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# Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current

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**The Antarctic ice sheet loses mass at its fringes bordering the Southern Ocean. At this boundary, warm circumpolar water can override the continental slope front, reaching the grounding line[1,2] through submarine glacial troughs and causing high rates of melting at the deep ice-shelf bases[3,4]. The interplay between ocean currents and continental bathymetry is therefore likely to influence future rates of ice-mass loss. Here we show that a redirection of the coastal current into the Filchner Trough and underneath the Filchner–Ronne Ice Shelf during the second half of the twenty-first century would lead to increased movement of warm waters into the deep southern ice-shelf cavity. Water temperatures in the cavity would increase by more than 2 degrees Celsius and boost average basal melting from 0.2 metres, or 82 billion tonnes, per year to almost 4 metres, or 1,600 billion tonnes, per year. Our results, which are based on the output of a coupled ice–ocean model forced by a range of atmospheric outputs from the HadCM3[5] climate model, suggest that the changes would be caused primarily by an increase in ocean surface stress in the southeastern Weddell Sea due to thinning of the formerly consolidated sea-ice cover. The projected ice loss at the base of the Filchner–Ronne Ice Shelf represents 80 per cent of the present Antarctic surface mass balance[6]. Thus, the quantification of basal mass loss under changing climate conditions is important for projections regarding the dynamics of Antarctic ice streams and ice shelves, and global sea level rise.**

The Weddell Sea (Fig. 1) is dominated by a cyclonic gyre circulation that allows Circumpolar Deep Water to enter only from the east[7]. Within the southern branch of the gyre, the water mass can be identified as the Weddell Sea's temperature maximum at a depth of ~300 m. The temperature decreases from 0.9 °C at the Greenwich meridian[7] to 0.6 °C off the tip of the Antarctic Peninsula[8]. Only traces of the relatively warm water penetrate the broad southern continental shelf[9], reaching the Filchner–Ronne Ice Shelf front with a temperature of −1.5 °C (ref. 10). However, no indications exist that this water mass advances far into the ice-shelf cavity[11]. Instead, locally formed high-salinity shelf water at the surface freezing temperature (about −1.89 °C) fuels a sub-ice-shelf circulation that brings the heat to the deep southern grounding line, where the base of the ice shelf touches the ground. High-salinity shelf water is the densest water mass in the Weddell Sea, and is formed by brine rejection during sea-ice formation on a southward-sloping continental shelf. The need for a dense water mass to transport heat to the grounding line was used as an argument for the Filchner–Ronne Ice Shelf to be protected in a warmer climate[12]. This hypothesis assumes that rising atmospheric temperatures reduce sea-ice formation and, thus, the densification of the shelf water masses. This view considers solely the formation of dense continental shelf water masses in a warmer climate, but less-consolidated sea-ice cover might also influence the Weddell Sea circulation, including the course of the coastal current.

The marine-based West Antarctic Ice Sheet has the potential to contribute 3.3 m to the global eustatic sea-level rise[13]. Its ice shelves fringing the Amundsen Sea are exposed today to Circumpolar Deep Water with temperatures of more than 1 °C. This water mass cascades nearly undiluted from the continental shelf break into ~1,000-m-deep trenches underlying the floating extensions of ice streams that drain the West Antarctic Ice Sheet[14]. Some ice streams from this ice sheet also feed the 449,000-km$^2$ Filchner–Ronne Ice Shelf (Fig. 1), forming the southern coast of the Weddell Sea. These ice streams pass over mountain ranges and thus would not face an increase in basal melting as the grounding line retreats. However, major ice streams entering the Filchner–Ronne Ice Shelf discharge large catchment basins of the East Antarctic Ice Sheet[15]. Once afloat, this ice interacts with the waters of the Weddell Sea.

We forced the Bremerhaven Regional Ice–Ocean Simulations (BRIOS) model[16] with the atmospheric output of two versions of the HadCM3 climate model (Table 1). Whereas HadCM3-A is the baseline simulation used in perturbed physics ensembles[17], HadCM3-B is a model configuration with an interactive carbon cycle and vegetation, and is used in the ENSEMBLES project[18]. We used the output of two simulations of the twentieth century (HadCM3-A (1900–1999) and HadCM3-B (1860–1999)) and the Intergovernmental Panel on Climate Change scenarios E1 (2000–2199)[19] and A1B (2000–2099/2199)[20] (Table 1). These scenarios are characterized by different carbon dioxide emissions, with atmospheric concentrations reaching

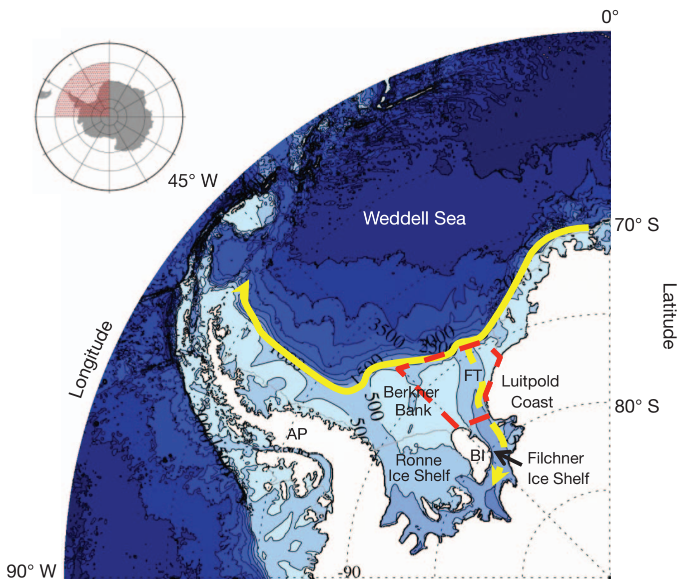


**Figure 1 | Map of Weddell Sea bathymetry south of 60° S.** Bathymetry is based on RTopo-1 (ref. 29) with a colour contour interval of 500 m. Inset represents the model domain, with the red dashed line showing the map location within the circumpolar Southern Ocean. The solid yellow arrow marks the present course of the coastal current in the Weddell Sea. The possibility of pulsing into the Filchner Trough (FT) is marked by the dashed yellow arrow. The region bounded by the dashed red line provided the integrated and mean values in Fig. 3. The solid grey line off the coastline indicates the ice-shelf front. AP, Antarctic Peninsula; BI, Berkner Island.

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**Table 1 | List of BRIOS model experiments**

| Model | Simulation | Period |
|---|---|---|
| HadCM3-A | 20th century | 1900–1999 |
| HadCM3-A | A1B | 2000–2099 |
| HadCM3-B | 20th century | 1860–1999 |
| HadCM3-B | A1B | 2000–2199 |
| HadCM3-B | E1 | 2000–2199 |

Atmospheric forcing was extracted from the results of the climate models HadCM3-A and HadCM3-B. HadCM3-A forcing extends only until 2099 and is not available for the scenario E1. Scenarios E1 and A1B are characterized by different carbon dioxide emissions, with atmospheric concentrations reaching 450 parts per million by volume (p.p.m.v.) and 700 p.p.m.v. by the year 2100, respectively.

450 p.p.m.v. and 700 p.p.m.v. by the year 2100, respectively. BRIOS is a coupled ice–ocean model that resolves the Southern Ocean at latitudes south of $\phi = 50^\circ$ S zonally with a resolution of $1.5^\circ$ and meridionally with a resolution of $1.5^\circ \times \cos(\phi)$. The water column is variably divided into 24 terrain-following layers. The sea-ice component is a dynamic–thermodynamic snow–ice model with heat budgets for the upper and lower surface layers[21] and a viscous-plastic rheology[22]. BRIOS considers the ocean–ice-shelf interaction underneath ten Antarctic ice shelves[16,23] with time-invariant thicknesses, assuming the flux divergence to be in equilibrium with both the surface and the basal mass balance. The model has been successfully validated by the comparison with mooring and buoy observations regarding, for example, Weddell gyre transport[16], sea-ice thickness distribution and drift in the Weddell and Amundsen seas[24,25], and sea-ice concentration related to iceberg drift[26].

Ocean characteristics of the simulations forced with the output of both HadCM3-A and HadCM3-B for the twentieth century agree well with those from hindcasts using the NCEP-reanalysis[27]. In the following, we focus on the results of the runs forced with the output from HadCM3-B for the A1B scenario, because this scenario provides stronger signals and only HadCM3-B extends to the end of the twenty-second century, covering a period of 200 years. For the simulated present-day period, a slope front separates shelf water at the surface freezing point from relatively warm water that is advected to the southern Weddell Sea by the coastal current. However, starting in around 2036, pulses of warm water sporadically cross the 700-m-deep sill of the Filchner Trough at its eastern flank (Fig. 1) but do not reach the southern ice-shelf front (Fig. 2a). As early as 2070, water warmer than 0 °C begins to enter the Filchner Trough continuously (Fig. 2b), reaching the grounding lines of the southern tributaries 6 years later (Fig. 2c). After a further 14 years, the whole trough plus the southern half of the Ronne Ice Shelf cavity are filled with water of open-ocean origin (Fig. 2d). This corresponds to a warming of the deep southern cavity by more than 2 °C. The sporadic flow of warm water into the Filchner Trough during the twenty-first century, as well as its southward

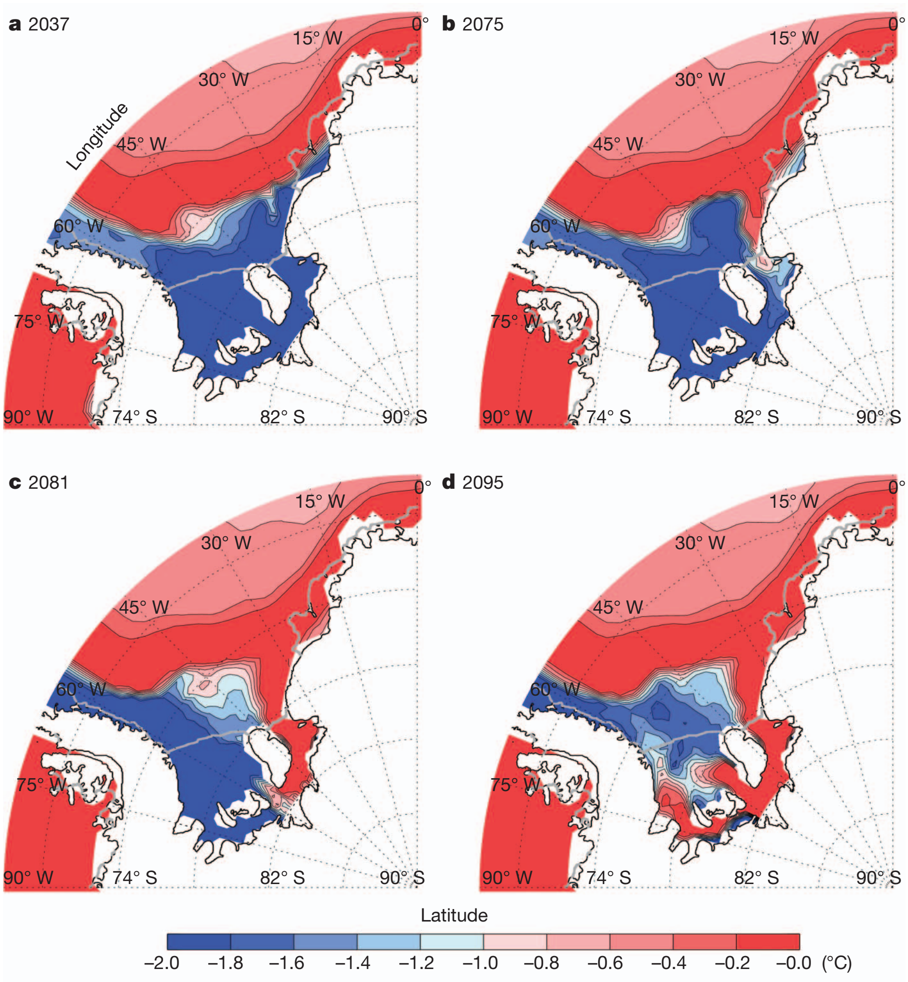


**Figure 2 | Simulated evolution of near-bottom temperatures in the Weddell Sea.** **a–d**, Values are from 60 m above bottom for the period 2030–2099 of the HadCM3-B/A1B scenario. Warm pulses into the Filchner Trough (2037; **a**) are followed by a return of the shelf water masses to the cold state typical for present conditions. The final (unrevoked) destruction of the slope front starts in 2066; by 2075 (**b**), the tongue of slightly modified warm deep water reaches the Filchner Ice Shelf front. It fills the deeper part of the Filchner Ice Shelf cavity and enters the Ronne Ice Shelf cavity near the grounding line south of Berkner Island in 2081 (**c**). By 2095 (**d**), warm water fills most of the bottom layer of the Filchner–Ronne Ice Shelf cavity, reaching a quasi-steady state. We note that a trend in the water mass properties of the interior Weddell Sea is not associated with any of these processes. The solid grey line off the coastline indicates the ice-shelf front.

propagation, is also suggested by results of the finite-element model FESOM[28] when forced with the HadCM3-B/A1B output (Supplementary Information). FESOM is a coupled ice–ocean model that also takes ice shelves into account, but it has a different architecture and a resolution that allows the simulation of eddies. Therefore, the model is expected to react more intensely to moderate perturbations in atmosphere and sea ice. Owing to the higher resolution of the marginal seas (~10 km) in FESOM, the warm water pulses reach the interior of the Filchner–Ronne Ice Shelf cavity less diluted (Supplementary Fig. 4) and thus cause earlier significant increases in basal mass loss (Supplementary Fig. 5).

The analysis of the forcing fields and the BRIOS output reveals that the redirection of the coastal current in the southeastern Weddell Sea is caused locally by an interplay between several climate components. During the twenty-first century, a continuous atmospheric surface warming (up to 4 °C per century) decreases the loss of sensible heat by the ocean. Together with an increase in long-wave downward radiation (up to 10 W $m^{-2}$ per century) this reduces the thickness and concentration of the sea ice, allowing its drift speed to increase and, thus, a more efficient momentum transfer to the ocean surface off the Luitpold Coast (Fig. 3a, b). The enhanced surface stress, which is not related to an increase in atmospheric wind stress, directs the coastal current southwards towards the Filchner–Ronne Ice Shelf front, as it approaches the 700-m-deep sill of the Filchner Trough. The importance of the different atmospheric forcing variables to the redirection of the coastal current and, thus, the increase in melting at the base of the Filchner–Ronne Ice Shelf is investigated by means of additional sensitivity experiments (Supplementary Information). Because about 80% of the changes occur in the twenty-first century, these experiments are confined to the period 2000–2099. The first simulation applies detrended atmospheric forcing variables only, followed by runs in which the trends of 2-m temperature (the air temperature at an altitude of 2 m) and/or long-wave downward radiation were consecutively added.

The warming of the whole Filchner–Ronne Ice Shelf cavity by more than 2 °C boosts average basal melting from 0.2 m $yr^{-1}$ to 4 m $yr^{-1}$ at the end of the twenty-first century, with the maximum exceeding 50 m $yr^{-1}$ near the deep southern grounding line. The values correspond to a jump in basal mass loss from 82 Gt $yr^{-1}$ to ~1,600 Gt $yr^{-1}$ (Fig. 3c), which represents 64% of the simulated circumpolar total. This total increases within two decades from ~1,000 Gt $yr^{-1}$ to ~2,500 Gt $yr^{-1}$. In contrast, basal mass loss beneath the Ross Ice Shelf remains constant at ~80 Gt $yr^{-1}$. A similar drastic change in Filchner–Ronne Ice Shelf basal mass loss and circumpolar ice-shelf basal mass loss also happens in the simulations (Table 1) forced with the A1B output of HadCM3-A, but with a delay of 10 years, and the E1 output of HadCM3-B, but with a delay of 50 years, respectively (Fig. 3c). Owing to our assumption of fixed ice-shelf thicknesses, we cannot accurately predict basal mass losses for long periods of high melting. However, if we assume that grounding lines retreat into deeper basins[29], our melt rates have to be considered as lower bounds. In addition, numerical experiments show that ice shelves adjust to perturbations in ocean temperature on timescales ranging from several decades to a few centuries[30].

As a consequence of the increased input of fresh water due to ice-shelf basal melting, the Weddell Sea surface layer and the water masses on the whole southern and western continental shelves freshen rapidly. Today the high-salinity shelf water of these areas is one ingredient for the formation of deep and bottom waters of the Weddell Sea[7,31]. These water masses change their characteristics as the shelf water freshens.

Given the differences among the climate scenarios and the model realizations, we do not intend to predict the exact date of the changes in the circulation of the southern Weddell Sea. Instead, we emphasize the sensitivity of a small Antarctic coastal region to climate change with potentially severe consequences for the mass balance of a large Antarctic ice shelf. Determining the extent to which this influences the dynamics of the East Antarctic Ice Sheet will require further simulation, forcing a coupled ice-sheet–ice-shelf model with the predicted

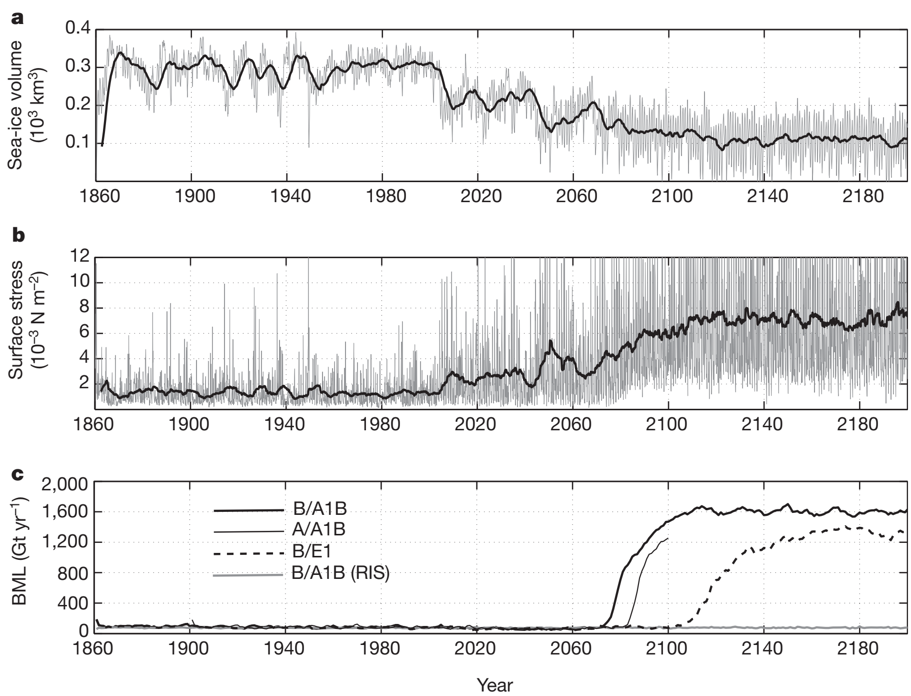


**Figure 3 | Modelled time series (1860–2199) for the southeastern Weddell Sea. a**, Area-integrated (Fig. 1) sea-ice volume for BRIOS forced with the twentieth-century and A1B atmospheric output of the climate model HadCM3-B. Grey and black lines represent monthly means and 5-year running means, respectively. **b**, Area-mean ocean-surface stress, for the same model as in **a**. Not only is the long-term decrease in the sea-ice volume reflected by an increase in the ocean-surface stress, but the coherence also holds for single events (for example, around 1940 and 2050). A correlation coefficient is not provided because of the dominance of the long-term variability. **c**, Basal mass losses (BMLs) in gigatonnes per year. Thin and thick lines represent simulations forced with the atmospheric output of the climate models HadCM3-A and HadCM3-B, respectively. HadCM3-A forcing is available only for the period 1900–2099 and the A1B scenario (Table 1). Solid and dashed lines represent results from forcing with twentieth-century and either A1B or, respectively, E1 output. Black lines show BML for the Filchner–Ronne Ice Shelf and the grey line shows that for the Ross Ice Shelf (RIS).

temperature perturbation. The use of the output of two different configurations of HadCM3 in different scenarios and the confirmation of the BRIOS results by FESOM, a coupled ice–ocean model with higher resolution and a different model architecture, reduces unavoidable uncertainties when dealing with processes related to climate change. Therefore, we are confident that our proposed mechanism is not a model artefact but quite a realistic mechanism. Consequently, we welcome the effort to monitor the coastal current during the upcoming expeditions to the southeastern Weddell Sea.

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**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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