Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent

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[1] Based on a new analysis of passive microwave satellite data, we demonstrate that the annual mean extent of Antarctic sea ice has increased at a statistically significant rate of 0.97% dec^{-1} since the late 1970s. The largest increase has been in autumn when there has been a dipole of significant positive and negative trends in the Ross and Amundsen-Bellingshausen Seas respectively. The autumn increase in the Ross Sea sector is primarily a result of stronger cyclonic atmospheric flow over the Amundsen Sea. Model experiments suggest that the trend towards stronger cyclonic circulation is mainly a result of stratospheric ozone depletion, which has strengthened autumn wind speeds around the continent, deepening the Amundsen Sea Low through flow separation around the high coastal orography. However, statistics derived from a climate model control run suggest that the observed sea ice increase might still be within the range of natural climate variability. **Citation:** Turner, J., J. C. Comiso, G. J. Marshall, T. A. Lachlan-Cope, T. Bracegirdle, T. Maksym, M. P. Meredith, Z. Wang, and A. Orr (2009), Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophys. Res. Lett.*, *36*, L08502, doi:10.1029/2009GL037524.

1. Introduction

[2] Since the 1970s the two polar regions have experienced markedly different trends in sea ice extent (SIE) (Figure 1). In the Arctic, late summer ice reached record minima in 2005 and 2007, with the ice in September 2007 covering only 4.1×10^6 km^2, which was 39% below climatology. In contrast, Antarctic SIE has actually increased over the same period. *Zwally et al.* [2002] showed that over 1979–1998 the SIE had increased by $11.2 \pm 4.2 \times 10^3$ km^2 yr^{-1} or 0.98 ± 0.37% dec^{-1}. Regionally the trends were positive in the Weddell Sea, Pacific Ocean and Ross sectors, and negative in the Indian Ocean and Amundsen-Bellingshausen Sea (ABS) sectors [see also *Yuan and Martinson*, 2000].

[3] Basing its conclusions on data processed with the Bootstrap algorithm [*Comiso*, 2003], the Intergovernmental Panel on Climate Change (IPCC) noted that there had been a small positive trend in total Antarctic SIE of $5.6 \pm 9.2 \times 10^3$ km^2 yr^{-1} or 0.47 ± 0.80% dec^{-1} over 1978–2005, an increase that they noted was not statistically significant.

[4] An improved version of the Bootstrap algorithm [*Comiso and Nishio*, 2008] also gave a positive trend in the monthly anomalies of total Antarctic SIE, with the value of 0.9 ± 0.2% dec^{-1} for 1978–2006 being very similar to the value produced by Zwally et al. The study reconfirmed the contrasting trends in the ABS and Ross Sea, which have been linked via model experiments to mean sea level pressure (MSLP) across the ABS where lower values result in enhanced northerly flow to the west of the Antarctic Peninsula and less SIE [*Lefebvre et al.*, 2004]. Similarly, the stronger southerly winds over the Ross Sea promote greater SIE.

[5] The mean tropospheric flow pattern at high southern latitudes has a strong wave number 3 pattern. Based on rotating tank experiments, *Baines and Fraedrich* [1989] proposed that the cyclonic eddies were forced by flow separation around coastal irregularities, with the Amundsen Sea Low (ASL) being present because of strong flow around the northward extension of the orography near 150° E and the presence of the Ross Sea embayment.

[6] *Lefebvre et al.* [2004] linked this pattern of pressure change across the ABS and ice increase/decrease to changes in the Southern Annular Mode (SAM). They found that, its name not withstanding, the non-annular component of the SAM had the greatest impact in the ABS/Ross Sea areas. The SAM has become more positive in recent decades, primarily because of the combined effects of increasing greenhouse gases and, most importantly, the development of the Antarctic ozone hole [*Arblaster and Meehl*, 2006]. Although the ozone hole is a phenomena of the austral spring, the impact on the tropospheric flow is greatest during summer and autumn. *Lefebvre et al.* [2004] noted that years when the SAM index was high there was more (less) sea ice in the Ross Sea (ABS) sector. However, they did not find that the trend in the SAM was related to the trend in the SIE.

[7] The observed pattern of SIE change across the ABS/Ross Sea, and particularly the periods of ice advance and retreat, has also been linked to the El Niño-Southern Oscillation [*Yuan*, 2004], although the correlations were less than those found with the SAM [*Stammerjohn et al.*, 2008].

[8] It is important to understand why Antarctic SIE has increased in recent decades and the potential role of greenhouse gas increase and stratospheric ozone depletion.

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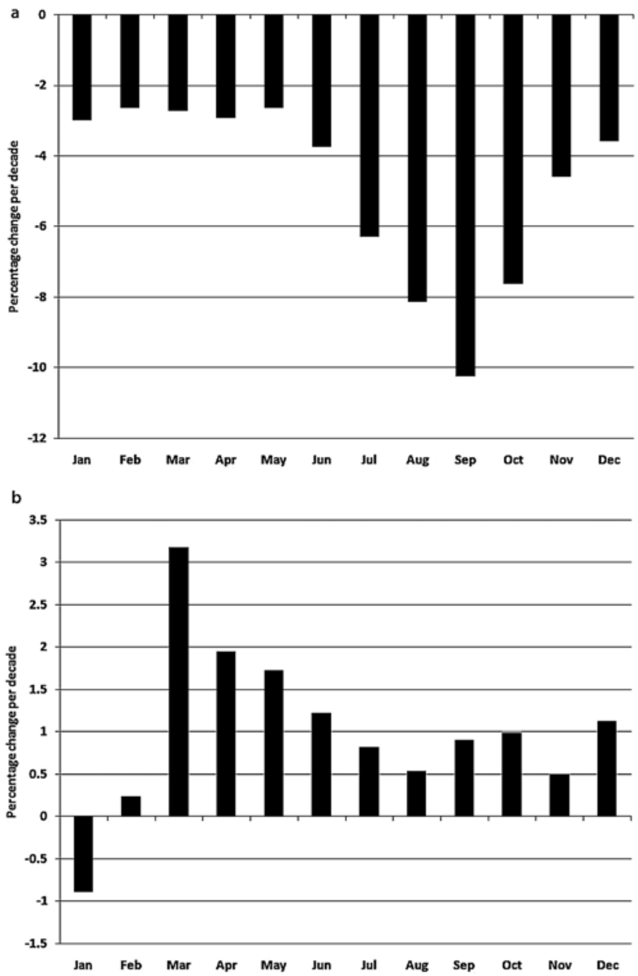

Figure 1. Monthly trends in sea ice extent for 1979–2007 (% per decade). (a) The Arctic and (b) the Antarctic.

Therefore, to gain insight into how ozone loss is influencing the atmospheric circulation and SIE we present the results of model experiments forced with different stratospheric ozone concentrations.

2. Data and Model Experiments

[9] We use the SIE data produced by the Bootstrap 2 algorithm of *Comiso and Nishio* [2008], which covers the period 1979–2007. The data are considered to be an improvement over the earlier Bootstrap algorithm data [see *Comiso and Nishio*, 2008]. Atmospheric circulation changes since 1979 are examined using the ECMWF 40 year reanalysis data and the recent operational ECMWF analyses.

[10] We consider how the models of the IPCC Fourth Assessment Report (AR4) have simulated recent atmospheric circulation changes and examine the relationship between sea ice changes and the anthropogenic forcing applied to these models. Our main focus is on model experiments that give insight into the linkage between Antarctic stratospheric ozone depletion and SIE. Coupled atmosphere-ocean models are the foundation for most climate initiatives. However, the models have many problems in simulating SIE, as small errors in the atmospheric circulation or oceanic conditions can give large errors in the SIE and area [*Lefebvre and Goosse*, 2008]. We have therefore run the atmosphere-only version of the Hadley Centre climate model (HadAM3) with pre-industrial levels of stratospheric ozone and ozone levels in 2000 [*Randel and Wu*, 2007]. In the model runs the sea surface temperature (SST) and SIE/concentrations were set to their mean 1979–2000 values.

3. Results

[11] We have examined the trends in SIE for the total Southern Hemisphere, and the five sectors of the Southern Ocean used in earlier studies [e.g., *Zwally et al.*, 2002] (Figure 2). Annual and seasonal trends and their statistical significance for these areas are shown in Table 1. Annually, the total Southern Hemisphere SIE has increased at a rate of 0.97% dec^{-1} ($p < 0.05$). The greatest increase of 2.08% dec^{-1} occurred in the autumn (Figure 1b), although this trend is not significant as a result of the large inter-annual variability of the SIE at this time of year. In this season the ABS and Ross Sea areas have the largest dipole of significant negative/positive trends.

[12] In contrast to the Ross Sea, the ABS sector has experienced an annual SIE decrease of −6.63% dec^{-1} ($p < 0.01$) with there being a pattern of increasing SIE in the Ross Sea sector and decrease in the ABS in all four seasons, although the trends are only significant in both sectors during autumn.

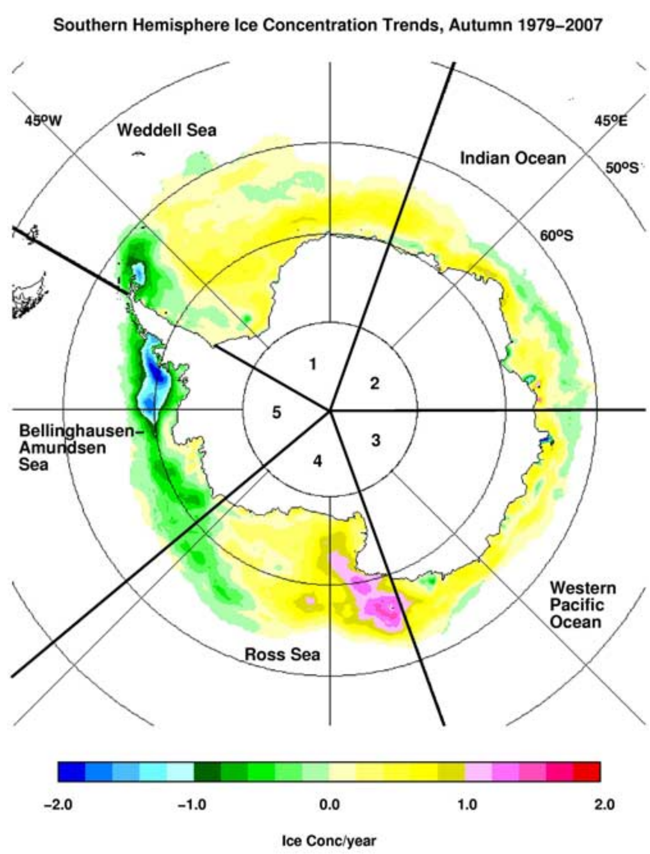

Figure 2. The spatial pattern of Autumn sea ice concentration changes over 1979–2007.

Table 1. Annual and Seasonal Trends in Antarctic Sea Ice Extent (Percent Dec^{-1}) for 1979–2007[a]

	Annual	Autumn	Winter	Spring	Summer
Antarctica	0.97**	2.08	0.82**	0.81*	0.05
Weddell Sea	0.90	3.00	0.46	0.05	1.62
Indian Ocean	1.68	3.97	1.00	1.61	1.74
West Pacific	0.85	4.50	1.54	−0.77	−0.34
Ross Sea	4.63**	4.64*	2.94	5.42*	5.04
ABS	−6.63***	−7.12***	−2.55	−5.99	−12.73**

[a]Values are presented for the total Southern Hemisphere and the five areas shown in Figure 2. The statistical significance of the trends is indicated as <10% (*), <5% (**) and <1% (***).

[13] The spatial pattern of sea ice concentration trend in autumn (Figure 2) indicates that the greatest increase has been in the northern Ross Sea. The southwest Ross Sea is a region of strong sea ice production and export, as a result of the persistent polynyas. The trend in autumn sea ice motion for this region as derived from passive microwave data (not shown) indicates that there has been greater transport of ice out of the Ross Sea at this time of year, suggesting an increase in southerly near-surface winds since 1979. We find this to be consistent with changes in the MSLP gradient across the edge of the shelf between McMurdo station and the 'Gill' automatic weather station (AWS) on the eastern side. The Gill-McMurdo MSLP difference has increased by about 4 hPa over 1985–2000, with a greater drop of pressure at the AWS site compared to McMurdo, implying stronger flow off the ice shelf.

[14] The increase in southerly flow will give lower air temperatures, and will help maintain the polynyas along the coast. Combined, these will lead to greater ice production [*Comiso*, 2000] and also promote enhanced ice advection northwards.

[15] The changes in atmospheric flow during the period can be seen in the trends in ECMWF autumn 500 hPa geopotential height for 1979–2006 (Figure 3a). The ECMWF fields for this period span the ERA-40 and operational data: there is no evidence of any jump in the height data across this transition. The trend towards generally lower (higher) atmospheric pressures/heights across the Antarctic (Southern Ocean) at this time of year is a result of the shift in the SAM towards its positive phase in this season. Figure 3a shows that the trend has enhanced the strong wave number 3 pattern. In particular, there has been a deepening of the trough over the Amundsen Sea (the ASL) resulting in greater flow off the Ross Ice Shelf and towards the coast, west of the Antarctic Peninsula. This is consistent with the spatial pattern of sea ice trends in the ABS, Weddell and the Ross Seas (cf. Figure 2) and the reports of higher cyclone counts in this region [*Simmonds et al.*, 2003].

[16] The relatively high negative correlation between autumn SIE in the Ross Sea and 500 hPa geopotential height (Figure 3b) shows that the sea ice changes are broadly associated with lower (increased) heights over the Antarctic continent (mid-latitude areas), which implies a link to the SAM. However, the largest correlation is over the Amundsen Sea close to 140°W, 70°S, where strong cyclonic circulation will promote southerly flow over the Ross Sea.

[17] To examine whether the amplification of the ASL during autumn has been a result of anthropogenic activity or natural climate variability, the mean trends in autumn 500 hPa geopotential height over 1979–2001 from the AR4 models were examined (Figure 3c). These were weighted according to the scheme of *Connolley and Bracegirdle* [2007] to maximise the use of output from models that have the greatest skill in simulating the Antarctic climate. The runs included directly the observed increases of greenhouse gases, but there were differences in the incorporation of stratospheric ozone depletion: some models simply used pre-ozone hole levels, while others included the observed springtime depletion. Figure 3c shows that the models simulated well the observed deepening of the ASL during the autumn (although its centre is located off the coast of Antarctica rather than inland), which suggests that anthropogenic forcing is primarily responsible for the circulation changes. The reanalysis fields indicate that the ABS region has a high inter-annual variability of atmospheric circulation (not shown), which has been attributed to the off-pole nature of the Antarctic orography [*Lachlan-Cope et al.*, 2001]. The AR 4 models have some difficulty in simulating this correctly, perhaps as a result of their coarse horizontal resolution being unable to adequately capture the steep coastal orography.

[18] To determine more fully whether the 500 hPa geopotential height changes across West Antarctica in the Twentieth Century AR4 model runs were a result of anthropogenic forcing factors, we examined the circulation variability in this area in the pre-industrial control runs of the AR4 models. It was found that the circulation changes in the AR4 runs were statistically significant at less than the 5% level when compared to pre-industrial control runs.

[19] To isolate the impact of ozone loss in changing the atmospheric circulation during the autumn, the HadAM3 model was run for 50 years using pre-industrial ozone values and using concentrations for 2000. The difference in 500 hPa geopotential height between these runs (Figure 3d) shows marked similarities in shape with Figure 3a. The difference in circulation was for stronger westerly winds just north of the Antarctic coast with a peak close to 60°S. Examination of the zonal winds around 180°W showed that the inclusion of ozone loss resulted in stronger winds from the surface into the stratosphere, but with the greatest increase close to 100 hPa.

[20] Comparison of the simulated and observed trends in autumn 500 hPa geopotential height of the ASL indicates that the ECMWF data over 1979–2006 decreased at a rate of about 9 m dec^{-1}, the AR4 data decreased by about 13 m dec^{-1} for 1979–2001, while the difference between the two HadAM3 runs showed that the inclusion of ozone loss resulted in a 500 hPa geopotential height decrease of

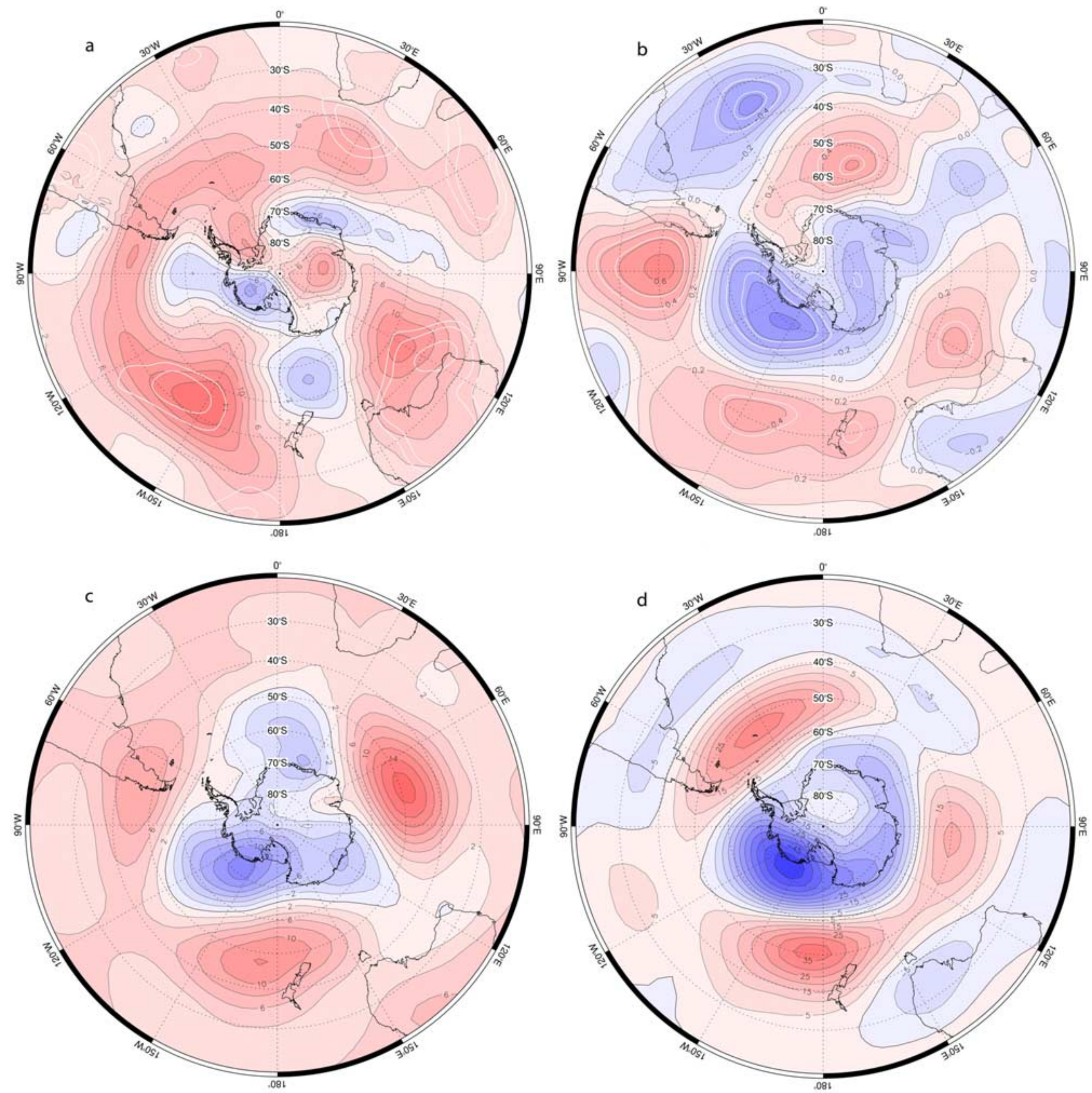

Figure 3. (a) The trend in Autumn 500 hPa geopotential height (m dec-1) for 1979–2006 derived from the ECMWF data. (b) The correlation of autumn Ross Sea SIE and autumn ECMWF 500 hPa geopotential height across the Southern Hemisphere. The areas bounded by the white lines have statistically significant correlations at the 1, 5 and 10% levels. (c) The mean trends in autumn 500 hPa geopotential height (m dec^{-1}) over 1979–2001 from the IPCC AR4 models weighted according to the scheme of *Connolley and Bracegirdle* [2007]. (d) The differences in 500 hPa height (m) between two 50-year runs of HadAM3 with pre-industrial levels of stratospheric ozone and ozone levels in 2000.

50 m. Assuming that ozone depletion started in 1975, this would imply a rate of about 20 m dec^{-1}.

4. Discussion and Conclusions

[21] Given the recent observed changes in atmospheric circulation and sea ice, it is highly likely that there have also been coupled changes in ocean characteristics. These are difficult to determine because of the scarcity of *in situ* data, although some changes have been observed. *Jacobs et al.* [2002] noted a freshening of the Ross Sea that they ascribed to increased precipitation and increased melting of the West Antarctic Ice Sheet. This would likely favour a sea ice increase by enhancing the vertical stratification of the upper ocean and reducing the vertical heat flux from the warmer layers below [*Zhang*, 2007]. The observed changes in the surface wind field are consistent with an increase in wind stress curl, which would tend to accelerate the Ross Gyre [*Wang and Meredith*, 2008], again consistent with stronger ice export.

[22] The realistic simulation of sea ice in coupled climate models is a major challenge and the AR4 models exhibit a very large range of skills in reproducing recent SIE changes. However, the weighted ensemble ice extents do show a small, non-significant increase in autumn in the Ross Sea sector. Projections of the climate for the rest of this century using the AR4 models suggest a large decrease (approximately 30%) in Antarctic sea ice by 2100 [*Arzel et al.*, 2006; *Bracegirdle et al.*, 2008] as stratospheric ozone levels recover but greenhouse gas concentrations rise. We can therefore expect to see a gradual slow down in the rate of increase of SIE before the reduction takes place later in the century. Many of the models used within the AR4 exercise incorporate an estimated recovery of stratospheric ozone amounts during the spring, with the ozone hole recovering by the second half of the century. This would tend to reduce the wind speeds around the continent and presumably result in a reversal of the trends in SIE that we have examined here.

[23] The model runs discussed above suggest that anthropogenic activity through stratospheric ozone depletion is responsible for much of the increase in depth of the ASL in recent decades and, therefore, the increase in SIE in the Ross Sea. However, the HadAM3 runs were carried out with an atmosphere-only model that had none of the observed Southern Ocean SST variability. Additionally, the coarse resolution of the HadAM3 model severely underestimates the coastal height of Antarctica, and thus the simulated atmosphere requires the sub-grid scale parameterization of low-level blocking and gravity wave drag. *Orr et al.* [2008] showed that these can result in overly strong flow separation, which suggests that the simulated ASL deepening trend from the HadAM3 runs is excessive.

[24] Nevertheless, climate model runs provide a means of determining whether the recent increase in Antarctic SIE could be a result of natural climate variability. We therefore employed a 340 year control run of the coupled model HadCM3 and examined the autumn change in Ross Sea SIE in 22 29-year periods with a 50% overlap – the 29-year period being chosen to be the same as the satellite record of sea ice. The satellite data indicate that over 1979–2007 the annual mean Ross Sea SIE increased by 0.126×10^6 km^2 dec^{-1}. However, the HadCM3 run had five periods when the Antarctic SIE increased by at least as much as was observed in recent decades. The model experiments discussed above suggest that the recent deepening of the ASL, and therefore the increase of SIE in the Ross Sea, are largely a result of the decrease of stratospheric ozone. However, the long control run of a coupled climate model does suggest that the recent increase in SIE might still be within the bounds of natural climate variability.

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