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Research Article

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Antarctic Sea Ice Trends: Insights from a Suite of Climate Models

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Abstract

Background: Antarctic sea ice concentration has been observed to increase from 1978 to 2015, in contrast with the decrease that most climate models show. Here, we aim to examine the respective roles of natural variability and anthropogenic forcing in shaping Antarctic sea ice trend.

Method: To do so, we use the GFDL-CM2 coupled climate model with varying horizontal resolutions in the ocean (1°, 0.25° and 0.10°) that displays a range of behaviours in natural variability with the representation of Weddell Sea polynyas, and different intensities in the decrease of sea ice under climate change.

Results: In the 0.10° model, a sea ice trend of similar sign and magnitude to that observed over the satellite record is found between two occurrences of the Weddell Sea polynya. In the 1° and 0.25° models, which do not simulate any polynya, no equivalent trend of what the satellite record shows is found. Under increasing CO_2 forcing, all models show a surface cooling on a short time scale (years) south of 50°S, followed by a warming on a longer time scale (decades), consistent with the delayed warming mechanism of Ferreira *et al*. (2015). Of all models, the higher resolution model shows the strongest surface warming and decrease in sea ice, suggesting an important role for mesoscale eddies in the response of Antarctic sea ice to climate change.

Conclusion: We conclude that the Weddell Sea polynya is key to the representation of the sea ice trend and that the disagreement between models and observations might partly arise from a desynchronization of the polynya cycles or a too weak natural variability of sea ice in models compared to observations.

Introduction

Despite global warming, Antarctic sea ice extent has been steadily increasing over recent decades and sea surface temperatures (SST) have been decreasing in contrast with the decrease in sea ice cover and the increase of SST in the Arctic.(1) The satellite passive-microwave data from 1978 to 2010 shows an overall increasing trend of 17 100 ± 2300 km^2 yr^{-1} south of the Antarctic Circumpolar Current.(2) The trend in sea ice concentration is not homogeneous around Antarctica however, with some regions even experiencing a strong decrease (e.g. Amundsen-Bellinghausen Sea).(2) In contrast, most models differ from observations by representing a mostly homogeneous decrease in sea ice extent.(3)

The current hypotheses that attempt to explain the observed increase in sea ice can be broadly separated into two categories: the ones caused by natural variability and the ones triggered by forced variability also referred to as anthropogenic forcing.

A study by Polvani and Smith (4) offers evidence that natural variability in sea ice overwhelms the response to anthropogenic forcing by showing that the current trend in Antarctic sea ice is well within the range of simulated trends from preindustrial simulations of Coupled Model Intercomparison Project Phase 5 (CMIP5) models, and that trends induced by anthropogenic forcing are comparatively small. One of the prominent features of sea ice natural variability in models is the appearance and disappearance of open-ocean polynyas that mostly form in the Weddell Sea.(5,6) These ice-free expanses in the otherwise sea ice covered region are caused by an upwelling of relatively warm water from depth and maintained by convection.(7) The first satellite observations of Antarctic sea ice have allowed us to observe an open-ocean polynya in the Weddell sea that lasted from 1974 to 1976 which shows that such events do take place outside from model simulations.(8) During the formation of a polynya, there is a decrease in the Antarctic sea ice extent. As the polynya closes, the Antarctic sea ice extent area increases back to a non-polynya state. Deep and abyssal warming have been reported since the late 1970s and can be partly attributed to a rebound from the 1974-1976 Weddell Sea polynya, which is often referred to as a recovery period.(9) That recovery period might be ending as the record low Antarctic sea ice extent of the Austral winter 2016 as well as the small polynya that opened in the Weddell Sea during 2017 early signs of a polynya.(10)

Anthropogenic forcing has also been posited to be the cause of the current sea ice increase in Antarctica. One theory postulates that increased basal melt of Antarctic ice shelves leads to the production of a cool and fresh surface layer that prevents warmer water from melting sea ice and favours the formation of more sea ice.(11) However, Swart and Fyfe (12) showed that freshening of Antarctic surface waters produces only a small effect on sea ice over the historical period and that a freshening of surface waters fails to reproduce the patterns of sea ice trends in the Southern Ocean. Another possible explanation is that increased downward heat flux from the surface to the deep ocean and increased precipitation minus evaporation leads to increased stratification in the upper ocean and inhibition of the upward flux of heat from warmer water at depth.(1) Alternatively, Holland and Kwok (13) attribute the current sea ice trend to wind changes in the Southern Ocean by demonstrating that local ice-motion is directly related to the local wind trend. They also note that regions with a meaningful increase in northward ice flow present an increase in sea ice concentration and vice versa.

On the other hand, anthropogenic forcing related to ozone depletion and increase in greenhouse gases has been posited to cause a decrease in sea ice.(14) Indeed, most models forced under an historical scenario simulate a decrease in sea ice.(12) In an attempt to reconcile results from models and observations, Ferreira et al.(15) proposed the delayed warming mechanism to explain the current decrease in SST and increase in sea ice solely due to anthropogenic forcing. This mechanism links the increase in westerly winds, caused by ozone depletion in the stratosphere over Antarctica (16), to the delayed warming of the ocean surface observed in the Southern Ocean. The mechanism involves a two-step response which is illustrated in Fig.1. First, in response to the wind intensification, there is an immediate increase in Ekman advection that produces an initial cooling around Antarctica (Fig.1a.). This cooling then leads to the production of more sea ice, which would explain the current sea ice trend. Then, the slow but persisting response is a warming at all latitude south of 30°S, causing a decrease in sea ice (Fig.1b.). This decrease in sea ice is due to the increased Ekman currents being divergent and causing anomalous upwelling of relatively warm water south of 50°S. (15) Armour et al.(17) suggested that Southern Ocean delayed warming is directly dependent on the timescale of North Atlantic deep waters warming due to the global meridional overturning circulation.

Mesoscale eddies have been found to be key players in the second step of the delayed warming mechanism.(18) These transient ocean features, 10 to 100 km large, are often referred to as the 'weather of the ocean', playing the role of cyclones and anticyclones in the atmosphere. They contain as much as half of the kinetic energy of the ocean and are responsible for transporting and mixing tracers in the Southern Ocean.(19) In particular, eddies are responsible for transporting heat poleward across the Antarctic Circumpolar Current. It has been shown that an increase in westerly winds is followed by an increase in eddy kinetic energy (EKE) with a 2 to 3 years lag.(20) This lag has been attributed to the time it takes surface changes to reach the circulation of the deep ocean. Indeed, the excess energy originating from the increased winds is first stored as potential energy until eddies gradually transfer momentum from the surface to the deep ocean. This increase in EKE is stronger as the resolution of the model is higher. Models which do not resolve eddies will not represent the full temperature response but will be able to show the short-term response of the delayed mechanism.(18)

The purpose of this study is to assess the respective roles of natural variability and anthropogenically forced ocean warming in shaping the Antarctic sea ice trend. First, we consider the role of natural variability and we hypothesize that the recovery from the 1970's polynya can largely explain the current observed positive sea ice trend. Second, we hypothesize that the increase in the westerly winds due to anthropogenic forcing induces a decrease in sea ice on the long term that is augmented by the presence of mesoscale eddies through southward heat transport. As such, we propose that a better representation of the Weddell Sea polynya and of mesoscale eddies in models will allow a more accurate prediction of the sea ice trend. To test these hypotheses, we use a suite of three coupled climate models that differ by the resolution of the ocean component thus allowing us to explore the role of mesoscale eddies in the transport of heat towards the seasonally sea ice covered region. These models also offer a range of behaviours in natural variability through the representation of the Weddell Sea polynya,

Methods

Observational Dataset

We study two variables: sea ice concentration and SST. Sea ice concentration corresponds to the fraction of each observed or modelled grid cell covered by sea ice. It is expressed between 0 and 1. The sea ice extent area, calculated from the former, is the total area covered by sea ice, in km^2, with a sea ice concentration threshold of 0.15 chosen to select which grid cells are included in the overall area of sea ice.

We study the sea ice concentration dataset from the National Snow and Ice Data Center (NSIDC V2) at the National Oceanic and Atmospheric Administration (NOAA). Its source is passive microwave data from satellites. This dataset is computed using two algorithms from the NASA Goddard Space Flight Center (GSFC). The final product uses the highest value from either algorithm for each grid cell.(21) We use monthly values from 1987 to 2015. The limitations of this dataset include a tendency to under-estimate sea ice concentration especially in Antarctic winter. The SST data originates from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST). It consists of monthly values from in-situ observations and adjusted satellite data. The data set extends from 1870 to 2017. Grid cells containing more than 90% of sea ice were set at the freezing point temperature (-1.8 °C). The greatest strength of this dataset is its overall global spatial completeness, though it is less so in the polar regions, especially the Southern Ocean.(22)

The CM2-O Climate Model Suite

We use a suite of three coupled climate models from the Geophysical Fluid Dynamics Laboratory.(23) Ocean, land, atmosphere, sea ice and their interactions are modelled. The models differ only by the horizontal resolution in the ocean. The lowest resolution model is CM2-1deg (1° horizontal resolution) and is the only model of the suite which is run with a mesoscale eddy transport parameterization.(23) CM2.5 has a resolution of 0.25° and CM2.6 has a resolution of 0.1°. A moderate and rich mesoscale eddy fields are resolved in each model respectively. The vertical ocean resolution is 50 levels with a thickness of 10 m at the surface increasing with depth to 210 m. CM2.6 resembles the most observational estimates of dynamic sea level, as expected from its refined resolution (see **Fig. 1** of Griffies et al.(23)).

Each version of the models has two different experiments available for both of which we analyse a period of 80 years. The control experiment is used to investigate the natural variability of the model. The CO_2 concentration is kept constant at a preindustrial level (286 ppm). The perturbation experiment is an idealized climate change scenario where the atmospheric CO_2 concentration undergoes a 1% increase per year. It comprises both the natural variability and the forced response of the system. The difference between the perturbation and control experiments allow us to estimate the response to anthropogenic forcing. Neither the perturbation nor the control experiments correspond to specific years in the historical record. To compare our model output with the observational dataset, we will use years 22 to 50 (352 ppm to 466 ppm) from the perturbation experiment as the atmospheric CO_2 concentration for model year 22 matches the CO_2 concentration in April 1989, which is near the start of the observational dataset.

Results

Evaluation of Models Against Observations

I. Mean State

We start by assessing the realism of the models in representing sea ice extent. Fig. 2 illustrates the seasonal variability of sea ice extent area around Antarctica for observations and the perturbation experiment of the models for the 30 years most similar to observations for CO_2 concentration (for years 1987-2015 of observations and years 22-50 of the models). Models and observations present the same general pattern. Both models and observations reach their lowest value in February and their highest value in September or October. The models present larger amplitude than observations in their seasonal cycle and show higher sea ice extent area in winter and also slightly lower sea ice extent area in summer. Indeed, we observe a maximum of 21% increase in amplitude between observations and CM2.5 in winter and 84% decrease in amplitude between observations and CM2.6 in summer. However, CM2.6 comes very close to observations for the winter period with only 2.5% larger sea ice extent area than observations. In general, the seasonal cycles are similar to the observational dataset.

We also compare maps of the SST averaged over the whole period of study in order to evaluate the spatial pattern of models against observations (Fig.s not shown here). The general pattern of models and observations is similar with temperature increasing from Antarctica to the Equator. The range of temperature is also the same from -1.8 °C to around 20 °C. Models show more spatial variability which is most likely due to higher resolution for CM2.5 and CM2.6. Overall, the models offer a reasonable comparison to observations.

II. Long-term Trend

Next, we ascertain the differences between the sea ice trends in observations and models. Plotted on Fig. 3 are time series of annual sea ice extent area in Antarctica for observations and the CO_2 perturbation experiment of the models. A linear regression over the complete time period is calculated for each data set with the coefficient of determination R^2 and the linear regression coefficient a. We observe that the models simulate a negative trend while observations show a positive trend. This is not an unexpected result as it is a typical discrepancy between models and observations for sea ice in Antarctica.(3) In addition, the amplitude of the sea ice trend for satellite observations is smaller than for all models (+0.3 vs -0.4, -0.7, -0.8 million km^2 per year for CM2-1deg, CM2.5 and CM2.6 respectively). CM2.5 and CM2.6 show trends of similar magnitude, differing from the sea ice extent trend in CM2-1deg, which does not decrease as much. It is also interesting to note that the decreasing trend for CM2.6 stalls between model years 20 to 50 because of the formation of large polynyas in the Weddell Sea.

Role of the Wedell Sea Polynya on Sea Ice Trend

We now consider the effect of natural variability on the sea ice trend in Antarctica to evaluate our first hypothesis. Fig. 4 shows a time series of the annual average of the sea ice extent area around Antarctica for observations and the control experiment of the models. The control experiment admits no anthropogenic changes in atmospheric CO_2 and ozone concentrations. CM2.6's variability largely differs from that of the two other models due to the simulation of Weddell Sea polynyas. CM2.6 is the only model of the suite that simulates open-ocean polynyas (Dufour et al.(24)). Polynyas form spontaneously in CM2.6 as is the case in many models. These polynyas induce a strong variability in the CM2.6 time series that is more obvious in the control simulation (Fig. 4) than in the perturbation simulation (Fig. 3), although both the control and perturbation experiments admit polynyas. In the perturbation experiment, the variability is due to the superposition of the climate change trend on the natural variability. In Fig. 4, we observe two polynyas, one from years 2 to 30 and one from years 62 to the end of the time series. These polynyas both form in the Weddell Sea, west of the Greenwich meridian like the one observed in the 1970s. The polynyas in CM2.6 are bigger in size than the one observed (2-3x10^5 km^2 for the 1970s polynya and 11x10^5 km^2 for the modelled polynya).(24, 25) At their widest, model polynyas are not completely enclosed by sea ice, like observed in the 1970s, but appear like embayments. Despite these differences, CM2.6 shows a positive trend in sea ice extent area similar in

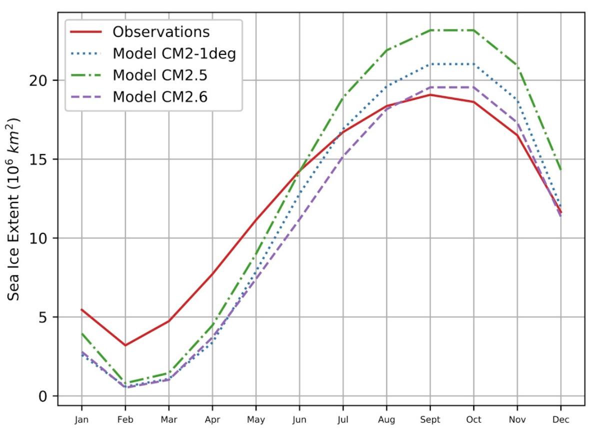

Fig. 2. Seasonal variability of sea ice extend area around Antarctica for observations for the 1987-2015 period and the perturbation experiment of the models.

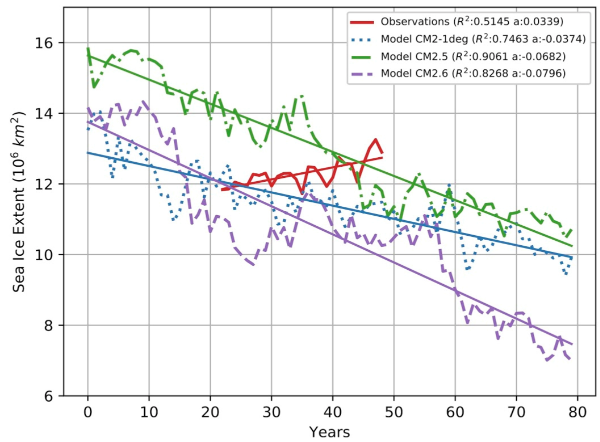

Fig. 3. Time series of annual sea ice extent area around Antarctica for observations for the 1987-2015 period and the perturbation experiment of the models. We calculate the coefficient of determination R2 and the trend a (millions of square kilometers). The time series of observations has been shifted so that the concentration of atmospheric CO2 in the model corresponds to the concentration of the first year of observations

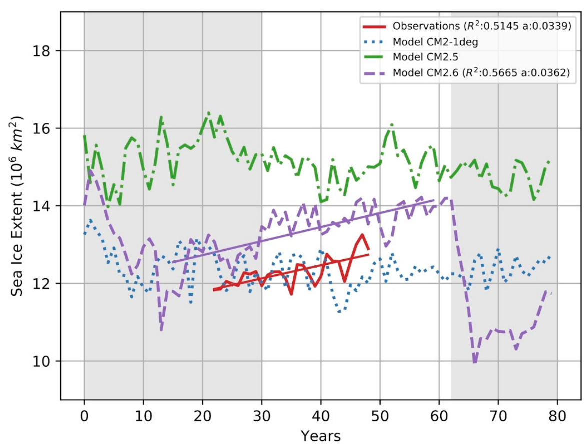

Fig. 4. Time series of annual average of the sea ice extent around Antarctica for observations for the 1987-2015 period and the control experiment of the models. The shading indicates the position of the two polynyas in the time series of the CM2.6 simulation only. The time series of observations has been shifted so that the concentration of atmospheric CO_2 in the model corresponds to the concentration of the first year of observations.

sign and magnitude to that of the observational dataset between years 15 and 60. Indeed, in the recovery period between the two polynyas, that is from the closing of the polynya until a return to the pre-polynya state, we observe a positive trend of 0.36 million km^2 per decade that compares well to 0.339 million km^2 for observations.

It is important to verify if this positive trend occurs only during the closing of the polynya or if it continues further. Indeed, as there is no polynya in the Southern Ocean for the period of observations analysed, this relationship would be meaningless if sea ice only increases during the period of closing. Using a series of maps of the sea ice concentration at the beginning of the Austral winter (July) for consecutive years, we ascertain that the first polynya closes at around year 30 of the simulation. Since the increasing trend in Fig. 4 continues until year 60, there is a period of approximately 30 years following the closing of the polynya that correspond to an increase in sea ice. It is unclear why that increase occurs and this constitutes a topic of further investigation. Considering that we have observed an open-ocean polynya in Antarctica from 1974-1976 (26), it is possible that the current positive trend in sea ice extent area could be due to a period of recovery from that polynya. However, this positive trend is found in the control experiment, which is a preindustrial simulation. When we look at the perturbation experiment, which includes anthropogenic forcing, we do not observe a positive trend but rather a stalling of the decreasing trend. This means that the positive sea ice trend induced by the polynya is compensated by the negative sea ice trend induced by anthropogenic forcing in the perturbation experiment. Still, these results suggest that the opening of the Weddell Sea polynya might have played an important role in the observed trend.

Role of Mesoscale Eddies in the Sea Ice Trend

In this section, we evaluate our second hypothesis that models with a higher ocean resolution, and consequently a better representation of mesoscale eddies, will simulate a greater response to anthropogenic forcing and as such a greater decrease in sea ice. To do so, we look at the response to climate change in the models. We subtract the control from the perturbation experiment to analyse purely the response to climate change. Then, we calculate the linear regression over time at each model grid cell for both sea ice concentration and SST (Fig.5). Overall sea ice concentration decreases (Fig.5 a.-c) while SST increases (Fig.5 d.-f.). We can see an area of intense SST warming along the western boundary current in all three models (Fig.5 d.-f.) and more warming along the Antarctic Circumpolar Current than close to Antarctica. CM2-1deg undergoes less of a decrease than CM2.5 or CM2.6 as indicated by the average decrease per decade, -0.5%/decade for CM2-1deg and -1%/decade or more for the other two. We can observe in CM2-1deg some areas of increase in sea ice corresponding to small areas of decrease in temperature although those trends are not significant. Overall, surface warming increases with resolution (0.12, 0.13 and 0.15 °C per decade for CM2-1deg (FIG. 5d.), CM2.5 (e.) and CM2.6 (f.) respectively). Hence, the model suite shows a clear link between a higher resolution on one hand and more warming and less sea ice on the other.

To evaluate if the models show evidence of the delayed warming mechanism as a response to climate change, we compute a Hovmöller diagram (latitude vs time) of the annual average of SST (Fig. 6). The first structure that we observe is a decrease in the SST for approximately the first two decades followed by a warming for the rest of the time period in all three models. This result supports Ferreira *et al.*(15) delayed warming mechanism (see Fig. 1). We note that the cooling phase is more prominent as the resolution increases. Indeed, CM2-1deg shows period of cooling within the warming period (Fig. 6a.). The second feature observed in Fig. 6 is that the warming is more intense as the resolution increases south of 50°S. This supports our previous results (see comments on Fig. 5).

A better representation of mesoscale eddies in models seems to be associated with a stronger warming of the SST in the Southern Ocean. These results suggest that mesoscale eddies have an important role in the response of Antarctic sea ice to climate change.

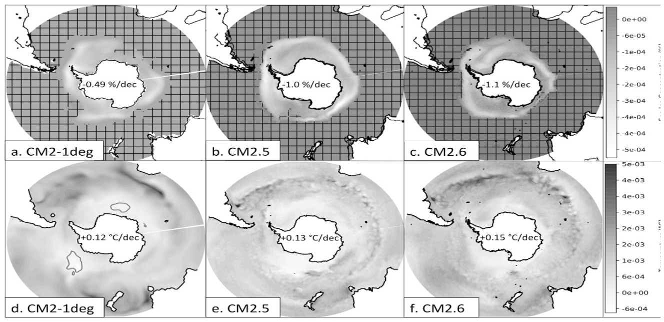

Fig. 5. Slope of the linear regression of the difference between the perturbation and control experiments of the sea ice concentration (a.-c.) and the sea surface temperature (d.-f.). We consider purely the response to climate change by subtracting the control from the perturbation experiment. The hashes point out trends that are not significant. Note the decadal trend (%/dec or °C/dec) inscribed on the Antarctic continent.

Discussion

The positive sea ice extent trend present in the control experiment of CM2.6 during the recovery period from the polynya is the only trend similar to that of observations detected in all models analysed (see Fig. 4). This trend in CM2.6 occurs during and after the closing of a Weddell Sea polynya, which is also the case in observations (1974-1976 polynya). As such, it supports our hypothesis that the recovery from the 1970's polynya can explain the current positive sea ice trend. This hypothesis could be further supported by the 2016 and 2017 sea ice trends. Indeed, we have observed the lowest sea ice extent seen in the satellite record in 2016 that was followed, in 2017, by the opening of a small Weddell Sea polynya.(10) If this polynya continues to grow in the next few years and the sea ice trend continues to decrease, it could offer supporting evidence that natural variability dominates over anthropogenic forcing for the sea ice trend in Antarctica.

Fig. 5 and 6 indicate a strong link between a higher ocean resolution and more intense warming in the Southern Ocean. Fig. 5 shows an increase in SST and a negative sea ice extent area trend for most of the Southern Ocean. The regionally averaged warming (30°S to 90°S) increases by 8% (CM2-1deg to CM2.5) to 15% (CM2.5 to CM2.6) with resolution. Bitz and Polvani (2012) (27) find the opposite result in their study which shows that the ocean warming observed due to atmospheric ozone loss is somewhat muted in their 0.1° ocean resolution model compared to their 1° ocean resolution model.(27) Differences between the models and experiments of Bitz and Polvani (2012) and ours are numerous and further investigation need to be done to elucidate the causes of the divergence in results. Fig. 6 also presents supporting evidence for the delayed warming mechanism of Ferreira *et al.*(15) caused by an increase in the westerly winds. This increase in the westerly winds has been observed in this suite of climate models (not shown). In the climate change scenario, we observe a cooling of the surface in the Southern Ocean followed by a strong warming that gets more intense as resolution increases. Our results supports the conclusions of Screen *et al.*(18) who demonstrated that models with a parameterization of eddies do not show

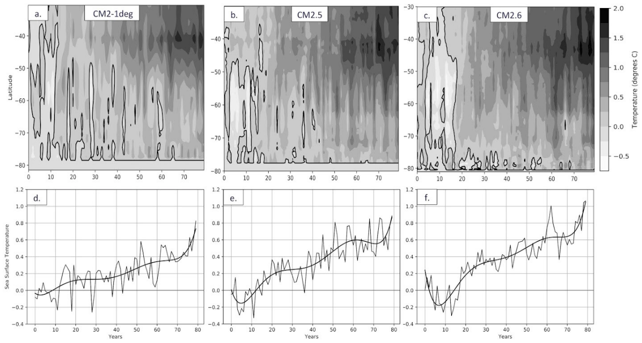

Fig. 6. a.-c. Hovmöller diagram (latitude vs time) of annual average of sea surface temperature for the difference between the sensitivity and control experiments (signal for anthropogenic climate change only). A solid line highlights the zero contours. d.-f. Annual average of the sea surface temperature in the Southern Ocean from 50°S to 90°S. A 6th degree polynomial fit is superimposed on the time series.

as strong of a warming as models that explicitly resolve mesoscale eddies. Both Fig. 5 and 6 support our second hypothesis that warming due to anthropogenic forcing will induce a decrease in sea ice that is augmented by the presence of mesoscale eddies.

If the current sea ice trend is indeed due to the recovery from the Weddell Sea polynya of the 1970s, it suggests a great influence of natural variability on the Antarctic sea ice cover, which might be underestimated in models like CM2-1deg or CM2.5. Because it resolves polynyas, CM2.6 might be more skilled to accurately simulate the Antarctic sea ice trend. However, an accurate simulation requires the model's natural variability be synchronized with that of the real world. It is unlikely though that such a synchronization will spontaneously occur in climate models.

Another source of misrepresentation of the sea ice trend in models relates to the response to anthropogenic forcing not being accurately simulated in models. One possibility is that natural variability could be masked in models by a strong response to anthropogenic forcing. If the natural and forced signals are opposed and if the anthropogenic forcing is too strong in models, then the trend would not be the same in models and in observations. Concurrently, the intensity of the long-term warming response might be too strong in this suite of models. Indeed, an increase of 1% per year in the perturbation experiment signifies that the doubling of the CO_2 concentration from preindustrial levels will occur over a period of 70 years only. In this intensity of the warming response, our results differ from those of Ferreira *et al.*(15) who use a weaker anthropogenic forcing that stay close to historical values. Indeed, they observe a maximum of 0.6°C of SST response in the ocean South of 30°S while we observe a maximum of 2.0°C. Still, the onset of the warming response is similar in time at around 20 years.

Conclusion

To conclude, our results clearly suggest the importance of representing polynyas to accurately simulate the Antarctic sea ice trend. Also, the role of mesoscale eddies in the response of Antarctic sea ice to climate change cannot be overlooked. Our results show their importance for the intensity of the warming response and subsequent decrease in sea ice present in models.

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