Historical Antarctic mean sea ice area, sea ice trends, and winds in CMIP5 simulations

Irina Mahlstein,[1,2,3] Peter R. Gent,[4] and Susan Solomon[5]

[1]   In contrast to Arctic sea ice, average Antarctic sea ice area is not retreating but has slowly increased since satellite measurements began in 1979. While most climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive simulate a decrease in Antarctic sea ice area over the recent past, whether these models can be dismissed as being wrong depends on more than just the sign of change compared to observations. We show that internal sea ice variability is large in the Antarctic region, and both the observed and modeled trends may represent natural variations along with external forcing. While several models show a negative trend, only a few of them actually show a trend that is significant compared to their internal variability on the time scales of available observational data. Furthermore, the ability of the models to simulate the mean state of sea ice is also important. The representations of Antarctic sea ice in CMIP5 models have not improved compared to CMIP3 and show an unrealistic spread in the mean state that may influence future sea ice behavior. Finally, Antarctic climate and sea ice area will be affected not only by ocean and air temperature changes but also by changes in the winds. The majority of the CMIP5 models simulate a shift that is too weak compared to observations. Thus, this study identifies several foci for consideration in evaluating and improving the modeling of climate and climate change in the Antarctic region.

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1.   Introduction

[2]   The historical and future scenarios of Arctic sea ice simulations of the Coupled Model Intercomparison Project Phase 3 (CMIP3) models [*Meehl et al.*, 2007] have been much discussed in the literature [*Boe et al.*, 2009; *Stroeve et al.*, 2007]. However, the modeled sea ice behavior in the Southern Hemisphere has received less attention from an intermodel comparison perspective. A model analysis for this area is of interest as a positive trend in Antarctic sea ice extent [*Turner et al.*, 2012] has emerged over the period 1979–2005, although there are uncertainties associated with the observations and not all observational data sets show a significant trend. In most cases, climate models have difficulty simulating a realistic positive trend over this period. *Lefebvre and Goosse* [2008] analyzed the Antarctic

sea ice distributions of the CMIP3 models and reported that in general, the modeled trends were too negative compared to observations. *Turner et al.* [2012] report a negative sea ice trend for most CMIP5 models. However, internal variability is large in this region [*Deser et al.*, 2010] and may play a role in the small, observed increase of sea ice. Internal variability includes all of the possible trajectories of the chaotic climate system. Examples of internal variability are El Niño, fluctuations in the thermohaline circulation, or internal changes in ocean heat content, and other oscillations. Internal variability may cause shifts or drifts in the climate over an extended time period, introducing what appears to be a trend, but is not due to external forcing. The observed sea ice trend [*Cavalieri and Parkinson*, 2008; *Comiso and Nishio*, 2008] might be due to internal variability and not external forcing; therefore, it is important to analyze the models in respect to this factor. If the observed trend is due to internal variability, then the models do not necessarily need to simulate the observed trend in any particular ensemble member of the twentieth century runs.

[3]   Furthermore, along with apparent shortcomings in simulated trends, the mean state of Antarctic sea ice is often poorly simulated [*Lefebvre and Goosse*, 2008], particularly its seasonal cycle [*Turner et al.*, 2012]. Here we show that the spread in the mean sea ice area across the CMIP5 models is larger than the observed range and hence appears unrealistic. Surface winds play an important role in creating the sea ice distribution, as the applied force on the sea ice pushes it in the direction of the wind stress. *Holland and Kwok*

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[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.
[2]NOAA Earth System Research Laboratory, Boulder, Colorado, USA.
[3]Now at MeteoSwiss, Zurich, Switzerland.
[4]National Center for Atmospheric Research, Boulder, Colorado, USA.
[5]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Corresponding author: I. Mahlstein, NOAA Earth System Research Laboratory, Boulder, CO 80305, USA. (irina.mahlstein@meteoswiss.ch)
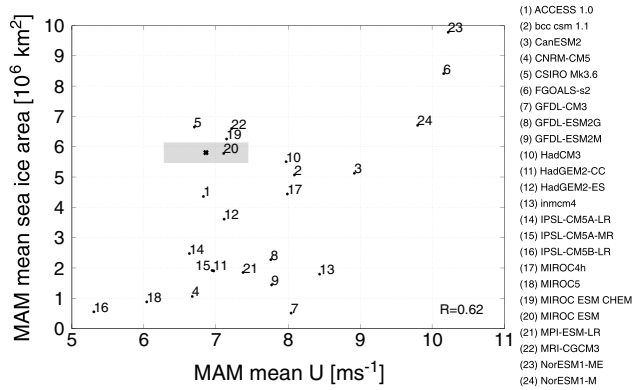
Figure 1. The MAM mean ice area versus MAM mean zonal wind speed for the period 1980–2001. The numbers correspond to the listed models. The black cross shows the observations and the grey shading the observed interannual variability.

[2012] showed that the sea ice drift in the Antarctic, which is caused by the changing winds, leads to the observed overall sea ice increase. Therefore, in section 3 we analyze the simulated mean wind fields south of 55°S with respect to the simulated sea ice area across the CMIP5 models and find a significant positive correlation. We also examine the mean cloud cover south of 55°S and find a significant negative correlation with mean sea ice area in the CMIP5 models.

[4] While *Turner et al.* [2012] focus on the seasonal cycle and the trends of Antarctic sea ice in the historical and control runs, this study focuses on internal variability and time scales and their implications for model spread and trends. Section 4 shows an intercomparison of the CMIP5 models in terms of their sea ice behavior with respect to internal variability. However, it is beyond the scope of this study to explain modeled or observed trends. Several previous studies offer explanations for the lack of a significant surface warming trend in the Antarctic (apart from the Peninsula) [*Turner et al.*, 2005]. For example, *Arblaster et al.* [2011] describe the two competing factors of stratospheric ozone recovery and increasing greenhouse gas concentrations and note that this might be a reason for the lack of warming. Furthermore, the trend toward more positive states of the Southern Annular Mode (SAM) tends to isolate the high southern latitudes [*Thompson and Solomon*, 2002], which could explain part of the "missing surface temperature trend." The influence of the SAM and El Niño–Southern Oscillation on surface temperature and sea ice is suggested in observations [*Stammerjohn et al.*, 2008] and models [*Holland and Raphael*, 2006; *Sen Gupta and England*, 2006], which may be linked in part to surface wind changes. Therefore, we also examine surface wind changes in the CMIP5 models in section 4. Our conclusions are given in section 5.

2. Data

[5] This study uses the historical runs from up to 25 atmosphere-ocean global climate models, available from the World Climate Research Program Coupled Model Intercomparison Project Phase 5 (CMIP5) [*Taylor et al.*, 2011]. The output from all models was regridded to a T42 grid. For Antarctic sea ice observations, the Met Office Hadley Centre's sea ice and sea surface temperature data set [*Rayner et al.*, 2003] and the National Snow and Ice Data Center bootstrap sea ice concentrations [*Comiso*, 1999, updated 2012] are used. The modeled surface air temperatures south of 55°S are compared to the Modern Era-Retrospective Analysis for Research and Applications data set (MERRA) [*Rienecker et al.*, 2011]. The cloud cover fraction and the surface zonal wind are taken from the ERA-40 reanalysis [*Uppala et al.*, 2005]. The models were compared to the historical period from 1980 to 2001, which is available in all observational data sets. For the trend analysis, we extended the period to the end of the historical runs in 2005, in order to better capture the sea ice increase that has been observed. In order to study the changes in the winds as differences of time mean averages, the time period considered is 1960–2001. Unfortunately, it is not possible to extend the period until the end of the historical runs, which is 2005, as the ERA-40 data set ends in 2001.

3. Historical Mean State of the CMIP5 Models

[6] Surface winds play an important role for the sea ice distribution, as the applied force on the sea ice surface pushes the ice in the direction of the wind stress. It was shown that the sea ice drift in the Antarctic, which is caused by changing winds, leads to the observed overall sea ice increase [*Holland and Kwok*, 2012]. As mentioned in section 1, the strength of the wind plays an important role in respect to how the Antarctic sea ice is simulated by the models and Figure 1 illustrates this relationship. The correlation across the CMIP5 models between the March-April-May (MAM) sea ice area and mean MAM maximal 10 m zonal wind for the time period 1980–2001 is 0.62 and significant at the 95% level. Only wind speeds south of 55°S are considered for the regional mean. Figure 1 shows that models with stronger zonal winds generally have a larger sea ice area for this season. The reason is that the stronger zonal winds result in a faster Ekman drift of the sea ice to the north by the Coriolis force. *Holland and Kwok* [2012] describe the relationship between sea ice and winds in greater detail. The grey shading in Figure 1 indicates the observed interannual variability over 1980–2005, in order to illustrate which models are within interannual variability and which appear to be unrealistic. The interannual variability is derived from the observational time series and is simply estimated as the standard deviation of the detrended data. Figure 1 only shows the austral fall, as the relationship maximizes for the fall and winter seasons, yet throughout the other two seasons, there is also a significant relationship between the strength of the zonal wind and sea ice area (see Table 1).

Table 1. Correlations Between Antarctic Sea Ice Area and 10 m Zonal Wind Speed or Cloud Fraction for All Seasons Averaged Over Area South of 55°S[a]

|	10 m Zonal Wind	Cloud Fraction
DJF	*0.42*	−0.35
MAM	*0.62*	*−0.61*
JJA	*0.64*	*−0.49*
SON	*0.53*	*−0.56*

[a]Bold and italic numbers denote significant correlations.
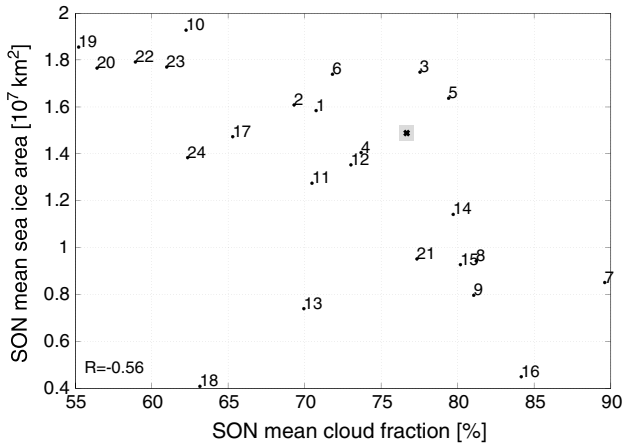
Figure 2. The SON mean ice area versus SON mean cloud fraction over the period 1980–2001. The numbers correspond to the models listed in Figure 1. The black cross shows the observations and the grey shading the observed interannual variability.

[7] Although the wind influences the sea ice area throughout all four seasons, it is not the only factor that is important. Cloud cover is another important factor in terms of simulated sea ice area. Figure 2 shows the correlation ($R = -0.56$, significant at the 95% level) between the

September-October-November (SON) mean sea ice area and mean SON cloud fraction for the time period 1980–2001. Clouds south of 55°S are averaged over the region. The correlation is significant during all seasons except December-January-February (DJF; the austral summer; see Table 1). Austral summer is the season when the shortwave radiation plays the most important role. During the darker seasons, shortwave radiation is less important while longwave radiation is absorbed and reradiated back to the surface by the clouds and therefore leads to higher temperatures. However, it is not clear whether the models with less sea ice evaporate more water and therefore have more clouds that trap the radiation, or whether the models with more clouds have higher temperatures and melt the sea ice. But it is evident from Figure 2 that the models with a higher cloud fraction have less sea ice. A similar relationship between sea ice and clouds was also found in the Arctic. *Vavrus et al.* [2009] looked at future changes in Arctic cloud amount in 20 CMIP3 climate models. They suggest that a future loss of sea ice leads to more evaporation and hence to an increase in low cloud amount. However, a study of future Arctic rapid sea ice loss events in the Community Climate System Model version 3 (CCSM3), *Vavrus et al.* [2011] correlated ice loss with increasing clouds using monthly lead-lag correlations. They found no clear evidence that sea ice loss was causing more low clouds or vice versa. A negative correlation also exists between longwave downward radiation at the surface averaged over the region south
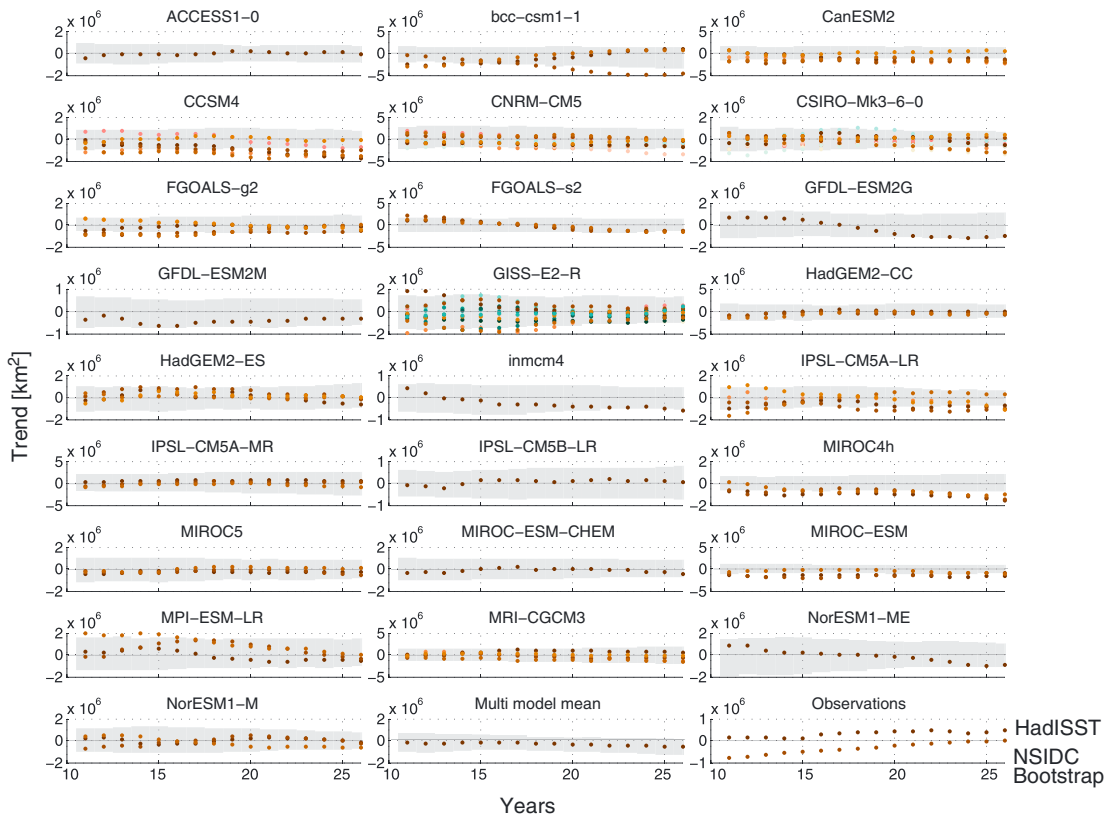
Figure 3. Trend of Antarctic sea ice area as a function of number of years included for trend estimation (10 up to 26 years). The total time period analyzed starts in 1980 and ends in 2005. The grey shading shows the 5–95% quantile of the trends estimated from the control runs. The different colors show the different ensemble members of every particular model. Also shown are the multimodel mean with the standard deviation across models in grey shading and two sets of observational data.
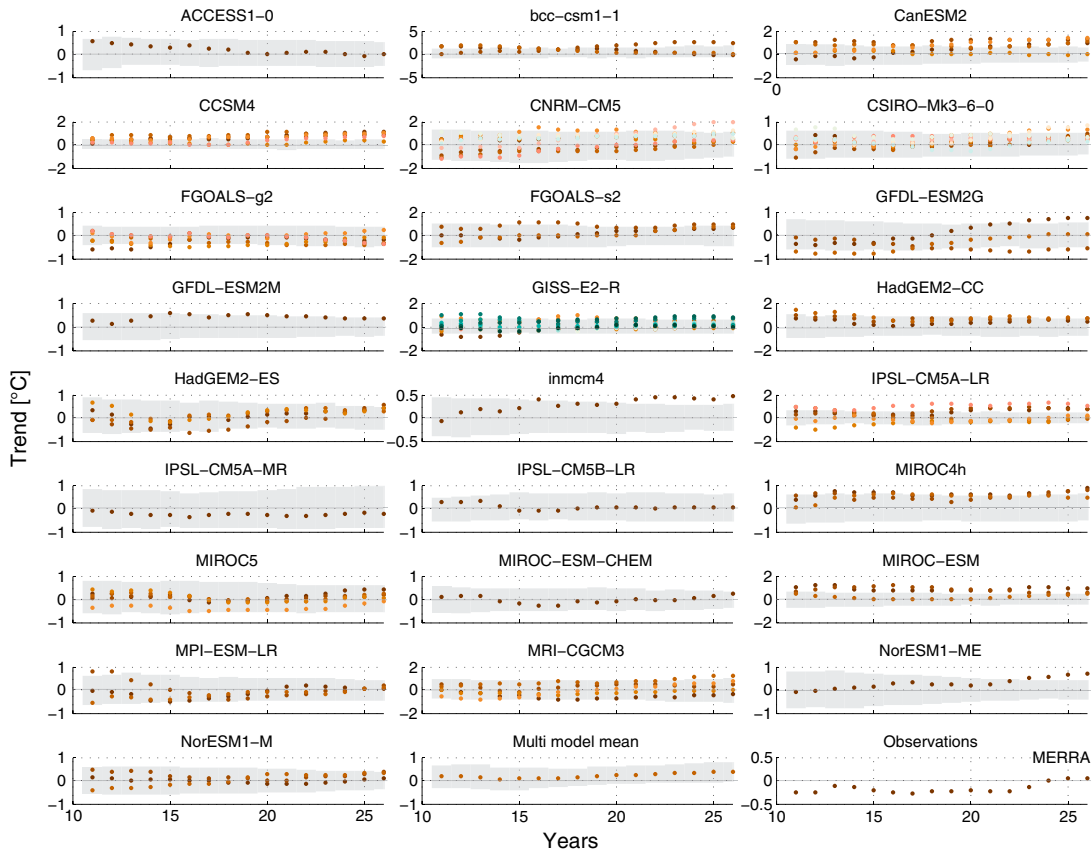
Figure 4. Trend of surface temperatures south of 55°S as a function of number of years included for trend estimation (10 up to 26 years). The total time period analyzed starts in 1980 and ends in 2005. The grey shading shows the 5–95% quantile of the trends estimated from the control runs. The different colors show the different ensemble members of every particular model. Also shown are the multimodel mean with the standard deviation across models in grey shading and the observational data.

of 55°S and sea ice area during the austral winter season. Thus, the clouds function as a heat trap in this season, rather than as a shield against incoming solar radiation. *Trenberth and Fasullo* [2010] documented a positive bias in net downward top of the atmosphere radiation over the Southern Ocean for the CMIP3 models. Figure 2 illustrates that a large fraction of the CMIP5 models also do not have enough clouds in this area.

[8] Overall, the spread in sea ice area in CMIP5 models has not decreased compared to the CMIP3 models [*Lefebvre and Goosse*, 2008] and is therefore still large despite the fact that the CMIP5 mean sea ice area is substantially smaller compared to CMIP3. A large spread is apparent not only for the sea ice area, but also for the other two variables examined, wind speed and cloud fraction. However, the large spread in sea ice area reduces confidence in the robustness of future trends and model studies which aim to explain the processes observed in the Antarctic.

4. Recent Trends

[9] As mentioned in section 1, *Turner et al.* [2012] report a significant positive trend in sea ice extent. However, most models simulate a negative trend as shown by *Turner et al.* [2012]. It is important to examine the extent to which internal variability may contribute to the observed growth of the sea ice. In order to get a deeper understanding of the

modeled trends, we analyze the trends as a function of number of years considered as described by *Santer et al.* [2011]. The trend is simply estimated by a linear fit, starting with the shortest time period of 10 years (1980–1989). Then one year at a time is added to the analysis up to the longest period consisting of 26 years (1980–2005). In order to determine whether the trend appears to be significant or not at least in the model context, the model control runs were split up into chunks of equivalent years. For each time length (10 up to 26 years) the 5–95% quantile is then estimated from these chunks. The trend is considered significant when the simulated recent trend is outside the 5–95% range. This range decreases when longer and longer time scales are considered for most models, as variability becomes smaller when an increasing number of years are considered. Those models that do not show a decrease in the range show extraordinarily large variability in their control runs. Furthermore, before estimating the short-term trends in the control runs, the model drift over the entire control run, which can be quite large [*Turner et al.*, 2012], was removed. Figure 3 shows the results of this analysis, where it can be seen (as shown in other studies) that most models show a negative trend. The figure also illustrates how for some models the trend becomes significant with increasing length of the time period, meaning the trend is outside of the 5–95% range. But while most models show a negative trend, only
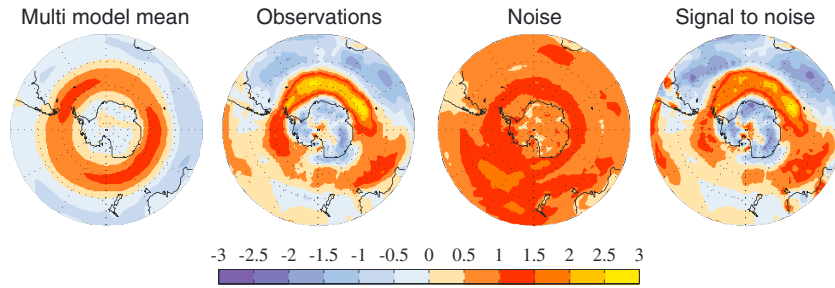
Figure 5. The first and second panels show the changes in 10 m zonal wind speed (ms^{-1}) as a time mean difference between 1960–1970 and 1990–2001 for the multimodel mean and the observations in DJF. The third panel depicts the observed interannual variability (noise) in DJF that is derived as described in the text. The fourth panel shows the observed signal to noise ratio in DJF, the change in the second panel divided by the noise in the third panel.

a few of them actually show a trend that can be considered significant on the time scale of the available observational data. Thus, for some models, it is clear that the time period is simply too short for the trends to become significant, and for quite a large number of models, the trends cannot be expected to become significant any time soon. Furthermore, the models with a larger number of ensemble members show quite a significant spread among them in terms of their trends, spanning both negative and positive trends in the amount of Antarctic sea ice. Different ensemble members are usually started from different times late in the control run.

[10] Figure 3 hence illustrates the importance of variability in the Antarctic region. Therefore, even if the models do not have the same sign of change as observations, only a few models can be dismissed as being wrong. This supports the argument that one of the reasons for the observed positive trend is likely to be internal variability, as this is the only reason why the different ensemble members show different trends. If a portion of the changes in the Antarctic is mainly due to internal variability, then there is no physical reason why the models should behave like observations, as long as the modeled behavior stays within the range of that variability (which implies that the trend is not necessarily externally forced). On the other hand, as shown in the first part of this study, the simulated mean state of most models is not very realistic, and therefore, trend studies for Antarctic sea ice using only these models have to be treated with caution.

[11] In contrast, the same trend analysis in the Arctic reveals that nearly all runs considered show a negative trend, and more than half of the models show significant negative trends in some of their ensemble runs (see the auxiliary material).

[12] Surface temperature and sea ice area in the Arctic are linearly correlated as shown in *Mahlstein and Knutti* [2012]. A similar linearity can be found in the Antarctic for sea ice area and surface temperatures south of 55°S in the model results and becomes more linear when excluding land areas (not shown). Therefore, in tandem with the negative sea ice trends, the modeled surface temperature trends south of 55°S are generally positive as shown in Figure 4. But, similar to the case of sea ice, most runs do not show a significant warming trend. The positive trend in the observations is due to the strong warming on the Peninsula and possibly in West Antarctica [*Bromwich et al.*, 2013; *Steig et al.*, 2009; *Turner et al.*, 2005].

[13] When analyzing the surface temperature trend over ocean only and the sea ice trend of three models with a large number of ensemble members, the spread of the trends and the linear relationship between the surface temperature trend and the sea ice become very clear. The different ensemble members show positive (negative) and negative (positive) sea ice (surface temperature) trends (see the auxiliary material). Hence, in these three models, different ensemble members show positive and negative trends for the same variable.

[14] Due to ozone depletion and increased greenhouse gas forcing, the maximum of the zonal wind speed has strengthened and shifted to the south in austral summer [*Fyfe and Saenko*, 2006; *Gillett and Thompson*, 2003; *Karoly*, 2003; *Kushner et al.*, 2001; *Son et al.*, 2009; *Thompson et al.*, 2011]. Figure 5 shows this change in 10 m zonal wind as a time mean difference between two time periods (1990–2001 and 1960–1970) in DJF for the reanalysis data and the multimodel mean of the CMIP5 models used in this study. The changes in the observations and in some models are larger than interannual variability (changes of the zonal wind for each model are shown in a figure in the auxiliary material). Hence, most models simulate a southward shift in the winds and an increase in the maximum wind speed as wind speeds north of 40°S are decreasing and increasing further south. But for most models, the shift is too weak as is illustrated in Figure 5. Whether the weaker change in most models is due to a poor coupling with the ozone depletion, an ozone forcing that is too weak, or other reasons is not clear. However, the influence of the winds on the climate in this region is significant, so that a good representation of the zonal wind shift is important for simulating future projections.

5. Conclusions

[15] The CMIP5 models do not show an overall improvement in the simulation of Antarctic sea ice compared to CMIP3, as the spread in sea ice area is not reduced compared to the previous models [*Lefebvre and Goosse*, 2008]. The spreads across cloud fraction and mean zonal wind speeds are also considerable. Models with higher wind speeds generally have a larger sea ice area, whereas models with more clouds during austral winter and spring have less sea ice.

[16] The trends in Antarctic sea ice area and atmospheric surface temperatures over the Southern Ocean are similar

to those obtained in the CMIP3 models. Across both CMIP archives, many models display a trend of retreating sea ice, but a large number of the runs show trends that are smaller than internal variability on the time scale of the available data. This supports the view that internal variability is likely to be an important factor in the observed trend to date. This implies that the models may not need to agree on the sign of the change because the observed trend could just be due to internal variability [*Tebaldi et al.*, 2011]. However, there are important deficiencies in the model simulations, such as the mean state of several variables presented here, including the strengthening and southward shift in the zonal winds due to ozone depletion and greenhouse gas forcing. As long as these issues are not resolved, future projections of the Antarctic will still be quite uncertain because the models will find multiple answers to the question of when the mean sea ice area in Antarctica will start to decrease. All models project that the sea ice area will start decreasing at some point in the future as greenhouse gas emissions continue to increase, although ozone recovery can also be expected to be important through the middle of the 21st century [*Smith et al.*, 2012]. Thus, the question of when this process will start is difficult to answer and depends on the future rate of greenhouse gas increase. Changes in the Southern Ocean will also greatly affect the climate in the southern high latitudes [*Cai*, 2006; *Gent and Danabasoglu*, 2011; *Gille*, 2002]. We conclude that climate models need to improve the representation of many processes in the atmosphere and ocean that affect the mean state and recent trends in Antarctic sea ice area. In particular, the variables analyzed here such as zonal wind and cloud cover show large biases that are outside climate variability in comparison to observed values.

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