Recent Changes in Antarctic Sea Ice

John Turner, J. Scott Hosking, Thomas J. Bracegirdle, Gareth J. Marshall and Tony Phillips

British Antarctic Survey, Natural Environment Research Council, High Cross,
Madingley Road, Cambridge, CB3 0ET

In contrast to the Arctic, total sea ice extent (SIE) across the Southern Ocean has increased since the late 1970s, with the annual mean increasing at a rate of 186×10^3 km^2 dec^{-1} (1.5% dec^{-1}) ($p<0.01$) for 1979 – 2013. However, this overall increase masks larger regional variations, most notably an increase (decrease) over the Ross (Amundsen-Bellingshausen) Sea. Sea ice variability results from changes in atmospheric and oceanic conditions, although the former is thought to be more significant, since there is a high correlation between anomalies in the ice concentration and the near-surface wind field. The Southern Ocean SIE trend is dominated by the increase in the Ross Sea sector, where the SIE is significantly correlated with the depth of the Amundsen Sea Low (ASL), which has deepened since 1979. The depth of the ASL is influenced by a number of external factors, including tropical sea surface temperatures, but the low also has a large locally-driven intrinsic variability, suggesting that SIE in this areas is especially variable. Many of the current generation of coupled climate models have difficulty in simulating sea ice. However, output from the better-performing IPCC CMIP5 models suggests that the recent increase in Antarctic SIE may be within the bounds of intrinsic/internal variability.

Keywords: sea ice; climate change; Southern Ocean; cryosphere

1. Introduction

Sea ice across the two polar regions has experienced remarkably different changes over the period since the late 1970s [1,2]. In the Arctic there has been a well documented decrease of sea ice extent (SIE), with a succession of record minimum extents being recorded in recent years [3]. In contrast, over the Southern Ocean there has been a statistically significant increase in ice extent and area throughout the year for the Antarctic as a whole [4-7], although this slight overall increase masks larger opposing regional trends [e.g. 3,8]. While 50-60% of the ice loss in the Arctic has been attributed to anthropogenic forcing [9], the mechanism or mechanisms responsible for the increase in sea ice around the Antarctic continent is still unclear. In this paper we review our current understanding of sea ice changes over the Southern Ocean. We first describe the data used to produce the figures in this paper. In Section 3 we then examine the annual and seasonal trends in SIE on a regional and Antarctic-wide basis. Section 4 discusses the various theories that have been put forward to explain the observed changes in Antarctic sea ice since the late 1970s, while Section 5 considers the simulation of these recent changes in Antarctic sea ice by the CMIP5 models. The final section draws conclusions and considers the future work required.

2. Data used

We examine changes in Antarctic mean sea ice concentration (SIC) and SIE (where SIC > 15%) based on the Bootstrap version 2 algorithm [10]. There has recently been a debate over the accuracy of the Bootstrap algorithms [11]; however, the extents derived using Bootstrap 2 agree well with those from the independently derived NASA Team and ESA algorithms so will be used here.

Monthly mean SIC fields were obtained from the US National Snow and Ice Data Center (www.nsidc.org) and re-gridded onto a 0.25° × 0.25° grid. SIE was computed as the total area of all 0.25° × 0.25° grid cells where the SIC exceeded 15%. Regional changes were considered for the five sectors shown on Figure 1 (Weddell Sea, Indian Ocean, western Pacific Ocean, Ross Sea and Bellingshausen/Amundsen Sea) used in a number of earlier studies. Modelling studies suggest the observed SIC/SIE changes are likely to be accompanied by ice thickness increases, implying an increase in Antarctic sea ice volume [8]. However, there are no observational, Antarctic-wide time series of sea ice thickness so it is not possible to consider variability and change in this quantity at present.

Atmospheric circulation changes were examined using the monthly mean ECMWF Interim reanalysis fields [12], which have a horizontal grid spacing of 0.7° × 0.7°.

3. The observed changes

The annual and seasonal trends in SIC are shown in Figure 1, with the SIE trends for the Southern Ocean as a whole and the five standard sectors [e.g. 6] summarized in Table 1. For the year as a whole the total Antarctic SIE has increased as at a rate of 186 × 10^3 km^2 dec^{-1} (1.5% dec^{-1}) ($p<0.01$) for 1979 – 2013. The pattern of change in annual mean SIE (Figure 1a) is dominated by an increase of ice in the Ross Sea Sector (117 × 10^3 km^2 dec^{-1} (3.9% dec^{-1}) ($p<0.05$)) [13] and a decrease in the Amundsen-Bellingshausen Sea (-54 × 10^3 km^2 dec^{-1} (3.4% dec^{-1}) (not significant)). The other three sectors have all experienced an increase in annual mean SIE, with the largest of these being in the Indian Ocean (55 × 10^3 km^2 dec^{-1} (2.7% dec^{-1}) ($p<0.01$)). For all the sectors the trends in sea ice area have the same sign as the trends in SIE [14].

The total Antarctic SIE has increased in each season (Table 1), with the largest trend being in autumn (220 × 10^3 km^2 dec^{-1} (2.8% dec^{-1}) ($p<0.01$)) and the smallest in summer (129 × 10^3 km^2 dec^{-1} (1.9% dec^{-1}) (not significant)). The couplet of increasing SIE in the Ross Sea and decrease in the ABS is present in all seasons, although in winter the trend in the ABS is essentially zero. Furthermore, Simpkins et al. [15] demonstrated that these trends are dominated by different temporal variability. Figure 1 shows that the largest positive SIC anomalies in the Ross Sea advance northwards during the sea ice growth season from close to the coast of Victoria Land in autumn to lie along the sea ice edge in spring, before retreating southwards again in summer. A recent paper by Holland [8] suggests that this large regional autumn SIE trend is primarily a response to decreased ice loss in the preceeding spring. The changes in sea ice between the Antarctic Peninsula and the western Ross Sea have resulted in marked alterations to the length of the sea ice season. Considering 1979 – 2010, Stammerjohn et al. [16] found that the ice started retreating 38.4 ± 12.8 days earlier and advancing 60.8 ± 16.0 days later in the ABS, whereas in the western Ross Sea, sea ice started retreating 38.4 ± 9.6 days later and advancing 41.6 ± 9.6 days earlier.

The Indian Ocean and Western Pacific Ocean sectors have experienced an increase in SIE in all seasons. However, the Weddell Sea sector is anomalous in having experienced an increase in SIE in the summer and autumn, and a decrease in the winter and spring.

The inter-annual variability of the total Antarctic SIE is large (standard deviation 0.29 × 10^6 km^2) (Figure 2) and the extent has varied on the decadal scale over the 35 years of data. Over the period 1979 – 1990 the total Antarctic SIE decreased at a rate of -153 × 10^3 km^2 dec^{-1} (1.3% dec^{-1}), predominantly due to a rapid decline in the Bellingshausen Sea [e.g. 15] although the trend in this short record is not significant. However, the decrease in ice seemed consistent at that time with the increasing concentrations of greenhouse gases and the loss of ice in the Arctic. However, from about 1990 there has been an overall increase in Antarctic SIE with record annual mean extents in 2003, 2008 and 2013. There have also been records in the annual daily maximum sea ice extent, with the extent on 24 September 2012 reaching 19.72 × 10^6 km^2 [17]. According to the NSIDC, the single-day maximum sea ice extent on 20 September 2014 of 20.14 × 10^6 km^2 was the highest observed during the satellite record.

4. Mechanisms that may be contributing to the observed sea ice changes

The extent of sea ice is influenced by both atmospheric and oceanic factors, including the strength of the near-surface winds, air temperature, ocean currents, and temperature and salinity of the ocean. We have reliable six-hourly atmospheric analyses since 1979 providing a high level of confidence of atmospheric change over that period. However, we don't have comparable time series of oceanographic data for the Southern Ocean.

4.1 The role of the atmosphere

Advection of sea ice occurs at about 2% of the near-surface wind speed, so changes in atmospheric circulation can affect the distribution of sea ice. Holland and Kwok [18] used sea ice motion data and reanalysis wind fields to show that wind-driven changes in ice advection are the dominant driver of SIC trends around much of West Antarctica (r~0.9). In contrast, wind-driven thermodynamic changes play a large role elsewhere, including the Bellingshausen Sea, where autumn SIE trends oppose those in near-surface winds [8].

The atmospheric environment of the Antarctic sea ice zone is dominated by the circumpolar trough, a low pressure belt over 60-70° S, which is present because of the large number of storms that have moved south from mid-latitudes or developed within this baroclinic region. There are three climatological low pressure centres within the circumpolar trough, located close to 20° E, 90° E and 150° W, and associated with the wave number 3 pattern in the atmospheric circulation around the continent [19]. The low pressure centre off West Antarctica at ~150° W is known as the Amundsen Sea Low (ASL) [20-22] and its variability has a major influence on the climate from the Antarctic Peninsula to the Ross Sea. Mean sea level pressure (MSLP) in the area of the ASL is more variable than anywhere else in the Southern Hemisphere, which is in part a result of the off-pole nature of the Antarctic orography [23]. The region is also where the strongest teleconnections from the tropical Pacific to the Antarctic are found [24,25]. During the El Niño (La Niña) phase of the El Niño-Southern Oscillation, MSLP values in the region of the ASL are higher (lower) [26], which influences the wind field and therefore the sea ice distribution between the Antarctic Peninsula and the Ross Sea. Trends in sea surface temperatures (SSTs) across the Atlantic Ocean have also recently been linked to MSLP and sea ice changes in this sector [27].

The annual mean SIE in the Ross Sea sector is significantly ($p<0.05$) anti-correlated with the annual mean MSLP in the area of the ASL (Figure 3a), indicating that years of greater SIE in this sector are associated with a deeper ASL. The Ross SIE is also positively correlated with the MSLP over the South Pacific across the latitude range of 40-50° S (Figure 3a). This pattern of correlation indicates that the Ross Sea SIE is positively correlated with the strength of the atmospheric polar front jet (PFJ). The PFJ is one of the two jets found over the South Pacific, with the other being the sub-tropical jet (STJ) located close to 30° S. The strength of the two jets is influenced by tropical SST variability and the phase of ENSO, with the PJF (STJ) being stronger during the La Niña (El Niño) phase of the cycle [26]. Conditions across the tropical Pacific can therefore influence the atmospheric circulation of high southern latitudes and the extent of sea ice.

Atmospheric conditions between the Antarctic Peninsula and the Ross Sea, and therefore the SIE, are also influenced by the phase of the Southern Annular Mode (SAM), which is the primary mode of climate variability at high southern latitudes [28]. The SAM is characterized by an oscillation of mass between mid- and high-latitude areas of the Southern Hemisphere; the SAM is taken to be in its positive (negative) phase when MSLP is relatively low (high) over the Antarctic (mid-latitudes) and high (low) in mid-latitudes (over Antarctica). The phase of the SAM has a large intrinsic variability, but is also influenced by the concentration of greenhouse gases, volcanic aerosols and the loss of stratospheric ozone [29]. Although the SAM is essentially an annular mode, the SAM's contribution to recent changes in the 500 hPa geopotential height includes a decrease of heights off West Antarctica [30], suggesting that periods when the SAM is positive are characterised by more cyclonic conditions in the area of the ASL, which will enhance the dipole of SIE decrease (increase) over the Bellingshausen (Ross) Sea. The atmosphere-only model experiments of Turner et al. [31], with and without stratospheric ozone depletion suggested that the ozone hole would result in a deeper ASL and more sea ice in the Ross Sea. This is consistent with the ASL being strongly influenced by the strength of the winds over the Southern Ocean [32], and the known result of the stratospheric ozone loss moving the SAM into its positive phase and strengthening the winds around the Antarctic. However, the role of stratospheric ozone depletion in the recent increase of Antarctic SIE was questioned by Sigmond and Fyfe [33] who carried out a study using a climate model forced with stratospheric ozone depletion from 1979 – 2005. They found that the loss of ozone gave a year-round decrease in Antarctic sea ice, with the largest decrease in austral summer. In contrast, Marshall et al. [34] suggested that the loss of stratospheric ozone above the Antarctic would lead to a decrease of SSTs around the continent, which would be conducive to more sea ice. While for the remainder of the 21st Century, a modelling study by Smith et al. [35] suggested that projected ozone loss will mitigate Antarctic sea ice loss.

Further evidence of the influence of the SAM on the SIE between the Peninsula and the Ross Sea comes from the work of Liu et al. [36], who examined sea ice trends over 1979 – 2002 and found that during the positive phase of the SAM there was more (less) sea ice in the eastern Ross/Amundsen (Bellingshausen/northern Weddell) sector of the Southern Ocean. In addition, Comiso et al. [13] noted that variability in the ice cover over the Ross Sea was linked to changes in the SAM and secondarily to the Antarctic Circumpolar Wave. The role of the interactions between SAM changes and the ocean are considered in the next section.

The ECMWF Interim Reanalysis data indicate that since 1979 the annual mean depth of the ASL has decreased by around -0.7 hPa dec^{-1} and that the strength of the southerly wind over the Ross Sea has increased by 0.1 m sec^{-1} dec^{-1}. However, these trends vary over the year with the greatest deepening of the ASL having occurred in May and September. The decrease in annual mean depth of the ASL is consistent with the slight shift in ENSO towards the La Niña phase of the ENSO cycle, however, this signal may be overwhelmed by the large intrinsic variability of the ASL. Nevertheless, the dipole of increasing (decreasing) SIE in the Ross Sea (Amundsen-Bellingshausen) sectors is consistent with deepening of the ASL since

1979 and appears to be a significant factor in the changes in SIE in this sector.

While the increase in total Antarctic SIE is dominated by changes in the Ross Sea sector, it is instructive to examine the relationships between SIE in the other parts of the Antarctic and the atmospheric circulation. The fields of correlation between the time series of annual mean SIE for the Antarctic as a whole and the other four regional sectors, and the annual MSLP over high southern latitudes are therefore presented in Figure 3. The field of correlation between the annual mean SIE in the Weddell Sea sector and MSLP (Figure 3b) is almost exactly the opposite to that for the Ross Sea, with SIE being positively correlated with the depth of the ASL. This is consistent with the 'Antarctic dipole' [37] that exists between the climatological atmospheric conditions that are found in the Weddell Sea and the area between the Antarctic Peninsula and the Ross Sea. The dipole can be considered as the southern component of the Rossby wave train that is found from the tropical Pacific to the area to the west of the Antarctic Peninsula and is also referred to as the Pacific-South American pattern. While the inter-annual variability of the annual mean SIE in the Weddell Sea is significantly correlated with MSLP in the area of the ASL, with more sea ice associated with a weaker ASL, the increase in SIE in this sector is not consistent with a weakening of the ASL since 1979. This suggests that other factors are playing a part in the sea ice increase in the Weddell Sea, which is small and non-significant for the year as a whole (Table 1).

Inter-annual variability of sea ice in the other sectors around the Antarctic show differing patterns of correlation with the atmospheric circulation. The SIE in the ABS is correlated with the MSLP in a similar way to that of the Weddell Sea (Figure 3c), suggesting that the atmospheric forcing on the sea ice is different between the Weddell Sea/ABS and the Ross Sea. The influence of the atmospheric circulation on the SIE in the West Pacific Ocean sector is limited to an area just to the west of 180° W, with more (less) cyclonic activity here giving greater (less) sea ice (Figure 3d). The correlation between the SIE in the Indian Ocean sector and the MSLP is quite different from the other sectors (Figure 3e). The pattern of correlation is very similar to that of the SAM, with SIE correlated (anti-correlated) with MSLP over mid-latitudes (the Antarctic). Since the annual mean SIE values in the five sectors have very different patterns of correlation with MSLP it's not surprising that the annual mean SIE for the whole Southern Ocean has a rather weak correlation with MSLP (Figure 3f). The overall pattern is similar to that of the SAM, but with a maximum anticorrelation in the area of the ASL and positive correlation values across the mid-latitude areas of the Pacific Ocean. The reasons for the different patterns of correlation between SIE and MSLP in the five sectors around the Southern Ocean may well be related to the shape of the continent, as well as different forcing from areas outside the Antarctic. However, more research is needed in this area.

While changes in the near-surface wind field have a significant influence on the extent of sea ice, other atmospheric parameters can also affect the sea ice. In particular, the amount of snowfall falling on the ice will influence the rate at which the ice melts and additional snow can maintain ice cover for longer. Liu and Curry [38] noted that there had been a warming of the Southern Ocean over recent decades and an enhancement of the hydrological cycle, leading to greater snowfall in the sea ice zone. The ECMWF Interim reanalysis data do indeed show an increase in snowfall across the sea ice since 1979, particularly over the Weddell and Ross Seas. However, the correlation is fairly low between the areas of greater snowfall and increase in sea ice extent.

4.2 The role of the ocean

A key explanation for the comparatively slow warming at high southern latitudes under global warming scenarios is anomalous heat uptake into the Southern Ocean. However, understanding the detail of the role of ocean change in the recent increase of Antarctic SIE presents a number of problems because of the lack of repeat ocean measurements around the continent. However, some broadscale changes have been observed. Gille [39] found an overall warming of the Southern Ocean during the second half of the Twentieth Century, which intuitively would tend to lead to less sea ice. However, as noted above, the enhanced hydrological cycle has given greater snowfall across parts of high southern latitudes.

The other major oceanographic change in the Antarctic coastal region has been a freshening of the ocean in the Ross Sea [40], which has been linked to the freshwater input to the area from melting of parts of the West Antarctic Ice sheet, along with greater preciptation. Bintanja et al. [41] suggested that freshwater input by Antarctic ice sheet melt has driven the observed sea ice trend by establishing a cool, fresh upper layer that shielded the surface ocean from the warmer deeper waters. However, Swart and Fyfe [42] carried out model experiments to determine the effects on the sea ice of freshwater injection and found that the impact was too small to explain the observed sea ice increase.

A mechanism to explain the SIE increase that involves a feedback between changes in the atmosphere and ocean was put forward by Zhang [43]. The study involved using a sea ice model coupled to an ocean model, with atmospheric forcing coming from the NCEP-NCAR reanalysis. The analysis suggested that with an increase of air temperature and downward longwave radiation there was an increase in upper-ocean temperature and a decrease in sea ice growth. This led to a decrease in salt rejection from the sea ice, in the upper-ocean salinity and in the upper-ocean density. These changes tended to suppress convective overturning, leading to a decrease in the upward ocean heat transport and the ocean heat flux available to melt the sea ice. The increase in overall SIE was explained by the ice melting from ocean heat flux decreasing faster than the ice growth in the weakly stratified ocean. However, records of surface temperature from the coastal Antarctic stations contradict this theory as they show little change over recent decades, and even a small cooling at some stations.

A more recent suggestion is that the responses of surface temperatures and sea ice in the Southern Ocean exhibit a two-timescale response to ozone-induced increases in the polarity of the SAM [34]. The initial short timescale response is a surface cooling and increase in SIE, which is then followed by surface warming and SIE reduction as upwelling of warm water from below becomes established. However, there is considerable uncertainty over the length of transition between the two timescales, ranging from a few years to a few decades. Although more research into this mechanism is required, it potentially helps to explain at least a part of the observed increase in Southern Hemisphere SIE.

5. The simulation of SIE by climate models

The Coupled Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP) is an initiative that brings together around 50 state-of-the-art coupled atmosphere-ocean-sea ice climate models that are run for past conditions and a range of future scenarios. The output of the models has proved a very valuable resource to help investigate how sea ice has varied in the past and how it might evolve in the future under conditions of increasing greenhouse gas concentrations and the recovery of the ozone hole. Three types of coupled model runs are of particular interest here:

1. Control runs with fixed pre-industrial concentrations of greenhouse gases, and fixed stratospheric ozone, aerosols and solar forcing.
2. Historical runs from the mid-Nineteenth Century to 2005 with observed concentrations of greenhouse gases and development of the ozone hole from about 1980.
3. Projections for the coming decades and centuries run with a range of Representative Concentration Pathways (RCPs).

Turner et al. [44] examined the Antarctic SIE trends over 1979 - 2005 in historical runs of 18 of the CMIP 5 models. Many of the models had difficulty in simulating the annual cycle of SIE, with extents differing markedly from those observed by satellite at various points in the year. Gross errors in some models were linked to large warm or cold biases in ocean temperatures. In contrast to the satellite observations, most of the historical runs of the CMIP5 models had Southern Ocean sea ice decreasing in extent over 1979 – 2005. The multi-model mean SIE had sea ice decreasing in every month of the year (Figure 4) with the largest percentage loss of about 12% per decade occurring in February. The annual cycle of the SIE trends for most of the models shown in Figure 4, with a maximum loss in late summer, is very similar to that of the changes observed in Arctic SIE since 1979. About 5% of the CMIP5 historical runs have Antarctic SIE increasing over 1979 – 2005, however, the spatial distribution of the increases and decreases in SIC are very different to what has been observed by satellites and shown in Figure 1. The trends are very similar to those found in CMIP3, where most of the models also had Antarctic SIE decreasing in each month of the year over recent decades.

As indicated above, many of the CMIP5 models have significant issues that preclude them from being used to investigate recent changes in Antarctic SIE. However, the better models can help in understanding how the trends over recent decades relate to the intrinsic variability of Antarctic sea ice. Polvani and Smith [45] used data from the control and historical runs of four of the CMIP5 models that they thought were 'suitable' and showed that the observed Antarctic SIE trends since 1979 fall well within the distribution of trends arising naturally in the coupled atmosphere-ocean-sea ice system. A similar result was found by Zunz et al. [46] who examined Antarctic sea ice in 24 models from the CMIP5 historical and hindcast experiments. They found that the models responded to the applied forcing by decreasing the extent of Antarctic sea ice. However, some simulations had SIE increasing in a similar fashion to that observed in the satellite data. They concluded that the observed positive trend in SIE is compatible with internal variability of the atmosphere-ocean-sea ice system. However, they did note that the models strongly overestimated the variance of SIE.

6. Conclusions and future work required

Here we have assessed changes in the SIE around the Antarctic continent over the period since 1979 and examined the various hypotheses put forward to explain the observed increase. Despite the SIE having a large inter-annual variability there was been a statistically significant increase ($p<0.01$) in the total Southern Ocean extent, although this masks large regional variations. The greatest increase in SIE has been in the Ross Sea sector, although there have been smaller increases in the Weddell Sea and around the coast of East Antarctica, and a small decrease in the ABS.

The Antarctic-wide, observational record of SIE is only 35 years long, which is very short in terms of climate change. However, at present we have no means of extending the record back reliably using proxy or other observational forms of data. For parts of the Southern Ocean there are indications that the sea ice edge was further north during the early to middle years of the Twentieth Century, compared to anything seen in the satellite era. This has been inferred from observations from whaling vessels [47], other vessels visiting the Antarctic [48] and via signals in ice cores [49]. However, questions have been raised as to how the locations of whale catches can be used to estimate ice edge positions that can be compared to satellite measurements. In addition, while it has proved possible to determine a reliable sea ice edge using ice core data in parts of the Antarctic, such as off East Antarctica, these techniques cannot easily be applied in other sectors, where the relationships between sea ice edge locations and aerosol transport to ice core sites are different. So for the moment the most useful form of data for investigating Antarctic-wide SIE variability on multi-decadal to century time scales is the output from control runs of climate models.

Various theories have been put forward to explain the recent overall increase in SIE, but changes in the atmospheric circulation/near-surface wind field have been identified as being particularly important. The increase of ice in the Ross Sea is closely linked to a deepening of the ASL, which is located in a region of large atmospheric variability. The depth of the ASL is affected by a number of tropical and high latitude forcing factors, but it is currently difficult to quantify the role of each factor. However, the increase in SIE in the Ross Sea is consistent with the deepening of the ASL and modelling studies suggest that the positive trend in SIE over the last 35 years is not outside the bounds of internal variability of the atmosphere-ocean-ice system.

A priority for further research is to improve the representation of sea ice in coupled models. Many of the CMIP5 models have a poor representation of sea ice, with large differences in the the annual cycle of SIE compared to the satellite data. However, some of the largest errors are a result of large biases in ocean temperatures, highlighting the fact that it's necessary to have both atmospheric and ocean conditions correct in order to correctly simulate sea ice.

While this paper has been concerned with examining changes in SIE, it's not currently possible to consider changes in total sea ice volume since there are few measurements of ice thickness. A modelling study [50] has suggested that the recent increase of wind speed and convergence in the sea ice zone may have increased ridging production, leading to an increase in volume of thick ice, although it is not possibly to verify this at present. Hopefully, future developments will allow sea ice thickness to be routinely monitored allowing the investigation of changes in ice volume.

Acknowledgement

We are grateful to the U.S. National Snow and Ice Data Center for making the sea ice concentration data available and to ECMWF for providing their Interim reanalysis fields. This work forms part of the Polar Science for Planet Earth programme of the British Antarctic Survey.

	Year	DJF	MAM	JJA	SON
Whole Antarctic	186**	129	220**	173**	201**
Ross Sea (160° E – 130° W)	117*	95	106*	123**	143*
Amundsen-Bellingshausen Seas (130° W – 60° W)	-54	-104**	-118**	0	-4
Weddell Sea (60° W – 20° E)	46	98	139*	-38	-23
Indian Ocean (20° E – 90° E)	55**	40	48*	71*	68
Western Pacific Ocean (90° E – 160° E)	22	13	43	16	9

Table 1. Annual and seasonal trends in SH SIE (10^3 km^2 dec^{-1}) for 1979 - 2013. Significance of the trends is indicated as follows ** (p<0.01), * (p<0.05).

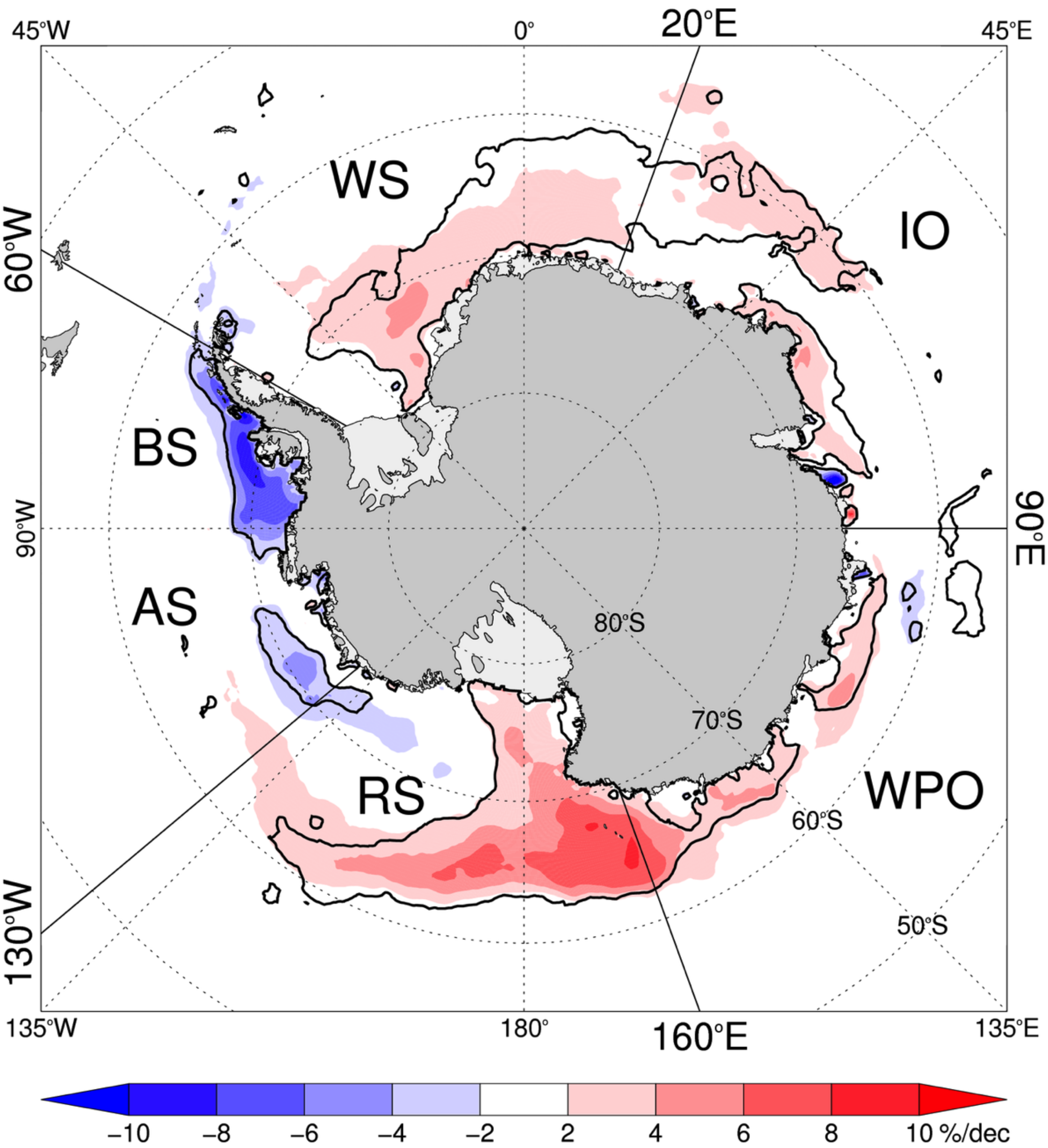

Figure 1. The trend in annual mean sea ice concentration for 1979 - 2013. Sectors referred to in the text are indicated as RS (Ross Sea), AS (Amundsen Sea), BS (Bellingshausen Sea), WS (Weddell Sea), IO (Indian Ocean), WPO (Western Pacific Ocean).

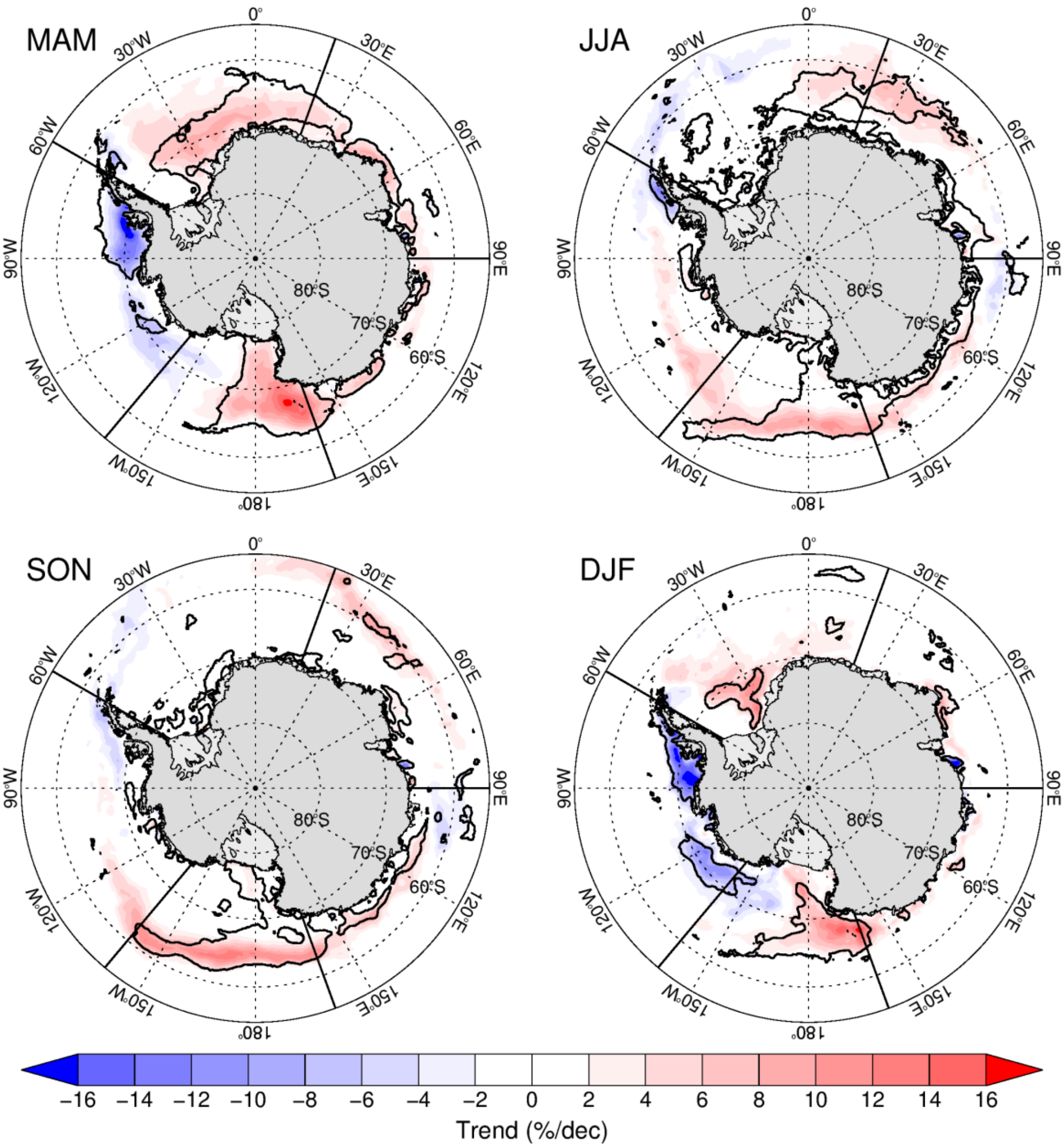

Figure 1. Annual and seasonal trends in mean sea ice concentration for 1979 – 2013 (percent per decade). Areas where the trend is significant at p<0.05 are enclosed by a bold line.

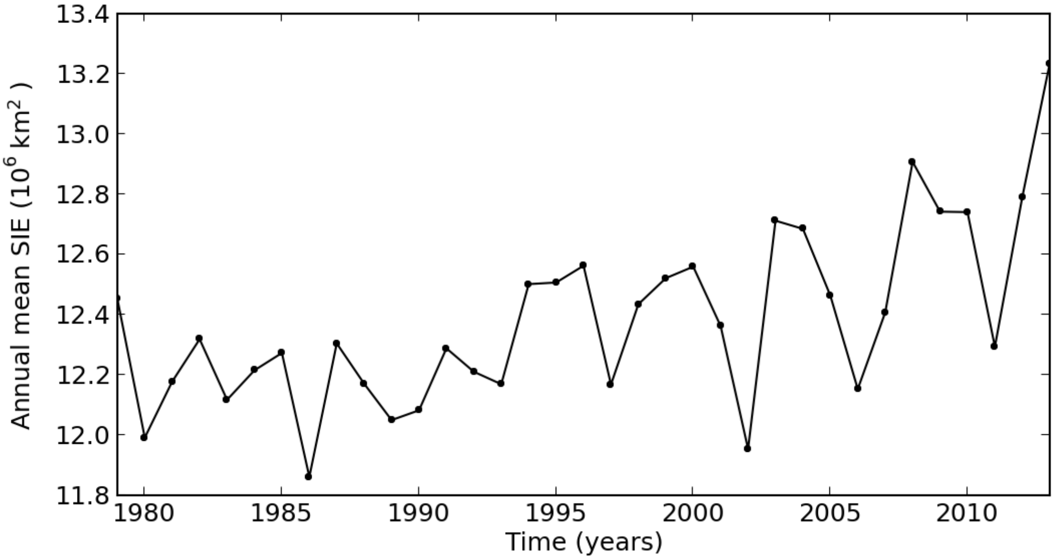

Figure 2. Total Antarctic annual mean sea ice extent.

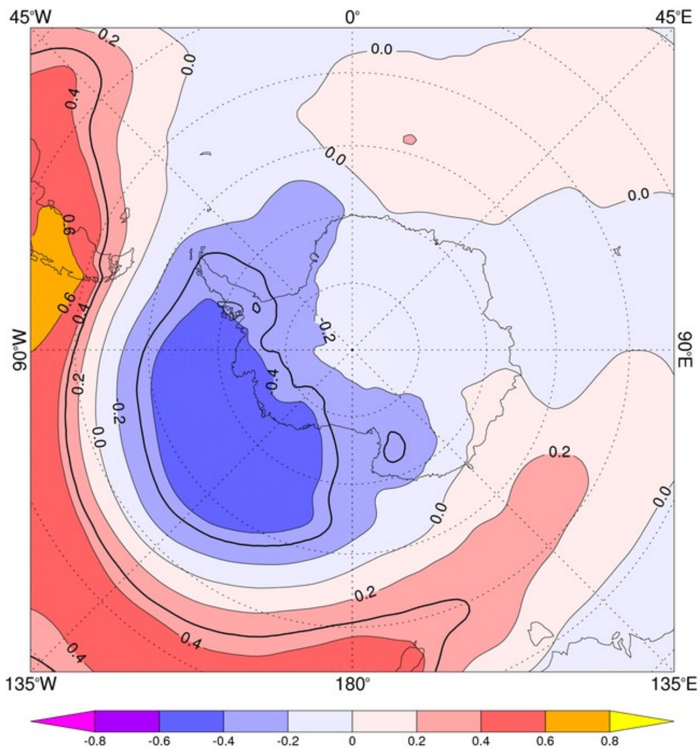

Figure 3a. Ross Sea sector.

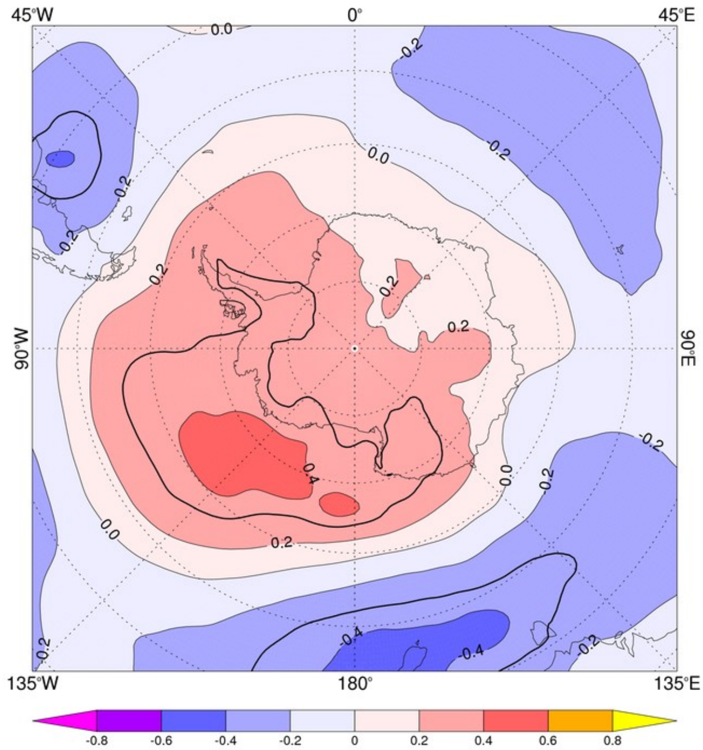

Figure 3b. The Weddell Sea sector

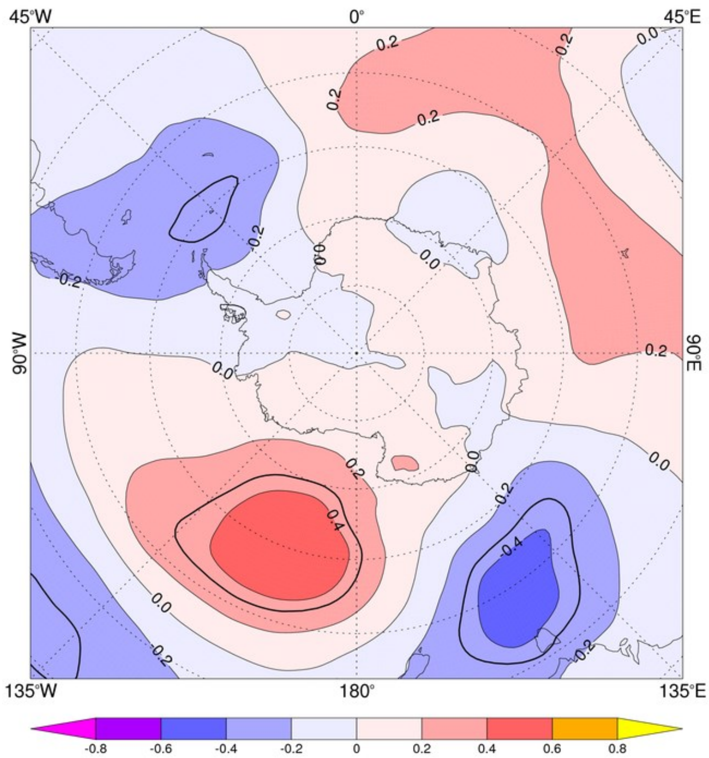

Figure 3c. The Amundsen-Bellingshausen Sea.

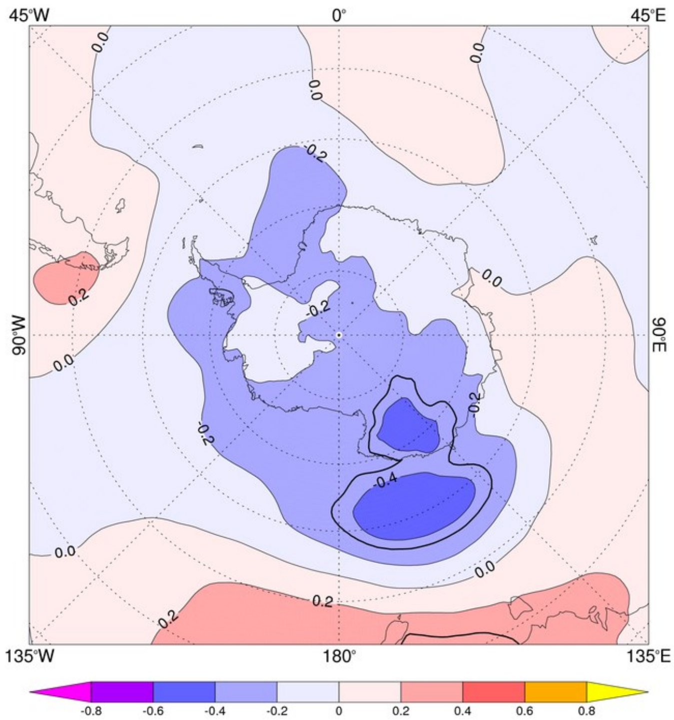

Figure 3d. West Pacific Ocean.

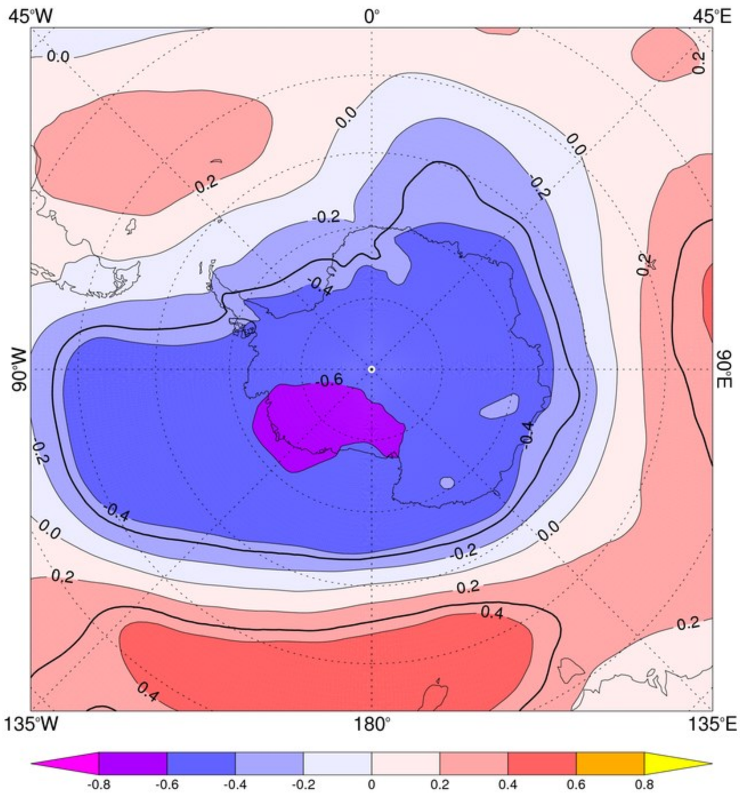

Figure 3e. The Indian Ocean.

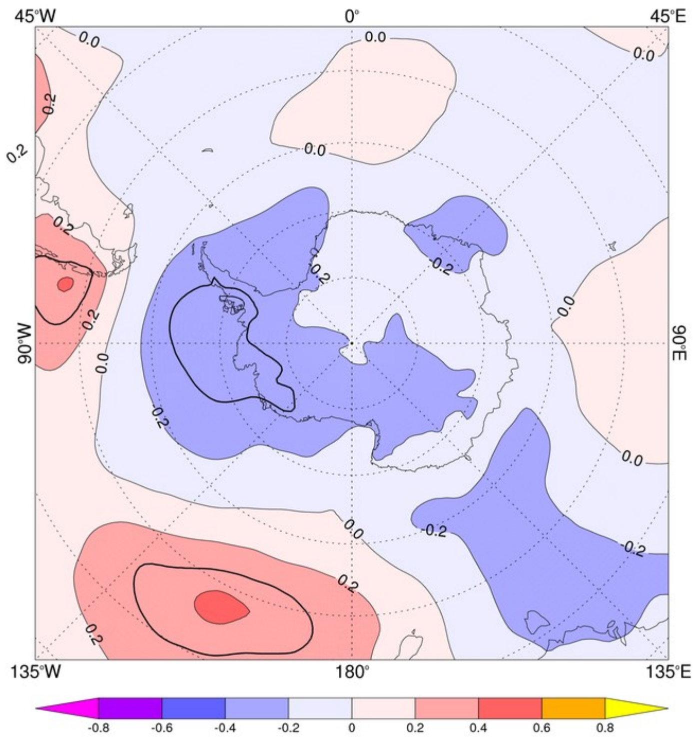

Figure 3f. Total Antarctic SIE.

Figure 3. Correlation of annual mean SIE for the five sectors around Antarctica and the total Southern Ocean SIE with MSLP across high southern latitudes.

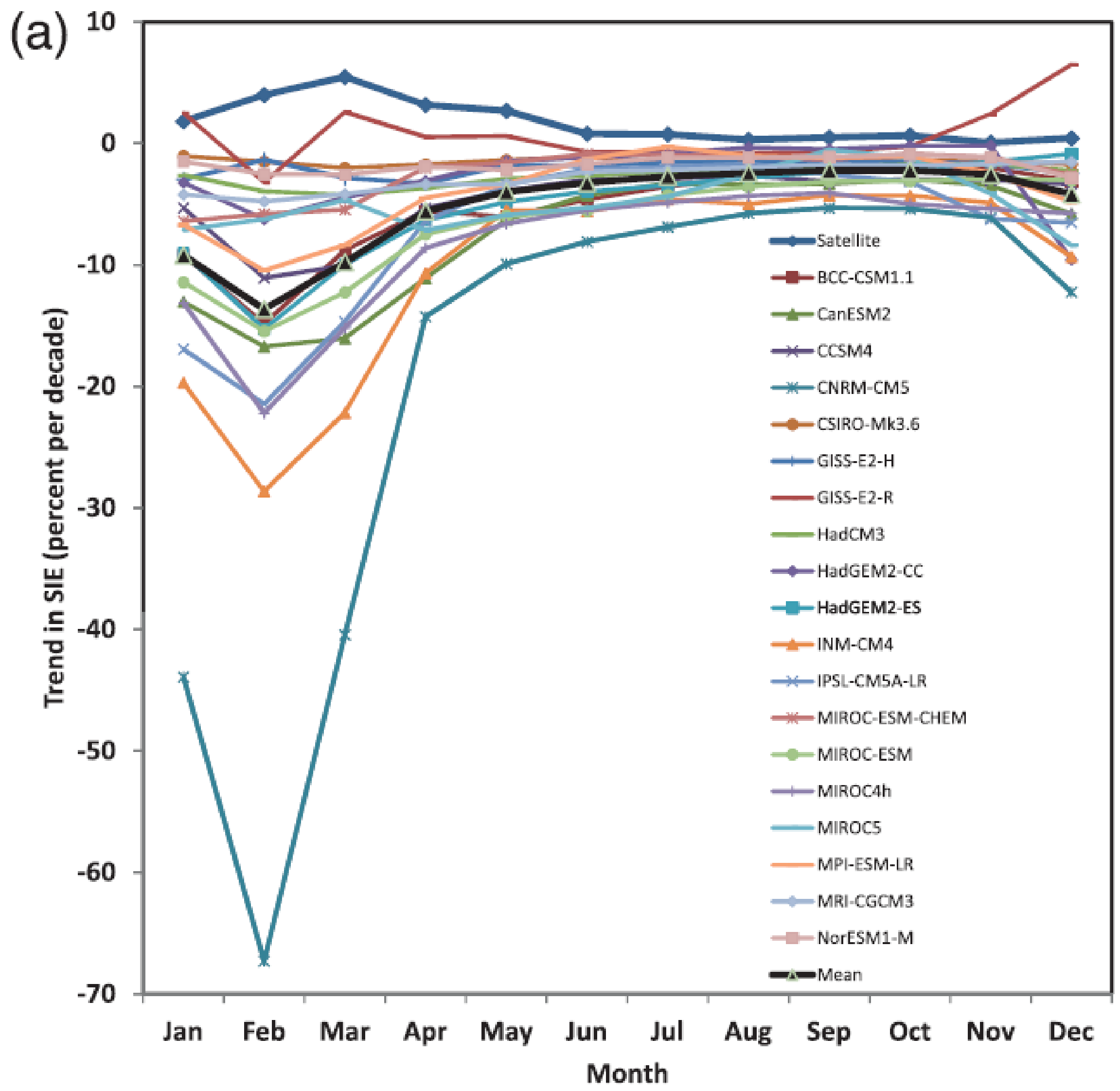

Figure 4. Monthly trends of SIE from the satellite data (thick blue line) and CMIP5 models over 1979–2005 (percent per decade). For models with more than one ensemble member the mean of the ensemble members is plotted. The mean of all the models is shown as a black line. From Turner et al. [44].

References

1. Turner J, Overland, JE. 2009 Contrasting climate change in the two polar regions. *Polar Res.* **28**, 146-164.

2. Simmonds I. 2015 Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35-year period 1979-2013. *Ann. Glaciol.* **56**, 18-28 (doi: 10.3189/2015AoG69A909).

3. Parkinson CL, Comiso, JC. 2013 On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm. *Geophys. Res. Lett.* **40**, 1356-1361. (doi: 10.1002/GRL.50349).

4. Comiso JC, Nishio, F. 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 .

5. Fan TT, Deser, C, Schneider, DP. 2014 Recent Antarctic sea ice trends in the context of Southern Ocean surface climate variations since 1950. *Geophys. Res. Lett.* **41**, 2419-2426.

6. Zwally HJ, Comiso, JC, Parkinson, CL, Cavalieri, DJ, Gloersen, P. 2002 Variability of Antarctic sea ice 1979-1998. *J. Geophys. Res.* **107**, 10.1029/2000JC000733.

7. Cavalieri DJ, Gloersen, P, Parkinson, CL, Comiso, JC, Zwally, HJ. 1997 Observed hemispheric asymmetry in global sea ice changes. *Science* **278**, 1104-1106.

8. Holland PR. 2014 The seasonality of Antarctic sea ice trends. *Geophys. Res. Lett.* **41**, 4230-4237.

9. Stroeve JC *et al.* 2012 Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophys. Res. Lett.* **39**, (doi: 10.1029/2012gl052676).

10. Comiso,J.C. *Bootstrap sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS. Version 2. Updated 2012*(NASA DAAC at the National Snow and Ice Data Center, Boulder, Colorado, 2000).

11. Eisenman I, Meier, WN, Norris, JR. 2014 A spurious jump in the satellite record: has Antarctic sea ice expansion been overestimated? *The Cryosphere* **8**, 1289-1296.

12. Dee DP *et al.* 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. Roy. Met. Soc.* **137**, 553-597.

13. Comiso JC, Kwok, R, Martin, S, Gordon, AL. 2011 Variability and trends in sea ice extent and ice production in the Ross Sea. *J. Geophys. Res.* **116**, (doi: 10.1029/2010JC006391).

14. Parkinson CL, Cavalieri, DJ. 2012 Antarctic sea ice variability and trends, 1979-2010. *The Cryosphere* **6**, 871-880.

15. Simpkins GR, Ciasto, LM, England, MH. 2013 Observed variations in multidecadal Antarctic sea ice trends during 1979-2012. *Geophys. Res. Lett.* **40**, 3643-3648.

16. Stammerjohn S, Massom, R, Rind, D, Martinson, D. 2012 Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophys. Res. Lett.* **39**, (doi: 10.1029/2012gl050874).

17. Turner J, Hosking, JS, Phillips, T, Marshall, GJ. 2013 Temporal and spatial evolution of the Antarctic sea ice prior to the September 2012 record maximum extent. *Geophys. Res. Lett.* **40**, 5894-5898.

18. Holland PR, Kwok, R. 2012 Wind-driven trends in Antarctic sea-ice drift. *Nature. Geosci.* **5**, 872-875.

19. Raphael MN. 2004 A zonal wave 3 index for the Southern Hemisphere. *Geophys. Res. Lett.* **31**, L23212, doi:10.1029/2004GL020365.

20. Turner J, Phillips, T, Hosking, S, Marshall, GJ, Orr, A. 2012 The Amundsen Sea Low. *Int. J. Climatol.*1818-1829.

21. Hosking JS, Orr, A, Marshall, GJ, Turner, J, Phillips, T. 2013 The influence of the Amundsen-Bellingshausen Seas Low on the climate of West Antarctica and its representation in coupled climate model simulations. *J. Clim.*6633-6648.

22. Fogt RL, Wovrosh, AJ, Langen, RA, Simmonds, I. 2012 The characteristic variability and connection to the underlying synoptic activity of the Amundsen-Bellingshausen Seas Low. *J. Geophys. Res.* **117**, (doi:10.1029/2011JD017337).

23. Lachlan-Cope TA, Connolley, WM, Turner, J. 2001 The role of the non-axisymmetric Antarctic orography in forcing the observed pattern of variability of the Antarctic climate. *Geophys. Res. Lett.* **28**, 4111-4114.

24. Hoskins BJ, Karoly, DJ. 1981 The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.* **38**, 1179-1196.

25. Ding Q, Steig, EJ, Battisti, DS, Kuttel, M. 2011 Winter warming in West Antarctica caused by central tropical Pacific warming. *Nature. Geosci.*DOI:10.1038/NGEO1129.

26. Turner J. 2004 The El Niño-Southern Oscillation and Antarctica. *Int. J. Climatol.* **24**, 1-31.

27. Li XC, Holland, DM, Gerber, EP, Yoo, C. 2014 Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature* **505**, 538-542 (doi: 10.1038/nature12945).

28. Thompson DWJ, Wallace, JM. 2000 Annular modes in the extratropical circulation. Part I: month-to-month variability. *J. Clim.* **13**, 1000-1016.

29. Arblaster J, Meehl, GA. 2006 Contributions of external forcings to Southern Annular Mode trends. *J. Clim.* **19**, 2896-2905.

30. Thompson DWJ, Solomon, S. 2002 Interpretation of recent Southern Hemisphere climate change. *Science* **296**, 895-899.

31. Turner J *et al.* 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.

32. Baines PG, Fraedrich, K. 1989 Topographic effects on the mean tropospheric flow patterns around Antarctica. *J. Atmos. Sci.* **46**, 3401-3415.

33. Sigmond M, Fyfe, JC. 2010 Has the ozone hole contributed to increased Antarctic sea ice extent? *Geophys. Res. Lett.* **37**, (DOI: 10.1029/2010GL044301).

34. Marshall J *et al.* 2014 The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing. *Phil. Trans. R. Soc. Lond. Ser. A* **372**, (doi: 10.1098/rsta.2013.0040).

35. Smith KL, Polvani, LM, Marsh, DR. 2012 Mitigation of 21st century Antarctic sea ice loss by stratospheric ozone recovery. *Geophys. Res. Lett.* **39**, (DOI: 10.1029/2012GL053325).

36. Liu J, Curry, JA, Martinson, DG. 2004 Interpretation of recent Antarctic sea ice variability. *Geophys. Res. Lett.* **31**, (doi:10.1029/2003GL018732).

37. Yuan X, Martinson, DG. 2001 The Antarctic dipole and its predictability. *Geophys. Res. Lett.* **28**, 3609-3612.

38. Liu JP, Curry, JA. 2010 Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 14987-14992.

39. Gille ST. 2002 Warming of the Southern Ocean since the 1950s. *Science* **295**, 1275-1277 (DOI: 10.1126/science.1065863).

40. Jacobs SS, Giulivi, CF, Mele, PA. 2002 Freshening of the Ross Sea during the late 20th Century. *Science* **297**, 386-389.

41. Bintanja R, van Oldenborgh, Drijfhout, SS, Wouters, B, Katsman, CA. 2013 Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature. Geosci.*DOI:1-.1038/NGEO1767.

42. Swart NC, Fyfe, JC. 2013 The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophys. Res. Lett.* **40**, 4328-4332 (DOI: 10.1002/grl.50820).

43. Zhang J. 2007 Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. *J. Clim.* **20**, 2515-2529.

44. Turner J, Bracegirdle, TJ, Phillips, T, Marshall, GJ, Hosking, JS. 2013 An initial assessment of Antarctic sea ice extent in the CMIP5 models. *J. Clim.* **26**, 1473-1484.

45. Polvani LM, Smith, KL. 2013 Can natural variability explain observed Antarctic sea ice trends? New modelling evidence from CMIP5. *Geophys. Res. Lett.*(doi: 10.1002/grl.50578).

46. Zunz V, Goosse, H, Massonnet, F. 2013 How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? *Cryosphere* **7**, 451-468.

47. de la Mare WK. 2009 Changes in Antarctic sea-ice extent from direct historical observations and whaling records. *Climatic Change* **92**, 461-493.

48. King JC, Harangozo, SA. 1998 Climate change in the western Antarctic Peninsula since 1945: observations and possible causes. *Ann. Glaciol.* **27**, 571-575.

49. Curran MAJ, Vanommen, TD, Morgan, VI, Phillips, KL, Palmer, AS. 2003 Ice core evidence for Antarctic sea ice decline since the 1950s. *Science* **302**, 1203-1206.

50. Zhang JL. 2014 Modeling the Impact of Wind Intensification on Antarctic Sea Ice Volume. *Journal of Climate* **27**, 202-214.