

# Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5

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[1] The recent observed positive trends in total Antarctic sea ice extent are at odds with the expectation of melting sea ice in a warming world. More problematic yet, climate models indicate that sea ice should decrease around Antarctica in response to both increasing greenhouse gases and stratospheric ozone depletion. The resolution of this puzzle, we suggest, may lie in the large natural variability of the coupled atmosphere-ocean-sea-ice system. Contrasting forced and control integrations from four state-of-the-art Coupled Model Intercomparison Project Phase 5 (CMIP5) models, we show that the observed Antarctic sea ice trend falls well within the distribution of trends arising naturally in the system, and that the forced response in the models is small compared to the natural variability. From this, we conclude that it may prove difficult to attribute the observed trends in total Antarctic sea ice to anthropogenic forcings, although some regional features might be easier to explain. **Citation:** Polvani, L. M., and K. L. Smith (2013), Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5, *Geophys. Res. Lett.*, 40, 3195–3199, doi:10.1002/grl.50578.

## 1. Introduction

[2] While Arctic sea ice is rapidly disappearing [Stroeve *et al.*, 2007], satellite observations clearly reveal a small, but statistically significant, positive trend in sea ice extent (SIE) around Antarctica [Parkinson and Cavalieri, 2012]. A recent study estimates this trend at  $+0.127 \times 10^6$  km<sup>2</sup> per decade, over the period 1979–2005 [Turner *et al.*, 2013]. It is important to note that unlike Arctic sea ice which has been decreasing in all months and at nearly all locations, Antarctic SIE trends have a marked seasonal cycle and their net positive value results from large cancellations from different sectors. The recent overall increases in Antarctic SIE, therefore, need not be an indication of climate change, since natural variability might play a large role, as suggested by Zunz *et al.* [2012].

[3] That Antarctic sea ice would increase in a warming world is surprising enough, in and of itself. Even more puzzling, however, is the fact that recent climate models consistently produce a negative trend over the same period when forced with all known natural and anthropogenic forcings

[Arzel *et al.*, 2006; Maksym *et al.*, 2012; Zunz *et al.*, 2012; Turner *et al.*, 2013]. Of the latter, the impact of increasing greenhouse gases has long been established; see, for instance, Figure 10.13 of Meehl *et al.* [2007]. In contrast, the impact of stratospheric ozone depletion—the other major anthropogenic forcing of the Southern Hemisphere climate system—has remained elusive until very recently. On the one hand, overwhelming evidence indicates that the formation of the ozone hole, in the last decades of the twentieth century, has been the primary cause of the observed summertime trends in the Southern Annular Mode (SAM): For a recent review, see Thompson *et al.* [2011]. On the other hand, the connection between SIE and SAM trends has been disputed in the literature: Some studies argue that Antarctic SIE trends are linked to SAM trends [e.g., Turner *et al.*, 2009], while others find no connection [e.g., Simpkins *et al.*, 2012]. That confusion has now cleared.

[4] Two independent studies [Sigmond and Fyfe, 2010; Bitz and Polvani, 2012]—using distinct coupled models—have compared model integrations with high and low stratospheric ozone and found a robust, if perhaps unexpected, result: that ozone depletion, over a period of several decades, causes Antarctic SIE to markedly decrease. This was further confirmed, in the context of ozone recovery, by a third study using a stratosphere-resolving model with interactively coupled stratospheric chemistry [Smith *et al.*, 2012].

[5] Since, at this point, both major anthropogenic forcings (greenhouse gas increases and stratospheric ozone depletion) are understood to cause negative SIE trends, the observed positive trends pose an even greater conundrum. In this paper we offer a simple solution. By analyzing the preindustrial (i.e., control) integrations of four different models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), we demonstrate that 27-year Antarctic SIE trends with amplitudes much larger than those observed between 1979 and 2005, and of both positive and negative signs, occur *spontaneously* in the control integrations, i.e., in the absence of any forcing of the climate system. Hence, we suggest, the recently observed positive SIE trends are primarily a manifestation of large internal variability of the coupled Antarctic sea ice system and not of anthropogenic forcings.

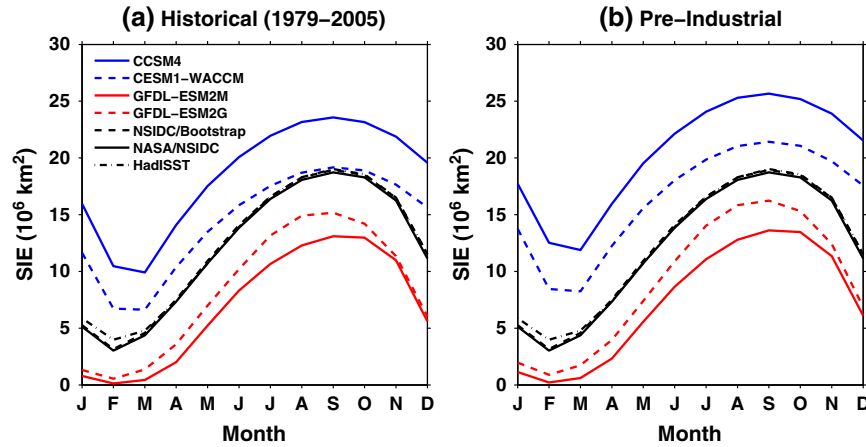
## 2. Methods

[6] As one may easily conclude from Turner *et al.* [2013, Figure 6], the majority of CMIP5 models are unsuitable for the present exercise, as they exhibit secular trends in their preindustrial control integrations. We here focus on four suitable CMIP5 models: two from the Community Earth System Model (CESM) project, the Community Climate System Model Version 4 (CCSM4) [Gent *et al.*, 2011]

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**Figure 1.** Climatological monthly Antarctic sea ice extent for the (a) historical (1979–2005) and (b) preindustrial scenarios. CESM models (blue lines). GFDL models (red lines). Three observational data sets (black lines): NASA/NSIDC (solid), NSIDC/Bootstrap (dashed), and HadISST (dash-dotted).

and the Whole Atmosphere Community Climate Model (CESM1-WACCM) [Marsh *et al.*, 2013], and two Earth System Models (ESMs) from the Geophysical Fluid Dynamics Laboratory (GFDL), GFDL-ESM2M and GFDL-ESM2G [Dunne *et al.*, 2012]. We note that CESM1-WACCM is a stratosphere-resolving model with interactive stratospheric chemistry, and that the two GFDL models include interactive biogeochemistry.

[7] Our reasons for selecting this subset of models are several. First, the time series of Antarctic SIE in the preindustrial integrations for these four models exhibit no secular trends. Second, CESM and GFDL use independently developed sea ice modules, allowing us to assess the robustness of our results. Third, these models allow us to compare natural variability in models with different biases in climatological Antarctic SIE and over a range of different model configurations: The two CESM models include identical sea ice and ocean components but different atmosphere components, while the two GFDL models have identical sea ice and atmosphere components but different oceans.

[8] For these four models, we analyze the monthly sea ice concentration for both the “preindustrial” and “historical” scenarios [Meinshausen *et al.*, 2011]. For the former, a 500-year long simulation is available for each model (except CESM1-WACCM, for which only 200 years were archived). For the latter, we focus on the period 1979–2005, when model output overlaps with observations: For that 27-year period, three-member ensembles are available for the CESM models but only one simulation each for the GFDL models. In all cases, we calculate SIE by summing the areas of all grid cells with sea ice concentration exceeding 15%, and we calculate trends as least squares linear fits to the SIE time series.

[9] In addition to the CMIP5 model data, we analyze three observational Antarctic sea ice data sets: NASA/National Snow and Ice Data Center (NSIDC) [Cavalieri *et al.*, 1999], NSIDC/Bootstrap [Comiso and Nishio, 2008], and the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) [Rayner, 2003], updated to 2005. Several other data sets are available, but we limit our analysis to these three, as they provide a sufficiently representative sample of the spread among the various data sets available.

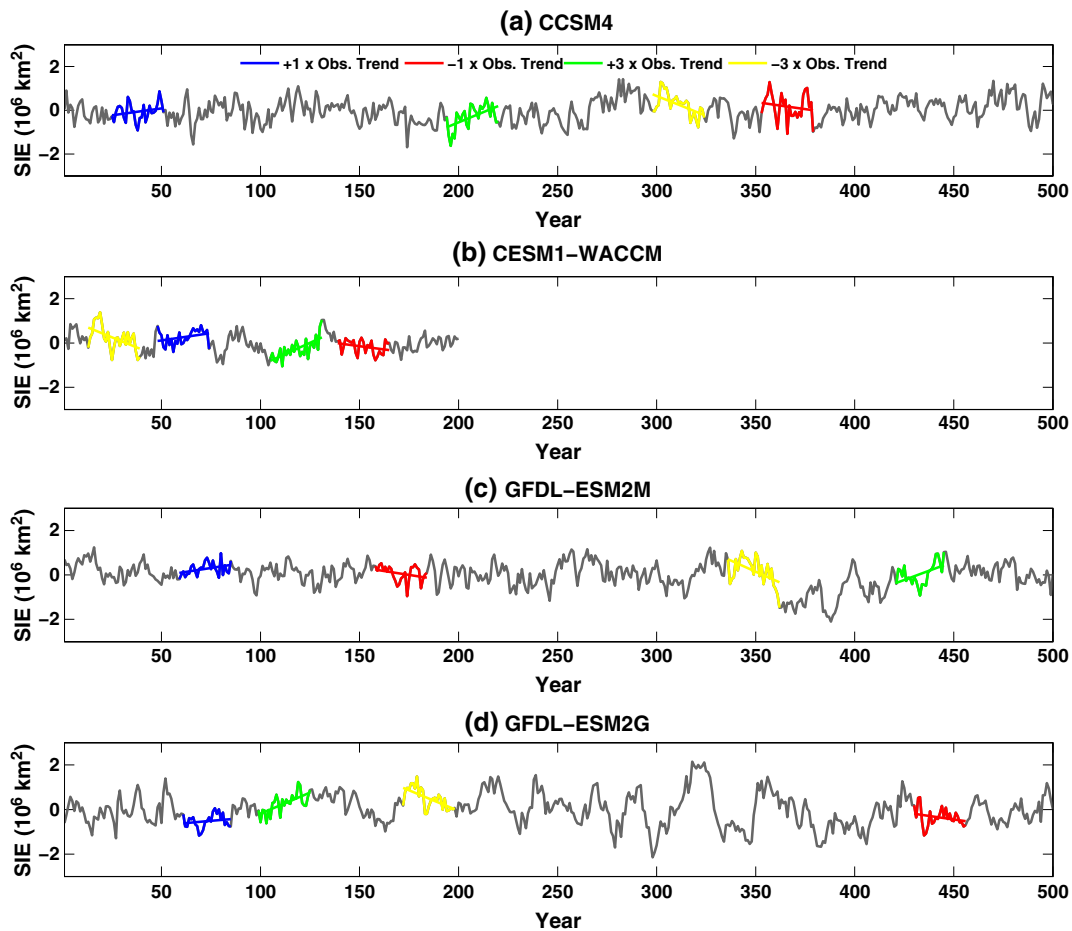
### 3. Results

[10] Before analyzing the trends, we examine the seasonal cycle of SIE in all the four selected CMIP5 models, to ensure that the simulated sea ice is in reasonable agreement with observations. For this, we use the historical simulations, over the 27-year period 1979–2005, for maximum overlap with satellite observations. The model SIE climatologies are shown by the colored curves in Figure 1a (when multiple ensemble members are available, we show the ensemble mean). The 1979–2005 climatological mean for the three observational data products is shown by the black curves. There are differences among the observational curves, but they are tiny in comparison to the spread across the four models.

[11] Such spread is typical of the larger CMIP5 ensemble [see, e.g., Turner *et al.*, 2013, Figure 2]. Both CCSM4 and CESM1-WACCM have excessive SIE relative to observations in all months of the year; this has been previously documented [Landrum *et al.*, 2012; Marsh *et al.*, 2013]. In contrast, GFDL-ESM2M and GFDL-ESM2G have too little SIE relative to the observations [Dunne *et al.*, 2012]. It is worth noting that the two models that come closest to the observations, CESM1-WACCM and GFDL-ESM2G, have different sea ice components, implying that one sea ice component is not systematically better than the other. The point of this figure is to show that the four models we have chosen are representative of the larger CMIP5 set, that they are not obviously anomalous in their behavior, and that their climatologies lie both above and below the observations, so we are not skewing out results with some systematic bias.

[12] Since the preindustrial control integrations are the primary focus of this paper, we show their climatologies in Figure 1b; the black curves are identical to those in Figure 1a and are only reproduced to help guide the eye of the reader. Comparing the colored and black curves in Figure 1b, one easily concludes that SIE is larger in the preindustrial integrations than for the period 1979–2005, for all four models. This is not surprising, as one expects SIE to decrease in a warmer climate.

[13] The key result of our paper is illustrated in Figure 2, where the individual time series of annual SIE are shown for the multicentury preindustrial integrations of each model.



**Figure 2.** Time series of preindustrial, annual mean Antarctic sea ice extent (SIE) anomalies for (a) CCSM4, (b) CESM1-WACCM, (c) GFDL-ESM2M, and (d) GFDL-ESM2G. Highlighted segments represent 27-year time periods with +1 (blue),  $-1$  (red),  $+3$  (green), and  $-3$  (yellow) times the magnitude of the observed trend in Antarctic SIE; linear, least squares fits to the highlighted 27-year sections are superimposed.

These time series clearly exhibit variability on many time scales (e.g., interannual, multidecadal, etc.). Note, however, that none of these time series shows obvious secular trends: This is in contrast to the vast majority of CMIP5 models, as already noted, most of which cannot be used for this analysis.

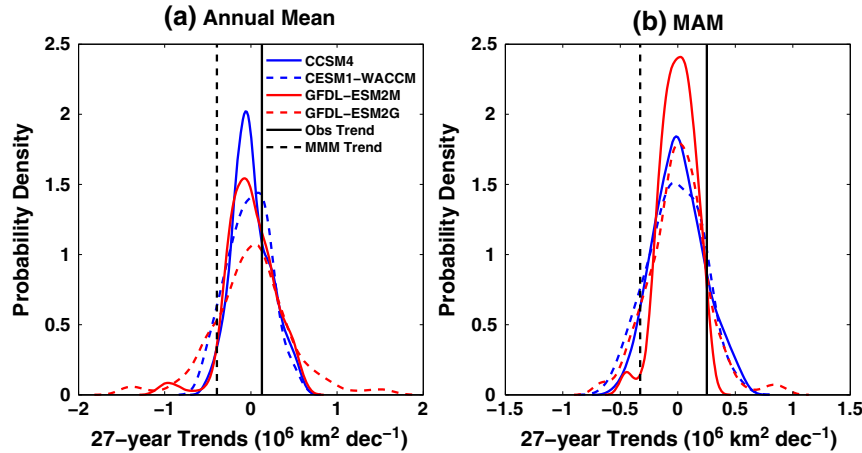
[14] More importantly, we draw the reader's attention to the 27-year segments highlighted in blue: Over these periods, the model trends are equal to  $+0.127 \times 10^6 \text{ km}^2$ , the observed value reported by Turner *et al.* [2013] for the 1979–2005 period. What is clear from Figure 2 is that the trends of this magnitude appear *spontaneously*, in all four models, in the absence of any external forcing, anthropogenic or otherwise.

[15] But, there is more. Consider now the segments highlighted in green. Over those periods, the trends are 3 times larger than those observed between 1979 and 2005 and, again, occur purely as a consequence of the natural (i.e., unforced) variability in the models. Furthermore, if the models are properly equilibrated, as they should be, one would not expect positive trends to be any more frequent than negative trends. The red and yellow segments demonstrate this fact, highlighting periods of SIE *decline* with magnitude identical to the one over 1979–2005 and 3 times larger, respectively.

[16] The colored segments in Figure 2 are meant to visually convey, by highlighting a few examples, that the range of 27-year Antarctic SIE trends in these preindustrial integrations is much larger than the observed 1979–2005 value. The entire range of trends, for each of the four models, is explicitly shown by the colored curves in Figure 3a. It is obtained by computing all consecutive and overlapping 27-year trends, starting from the first year, for each of the four time series in Figure 2. The probability density distributions shown in Figure 3a are then computed from these using a kernel density estimator, which performs a nonparametric, smoothed fit to the data. The area under each curve is one.

[17] There are two points to be gathered from Figure 3a. First, consider the solid black vertical line, which marks the value of the observed 27-year trend of Antarctic SIE (from the NASA/NSIDC data set, for 1979–2005). The observed value lies well within the distribution of trends obtained from the preindustrial time series, for all four of the models here analyzed. This result suggests that to the degree that the latest generation of climate models can be trusted, the magnitude of the observed trend cannot be distinguished from unforced, naturally occurring multidecadal trends.

[18] Second, consider the dashed, black vertical line in Figure 3a, which represents the multimodel mean (MMM) of the 1979–2005 SIE trends for the historical integrations



**Figure 3.** Density distributions of 27-year trends of SIE in the preindustrial integrations for (a) the annual mean and (b) March-April-May (MAM). Colored curves represent different models, as indicated in the legend. The observed trend for 1979–2005 (from NASA/NSIDC) (solid black lines). The multimodel mean (MMM) 1979–2005 trend, from the historical simulations (dashed black lines).

of the four models. The trends for each of the eight simulations are first independently computed and then averaged to obtain the MMM. Because the MMM comes from combining many different simulations, the natural variability is “averaged out”: The MMM, therefore, is an estimate of the forced response in the models.

[19] Note first that the MMM response is negative, as one might expect, since both increasing greenhouse gases and stratospheric ozone depletion cause sea ice loss around Antarctica. More interesting, however, is the fact that the amplitude of the forced response is quite a bit smaller than the naturally occurring multidecadal trends. This implies that in any one model simulation, the natural variability of the atmosphere-ocean-sea-ice coupled system can easily overwhelm the forced response.

[20] As a further validation of this result, we recompute the distribution of 27-year trends but confine the analysis to the March-April-May (MAM) season. It is interesting to focus on MAM because the observed SIE trends are largest in that season [Turner *et al.*, 2009]. The results are shown in Figure 3b. The solid black line, showing the observed 27-year trend, is clearly larger than that for the annual mean: Despite this, it again lies well within the distributions of the unforced, preindustrial model trends, confirming our key result.

[21] Finally, we mention that we have repeated these analyses with periods other than 27 years. Using 10, 20, or 34 years (to cover the entire 1979–2012 observational period) yields identical conclusions. The reason we present the 27-year results is that the period 1979–2005 is the largest possible overlapping interval between the observations, which started in 1979, and the CMIP5 historical simulations, which terminate in 2005. Recall, however, that the probability density distributions in Figure 3 are computed using the preindustrial control integrations.

#### 4. Summary and Discussion

[22] Analyzing four CMIP5 models, we have here shown that the SIE trends observed in recent decades around Antarctica lie well within the natural variability of the mod-

eled sea ice system. We have also shown that the amplitude of the forced response in the models is smaller than the observed natural variability. These findings suggest that the recent observed trend in Antarctic SIE cannot be simplistically attributed to anthropogenic forcings.

[23] In many ways, our paper is the Antarctic counterpart of the recent study of Kay *et al.* [2011]. In that work, contrasting trends in forced and control integrations of CCSM4, the modeling evidence suggested that the negative observed late twentieth century trends in Arctic SIE *cannot* be explained by natural variability alone. In our study, we reach the opposite conclusion for Antarctic sea ice.

[24] In fact, we believe that our result is stronger, because we have here analyzed four different climate models. The subset of models used in this study covers a significant span of the available CMIP5 model configurations, as they include three different atmosphere and ocean models, two different sea ice models, and even a stratosphere-resolving coupled-chemistry model. And, although it has recently been suggested that CMIP5 models may overestimate Antarctic SIE variability relative to observations [Zunz *et al.*, 2012], we contend that 30 years of observations are probably not sufficient to accurately estimate Antarctic SIE variability. While our models show a SIE standard deviation larger than the observations when the entire 500 (or 200 for CESM1-WACCM) year time series is used, over selected 27 year time periods (not shown), their standard deviation is very similar to the observed one.

[25] Finally, we note that our results do not invalidate the recent findings of Holland and Kwok [2012], who have argued that recent Antarctic sea ice trends are caused primarily by wind-driven changes in sea ice advection. We are not here concerned with the specific physical mechanisms which may or may not be responsible for the observed trends (e.g., dynamic versus thermodynamic processes). Our finding is that whatever the physical mechanism, if the present generation of models faithfully captures the Antarctic climate system, the natural variability may be large compared to the forcings. If that is the case, it is very unlikely that climate models—whose atmosphere, ocean, and sea ice states are not initialized from observations to match any specific

point in time—would reproduce observations over specific periods of several decades, as the natural variability would overwhelm any forced signal. (At the completion of this manuscript, we have become aware of a study by *Mahlstein et al.* [2013] which further supports our findings.)

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## References

- Arzel, O., T. Fichefet, and H. Goosse (2006), Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, *Ocean Modell.*, *12*(3–4), 401–415, doi:10.1016/j.ocemod.2005.08.002.
- Bitz, C. M., and L. M. Polvani (2012), Antarctic climate response to stratospheric ozone depletion in a fine resolution ocean climate model, *Geophys. Res. Lett.*, *39*, L20705, doi:10.1029/2012GL053393.
- Cavalieri, D. J., C. L. Parkinson, P. Gloersen, J. C. Comiso, and H. J. Zwally (1999), Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets, *J. Geophys. Res.*, *104*(C7), 15,803–15,814, doi:10.1029/1999JC900081.
- Comiso, J. C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.*, *113*, C02S07, doi:10.1029/2007JC004257.
- Dunne, J. P., et al. (2012), GFDL's ESM2 global coupled climate carbon earth system models. Part I: Physical formulation and baseline simulation characteristics, *J. Clim.*, *25*, 6646–6665, doi:10.1175/JCLI-D-11-00560.1.
- Gent, P. R., et al. (2011), The Community Climate System Model Version 4, *J. Clim.*, *24*, 4973–4991, doi:10.1175/2011JCLI4083.1.
- Holland, P. R., and R. Kwok (2012), Wind-driven trends in Antarctic sea-ice drift, *Nat. Geosci.*, *5*, 872–875.
- Kay, J. E., M. M. Holland, and A. Jahn (2011), Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world, *Geophys. Res. Lett.*, *38*, L15708, doi:10.1029/2011GL048008.
- Landrum, L., M. M. Holland, D. P. Schneider, and E. Hunke (2012), Antarctic sea ice climatology, variability, and late twentieth-century change in CCSM4, *J. Clim.*, *25*, 4817–4838, doi:10.1175/JCLI-D-11-00289.1.
- Mahlstein, I., P. Gent, and S. Solomon (2013), Historical Antarctic mean sea ice area, sea ice trends, and winds in CMIP5 simulations, *J. Geophys. Res. Atmos.*, in press.
- Maksym, T., S. Stammerjohn, S. Ackley, and R. Massom (2012), Antarctic sea ice—A polar opposite?, *Oceanography*, *25*(3), 140–151.
- Marsh, D., M. Mills, R. Garcia, and D. Kinnison (2013), Climate change from 1850 to 2005 simulated in CESM1 (WACCM), *J. Clim.*, doi:http://dx.doi.org/10.1175/JCLI-D-12-00558.1, in press.
- Meehl, G. A., et al. (2007), *Global climate projections*, in *Climate Change 2007: The Physical Sciences Bases. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Meinshausen, M., et al. (2011), The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, *Clim. Change*, *109*, 213–241, doi:10.1007/s10584-011-0156-z.
- Parkinson, C. L., and D. J. Cavalieri (2012), Antarctic sea ice variability and trends, 1979–2010, *Cryosphere*, *6*, 871–880, doi:10.5194/tc-6-871-2012.
- Rayner, N. A. (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.
- Sigmond, M., and J. C. Fyfe (2010), Has the ozone hole contributed to increased Antarctic sea ice extent?, *Geophys. Res. Lett.*, *37*, L18502, doi:10.1029/2010GL044301.
- Simpkins, G. R., L. M. Ciasto, D. W. J. Thompson, and M. H. England (2012), Seasonal relationships between large-scale climate variability and Antarctic sea ice concentration, *J. Clim.*, *25*, 5451–5469, doi:10.1175/JCLI-D-11-00367.1.
- Smith, K. L., L. M. Polvani, and D. R. Marsh (2012), Mitigation of 21st century Antarctic sea ice loss by stratospheric ozone recovery, *Geophys. Res. Lett.*, *39*, L20701, doi:10.1029/2012GL053325.
- Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.
- Thompson, D. W. J., et al. (2011), Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change, *Nat. Geosci.*, *4*, 741–749, doi:10.1038/ngeo1296.
- Turner, J., et al. (2009), Nonannular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophys. Res. Lett.*, *36*, 1–5, doi:10.1029/2009GL037524.
- Turner, J., T. Bracegirdle, T. Phillips, G. J. Marshall, and J. S. Hosking (2013), An initial assessment of Antarctic sea ice extent in the CMIP5 models, *J. Clim.*, *26*, p. 120821114723004, doi:10.1175/JCLI-D-12-00068.1.
- Zunz, V., H. Goosse, and F. Massonnet (2012), How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent?, *Cryosphere Discuss*, *6*, 3539–3573, doi:10.5194/tcd-6-3539-2012.