The impact of ocean warming and ice shelf geometry on the basal mass balance of the Filchner Ronne Ice Shelf

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Introduction and model setup

Recent studies have highlighted the impact of the Eastern Weddell Ice Shelves (EWIS) on water masses in the south eastern Weddell Sea (Thoma *et al.*, 2006) and the modifications of ocean warming in this area (Thoma *et al.*, 2007). Both studies used the regional ocean model Rombax, applied to the Eastern Weddell Sea. In this study we extend the model domain into the Weddell Sea to 0°–90°W and 83°–60°W (Figure 1a). The model numerics

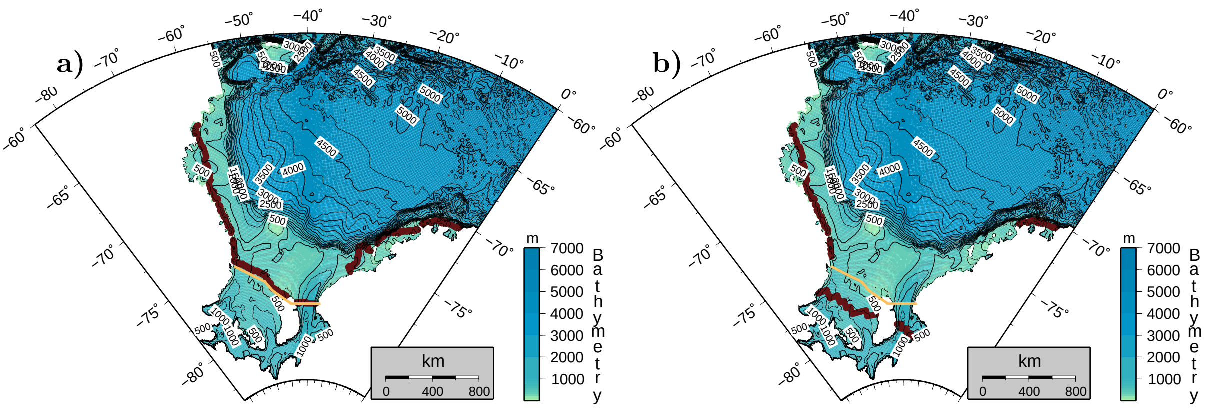

Figure 1: Bathymetry of the model region for scenarios $\mathcal{S}_{\rm CR}$ (a) and $\mathcal{S}_{\rm EF}$ (b). The ice shelf edges is shown in red. The orange line shows the position of track cross sections.

and the model configuration have been described in Thoma *et al.* (2006). Surface restoring of salinity and temperature is based on summer observations (Gouretski *et al.*, 1999). The values are interpolated to a constant temperature of −1.9°C and a latitude and shelf-depth dependent salinity in winter (Figure 2). The chosen winter salinities of 34.4 and 34.5 are adequate in the EWIS region (Thoma *et al.*, 2006) but over the broad continental shelf of the southern Weddell Sea, sea ice production yields to much higher salinities at present (Nicholls *et al.*, 2003). Therefore the actual model study should be seen as a scenario where less sea ice is produced on the Filchner-Ronne shelf, as a result of atmospheric warming, for example (Nicholls, 1997).

We discuss four different scenarios, a control run $\mathcal{S}_{\rm CR}$ and three hypothetical set-ups: In scenario $\mathcal{S}_{\rm E}$ we assume that the EWIS has disintegrated, in scenario $\mathcal{S}_{\rm E}^{0.5}$ an additional

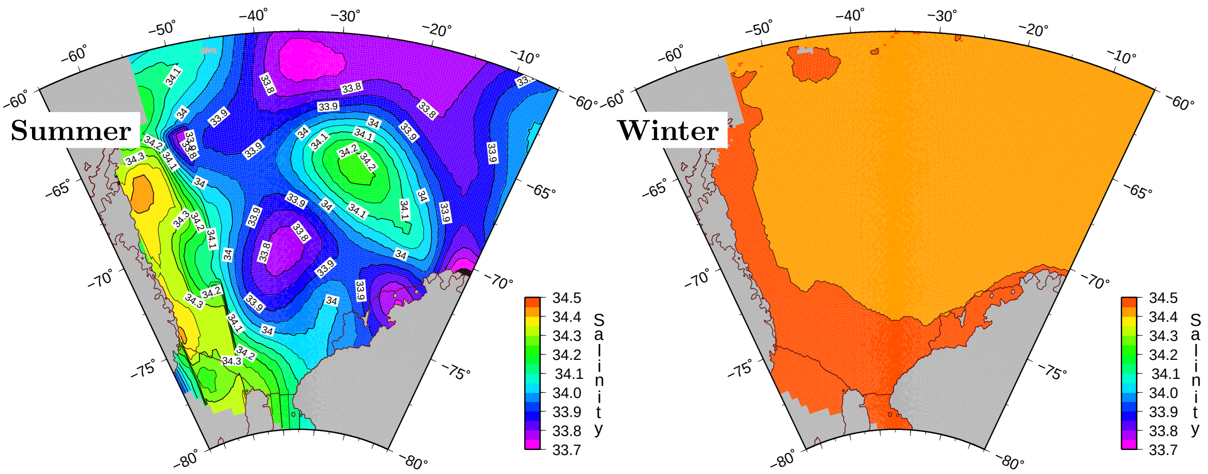

Figure 2: Surface salinity restoring in summer (left) and winter (right).

ocean warming of +0.5°C is applied at the eastern (inflow) boundary, and in $\mathcal{S}_{\mathrm{EF}}$ we assume that the EWIS and parts of Filchner-Ronne Ice Shelf (FRIS) have disintegrated. Note that in this last scenario no ocean warming is applied. The edge of the reduced ice shelf extent is shown in Figure 1b. After the initial spin-up of the model at about 7.5 years (arbitrary chosen) we restart the integrations for the different model scenarios.

Results and discussion

The control run $\mathcal{S}_{\mathrm{CR}}$

The model reaches a quasi steady state after about 20 years (Figure 5). The results presented in this study represent averages over the model years 23 to 28. The modelled basal mass balance of the EWIS region is 1.61 mSv, corresponding to a basal melt rate of 0.68 m/a. In Thoma *et al.* (2006) we determined somewhat higher average values of 2.10 mSv and 0.88 m/a. A possible explanation for this difference on the one hand could be the larger domain of the Weddell Sea model, with the relatively warm inflow at the eastern boundary, which is mostly responsible for the melting in the EWIS region, extending over a greater distance. Hence, the heat provided to the EWIS is smaller than in the regional EWIS study. On the other hand Thoma *et al.* (2006) estimated fresh water production rates of 1.60 to 3.91 mSv, equivalent to 0.67–1.65 m/a of basal melting for varying boundary conditions. Therefore the basal melt rate of the EWIS in the current study is within the limits of the former study. The basal melt rate of FRIS is estimated to be 3.35 mSv or 0.25 m/a in the control run (as shown in Figure 5 and Table 1), comparable to earlier estimates (Grosfeld & Gerdes, 1998a).

Figure 3 shows the vertically integrated mass transport stream function and the basal melt rate over the FRIS region. The negative stream function values around Berkner Island are in agreement with previous model studies (Grosfeld & Gerdes, 1998b; Beckmann *et al.*, 1999). The stronger positive gyre in the Filchner Trough is also a feature of other studies (Grosfeld & Gerdes, 1998a,b) as is the increased circulation north-west of Korff

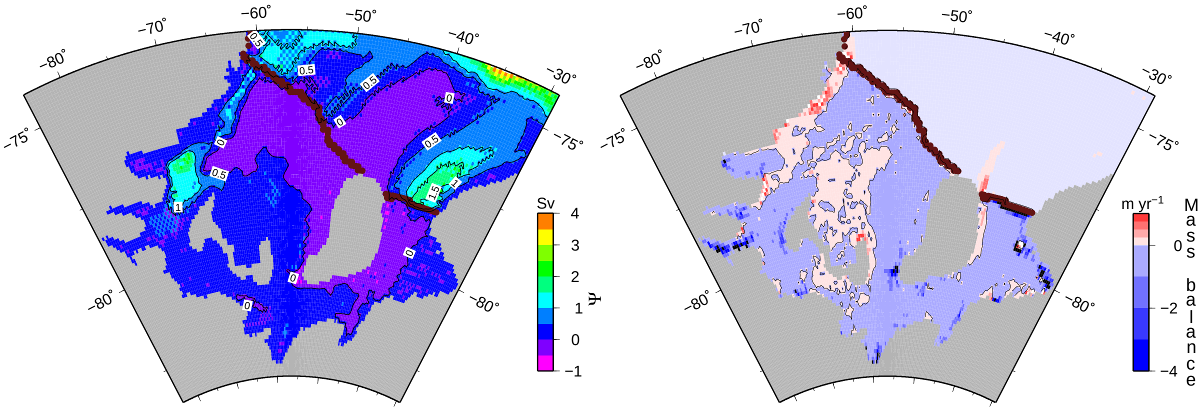

Figure 3: Vertically integrated mass transport stream function (left) and basal melt rate (right) for the control run $\mathcal{S}_{\mathrm{CR}}$.

Ice Rise (Grosfeld & Gerdes, 1998b). The pattern of basal mass balance, with freezing in the western and central Ronne Ice Shelf, and east of Berkner Island, together with basal melting at Filchner Ice Front, and the deep grounding lines, is in close agreement with observations and other model studies (Grosfeld *et al.*, 1998; Grosfeld & Gerdes, 1998b; Sandhäger *et al.*, 2004; Joughin & Padman, 2003).

The bottom layer temperature and a cross section along the track indicated in Figure 1 are shown in Figure 4. The bottom layer temperature shows large areas of warm Modified

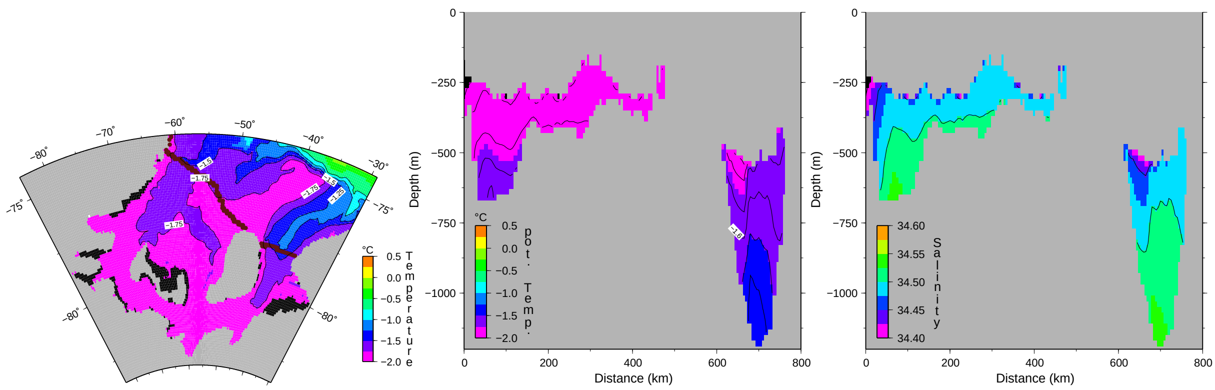

Figure 4: Bottom layer temperature (left), and temperature (middle) and salinity (right) cross sections along the track shown in Figure 1 for the control run $\mathcal{S}_{\mathrm{CR}}$.

Weddell Deep Water (MWDW) crossing the continental shelf and entering the cavity beneath FRIS via the Filchner and Ronne Troughs. The temperature section along the models ice front confirms that relatively warm, low salinity water masses enter these troughs. Observations over the continental shelf and along the ice front region typically show Ice Shelf Water (ISW) occupying the water column below 300–400 m, with salinities of 34.6–34.7 in Filchner Trough and 34.7–34.8 in Ronne Trough (Foldvik *et al.*, 1985; Gammelsrød *et al.*, 1994). The modelled relatively high temperatures and low salinities result from the simplified surface salinity restoring of 34.6 used during winter. The lower density water masses over the continental shelf result in a reduced density contrast between these water masses and the MWDW. Hence these warmer water masses can enter the shelf with relative ease and subsequently the sub-ice shelf cavity.

Scenario Studies

Table 1 and Figure 5 summarise the fresh water production and the basal melt rates for the control run $\mathcal{S}_{\mathrm{CR}}$ and the three scenarios $\mathcal{S}_{\mathrm{E}}$, $\mathcal{S}_{\mathrm{E}}^{0.5}$, and $\mathcal{S}_{\mathrm{EF}}$. All scenarios lead to an overall increased melting at the FRIS. When the EWIS are removed from the model domain no

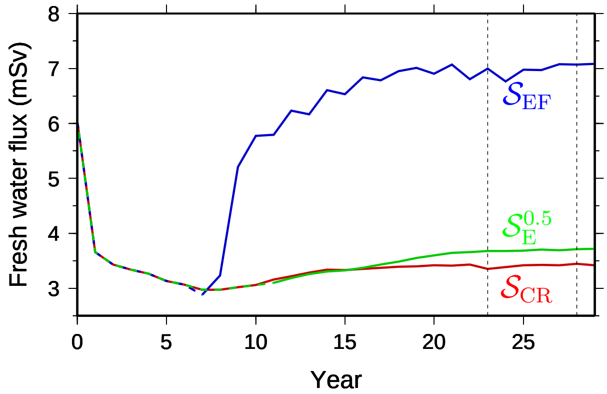

Figure 5: Fresh water production of the FRIS for the control run $\mathcal{S}_{\mathrm{CR}}$ and the scenarios $\mathcal{S}_{\mathrm{E}}^{0.5}$ and $\mathcal{S}_{\mathrm{EF}}$. The dashed line indicates the period that is used to get averaged results.

water mass (pre)cooling or freshening takes place in this region, and warmer water masses reach FRIS. The impact of removing the EWIS (scenario $\mathcal{S}_{\mathrm{E}}$) is a 6.4% increase in basal melt rates beneath FRIS, while the impact of additional warming (scenario $\mathcal{S}_{\mathrm{E}}^{0.5}$) leads to a further increase of only 3.1%. The more surprising result is the 109% increase of fresh water production, when parts of FRIS are removed. Because of the reduced size of FRIS, from $4.2 \times 10^5\,\mathrm{km}^2$ in $\mathcal{S}_{\mathrm{CR}}$ to $2.7 \times 10^5\,\mathrm{km}^2$ in $\mathcal{S}_{\mathrm{EF}}$, the basal melt rate increases to 231.4%. This high melt rate results mainly from the modified circulation pattern, shown in Figure 6a. The clockwise transport in the Filchner Trough is extended southward to the new ice shelf front but is slightly reduced. The anticlockwise flow around Berkner Island is notably increased. However, the anticlockwise circulation along the eastern Ronne Ice Front is replaced by a clockwise circulation extending from the Ronne Trough. This leads to the strongly modified basal mass balance pattern shown in Figure 6b. The freezing east of Berkner Island has mainly ceased and the area north of the ice rises where extended freezing took place in scenario $\mathcal{S}_{\mathrm{CR}}$ is notably reduced. At the same time, melting in the vicinity of the Filchner Ice Front, west of Berkner Island and west of Korff Ice Rise has increased.

Figure 7 shows the impact of the modified geometry and the accompanied circulation

Model	Description	Fresh Water Flux (mSv)	Increase	Aver. Melt Rate (m/a)	Increase
$\mathcal{S}_{\mathrm{CR}}$	Control Run	3.35		0.249	
$\mathcal{S}_{\mathrm{E}}$	No EWIS	3.57	6.4%	0.265	6.4%
$\mathcal{S}_{\mathrm{E}}^{0.5}$	No EWIS & +0.5°C	3.67	9.5%	0.273	9.5%
$\mathcal{S}_{\mathrm{EF}}$	No EWIS & Retreated FRIS	7.00	108.5%	0.826	231.4%

Table 1: Basal melt balance of FRIS for the control run $\mathcal{S}_{\mathrm{CR}}$ and the scenarios $\mathcal{S}_{\mathrm{E}}$, $\mathcal{S}_{\mathrm{E}}^{0.5}$, and $\mathcal{S}_{\mathrm{EF}}$.

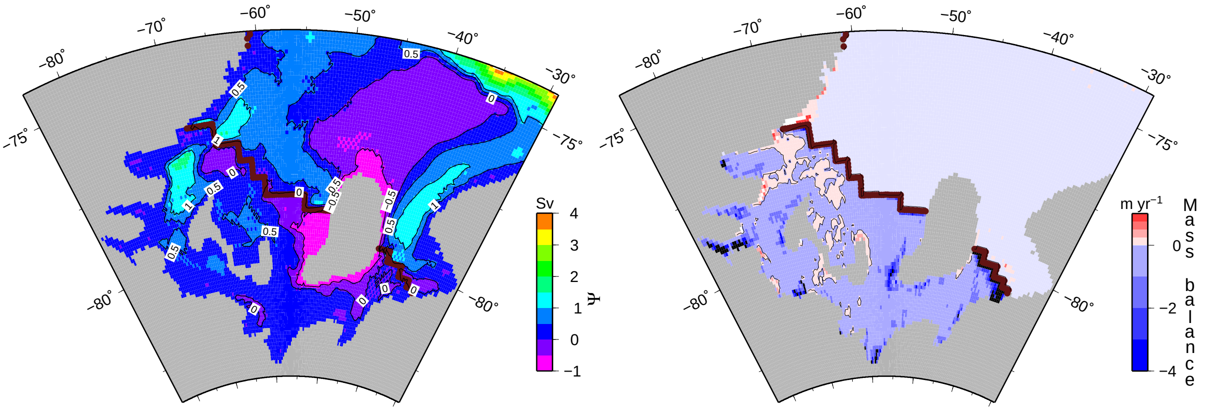

Figure 6: Vertically integrated mass transport stream function (left) and basal melt rate (right) for the scenario $\mathcal{S}_{\mathrm{EF}}$.

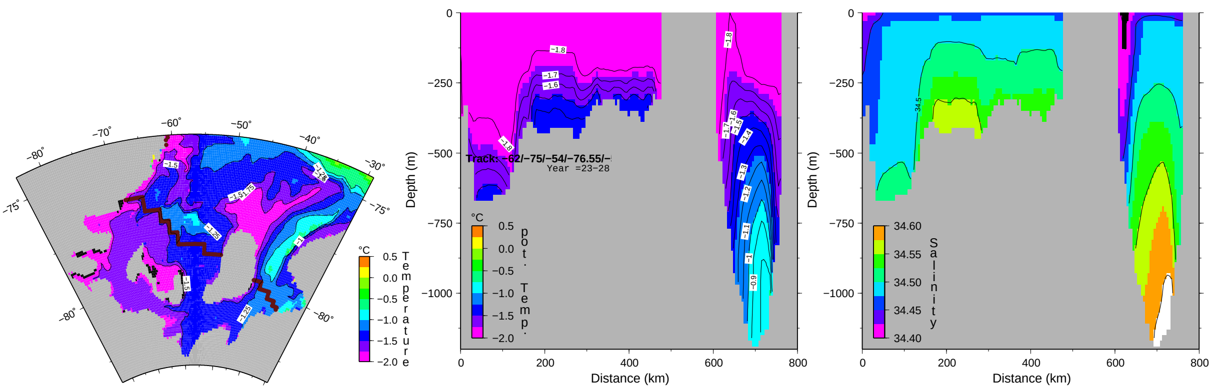

Figure 7: Bottom layer temperature (left), and temperature (middle) and salinity (right) cross sections along the track shown in Figure 1 for the scenario $\mathcal{S}_{\mathrm{EF}}$.

changes on the temperature and salinity distribution. Much warmer and higher salinity waters flood the shelf, particularly in the deep troughs. However, higher in the water column the massive melting freshens the upper water masses, which stratifies (and therefore stabilises) the water column.

Summary

Modelling the ice-ocean interaction in the Weddell Sea we have shown that the EWIS domain preconditions the water masses entering the FRIS embayment. A moderate warming of 0.5°C has less influence on the basal mass balance of FRIS than the existence (or absence) of EWIS itself. Our model forcing is somewhat simplified and does not represent present conditions, but rather those expected in a warmer climate with less High Salinity Shelf Water in the south-western Weddell Sea and more Modified Weddell Deep Water entering the FRIS cavity. However, the pattern of the vertically integrated mass transport and the basal mass balance corresponds well with previous studies and observations. Finally we have shown that the geometry of FRIS is of high importance for water mass formation in the Weddell sea: If the size of FRIS is reduced by about 35%, much warmer waters enter the sub-ice shelf cavity. Consequently the freshwater flux increases by about 109%, corresponding to an increase of the average melt rate of 231%.

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