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Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion

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Changes in sea ice significantly modulate climate change because of its high reflective and strong insulating nature. In contrast to Arctic sea ice, sea ice surrounding Antarctica has expanded[1], with record extent[2] in 2010. This ice expansion has previously been attributed to dynamical atmospheric changes that induce atmospheric cooling[3]. Here we show that accelerated basal melting of Antarctic ice shelves is likely to have contributed significantly to sea-ice expansion. Specifically, we present observations indicating that melt water from Antarctica's ice shelves accumulates in a cool and fresh surface layer that shields the surface ocean from the warmer deeper waters that are melting the ice shelves. Simulating these processes in a coupled climate model we find that cool and fresh surface water from ice-shelf melt indeed leads to expanding sea ice in austral autumn and winter. This powerful negative feedback counteracts Southern Hemispheric atmospheric warming. Although changes in atmospheric dynamics most likely govern regional sea-ice trends[4], our analyses indicate that the overall sea-ice trend is dominated by increased ice-shelf melt. We suggest that cool sea surface temperatures around Antarctica could offset projected snowfall increases in Antarctica, with implications for estimates of future sea-level rise.

In the Antarctic and Arctic regions, the temporally varying sea-ice extent is one of the main features associated with climate variability and long-term changes, both on the seasonal and multi-year timescales. In the Arctic, observations reveal that sea-ice area, extent[2] and volume[5] have been declining rapidly during the past decades, with the trend in extent being $-5.3 \pm 0.6\%$ per decade since 1985 (2σ error; the September trend has reached as much as $-27 \pm 8\%$ per decade since 1995). This strong sea-ice retreat is considered to be associated with global climate warming. However, sea ice does not respond passively to climate change. Sea-ice retreat reinforces climate warming through the surface-albedo feedback, and is as such a prominent contributor to amplified Arctic warming[6]. In the Southern Hemispheric polar region, however, ongoing climate change differs radically from that in the north. One of the most vivid examples of that is Antarctic sea-ice area, which has been increasing at a statistically significant rate of $1.9 \pm 1.3\%$ per decade since 1985 (annually averaged; 2σ error, $p < 0.01$). This increase has a pronounced seasonal cycle, peaking in austral autumn and early winter[1]. (Generally, Antarctic sea-ice concentration trends may be affected by a discontinuity in the observations[7], but the effect on Autumn (extent) trends is probably limited, as these are in line with local temperature trends.) Against the background of global climate warming, the expansion of Antarctic sea ice (Fig. 1a) is an exceptional feature, which seems to be associated with decreasing sea surface temperatures (SSTs) in the Southern Ocean (Fig. 1b). Both observed sea-ice trends (positive) and SST trends (negative)

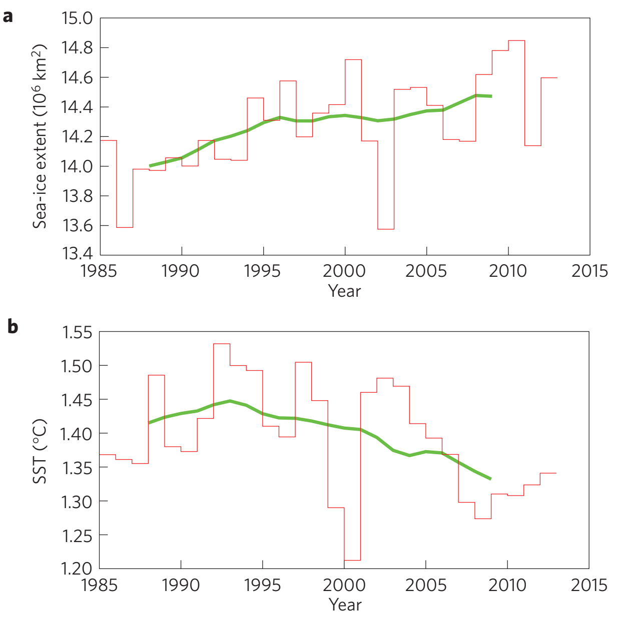

Figure 1 | Austral winter half-year (April–September) trends in sea-ice extent (total Southern Hemisphere) and SST (averaged over 50°–90° S). **a**,**b**, Sea-ice extent trends (**a**) are based on a combination of data from the final analysis[2], the preliminary analysis and near-real-time data (2009–2012); SST data (**b**) were taken from the NCEP (National Centers for Environmental Prediction) merged satellite data set and the *in situ* SST data set SST OI v2 (ref. 29; the same data sources apply for Figs 2 and 3). The green line represents the 10-year running mean.

are maximum near the sea-ice margin (where ice expansion can occur), in particular north of the Ross Ice Shelf (Fig. 2).

A number of mechanisms have been proposed to explain this anomalous increase in Antarctic sea ice. One theory suggests that it is due to a negative sea-ice/ocean feedback, in which the ocean heat flux available to melt sea ice has decreased as a result of sea-ice-induced upper-ocean density changes[8]. Another explanation relates to the present positive trend in the Southern Annular Mode (SAM), which involves an intensification and southward migration of the Southern Ocean westerlies. This causes stronger dynamic isolation (through a reduced poleward heat transport) and a subsequent atmospheric cooling of the Antarctic regions[3,9]. As the austral autumn and winter SAM index is found to have increased steadily from the 1980s up to 2000, this would favour Antarctic cooling and sea-ice expansion; we indeed find that the SAM partly explains the total autumn sea-ice trend (albeit by only about 25%, see Supplementary Information) through governing sea-ice trends

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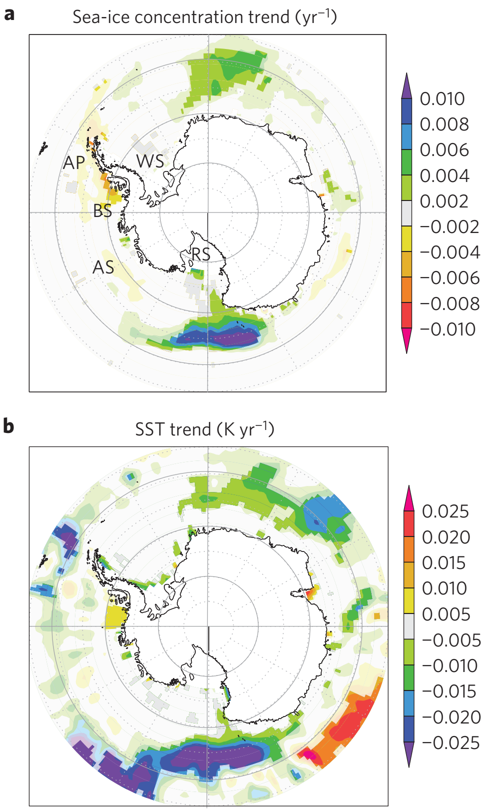

Figure 2 | Spatial distributions of Antarctic sea-ice concentration and SST trends over the period 1985–2010. a,b, Sea-ice concentration trends (**a**) and SST trends (**b**). Colouring (bright or faint) indicates whether the trends are significant (yes or no) at $p < 0.1$ according to a two-sided t-test. The locations of the Antarctic Peninsula (AP), Amundsen Sea (AS), Ross Sea (RS), Weddell Sea (WS) and Bellingshausen Sea (BS) are indicated in **a**.

in certain regions (for example, the Amundsen Sea[9]); significant regional correlations were also found using other atmospheric dynamics indices[4,10]. Similar dynamical influences were proposed to result from observed decreases in stratospheric ozone[11], but we find no correlation between ozone and sea ice beyond common trends (Supplementary Information).

An alternative mechanism that potentially contributes to observed increases in Antarctic sea ice involves increased mass loss of the Antarctic ice sheet as caused by ocean warming and subsurface ice-shelf melt. Whereas in most regions the upper layers (~100 m) of the Southern Ocean adjacent to Antarctica have cooled during the past decades (a notable exception includes the Bellingshausen Sea, see Fig. 2, which exhibits a warming trend and a concurrent reduction in sea ice), the remainder of the upper 1,000 m warmed significantly since the 1930s[12] in conjunction with climate warming. In fact, subsurface Southern Ocean seems to have warmed faster than any other part of the world oceans[13], with relatively warm Circumpolar Deep Water (CDW) protruding onto the continental shelves[1] through submarine troughs. However, this transport of CDW towards the sub-ice-shelf cavities is prone to substantial variability involving local feedbacks[14]. Basal ice-shelf melt thus largely depends on warming of CDW as well as on the effectivity by which CDW can reach the ice shelves[14]. In any case, warm subsurface water has significantly enhanced basal melt rates of the Antarctic ice sheet, in particular the ice shelves, as suggested by a number of observational[15] and modelling[16] studies, because ice shelves are very sensitive to ocean temperature changes[1]. Ocean warming is quite effective in melting ice at the ice/ocean interface, eroding the marine-based parts[17]. Ice-sheet mass imbalance estimates show that at present Antarctica loses

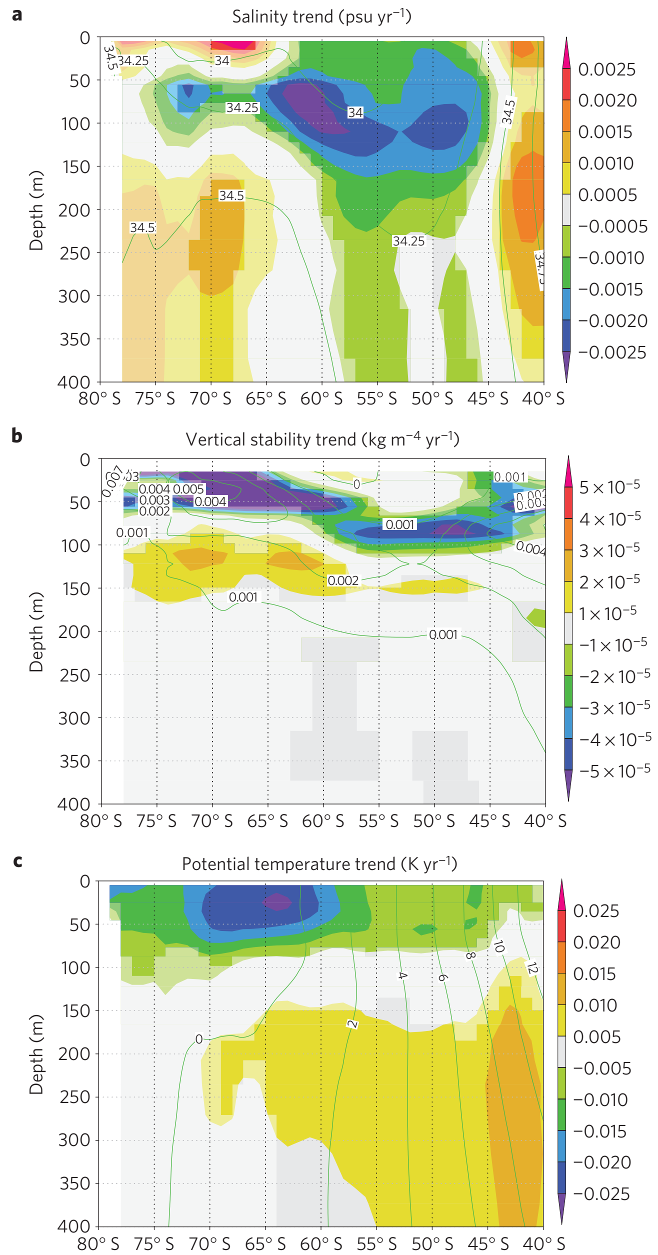

Figure 3 | Austral winter half-year (April–September) zonal mean trends (1985–2010) of observed salinity, vertical density gradient and potential temperature, in the Southern Ocean. a, Salinity. **b**, Vertical density gradient. **c**, Potential temperature. Contours indicate the 1985–2010 mean state (psu, kg m^{-4}, °C). Colouring (bright or faint) indicates whether the trend is significant (yes or no) at $p < 0.1$ according to a two-sided t-test. The near-surface increase in salinity between 65° and 70° S is most likely due to brine rejection when sea ice forms. The sub-surface ocean observations were taken from the Met Office EN3 analysis, which is based on *in situ* observations[30].

about 250 Gt of mass annually, and basal melt is occurring at a significant number of ice shelves around the entire continent[18]. Antarctic mass loss seems to be accelerating[19] and will most likely continue to increase in the future when relatively warm CDW will be able to reach the southernmost ice shelves[20].

Melt water from the ice shelves has a comparatively low density and therefore accumulates in the top ocean layer[15]. Observations confirm that the upper ocean layers get fresher (Fig. 3a), with the resulting cold halocline[21] stabilizing the ocean[22] at the base of this layer—between 100 and 200 m depth (Fig. 3b). This reduces

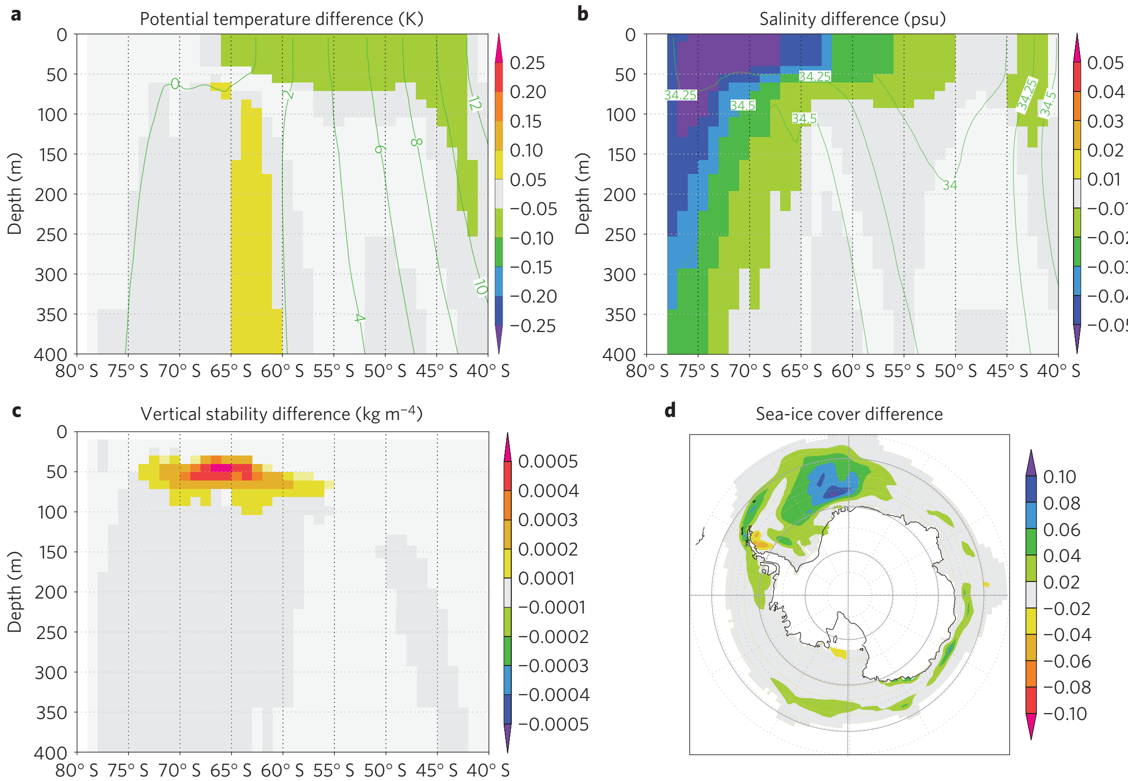

Figure 4 | Simulated changes in austral winter (April–September) temperature, salinity and sea-ice cover resulting from a 250 Gt yr^{-1} increase in Antarctic mass loss (relative to the control run). a, Zonal mean potential temperature change. **b**, Zonal mean salinity change. **c**, Zonal mean vertical stability change. **d**, Spatial sea-ice concentration change. In **a–c** contours indicate the 31-year mean states in °C, psu and kg m^{-4}, respectively. Results represent means over the 31-year simulation period. In **a–c** colouring (bright or faint) indicates whether the difference is significant (yes or no) at $p < 0.1$ according to a two-sided *t*-test.

convective mixing between the cold, fresh surface waters and the warmer, saltier subsurface layers in winter, associated with the deepening of the winter mixed layer. As a consequence, the overlying cold atmosphere cools the upper 100 m more effectively (Fig. 3c), especially in autumn and winter when the atmosphere–ocean temperature contrast peaks. These relatively cold and fresh surface waters can then freeze over more easily, which probably explains why observed Antarctic sea-ice trends peak in autumn and early winter[1] in regions where the surface waters have become fresher (Fig. 2). The Southern Ocean thus exhibits a remarkable signature, with warming in the deeper layers being accompanied by a cooling trend in the upper 100 m. This is consistent with our hypothesis that increased subsurface melt of ice shelves[23] contributes significantly to Southern Ocean surface cooling. We predict that this mechanism will be a sizable contributor to the factors that regionally and seasonally offset greenhouse warming and the associated sea-ice retreat (an analogous mechanism may contribute to increased sea ice around Greenland, see Supplementary Information).

A good test of the meltwater-induced sea-ice expansion would be a coupled climate model reproducing the observed changes. For that reason we performed an idealized sensitivity experiment by forcing a state-of-the-art global coupled climate model (EC-Earth[24]) with an increase in meltwater flux from Antarctica (see Methods) that is representative for the observed changes over the past decade. Similar to the observed trends, the enhanced melt water accumulates in a cool, fresh layer surrounding the continent (Fig. 4a,b), thereby increasing the vertical stability (Fig. 4c) and promoting sea-ice expansion (Fig. 4d) through the proposed mechanism. Even though (spatial) details of the simulated effects differ from the observed trends (which is probably related to the simplified freshwater forcing, to model deficiencies, and to other regional effects on sea-ice expansion, see Supplementary Information), the climate model simulations clearly confirm that the mechanism proposed here indeed causes sea ice to increase at a rate larger than the natural variability of the coupled climate model. We also performed further long simulations using an ocean-only model (see Supplementary Information), which also indicate that expanding Antarctic sea ice and reduced SSTs are governed by realistic increases in ice-shelf basal melting, and only to a lesser extent by atmospheric forcing.

A number of observational studies have related recent sea-ice trends and variability to changes in atmospheric dynamics[4,10,25]. These indeed show significant correlations between atmospheric dynamics indices (for example SAM and Antarctic Oscillation) and regional sea-ice trends, mainly surrounding West Antarctica: in the Ross and Weddell seas[25], the Ross and Amundsen seas[10], Antarctic Peninsula region[4] and the Amundsen Sea[9]. Recently, it was demonstrated that surface-wind-driven trends in ice advection can be linked to regional sea-ice concentration trends[26]. Meridional (surface) winds do indeed explain local sea-ice variations, but owing to their barotropic nature, for every region where winds advect sea ice northward there is another region with southward winds, implying that the net effect on sea ice is small. Indeed, total atmospheric-variability-induced sea-ice trends were found to be small and not significant[9]. We find here that the autumn SAM trend does in fact explain about one-quarter of the total sea-ice trend, but that it does not explain observed SST trends (Supplementary Information). Our modelling results show that subsurface ice-shelf melt leads to sea-ice increases and concurrent SST cooling (Fig. 4) through the mechanism proposed here; atmospheric dynamics dominate regional sea-ice trends, in particular in the seas surrounding West Antarctica, which (at least partly) explains the differences between observed (Fig. 2a) and simulated sea-ice changes (Fig. 4d).

Virtually all state-of-the-art coupled climate models do not incorporate realistic changes in ice-sheet mass, let alone temperature-dependent ice-shelf basal melt. This is one of the reasons (besides inaccurate model sea-ice and ocean-temperature climatologies) why most climate models fail to simulate sea-ice expansion over the past few decades; instead they project a steady decline in sea ice, albeit slower than in the Arctic. Not surprisingly, they also project a strong reduction in sea ice for the twenty-first century (for an average radiative forcing scenario), which may well be unrealistic if our hypothesis of a strong negative sea-ice feedback is correct. This deficiency also potentially affects estimates of ongoing and future sea-level rise, as virtually all present climate models (which exclude this mechanism) predict an increase in precipitation rate over the Antarctic ice sheet as part of the atmospheric warming signal[27]. In contrast, observations show that accumulation over the Antarctic ice sheet has remained fairly constant over the past decades[28], in line with its theoretical and statistical connections to SST in the Southern Ocean. The cooling feedback therefore results in an underestimation of eustatic sea-level rise.

Given the likely strong effect on sea-ice extent during the past few decades, and present projections of accelerating subsurface Southern Ocean warming and Antarctic ice-shelf melt in the near future[17,19,20], we anticipate that the proposed mechanism may continue to contribute to expanding sea ice and significantly reduced surface warming (or even continued cooling) in the Southern Ocean for the coming years/decades. As such, the link between subsurface ocean warming (which is associated with climate warming), ice-sheet mass loss by ice-shelf melt, and expanding sea ice may constitute a feedback that has the potential to oppose Southern Hemispheric atmospheric warming and amplify increases in global sea level.

Methods

As interactions between ice-sheet runoff/melt, ocean and atmosphere are key to the proposed mechanism, a global coupled climate model is required to simulate its effect. For this purpose we use the recently developed Earth system model EC-Earth[24], which encompasses the following components: atmosphere, ECMWF's Integrated Forecast System, resolution T159L62; ocean, NEMO V2, resolution 1°; sea ice, LIM2, resolution 1°; coupled through the OASIS3 coupler. The performance of EC-Earth in terms of its simulation of the present-day climate (means, spatial patterns, seasonal cycle, and variability) is quite good[24] even though EC-Earth, like most coupled climate models, has difficulties in accurately simulating certain aspects of the Southern Ocean (such as thermocline depth). As a control experiment, the model was run with present-day (year 2000) forcing for 440 years. We then performed a 31-year sensitivity experiment, which consists of adding an additional 250 Gt of fresh water annually[19] to the surface waters adjacent to Antarctica (the top ocean model layer), distributed uniformly around the coast (the control run has a reference Antarctic runoff of 1,905 Gt yr^{-1}). Note that this is (necessarily) a schematic sensitivity test, and that results should therefore be interpreted generically (meaning that, for instance, in certain regions the effects of the extra melt water may be—partially—counteracted by other physical mechanisms, or by random model variability).

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Author contributions

G.J.v.O., R.B. and S.D. developed the ideas that led to this paper. G.J.v.O. analysed the observational data. B.W. and R.B. conducted the climate model experiments and analyses. R.B. wrote the main paper, with input from all authors, who discussed the results and implications and commented on the manuscript at all stages.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.B.

Competing financial interests

The authors declare no competing financial interests.