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The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice

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ABSTRACT. Observations show that, in contrast to the Arctic, the area of Antarctic sea ice has increased since 1979. A potential driver of this significant increase relates to the mass loss of the Antarctic ice sheet. Subsurface ocean warming causes basal ice-shelf melt, freshening the surface waters around Antarctica, which leads to increases in sea-ice cover. With climate warming ongoing, future mass-loss rates are projected to accelerate, which has the potential to affect future Antarctic sea-ice trends. Here we investigate to what extent future sea-ice trends are influenced by projected increases in Antarctic freshwater flux due to subsurface melt, using a state-of-the-art global climate model (EC-Earth) in standardized Climate Model Intercomparison Project phase 5 (CMIP5) climate-change simulations. Virtually all CMIP5 models disregard ocean–ice-sheet interactions and project strongly retreating Antarctic sea ice. Applying various freshwater flux scenarios, we find that the additional fresh water significantly offsets the decline in sea-ice area and is even able to reverse the trend in the strongest freshwater forcing scenario that can reasonably be expected, especially in austral winter. The model also simulates decreasing sea surface temperatures (SSTs), with the SST trends exhibiting strong regional variations that largely correspond to regional sea-ice trends.

KEYWORDS: sea ice

INTRODUCTION

In contrast to the Arctic, observations indicate that sea ice near Antarctica has been expanding over the past few decades (Turner and Overland, 2009; Collins and others, 2013). This is a counter-intuitive observation, since it requires an explanation of how two seemingly opposing factors, namely an increase in sea ice and climate warming, can coexist. Various mechanisms have been proposed to explain this 'paradoxical' increase in Antarctic sea ice. Changes in atmospheric dynamics and winds are generally considered to be an important driver of regional sea-ice trends especially (e.g. Raphael, 2007; Goosse and others, 2009; Holland and Kwok, 2012). Ozone and greenhouse forcings cool the Antarctic stratosphere, which increases the stratospheric vortex and thereby the tropospheric zonal winds (Thompson and Solomon, 2002). The associated increase in the Southern Annular Mode (SAM) index signifies intensified westerlies and a more rigorous thermal isolation of the Antarctic continent, causing cooling and an increase in sea-ice cover (Thompson and Solomon, 2002).

Other mechanisms that potentially contribute to increases in Antarctic sea ice include increased ocean stratification due to enhanced run-off (e.g. Swingedouw and others, 2008) causing diminished convective overturning (Aiken and England, 2008), increased precipitation (Marsland and Wolff, 2001; Liu and Curry, 2010), and sea-ice–ocean feedbacks (Zhang, 2007). Basal melt from Antarctic ice shelves induced by deep-ocean warming has also been identified as an important cause of Southern Ocean surface freshening and sea-ice increases (Hellmer, 2004; Bintanja and others, 2013). The Antarctic ice sheet has been losing mass over the past two decades (Rignot and others 2011); moreover, Antarctic ice-shelf melt is widespread (Pritchard and others, 2012) and most likely accelerating, providing a potentially potent mechanism to relate subsurface ocean warming (Gille, 2008; Yin and others, 2011) to an increase in sea ice.

Whereas observations depict a small yet significant increase in the area of Antarctic sea ice over recent decades (Cavalieri and others, 1996), virtually all climate models simulate a strong decrease (Collins and others, 2013). This mismatch may be attributed primarily to the fact that current global climate models do not incorporate ice-sheet/shelf–climate interactions, even though they do simulate ozone depletion, increased precipitation and the effects of these on winds, sea surface temperature (SST) and sea ice. Hence, ocean–shelf interactions and the associated changes in subsurface (basal) melt are disregarded in current global climate models. Simulations with a state-of-the-art global climate model including extra Antarctic fresh water (Bintanja and others, 2013) clearly suggest that ocean–ice-shelf interactions may be at least partly responsible for the added fresh water and associated ocean surface cooling required to oppose the downward sea-ice area trend, although simulations with an Earth system model suggests that this effect may not be strong enough to reverse the trends to match the observed sea-ice area trend (Swart and Fyfe, 2013).

In any case, since recent coupled regional ocean–ice-shelf models indicate that ice-shelf melt will increase and possibly even accelerate in the future (e.g. Hellmer and others, 2012; Timmermann and Hellmer, 2013), the contribution of Antarctic basal melt and the associated freshwater production to sea-ice trends will likely increase in the future. In this paper we test the effect of additional fresh water on Antarctic sea-ice and SST trends by deploying the state-of-the-art global climate model EC-Earth (Hazeleger and others, 2010) in standardized future climate-change simulations with extra fresh water added around the Antarctic continent (Bintanja and others, 2013). We will present and analyze the overall, seasonal and spatial trends in sea-ice area and SST for various magnitudes of the freshwater forcing, so as to infer to what extent future increases in Antarctic ice-shelf melt will contribute to sea-ice and SST trends in the Southern Ocean.

METHOD

Here we use a similar methodology and model set-up to that used by Bintanja and others (2013), who addressed the effects of increased fresh water on simulated sea-ice trends over recent decades. We use the recently developed Earth system model EC-Earth version 2.3 (Hazeleger and others, 2010). In this model the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (resolution T159L62) is used for the atmospheric component; NEMO V2 (46 vertical layers of variable depth, with the top layer thickness 10 m; horizontal resolution 1°) for the ocean; LIM2 (resolution 1°) for sea ice – all numerically coupled by the OASIS3 coupler. EC-Earth simulations of the current climate compare well with observations with regard to means, spatial patterns, seasonal cycle and variability (Hazeleger and others, 2012), even though EC-Earth, like most coupled climate models, has problems in accurately simulating certain aspects of the Southern Ocean (e.g. SSTs and thermocline depth) (Sterl and others, 2012). More specifically, EC-Earth exhibits a warm bias in terms of Southern Ocean SSTs, which leads to present-day minimum and maximum sea-ice extents (Fig. 1) that are somewhat too small compared with observations, especially in summer.

EC-Earth was part of the Climate Model Intercomparison Project, phase 5 (CMIP5). As such, an ensemble of standardized historical and future forcing simulations were carried out (Taylor and others, 2012). For the purpose of this study we focus on the future scenario RCP8.5, which causes the strongest warming of all CMIP5 forcing scenarios. In this scenario, greenhouse gases will rise considerably, and stratospheric ozone will recover to some extent (leading to opposing effects on the trends in the strength of the circumpolar stratospheric vortex and thereby on tropospheric circumpolar westerlies). Using the RCP8.5 forcing, which starts in 2006, all contributing CMIP5 models exhibit a strong decrease in Antarctic sea ice (Collins and others, 2013), and so does EC-Earth.

In a similar way to Bintanja and others (2013), we apply a freshwater forcing that is uniform along the Antarctic coastline as an additional water flux into the top ocean model layer (taking into account the latent heat of fusion). In addition to the standard RCP8.5 simulation, which has zero 'extra' freshwater forcing, we have applied four additional idealized freshwater scenarios: 10, 20, 60 and 120 Gt a^{-1} constant input. All simulations are 40 years long, meaning that, for instance, in the 60 Gt a^{-1} increase simulation the accumulated freshwater forcing in year 40 equals 2400 Gt. Recent studies of future freshwater production based on coupled ocean–ice-shelf/sheet models forced with reasonable future ocean-warming rates (Hellmer and others, 2012; Timmermann and Hellmer, 2013) show a wide range of Antarctic ice-sheet mass-loss estimates, including, for instance, an up to 2000 Gt a^{-1} (20 year mean) mass loss for only the Filchner–Ronne Ice Shelf. Based on these results, we consider the 120 Gt a^{-1} freshwater increase to be the maximum scenario that can reasonably be expected in the coming 40 years. To put this into perspective, the 10 Gt a^{-1} scenario is fairly close to the rate that is 'observed' over the past few decades. The rate of increase in additional fresh water is the sole difference between the five model simulations, which all start on 1 January 2006 from the same initial conditions using standardized RCP8.5 radiative forcing (greenhouse gases, aerosols, etc.).

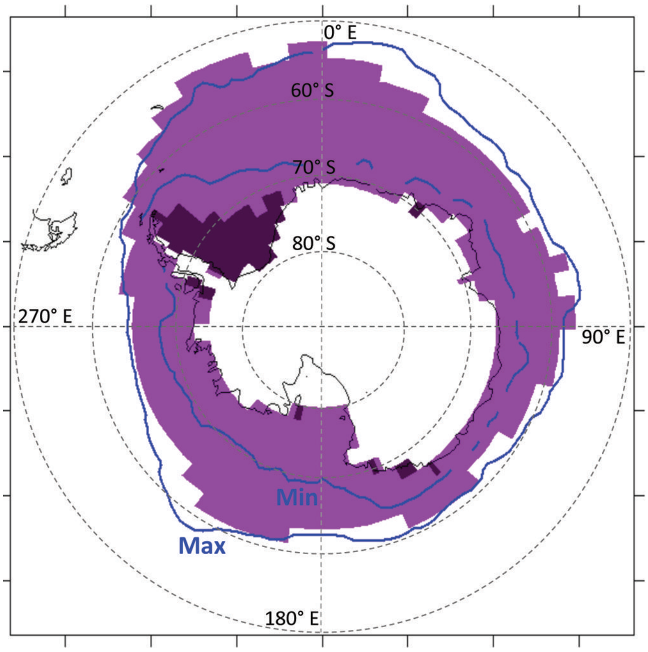

Fig. 1. Geographical distributions of minimum (dark purple) and maximum (light purple) sea-ice cover as simulated by EC-Earth for perpetual present-day (2006) forcing. Coloured regions represent areas with average sea-ice coverage of >10%. Blue lines are observed (Hadley Centre sea-ice and sea surface temperature (HadISST)) sea-ice cover, showing minimum (Min) and maximum (Max) coverage averaged over the period 2000–12 (Rayner and others, 2003); lines represent the 10% coverage limits.

RESULTS

Simulated annual mean Antarctic sea-ice area exhibits a strong downward trend of about –0.4 × 10^6 km^2 per decade for the standard RCP8.5 forcing without additional fresh water (Fig. 2, black line), with strong interannual fluctuations superimposed on this decrease (throughout this paper, trends are determined from linear fits to the simulated time series). This rate of decrease is near the average of the CMIP5 models (Collins and others, 2013). Adding more fresh water progressively diminishes the negative sea-ice trend (Fig. 2), showing the effect of the enhanced ocean stratification on SST cooling and increases in sea ice, as discussed in detail by Bintanja and others (2013). The strongest freshwater forcing of 120 Gt a^{-1} even reverses the sign of the sea-ice trend, which for this extreme scenario is thus positive (albeit slightly). In interpreting these results, one should bear in mind that the RCP8.5 is the strongest of all CMIP5 scenarios, in which simulated Antarctic sea ice strongly declines when additional fresh water is not taken into account. Hence, in these simulations the freshwater–sea-ice feedback has to overcome a relatively high 'background' sea-ice melt rate associated with strong radiative forcing and the accompanying climate warming. Moreover, EC-Earth, like most current global climate models, has a warm bias in the Southern Ocean, and too little sea ice in the current climate (Fig. 1), which probably has an effect on sea-ice trends. Also the top ocean layers in EC-Earth are too

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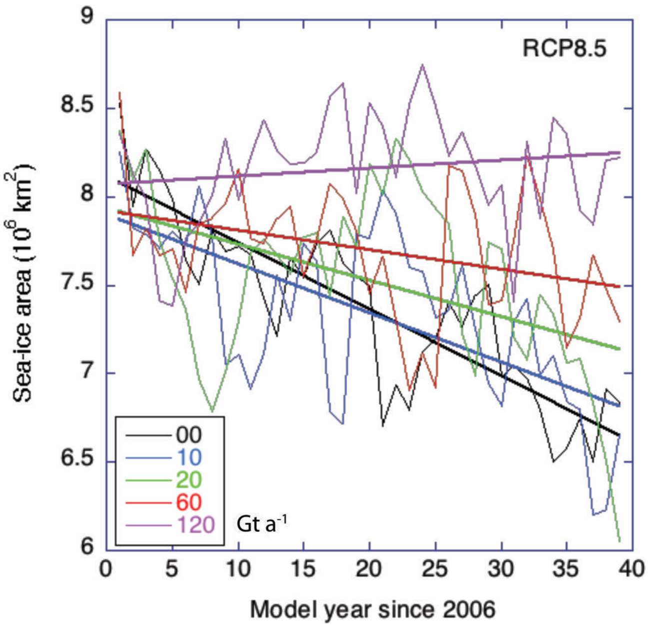

Fig. 2. Simulated annual mean values of Antarctic sea-ice area for the five freshwater forcing scenarios. The black line represents the control run, which equals the 'standard' RCP8.5 simulation without any extra fresh water. The straight lines are the best linear fits (the trends) for the various scenarios. The correlation coefficients of the linear regressions are 0.86, 0.64, 0.44, 0.34 and 0.16 for the 0, 10, 20, 60 and 120 Gt a^{-1} freshwater forcing cases, respectively.

strongly stratified to begin with, rendering any additional stratification due to the input of surface fresh water less effective than it would otherwise have been.

The simulated trends in sea-ice area exhibit a pronounced seasonal dependence, with the strongest simulated freshwater-induced trends occurring in winter (Fig. 3a) in accordance with observed trends in sea-ice area over the past few decades (Turner and Overland, 2009). This also agrees with the findings of Bintanja and others (2013), and is due to the fact that the freshwater-induced cooling of the top ocean layer most effectively promotes increases in sea ice in winter, when the temperature difference between the atmosphere and the ocean surface is greatest. Interestingly, the peak difference in sea-ice area with the standard RCP8.5 simulation shifts to later in the season with increased freshwater forcing. This may be because, with increased freshwater forcing, the main differences in sea-ice cover shift to lower latitudes (i.e. farthest away from the Antarctic mainland), which freeze over progressively later in the season, even though the direct effect of fresh water is obviously strongest closest to the continent, where the fresh water representing enhanced basal melt originates.

Associated with the increased sea-ice-area trend (relative to the zero extra fresh water RCP8.5 scenario) is an overall reduction in SSTs (Fig. 3b). Perhaps surprisingly, the ocean surface cooling is maximum in austral summer, and not in winter when the effect on sea-ice trends is maximum. This is because summer SSTs are generally too warm initially to promote significant changes in sea-ice cover. In autumn and winter the climatological SSTs are low enough for further cooling to promote sea-ice formation in response to the additional fresh water. The annual average relative cooling trend in the strongest freshwater scenario equals –0.12 K per decade, or roughly –0.5 K in the 40 years of simulation. This

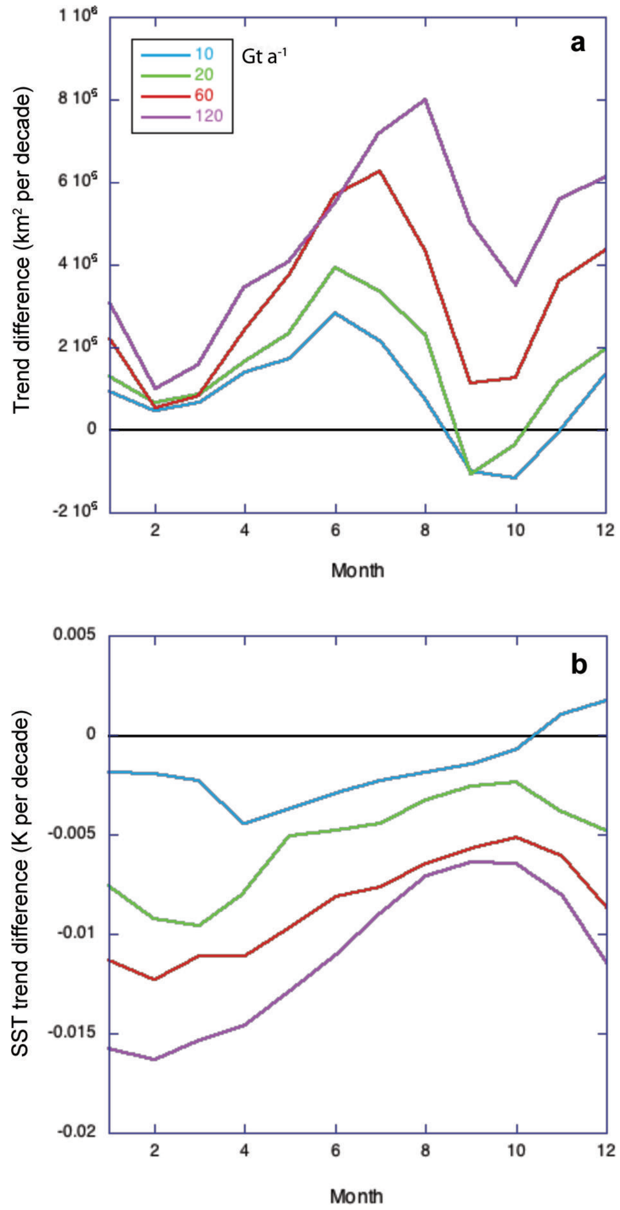

Fig. 3. Monthly trends in (a) Antarctic sea-ice area and (b) sea-surface temperature, averaged over 50–90° S. Values represent the difference between the extra freshwater trends (four cases) and the standard RCP8.5 trend (no extra fresh water) to show the seasonal variation of the effect of additional fresh water on simulated sea-ice area and SST trends.

means that Southern Ocean SSTs south of 50° S will have cooled by ~0.5 K in 2046 in the 120 Gt a^{-1} scenario due solely to the inclusion of extra fresh water.

Apart from their seasonal dependence, the simulated trends in sea-ice area also exhibit strong regional variations (Fig. 4). Whereas in the zero-freshwater scenario, sea ice decreases practically everywhere, adding fresh water to the model produces regions where the trends in sea-ice area become positive. These regions of positive trend in sea-ice area are not always the same for the different freshwater forcing scenarios, however, although some coherence between the difference scenarios is evident (e.g. the persistent negative trend north of the Weddell Sea and the emerging positive trend in the Amundsen Sea). Evidently, there is significant variability (e.g. in atmospheric dynamic modes) to regionally offset or amplify the freshwater-induced trends. In

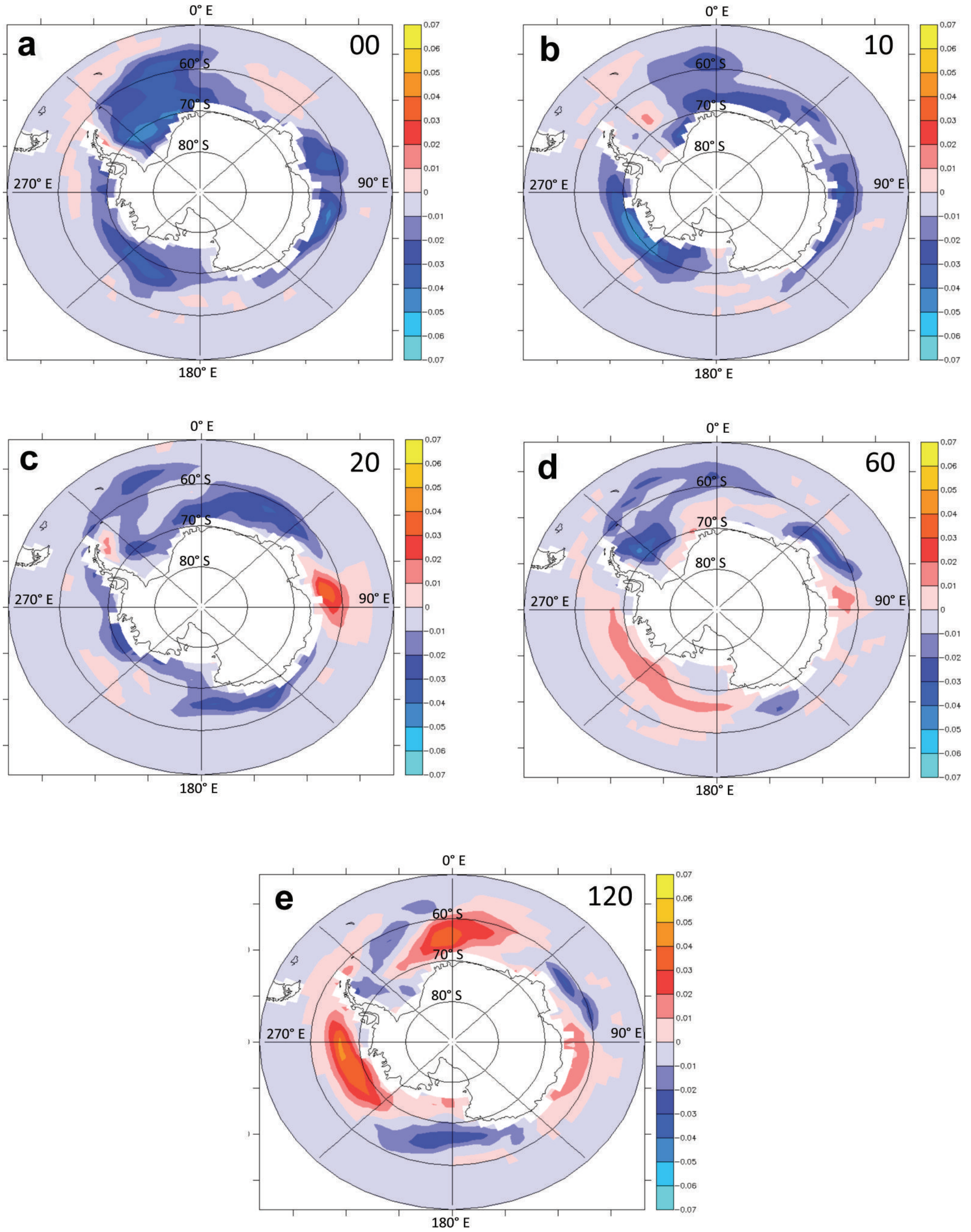

Fig. 4. Geographical patterns of the simulated sea-ice-area trend (unit: per decade) for (a) the no extra freshwater forcing case, (b) 10 Gt a^{-1} freshwater forcing, (c) 20 Gt a^{-1}, (d) 60 Gt a^{-1} and (e) 120 Gt a^{-1}.

particular the alternating positive and negative trends in a wave-like pattern around the Antarctic continent in the 120 Gt a^{-1} simulation suggest that changing modes of atmospheric variability and their associated geographical imprint heavily influence regional sea-ice trends. One reason for this is that the freshwater transport towards the open ocean is quite regionalized owing to the presence of gyres and eddies along the Antarctic coast; this effect can clearly be seen in the simulations of Bintanja and others (2013). Another factor is atmospheric variability, which is known to contribute to a regionalized response (Raphael, 2007; Goosse and others, 2009; Holland and Kwok, 2012): the various model runs will most likely exhibit a different mode of atmospheric variability, thus contributing to regional differences in sea ice. In any case, the overall effect of additional fresh water on the simulated trends in sea-ice area is evident, but superimposed on these are strong regionalized trends that are most likely associated with changing atmospheric dynamics (either variability or long-term trends).

Simulated trends in SST exhibit strong warming all around the Southern Ocean in the no-freshwater scenario (Fig. 5). As with sea ice, this warming trend is regionally offset by the freshwater-induced cooling, with progressively more extensive areas showing cooling trends as the freshwater forcing becomes larger. The strongest freshwater forcing simulations show good coherence between sea-ice increase and SST cooling. A telling example of this is the strong simulated cooling trend in the Amundsen Sea (for the 60 and 120 Gt a^{-1} runs), which is firmly associated with sea-ice increase regions (see Fig. 4). Evidently, also with regard to SST trends the internal climate variability has a considerable impact regionally. One has to bear in mind, however, that the freshwater forcing in our simulations was distributed evenly along the Antarctic coastline, whereas in reality the

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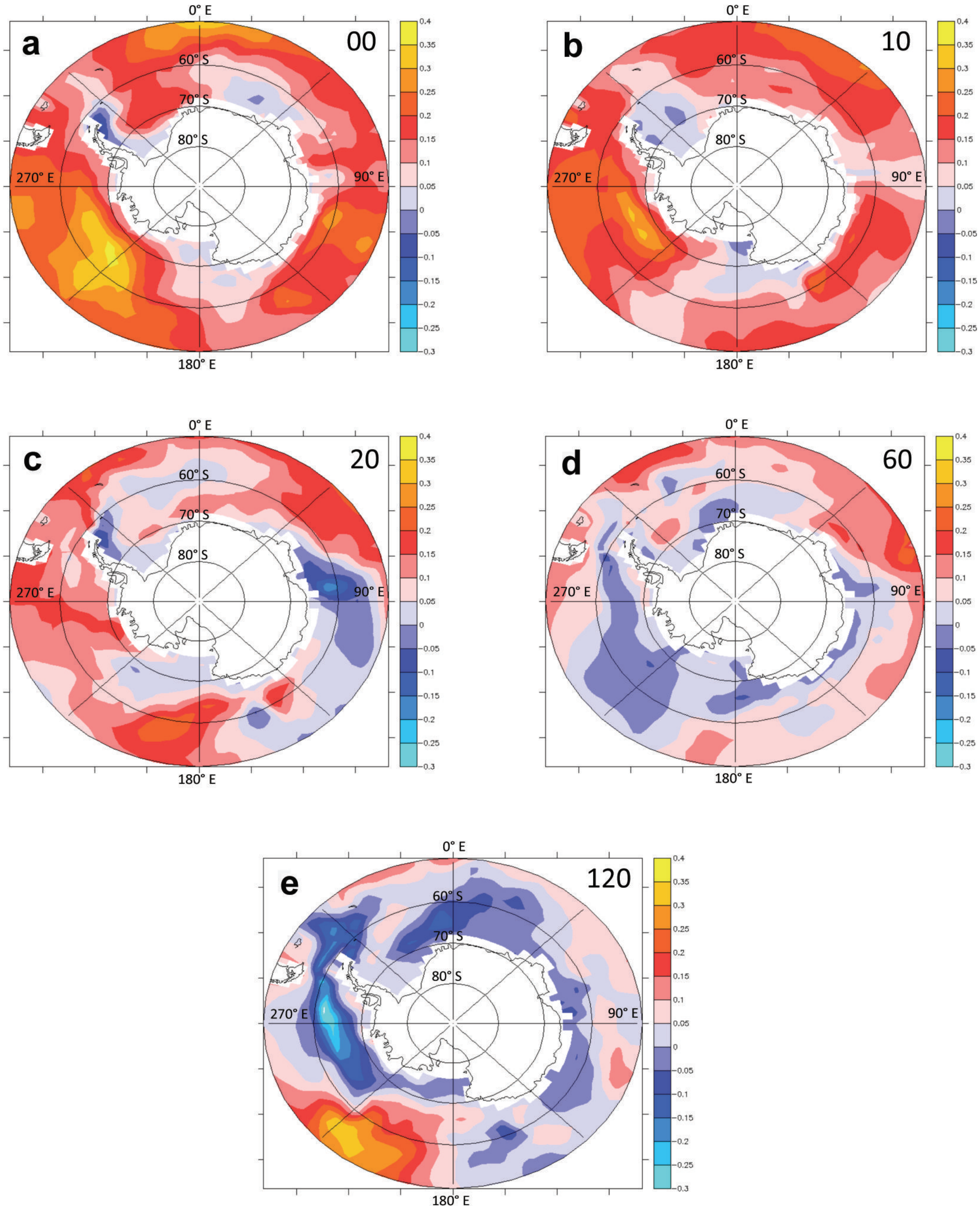

Fig. 5. Same as Figure 4, but for simulated SST trends (K per decade).

freshwater forcing will have a strong regional dependency (i.e. it will vary along the Antarctic coastline depending on where the ice-shelf configuration and ambient ocean warming favor producing basal melt). Hence, this simplified freshwater forcing will undoubtedly affect the corresponding simulated sea-ice and SST trend distributions, even though Swart and Fyfe (2013) found little difference between two freshwater forcing distributions. Moreover, they concluded that fresh water has little influence on the sea-ice trends, which are dominated by internal variability. This inter-model difference clearly calls for a comparison between models (with all models using the same forcing) to assess the reasons behind these differences.

Another possible caveat is that our freshwater forcing is applied in the top ocean layer, whereas in reality the fresh water originates from the base of the ice shelves, which can be down to 1 km below sea level in some regions. Hence, we have implicitly assumed that the fresh water induced by basal melt will ascend rapidly towards the surface, but the specific geometry of both the ice shelf and ocean bathymetry, as well as the prevailing ocean currents, may render this assumption too simplistic to be generically applicable; moreover, part of the basal ice-shelf melt in the Weddell Sea, for example, is immediately incorporated into deep bottom water (Nicholls and others, 2009) and therefore never reaches the surface (meaning that in this sense our freshwater forcing may be an overestimate). For these reasons, it should be borne in mind that the simulated distributions of sea-ice and SST trends as shown in Figures 3 and 4 are subject to significant uncertainty and should therefore be interpreted only in a generic sense.

Given its effect on regional sea-ice trends, does atmospheric variability also play a role with respect to the mean trends? To find out, we consider here the trend in the SAM, since a number of studies have argued that SAM trends adequately characterize changes in the Southern Hemi-

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spheric extratropical atmospheric dynamics. As such, an increase in SAM could affect Antarctic sea-ice trends (see, e.g., Holland and Kwok, 2012) through intensified circumpolar westerlies and the associated continental cooling (in case of a SAM increase). Whereas overall simulated winter half-year sea-ice and SST trends exhibit a consistent change with the magnitude of the freshwater forcing (Fig. 6a and b), the simulated annual trends in the SAM do not show a similar change, although SAM trends may exhibit significant seasonal variations (Thompson and Solomon, 2002) (Fig. 6c). (Bear in mind again that the uncertainties will be much larger locally and/or monthly.) Even though the annual SAM trend is positive in all extra freshwater scenarios, consistent with Antarctic cooling and an increased meridional pressure gradient, the annual SAM trend does not steadily increase with freshwater forcing and is also subject to significant uncertainty (Fig. 6c), which may be related to the opposing effects of stratospheric ozone recovery and accelerating greenhouse forcing mentioned earlier. In any case, our simulations clearly suggest that changes in the SAM are not a dominant driver of overall sea-ice trends, which agrees with Bintanja and others (2013), who showed that the SAM explains only about one-quarter of the total sea-ice area trend. Nonetheless, changes in the SAM probably contribute significantly to regional sea-ice trends, as addressed and demonstrated in various studies (e.g. Raphael, 2007; Goosse and others, 2009; Holland and Kwok, 2012), although Simpkins and others (2012) found no appreciable relation between (seasonal) trends in SAM and those in sea ice.

An interesting feature of Figure 6a and b concerns the apparent leveling-off of the sea-ice and SST trends as the freshwater forcing increases. This suggests that increasing the amount of Antarctic fresh water will not indefinitely affect sea-ice and SST trends. At some point, sea ice may cease to expand further north because there the ambient ocean is too warm and also because the distance between the Antarctic continent and the zones of sea-ice increase becomes too large (diluting the freshening effect of the added Antarctic meltwater). However, Swart and Fyfe (2013) did not see a similar 'saturation' of the effect of fresh water on sea-ice trends, so this could be a model-dependent feature.

Finally, there are indications that variations and trends in precipitation (Marsland and Wolff, 2001; Liu and Curry, 2010) may account for (part of) the surface fresh water that determines variations/trends in vertical mixing discussed here. While precipitation undoubtedly plays a role, there are obvious differences in precipitation forcing versus a freshwater forcing from the Antarctic ice sheet. For instance, the spatial pattern of Antarctic fresh water (all released near the edge of the continent) is markedly different from a precipitation anomaly, which is distributed more evenly over the Southern Ocean. Moreover, it is actually precipitation minus evaporation (of the ocean surface) that drives salinity changes of the ocean surface, which strongly depend on sea-ice cover. This further complicates the associated spatial forcing pattern driving surface salinity changes. Additionally, differences in the seasonality of the forcing play a role. As a result, changes in precipitation are not easily compared with changes in Antarctic mass loss in terms of their effect on sea-ice trends.

CONCLUSIONS

We have assessed the impact of increased (basal) melt rates of the Antarctic ice sheet and the associated freshwater

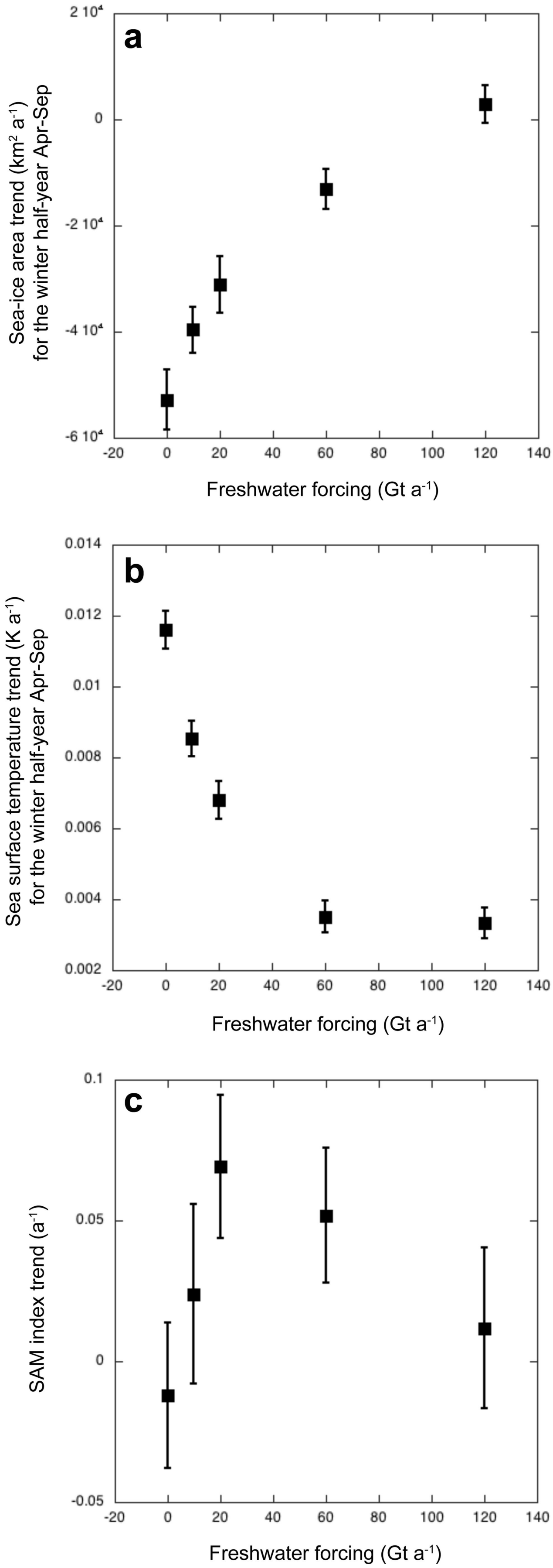

Fig. 6. Simulated trends in (a) winter half-year (April–September) Antarctic sea-ice area, (b) winter half-year (April–September) SST averaged over 50–90° S and (c) annual SAM index, as a function of the applied freshwater forcing. Error bars represent the uncertainty in the trend estimates (i.e. the uncertainty in the slope of the linear fits).

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fluxes on future sea-ice trends in the Southern Ocean through detailed climate model simulations. It is found that projected mass losses of the Antarctic ice sheet impact future sea-ice trends; for the strongest freshwater forcing considered here (120 Gt a^{-1} increase), the strong negative trend in sea-ice area in the no-freshwater simulation is even reversed into a small positive trend. Simulated freshwater-induced sea-ice trends exhibit a strong seasonal dependence, peaking in late fall and winter, when seasonal increases in sea-ice area occur. They also show strong regional variations, mostly coherent with SST trends, which can presumably be attributed to the impact of changing atmospheric variability and wind patterns on the sea-ice trends (and also to the specific way in which the extra fresh water was added in our simulations, i.e. uniformly along the Antarctic coastline). Atmospheric variability is unlikely to have an appreciable effect on the mean sea-ice trends in these model simulations.

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