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# Ocean processes below Fimbulisen - modelling results

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## Introduction

Fimbulisen is the largest ice shelf in the north-eastern Weddell Sea and is unique among major Antarctic ice shelves in the way that it in places overhangs the continental slope (Nøst 2004). The continental shelf north of the $\sim$ 200 m deep Fimbul ice front is a maximum of 40 km wide, meaning that the ice shelf is directly exposed to the Antarctic coastal current. This coastal current act as a dynamic barrier toward the warm Weddell Deep Water (WDW) to the north. WDW, defined by temperatures above 0 °C, has core temperatures up to 1 °C at 200m depth within 200 km of the ice shelf.

A recent circumpolar model study of all Antarctic ice shelves indicate that the freshening and cooling of the water masses due to melting of the ice shelves here has a large scale impact on the Weddell Sea circulation, stratification, sea ice cover, open ocean convection, and deep water characteristics (Beckmann and Goosse 2003).

The deep waters around Antarctica have been warming faster than the average global ocean since 1950 (Gille 2002), and heat content close to the continent along the Greenwich meridian has been increasing steadily over the last 25 years, close to 4 W/m$^2$ on average (Smedsrud 2004). This means that Fimbulisen is likely to be the Antarctic ice shelf that will be first exposed to a global warming signal.

## The Model

We here apply the ocean and ice shelf models of the POLAIR (Polar Ocean Land Atmosphere and Ice Regional) modeling system to the area surrounding Fimbulisen. The ocean component of POLAIR is a version of the MICOM model (Bleck 1998) modified to allow for an ice shelf cavity (Holland and Jenkins 2001). The model grid (Figure 1) covers Queen Maud Land between 12 °W and 12 °E, and incorporates the southern most part of the ice shelf and reaches well into the Weddell Sea (72 °S to 67 °S). Grid boxes are locally square, and have a resolution of 0.25° longitude. This makes the grid boxes increase from 8.8 km size to 10.9 km from the southern to the northern boundary in the domain.

A new set of ice thickness and seabed topography data (Nøst 2004) was blended in with the BEDMAP data set (Lythe and Vaughan 2001) to make a consistent model domain as shown in Figure 1. The new data covers the region 3 °W to 6 °E, and we present results within this region as the topography outside this domain is probably of an approximate nature. The most important topographic feature is a 570 m deep sill at 1 °W and 70 °S,

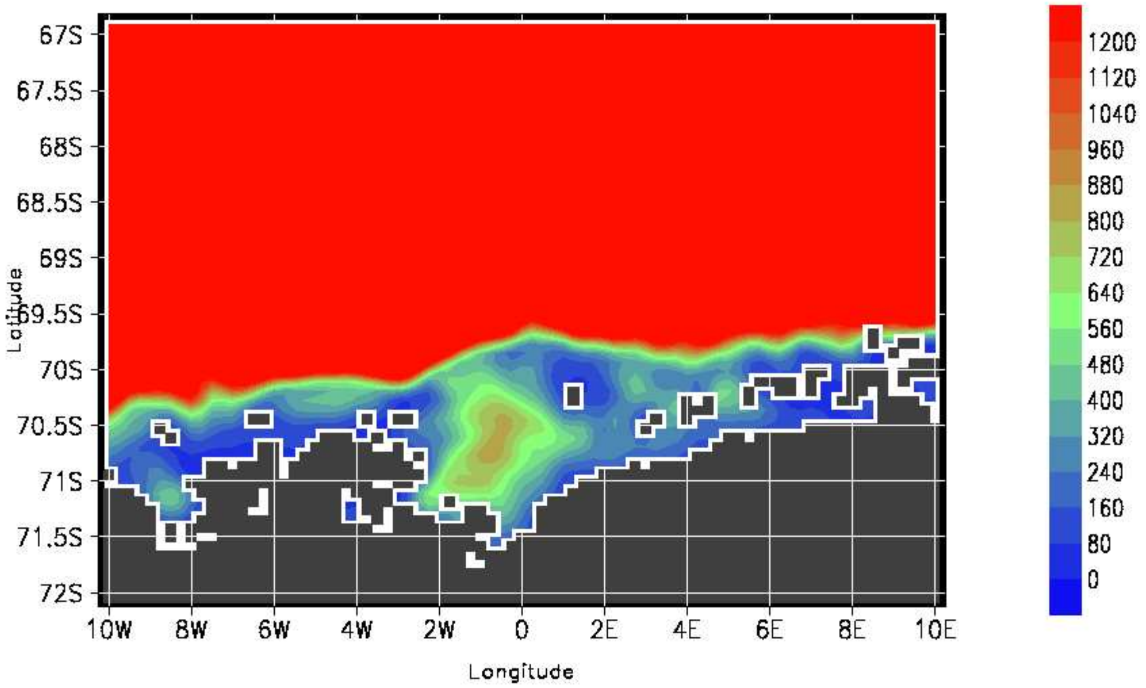


Figure 1: Water column thickness for the model domain. Water column thickness is truncated at 1200 m to show the fine bathymetric features below Fimbulisen. North of the ice shelf and continental shelf the open ocean is up to 2500 m deep. Model grid cells and resolution are indicated by the black land mask. Fimbulisen is generally overlying the continental shelf out to where water column thickness reaches 1000m.

visible in figure 1 as a change in water column thickness from 300 m at the sill to 800 m in the ~1100m deep basin to the south. We will refer to this basin as the Jutul basin here. The Jutul basin connects with two other basins to the east at 3 °E and 5 °E through sills at 520 m depth. These basins also connects directly with the ocean to the north with 3 sills between 3-5 °E at 370 m depth, so the topography is fairly complex.

The ice stream Jutulstraumen is the main discharge from Queen Maud Land. It flows along the Greenwich meridian, and the ice shelf base is at roughly 400 m depth in the central part, and ~200 m at the sides.

Model runs use 16 vertical coordinates of the isopycnic layers. To resolve the less stratified deep water properly, the lower 8 layers of virtual potential density were set to be linearly interpolated between 27.85 kg/m$^3$ and 27.80 kg/m$^3$. The surface layer was assigned a nominal density of 27.10 kg./m$^3$ and the upper 8 density layers were then linearly interpolated between this value and 27.80 kg/m$^3$. The surface layer can directly receive buoyancy fluxes, and thus through time its density can vary from the nominal value of 27.10 kg/m$^3$. Initialization of the temperature and salinity fields were taken from the Hydro-graphic Atlas of the Southern Ocean (Olbers, Gouretzki, Seiss, and Schröter 1992). An extrapolation scheme fills the cavity below the ice shelf with waters from the same depth found at the ice shelf front.

Along the solid western, northern, and eastern side walls of the domain, temperature and salinity are restored toward the initialization fields over 5 grid cells from the walls. The scheme ensures that properties at the boundary can be kept close to observed values without generating excessive gradients in the interior domain, and uses a 15 day time scale near the wall, and a 30 day timescale away from the wall.

Surface forcing over the open ocean is a seasonally variable thermohaline field as well as an imposed north-south gradient in surface pressure. Surface salinities are increased from $\sim$33.8 in February to $\sim$ 34.4 in August due to growth of sea ice. Temperature of the mixed layer is increased during summer due to incoming solar radiation, from a minimum in August-October, to a maximum of 0.8 °C during December-April.

The central process to describe in this study is how, and to what extent, WDW comes into contact with Fimbulisen and causes ice shelf melting. A steady state situation in the model integration is reached within 5-6 years, and from then onward a 'standard yearly cycle' is established. Results presented below are from this 'steady state' situation in model year 15.

## Hydrography

Figure 2 illustrates the situation with the WDW at 150 m depth confined to north of 68.5 °S, and patches of melt water from the ice shelf are found along the ice front. The colder water in the south has a salinity around 34.35, and is thus less dense than the WDW with its salinity of 34.65. This forms a kind of estuarine circulation pattern within the cavity, with an upper outflowing fresher layer, and a deeper inflow of denser more saline water.

Figure 3 shows a section along 1 °W, and reveals the vertical structure of the flow and water masses. This is the longitude of the deepest sill as shown in figure 1, and it is clear that the core of the WDW is found at the same depth as the 550 m deep sill. Below the ice shelf there is a $\sim$100 m thick layer of water colder than the surface freezing point, defined as ice shelf water (ISW). This water is cooled to the local freezing point in situ through warming and melting of the ice shelf above. Water above 0 °C enter the cavity as part of the compensating flow to the melting, freshening, and outflow in the upper layer. The vertical structure in salinity (not shown) mimics that of temperature, so the lowest temperatures have the lowest salinities, and the warmest water is the most saline. Salinity usually determines the density structure (not shown). In the deep water below the WDW core however, the larger compressibility of colder water works so that the decreasing salinity and temperature with depth is slightly stable.

The stratification works so that the isopycnals follow the isotherms in figure 3. Thus there is a lowering of isopycnals when approaching the coast from the north in the upper layer as one enters into the fresher and colder coastal current. In the lower layer there is a rising of isopycnals up to the mid depth of the water column in the sill, where the deep water is flowing into the cavity. The depth of the upper 0 °C isotherm, or the WDW, is not constant along the ice front. In figure 3 it is close to 400 m at 1 °W.

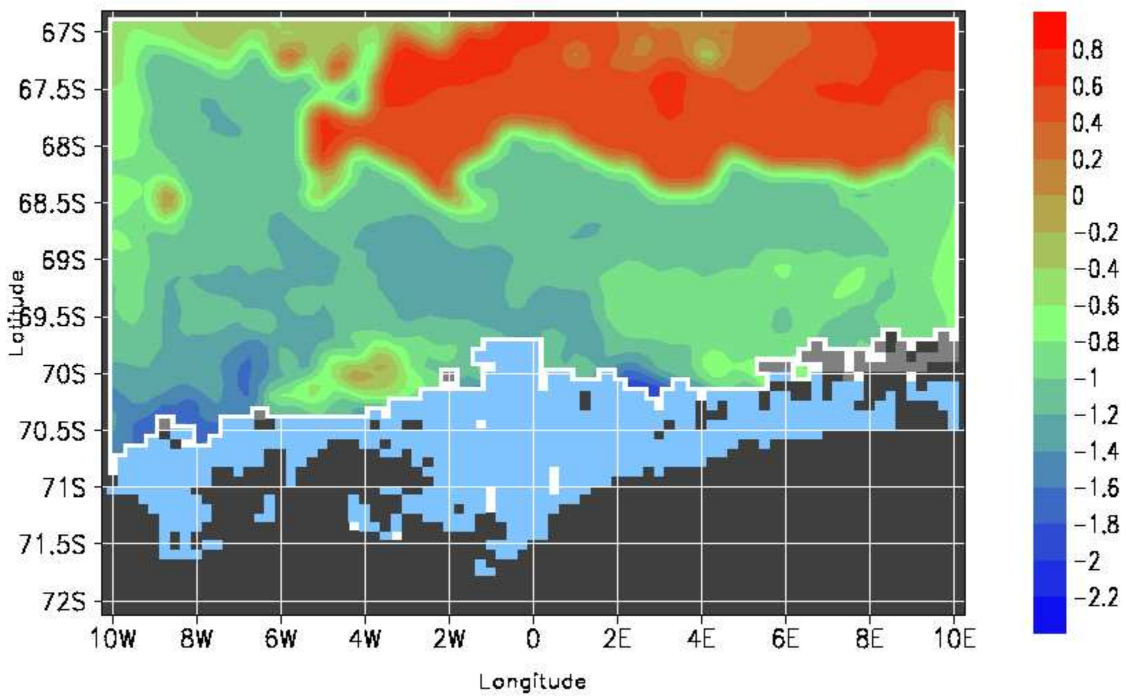


Figure 2: Potential temperature (°C) at 150 m depth in August in the standard model run at steady state (year 15). Fimbulisen is shown in blue, and the minimum thickness is 150 m so the white areas within the ice shelf denote the ice shelf base. Water depths shallower than 150 m are shown as light gray.

## Circulation

A coastal current follows the ice shelf front flowing westward. It extends down to about ~300 m depth and varies in speed between 4-6 cm/s. The horizontal extent north from the ice front varies along the coast, and eddies meander westward. The deep ocean to the north remains stagnant, and has close to zero velocities at all times. A strong eastward flow at the level of the sills is also a permanent feature, and follows the ice shelf front at depth along the coast to 6 °E.

There is southward flow of warm water over the sills. The deepest (570 m) sill north of the Jutul basin has the WDW core directly to the north (figure 3). The flow across this sill enters with the eastward flow described above, and is shown in figure 4. The flow at the sill oscillates between 5 and 12 cm/s in strength, with a southward component close to 5 cm/s. The 380 m ice draft of Jutulstraumen diverts the inflow above this depth into a cyclonic gyre to the west, and a southeast ward flow to the east. The cyclonic gyre flow continues south toward the grounding line of Jutulstraumen, and brings melt water along to the western coast of the basin at ~350 m depth.

The two other main branches of inflow are also shown in figure 4, although the 370 m deep sills between 3 and 5 °E are above the level shown. The southward component of

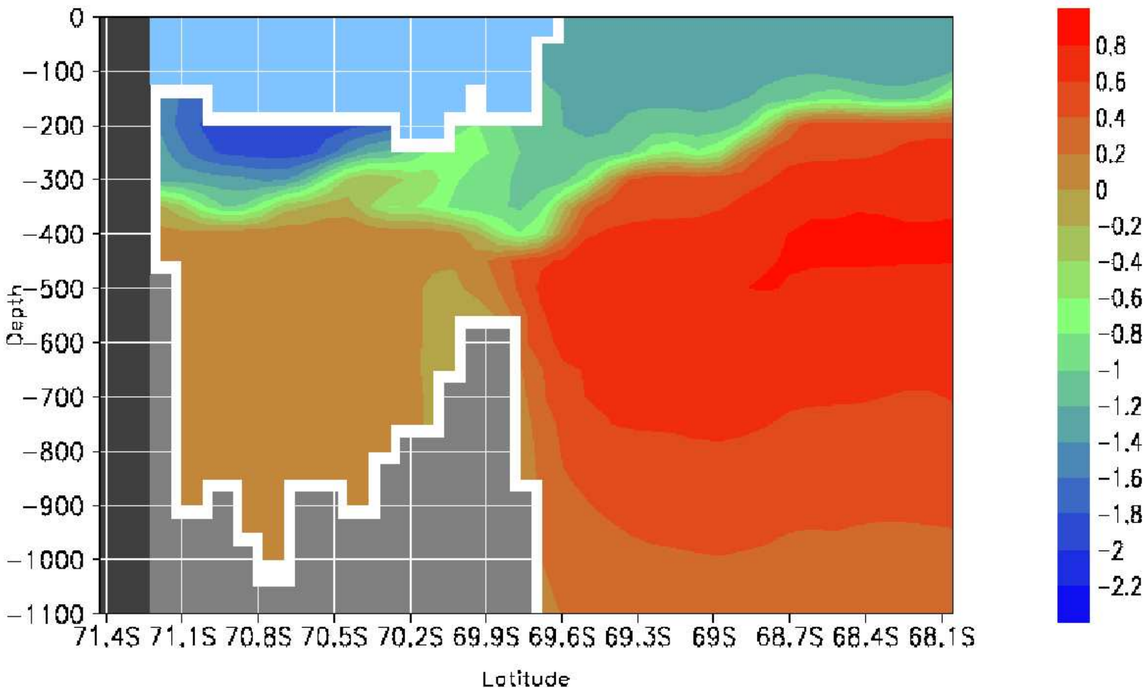


Figure 3: Potential temperature (°C) in August along 1 °W in the standard model run at steady state (year 15). Fimbulisen is shown in blue, and the bedrock in gray.

the flow over the two sills is close to 6 cm/s. This inflow reach the grounding line of the eastern parts of Fimbulisen, and fills most of the water column up to the mixed layer. Nearly all outflow of melt water is confined to the mixed layer. The only exception being the cyclonic gyre in the Jutul basin noted above.

## Basal melting

Inflowing water above 0 °C below an ice shelf cause high rates of basal melting as expected, but the areas of maximum melt is not so intuitive. This is a result of where the warm water access the ice base, and is thus a product of the flow. Figure 5 shows areas of high melt rates at the 700 m deep grounding line in Jutulstraumen as expected, but the highest melt rates of over 25 m/y are found to the east on the ice shelf and close to the ice front.

The area with high melt rates to the east around 8 °E has an ice base 500 m deep. The efficient melting is caused by the inflow over the nearby sills to the north. Also along the ice front efficient melting is taking place. The northern most tip of the ice shelf has a maximum melt rate of 18 m/y. Areas that have low melt rates along the ice front in figure 5 are generally areas of outflowing ISW. Only minor areas grow marine ice, the maximum being around 0.2 m/y.

Average melt rates over the whole domain reaches a minimum of 4.8 m/y during spring,

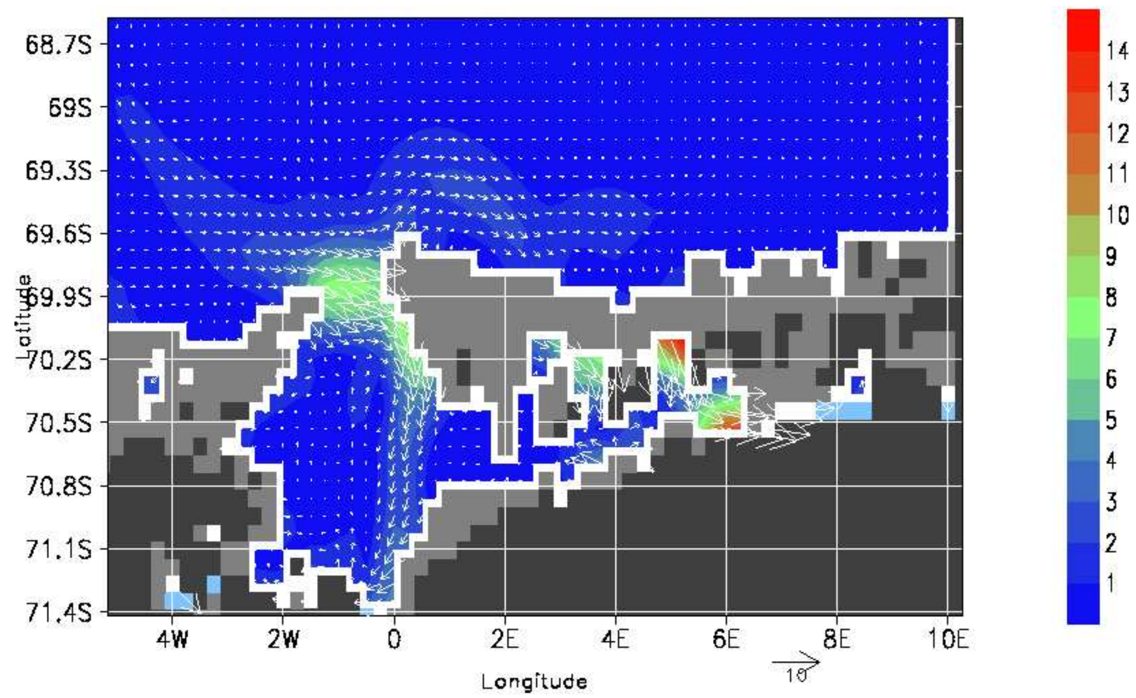


Figure 4: Yearly mean flow at 450 m depth in the steady state solution (year 15). The color scale shows current magnitude (cm/s) and the arrows are current vectors with a 10 cm/s arrow to scale in the lower right corner.

and as high as 6.8 m/y in the fall, with an average of 5.3 m/y. Average temperature of the cavity in the domain is varying between 0.05 and 0.1 °C in a yearly cycle, while average salinity varies between 34.632 and 34.640 psu. The melting results in a melt water flux from the ice base of 11 mSv.

## Discussion

Overall the modeled hydrography is close to the available data in the region. The model is set up for a small area, and no flow is specified at the boundaries. We find that the restoring toward climatology at the solid boundaries are sufficient to let the ice shelf - ocean interaction take place in a realistic way. We do not expect the results to describe the large scale circulation patterns like the flow of the Weddell Gyre, but the surface pressure restoring creates a westward surface flow.

Melting is generally controlled by inflow of warm water. The only available CTD data from below Fimbulisen are casts in Jutulgryta, a crevasse besides Jutulstraumen at 71.3 °S, 0.25 °E. In the layer below the proper ice shelf temperature and salinity increase downwards, confirming influence of warmer and more saline water masses below the ice shelf. Maximum values at the 400 m deep ocean floor is -1.8 °C and 34.35 psu. A 6 month long temperature series from 370 m depth also show intrusions of warmer water up to -1.7 °C (Østerhus and Orheim 1992). This downward increase compares qualitatively with model

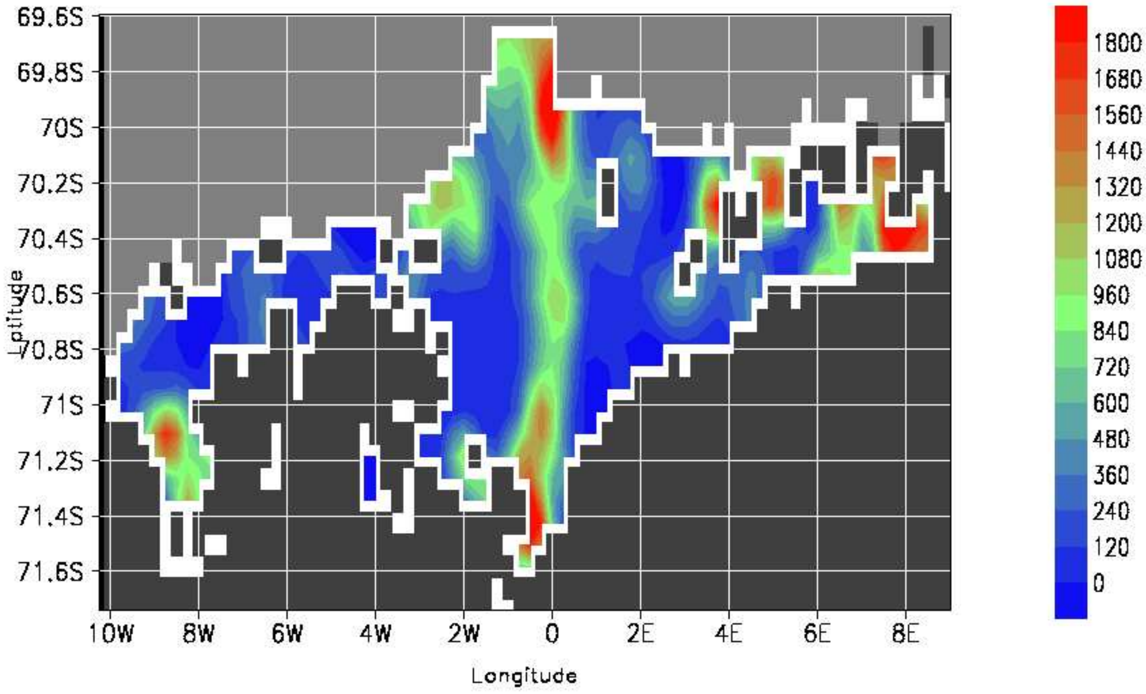


Figure 5: Yearly mean basal melting (cm/y) below Fimbulisen in steady state (year 15).

results, but the model results increases from -1.8 at a 200 m deep ice base to 0 °C at 400 m depth at 0.25 °E. This is very similar to results shown in figure 3 for 1 °W. How well the lower 100 m in Jutulgryta is representative for the rest of the sub ice shelf water mass is an open question, and the model results of above zero temperatures below 400 m depth beneath Fimbulisen in general can not be validated.

Some ship-borne CTD casts have actually ended up below Fimbulisen with the advance of the ice front. A profile from 1992 at 69.7 °S and 0.7 °W (World Ocean Database 1998) shows that the 0 °C isotherm is at 950 m depth, this being the upper boundary of the WDW. The model results vary between 350 and 500 m depth through the year.

The model predicts an inflow of warm water below Fimbulisen at 2.5 °E, where the upper WDW model boundary is at 300 m depth. This is close to a recent CTD section showing the upper WDW boundary at 290 m at 69.75 °S (O'Dwyer 2002). However, south of this towards the ice front the measurements show a depressed thermocline. The southernmost station at 69.9 °S is 900 m deep, and here the thermocline is as low as 500 m deep i.e. well below the 300 m deep sill. This position is still 20 km north of the ice front, and more importantly, still well north of the sill. It is possible that an elevated thermocline exists in areas of warm water inflow below Fimbulisen, i.e.in sill areas, and that this has escaped measurements up to now. Very few measurements exist on the continental shelf in this area.

However, it is clear that the model results show a shallower WDW than observations along the coast. This may be a consequence of the onshore wind stress as noted by (Sverdrup 1953). As a surface wind stress is not applied here, this is not captured by the model. The maximum temperature and salinity at 2.5 °E is found close to 500 m depth both for the measurements (0.66 °C and 34.673 psu) and in the model results (0.58 °C and 34.695 psu), so the water mass distribution north of Fimbulisen seems reasonable.

Earlier estimates of average basal melt rates of Fimbulisen were given as 4 m/y for the region close to the grounding line (Jutulstraumen) by Rignot and Jacobs (2002), and as 3.7 m/y for the whole northeastern Weddell ice shelves by Beckmann and Goosse (2003). Our estimates are higher than both of these, but as we have shown here; the inflow of WDW below the ice shelf is directly dependent on topography that has not been known before now. The low estimate of Rignot and Jacobs (2002) is explained by a mean temperature of the surrounding ocean of -1.7 °C, yielding a $\Delta T$=0.9 °C above the in situ freezing point taken as -2.6 °C. This value must be regarded as an unrealistically low value compared to our results. The 'mean surrounding ocean temperature' of Beckmann and Goosse (2003) was -0.14 °C, and this is somewhat more comparable with our results. Using the latter value in the linear relation of Rignot and Jacobs (2002) for basal melt rate dependent on a $\Delta T$=2.46 gives a melt rate close to the grounding line of $\sim$ 25 m/y, close to our maximum melt rates. The mean fresh water flux from Fimbulisen of 11 mSv is 30 % higher than the estimate from (Beckmann and Goosse 2003). If the overall flux from all Antarctic ice shelves given as 29.6 mSv is about right, Fimbulisen supplies around a third of all the fresh water from the continent.

The fairly high melt rates on the eastern parts of Fimbulisen are somewhat surprising. However, results from the Antarctic ice sheet model of Warner and Budd (1998) show that there is a north flowing ice stream that enters Fimbulisen at 7 °E (Personal communication R. Warner, Antarctic CRC). This ice stream has an ice flux around 5 km$^3$/y, and a mean speed around 300 m/y. This ice flux is 35% of the flux in Jutulstraumen, and indicates that efficient melting probably takes place below the nearby part of Fimbulisen. Despite its potentially fairly large ice flux the ice stream/glacier have not yet received a name as far as we know.

## Conclusion

The model results presented here suggest that Warm Deep Water (WDW) flows southward beneath Fimbulisen over the sub ice shelf sills of depths in the range 370-570 m. This leads to high levels of basal melting, up to 25 m/y, and an average melting over the whole ice shelf close to 5 m/y. The southward flow is a compensating inflow due to the northward flow of fresh and cold water produced by the basal melting. Model results compares well with measured hydrography, but the upper extent of the Warm Deep Water is in places found at 300 m in the model, while measurements usually indicate that a depth of 500 m is more correct. The melting estimates are therefore likely to be too high, and further modelling is in progress, including applying a westward windstress.

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