Exploring the impact of ice sheet melting and iceberg calving on Southern Ocean circulation

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Abstract

Models of the Southern Ocean are highly sensitive to their freshwater input and are very unstable if it is not modelled correctly. The NERC Exposé project to investigate carbon uptake pathways uses an ocean model with an outdated freshwater runoff file and is unstable unless surface salinity is constantly restored to preset values. To create a more realistic runoff file, we used recent ice shelf and iceberg observations to model the distribution of freshwater input to the Southern Ocean. This paper explains how these observations were modelled, and discusses the results of sensitivity tests on the resulting runoff file. We found that the new distribution improved the stability of the system, and that adding a further 50% more freshwater to the new file greatly stabilised the Ross Sea. In conclusion, the new runoff file is a much better representation of current observations than the old, and has a positive effect on the stability of this Southern Ocean model.

1 Introduction

Numerical ocean models require external forcing fields to correctly reproduce realistic behaviour. These fields have a pre-defined effect on the model, adding or removing quantities such as water, salt, or heat while it runs. Ocean models can be very sensitive to these fields so it is very important that they are derived from real observations. The Southern Ocean is a particularly unstable system to model, as it is highly prone to vertical mixing and polynya formation.

Currently the NERC Exposé project uses the MIT General Circulation Model (MITgcm) constrained by the Southern Ocean State Estimate (SOSE) to model the Southern Ocean. This set-up is highly unstable unless the surface salinity is constantly artificially restored to realistic values. This may be due to an unrealistically weak Antarctic freshwater runoff forcing field, which causes salinity to increase leading to runaway vertical mixing.

This project aims to find whether this Southern Ocean model set-up can be stabilised with a more realistic freshwater runoff field. This paper describes how a new field was produced using recent observations, and discusses the results of sensitivity experiments using variations of this new field.

2 Freshwater Runoff

The current SOSE runoff shown in Figure 1 has a total freshwater volume of 1667 Gtyr^{-1}. It is distributed uniformly around a low-resolution Antarctic coastline, and is normally distributed northwards with a standard deviation of 100km.

The updated runoff field made in this project is based on observations of ice sheet basal melting and iceberg calving, which contribute roughly equally to the total freshwater flux. Precipitation and evaporation are the other factors in freshwater flux in this model.

P-E input is similar in magnitude to the freshwater runoff below 60S - above this latitude P-E generally dominates. This project will consider the P-E field used in the model (six-hourly ERA-Interim data from 2008-2010 with the three-year linear trend removed) to be correct and will only investigate the effect of changing the runoff field.

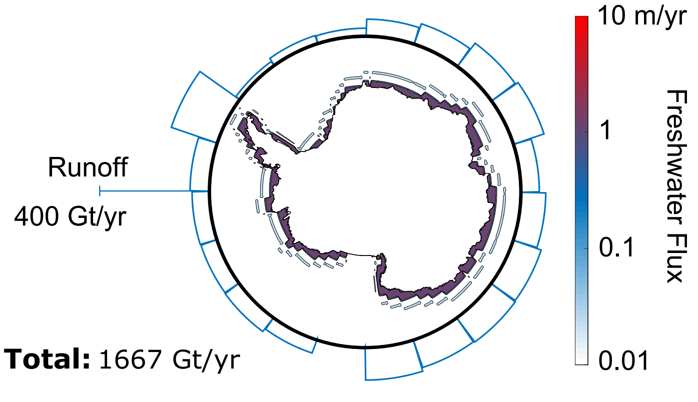


Figure 1: Previous SOSE Runoff Field

2.1 Basal Melting

Ice sheet melting causes approximately half of the Antarctic freshwater runoff. The distribution of this basal melting runoff is not simple as it depends on local ocean temperature and circulation. For example, the Filchner-Ronne and Ross sheets cover 61% of the total ice sheet area but only produce 15% of the meltwater. Conversely, the Southeast Pacific-Antarctic sector only covers 8% of the area but produces 48% of the meltwater[1].

Basal surface meltwater is highly important as it leads to thicker sea ice[2]. It has been suggested that climate change has increased meltwater which protects the surface ice from warmer waters below[3]. Freshwater input also keeps surface salinity low, which protects the stratification of levels of cold and warm water. This prevents deep convection and the formation of polynyas[4].

Therefore, it is important to accurately model the freshwater runoff into the Southern Ocean. A constant release of meltwater around the coast is not an accurate model as in reality basal melting varies greatly with location. This project uses the data of Rignot[1] to create a new runoff field. It approximates the melting as being only at the surface at the coastline, as the SOSE grid does not extend underneath the ice sheets.

2.2 Iceberg Calving

The other source of runoff is the melting of icebergs which calve off ice sheets. This is a more complex effect than basal melting, which only takes place at the coastline. Icebergs melt over a period of time as they move away from the coast, following paths which depend on factors such as their size and starting location[5]. Some models simplify iceberg melting greatly, such as to a constant 2000 Gtyr^{-1} normally distributed away from the coast[6].

The first factor to consider is the locations of the icebergs, which is by no means uniform. For example, 30% (by mass) of the icebergs are produced in the Weddell Sea sector, while just 3% are produced in the Bellingshausen Sea sector[7].The distribution of meltwater is then further complicated by the paths that icebergs take. These are non-trivial, depending on many factors such as size, shape, and ocean currents. These paths can be simulated to give a meltwater climatology[8]. This project uses satellite tracking data to model the distribution of icebergs in the Southern Ocean.

2.3 River Runoff

Rivers on other continents supply the remaining freshwater. This project did not investigate this source in detail, as river runoff is an order of magnitude less than Antarctic runoff in the Southern Ocean. The rivers are also far away from this project's areas of interest - the Ross and Weddell Seas, and the Antarctic coastline. The runs in this project used the previous SOSE river runoff field[9].

The MATLAB script written in this project for basal melting was adjusted to take more accurate river data and plot it on a higher-resolution grid. This new river field was not used for any sensitivity tests, but could be the subject of further tests.

3 Runoff Field design

The updated runoff field has a total freshwater volume of 2414 Gtyr^{-1}, compared to the old field which had an (effective) volume of 1670 Gtyr^{-1}. It is based on three data sets:

1. The basal melting rate from the major ice shelves around the Antarctic coastline[1]

2. The iceberg calving rates from the same ice shelves (via the proxy of ice-front flux)[1]

3. The satellite-tracked positions of 'big" icebergs (over $\tilde{1}$km in size) from 1999 to 2009[10]

It has three independent variables which were adjusted to produce a runoff field which was practical for the model and reflected real data as well as possible:

1. The meltwater distribution standard deviation for icebergs and ice sheets

2. The standard deviation of a uniform normal distribution of "small" (non-tracked) icebergs

3. The proportion of "small" to "big" icebergs

The next section will explain how these variables are used with the empirical observations to produce the practical runoff field shown in Figure 2. This new runoff field differs from the old (Figure 1 in several main ways. There is roughly 50% more freshwater, the distribution is weighted far more strongly towards the West Antarctic coastline, and the flux extends much further away from the coast.

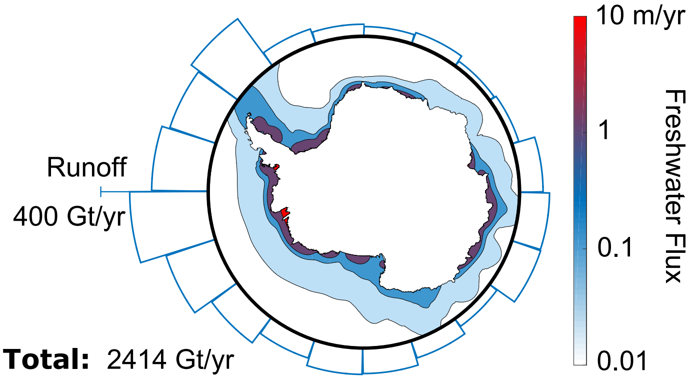


Figure 2: New Runoff Field

3.1 Basal Melting

The new field represents basal melting flux as a normally decaying field from each ice shelf (standard deviation 100km to ensure a smooth distribution on the grid). The MATLAB script takes a list of ice shelf names, basal melt rates, and opening and facing angles. It uses BEDMAP2 data[11] to locate an outline of each shelf on the grid and places flux sources along this outline. This means that the geometry of the shelf is taken into account - a long shelf is not represented by only one source point.

The flux from each shelf can also be restricted by specifying facing and opening angles, so that a shelf on one side of the Antarctic Peninsula will not produce flux on the other side. Finally, the script applies the land mask and a weak Gaussian filter and rescales the flux from each shelf to the correct total value.

3.2 Iceberg Calving

Iceberg calving is more complex to model than basal melting, as we must consider their origins as well as their paths and distribution away from the coastline. Other models have simplified iceberg melting to a uniform distribution away from the coastline because of the difficulty in modelling their paths and melting behaviour[4][6]. This new field models "big" icebergs using a tracking database and "small" icebergs with a normal distribution away from the ice shelves.

3.2.1 Big Iceberg Modelling

"Big icebergs" add flux to a distribution generated from the Antarctic Iceberg Tracking Database[10]. This is a database of icebergs positions. This distribution uses the QSCAT data from 1999-2009, which tracks icebergs with sizes above 1km. The positions are binned onto the grid to give a distribution weighted by the observations of icebergs at each grid point. This distribution has a Gaussian filter applied to smooth it, with the same standard deviation as the basal melting distribution for consistency. This gave a climatology which is similar to current iceberg meltwater simulations[8].

3.2.2 Small Iceberg Modelling

"Small icebergs" (i.e. those not represented by the tracking database) are simply modelled by a normal distribution away from the source ice shelf. The standard deviation of 500km was chosen so that 95% of the total small iceberg flux is below 60S, following other models' choices[6].

3.2.3 Total Iceberg Flux

The final free variable is the proportion of "big" to "small" icebergs. This was constrained by finding the proportion (50% of each) which gave a field that most closely matched the observed iceberg calving distribution. The script also slightly rescales the total iceberg flux in four sectors (Ross Sea, Weddell Sea, East and West Antarctica) to match observations more closely[1].

4 Results and Discussion

These sensitivity tests will discuss the stability of the Southern Ocean model when forced by the different runoff files. The main instability is the formation of polynyas in the Weddell and Ross Seas. These can grow over a period of years and remove most of the sea ice from the Southern Ocean. This section will discuss the behaviour of proxies for these instabilities, such as sea ice volume and coverage, gyre strength, and mixed layer depth.

The tests varied two parameters: the total freshwater volume and the distribution of freshwater. Each test was therefore given a name such as "New Volume, Old Distribution" or "NVOD" and are referred to as such in this paper. The different files used are listed in 1. The effect of these differences is discussed in this section.

	Total Volume/Gtyr^{-1}	Distribution	Salt Restoring?
OVOD	1670	Old	No
OVODR	1670	Old	Yes
NVOD	2414	New	No
NVND	2414	New	No
NVNDR	2414	New	Yes
NVNDx	3621	New	No
NVNDxx	5432	New	No

Table 1: Runoff Fields used in sensitivity tests

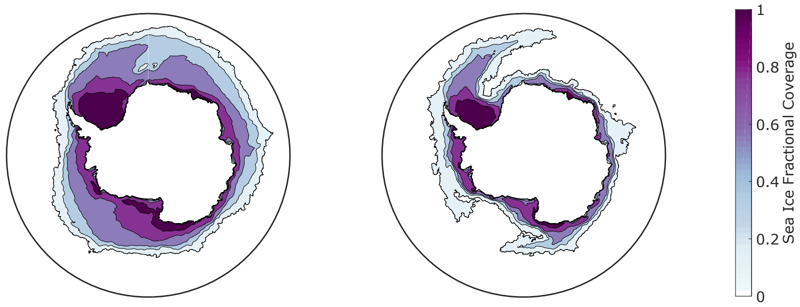
4.1 Increased Freshwater Volume

The new runoff file NVND differs from the old runoff file OVOD in two ways: it has a greater total yearly runoff, and this runoff is distributed differently around the Antarctic coastline and seas.

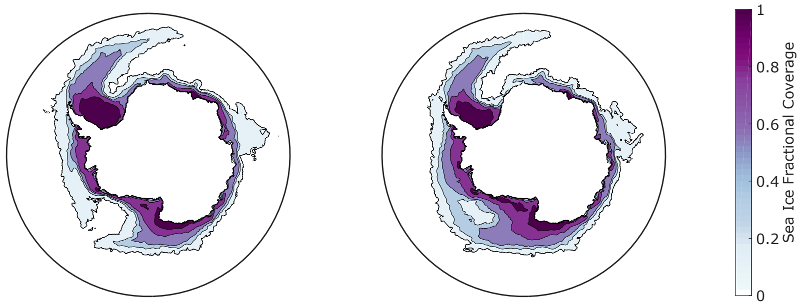
The effect of increasing the total freshwater volume is shown by Figure 5a. The runs NVOD and NVND with a higher total volume also have a higher volume of sea ice every year. However they are still unstable and decay compared to the salt-restored OVODR run.

Figure 3 shows the annual mean sea ice coverage after 5 years. Polynyas have opened in OVOD and NVOD in the Weddell and Ross Seas; typically these open after a period of stability then grow, reducing the sea ice around them. Figure 4 shows the instability in these runs - the mixed-layer depth has increased greatly in both seas.

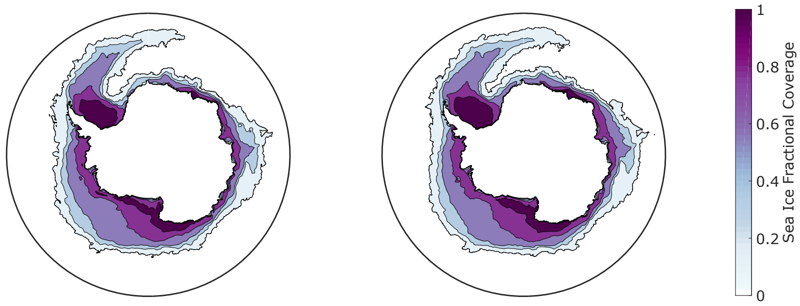
The OVOD run's instability is also shown in Figure 6. With each successive year, salinity and temperature increases at the surface of the centre of the Ross and Weddell Gyres until a polynya forms. This temperature change may be partly due to the fact that the freshwater is input at 0°C - in reality the surrounding water will have to expend energy because of the latent heat of melting the ice. This could be approximated by changing the freshwater input temperature to -80°C (latent heat divided by heat capacity).



(a) OVODR (b) OVOD



(c) NVOD (d) NVND



(e) NVNDx (f) NVNDxx

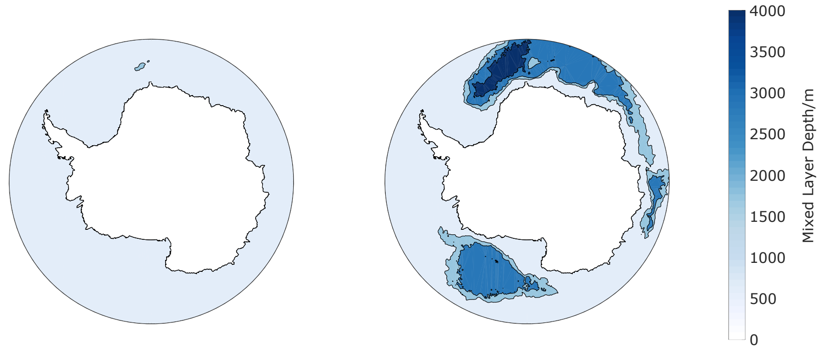
Figure 3: Fractional sea ice coverage (annual mean) at year five

4.2 Increased Volume and New Distribution

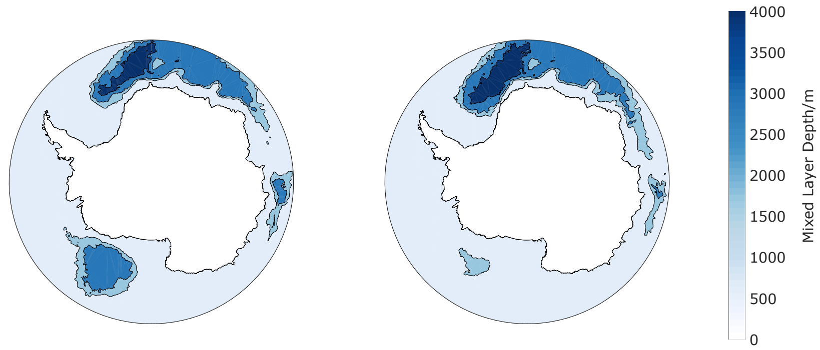
The new freshwater runoff field is very different to the old distribution. The basal melting observations lead to much more freshwater flux into the Ross Sea, and far less from East Antarctica. Modelling an iceberg distribution also means that the flux spreads further out to sea than in the old model.

This new distribution appears to have a positive effect on sea ice coverage, especially in the Ross Sea. Figure 3 shows a clear difference between NVOD and NVND - two runs with the same total freshwater volume, but a different distribution. After five years, a Ross Sea polynya has opened in the NVOD run but not in the NVND run.

This is backed up by Figure 5b which shows that the Ross Gyre begins to spin up after four years in NVOD, but after six years in NVND. The new distribution postpones the formation of a polynya by two years. Figure 4 also shows the improvement in the Ross Sea - after 5 years, the mixed-layer in NVND is much less deep. This indicates there is less vertical mixing, so less sea ice is lost.

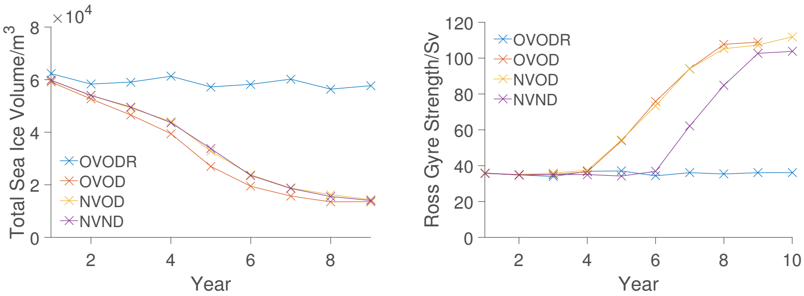


(a) OVODR (b) OVOD



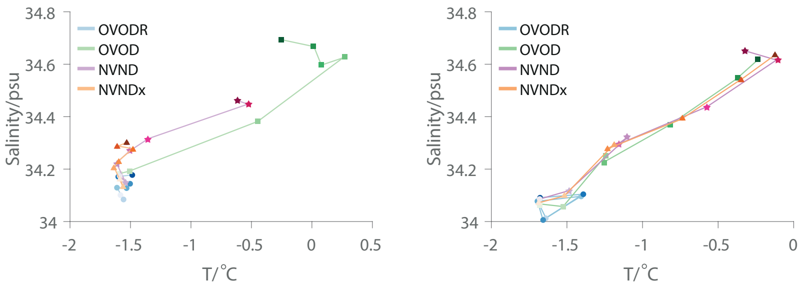
(c) NVOD (d) NVND

Figure 4: Mixed-Layer Depth (annual mean) at year five



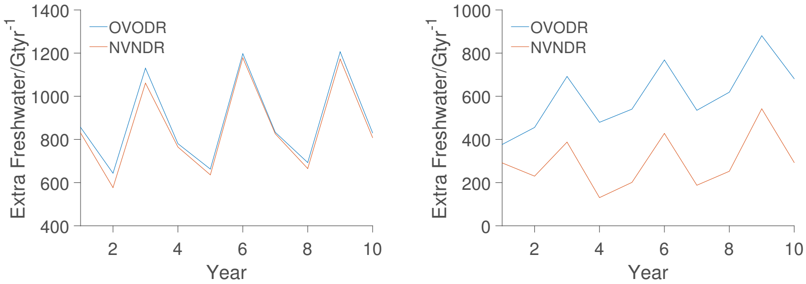
(a) Sea ice volume trends (b) Ross Gyre strength

Figure 5: Yearly sea ice volume and yearly Ross Gyre strength



(a) Ross Centre Surface TS (b) Weddell Centre Surface TS

Figure 6: Yearly temperature against salinity at surface of Weddell and Ross Gyres



(a) Extra Weddell FW (b) Extra Ross FW

Figure 7: Freshwater added to Weddell and Ross Seas by salt restoring

4.3 Effect on Salt Restoring

SOSE is currently stabilised with salt restoring - salt is artificially added to the surface to restore it to a predefined monthly salinity. The amount of salt required to stabilise the system can be converted into an effective amount of freshwater. Assuming that the salt restoring only affects the mixed layer, we can calculate the amount of freshwater that produces the same change in salinity. For a mixed layer depth d, change in salt s , freshwater density ρ_f and seawater density ρ_s, the change in salinity S is:

$$\Delta S = \frac{\Delta s}{(d \times \rho_s)} \tag{1}$$

Seawater density is taken to be a constant 1030 kgm^{-3} as it only varies by 1% over the range of salinities in this model. The effective change in mixed layer depth is then:

$$\Delta d = \frac{(-d \times \rho_s \times \Delta S)}{(\rho_f \times (S + \Delta S))} \tag{2}$$

Multiplying by the area of the grid cell then gives the effective freshwater increase:

$$\Delta V = \Delta d \times \Delta x \times \Delta y \tag{3}$$

Figure 7 shows the total effective extra freshwater added to the Ross and Weddell Seas by salt restoring. It compares two runs with salt restoring turned on; one with the OVOD file and one with NVND.

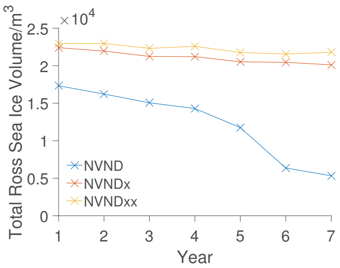
The two files have almost the same freshwater "deficit" in the Weddell Sea (both have a mean of 510 Gtyr^{-1}). However, NVNDR requires much less extra freshwater in the Ross Sea (it has a mean of 230 Gtyr^{-1} while OVODR needs 473 Gtyr^{-1}).

This indicates that NVND is a step in the right direction in the Ross Sea, but performs about as well as OVOD in the Weddell Sea. It is worth noting that these freshwater "deficits" may be overestimates - the system may be stable with less freshwater. This is because the salinity is restored to a monthly averaged field from SOSE simulations of the period 2008-2010[12]. This does not necessarily correspond to the minimum amount of freshwater needed for stability, or to the actual amount of freshwater in reality.

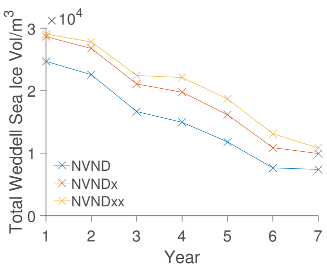
4.4 Further Increased Freshwater

This section will discuss the effect of increasing the total freshwater input of NVND by 50% (NVNDx) and 125% (NVNDxx). These runoff fields appear to significantly stabilise the Ross Sea, but to have little effect on the Weddell Sea.

Figure 8 compares the amount of sea ice in the Ross and Weddell Seas. Sea ice in the NVND run decays constantly in both seas. Sea ice in NVNDx and NVNDxx is greatly stabilised in the Ross Sea - there is only a small decrease over the first seven years. On the other hand, the new runs do not appear to stabilise the Weddell Sea much - sea ice volume is higher for each new run, but it still decays constantly.



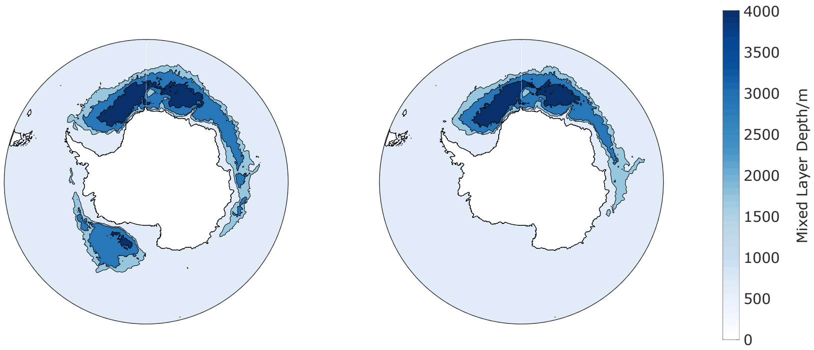
(a) Ross



(b) Weddell

Figure 8: Sea ice volume trends in the Ross and Weddell Seas

Figure 9 shows the mixed layer depth after seven years for NVND and NVNDx, and confirms again that the Ross Sea is still stable with respect to vertical mixing after seven years. A longer run would be required to find the length of time for which the model is stable in the Ross Sea.



(a) NVND

(b) NVNDx

Figure 9: Annual Mean Mixed-Layer Depth at year seven

This difference between the Ross and Weddell Seas is also shown in Figure 6. These show TS trends for the surface of the centre of each gyre. OVOD is clearly unstable in both cases, as salinity increases continuously. In the Ross sea, each increase in freshwater (NVND then NVNDx) makes this trend smaller. NVNDx appears roughly as stable as OVODR in the Ross Sea.

Conversely, increasing freshwater does not seem to stabilise the Weddell Sea. The OVOD, NVND, and NVNDx runs all follow approximately the same trend of increasing salinity and temperature towards polynya formation. This suggests that the Weddell Sea system may be more difficult to stabilise than the Ross Sea, and that we need a more sophisticated method than a constant annual runoff field. It could also be that another source of freshwater such as P-E is inaccurate, or that the addition of freshwater at the surface only is unrealistic.

5 Conclusion

This project has produced a new freshwater runoff field for the SOSE iteration of MITgcm. This field has a total volume and distribution based on observations of basal melting rates, iceberg calving rates, and iceberg paths. It represents current data much better than the old runoff field, which was distributed uniformly and had an out-of-date total volume.

Sensitivity tests showed that the new field improved the stability of the model in some places, taking six years rather than four for the Ross Sea Polynya to form. When the new field had 50% more freshwater added, it appeared to stop the constant decrease in sea ice in the Ross Sea. The yearly trend on a TS plot was also greatly reduced with each increase in freshwater volume. However, no constant freshwater forcing file in this project could prevent the Weddell Sea from forming a polynya. TS plots indicated that increasing the total freshwater volume did little or nothing to stabilise the Weddell Sea.

More tests could be done to find the critical amount of freshwater needed to stabilise the system. The instability of the Weddell Sea in all tests without salt restoring indicates that an improved freshwater forcing file may not be enough to fully stabilise it, so other factors could be investigated.

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