al., 2008; Close & Goosse, 2013), exposing relatively cold, fresh waters to the atmosphere and allowing more effective cooling and freezing of water in the Southern Hemisphere autumn (Bintanja et al., 2013; Zhang, 2007). This negative feedback could act to moderate Southern Hemisphere warming, but at the same time is likely to result in rising global sea levels (e.g. Swingedouw et al., 2008; Bintanja et al., 2013). However, studies investigating the influence of freshwater input on trends of sea ice extent in Antarctica have yielded contrasting results. For example, Swart and

Fyfe (2014) model an accelerating rate of freshwater input to the surface water and argue that ice sheet melting has minimal effect on sea ice extent, but conclude that basal melting of ice shelves requires further exploration. In contrast, Bintanja et al. (2013) implement a sensitivity study with a constant rate of freshwater input from surface and basal accumulation that suggests the influence of freshwater on sea ice extent could be substantial. Due to the lack of consensus as well as the lack of model representation of freshwater stratification dynamics, this is clearly an area requiring additional focus.

#### NATURAL VARIABILITY

It has also been argued that, due to large internal variability, current trends in sea ice extent in Antarctica could fall within the bounds of natural variability of interactions between the atmosphere, ice and ocean (Polvani et al., 2013; Mahlstein et al., 2013). Turner et al. (2013a) estimate that, if the CMIP5 models are assumed to be simulating a reasonable representation of natural climate variability, the probability that the observed positive trend in Antarctic sea ice extent is due to natural variability is approximately 1 in 10. However, most models still currently overestimate annual intrinsic variability, reducing the value of model output in determining the attribution of the positive trend in sea ice extent to natural variability (Turner et al., 2013a; Zunz et al., 2013). Polvani et al. (2013) suggest that while attributing annual trends of Antarctic sea ice extent to anthropogenic forcing may be difficult, it is likely to be easier to do so for regional trends.

#### CONCLUSION

At present, it remains the subject of intense debate as to whether the disparity between the observed trend of increasing seasonal sea ice extent in Antarctica and current climate model simulations is likely attributed to problems within the existing physical representations in coupled climate models, or to drivers and dynamics that are not yet understood or represented in these models. Several biases and deficiencies within the models have been identified, particularly for climate signals and in the ocean and albedo components. Potential drivers of sea ice extent that may explain the trend include increased ocean stratification due

to freshwater input, changes to atmospheric circulation and wind, and ocean-ice-atmosphere interactions. It is also possible that this trend is part of natural variability, though simulations from coupled climate models are currently unable to conclusively state this.

Perhaps the most important point is that there is, as yet, no clear consensus on the processes and dynamics driving the increase in Antarctic sea ice. Studies on changes to atmospheric circulation and freshwater input, the most compelling theories to date, require verification and validation before these theories can be accepted (IPCC, 2013). However, while biases and deficiencies within model physics exist and must be dealt with, measures to improve parameterisation and physical representation of the system can arguably be of limited use in predicting future sea ice trends if the drivers and processes contributing to the observed increase in sea ice extent remain poorly understood. Therefore, a focus on investigating these potential drivers is of paramount importance.

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