Tipping of the Filchner-Ronne and other Antarctic ice shelf cavities

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TiPACCs
Tipping Points in Antarctic Climate Components

HELMHOLTZ

Introduction

cold state

warm state

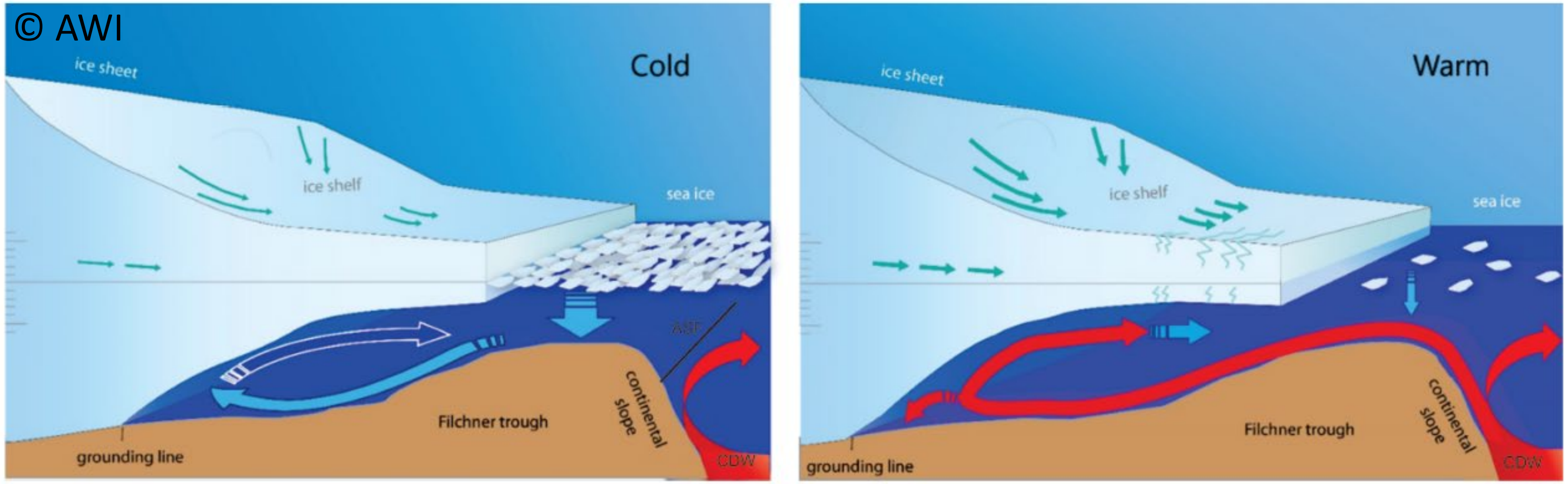


Figure 1: schematic of cold and warm state on continental shelf

Within the framework of the TiPACCS project we look at the tipping of the Antarctic continental shelf from a cold to a warm state. Specific focus is on the conditions under which the inflow of warm water occurs. We ran several model experiments with varying manipulations of the atmospheric forcing in order to force the model into a tipped state. We only achieved this for the Weddell Sea shelf which is most vulnerable due to the deep Filchner Trough with a sill depth of 640 m.

Method

Sea.ice ocean model **FESOM 1.4**

Global domain, unstructured grid,

horizontal resolution varying from up to **300 km** in open ocean basins to typically **7-4 km** resolution in Antarctic ice shelf cavities

Vertically 100 z-levels (5 m spacing at surface)

Reference run: ERA Interim (1979-2017, repeated 39-year cycle)

Initialisation: World Ocean Atlas

Spin up: 39-year cycle with ERA Interim atmospheric forcing

Experiments with varying alterations of the surface forcing are branched off after the spin-up period.

Atmospheric Forcing

HadCM3 20C (H20C)

ERA Interim (ERAI)

HadCM3 21C A1B (H21C)

Anomaly(day of year, lon, lat)= mean(H21C(**2070-2089**)) – mean(ERAI(**1980-1999**))

SC_H21C_g = ERAI + Anomaly(global)
SC_H21C_S = ERAI + Anomaly(South of 50° S)
SC_H21C_W=ERAI + Anomaly(Weddell Sea region)

In effect: short-term and interannual variability of ERAI
Seasonal cycle and annual mean of H21C

SUMMER_S=ERAI(January x3, July&August eliminated; South of 50° S)
SUMMER_S_SCw_W=SUMMER_S with fitted sine-anomaly (seasonal) in wind field over Weddell Sea region

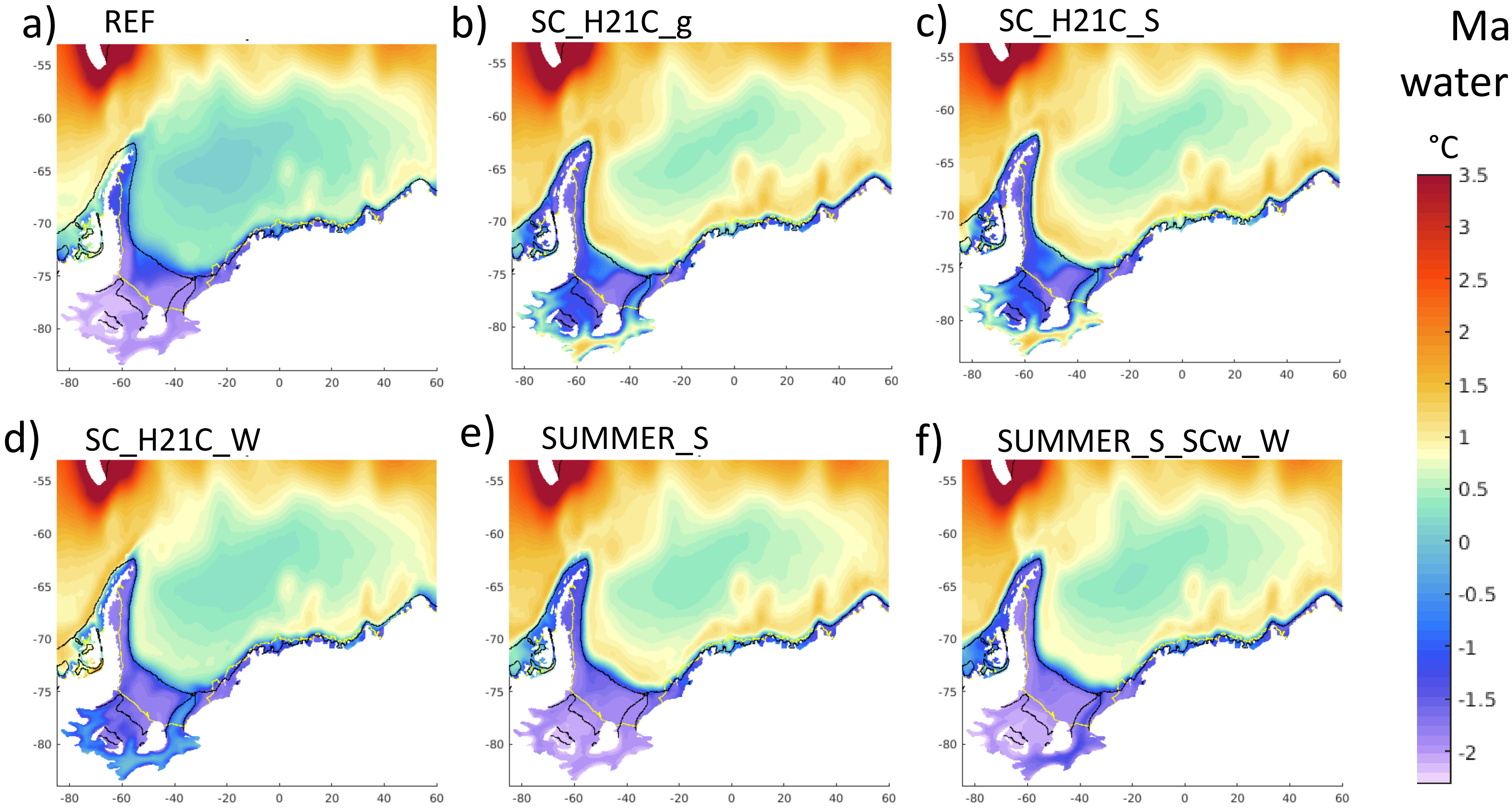
Atmospheric Forcing

For the forcing we used ERA Interim data and output of the HadCM3 climate model (1) for the 20th century: H20C and (2) for the A1B climate scenario in the 21st century (H21C).

In total 9 experiments are presented:

- The reference run **REF** is forced with ERA Interim data (6-hourly/12-hourly).
- The **SC_H21C_*** experiments have a seasonally varied anomaly added in different regions (see previous slide), so that in this region the short-term and interannual variability of ERAI is maintained, while the seasonal cycle and annual mean are approximated to that of H21C for 2070-2089.
- In **SUMMER_S** the seasonal cycle of ERAI is changed toward longer summers and short, mild winters, **SUMMER_S_SCw_W** adds a seasonal anomaly to the Weddell region wind field that is slightly abstracted from H21C by fitting a sine-curve
- Both **H20C** and **R_H20C** use the unaltered output of HadCM3. **R_ERAI** uses unaltered ERA Interim data, like REF.

Warm water inflow



Mean of years 69-78

Figure 2: maps of maximum temperature in the water column

Warm water inflow

The Weddell Sea continental shelf is in a cold state in REF.

The SC_H21C_* family of experiments features a clearly visible trace of **warm water inflow into the ice shelf cavity** through the Filchner Trough. This inflow is least warm in SC_H21C_W, which underlines the **strong influence of the far-field** processes affecting the Weddell Gyre through the Antarctic Circumpolar Current and the Antarctic coastal current. A comparison of SC_H21C_g and SC_H21C_S shows only a limited influence of the processes north of 50° S.

The Weddell Sea continental shelf remains in a cold state in SUMMER_S. The additional manipulation of the regional wind pattern in SUMMER_S_SCw_W pushes the sea ice more into the southwestern corner of the Weddell Sea. Thus, sea ice production in front of Ronne Ice Shelf is decreased and in consequence the salinity of the water on the continental shelf. A threshold is passed and inflow of slightly warmer water through the Filchner Trough is facilitated.

Mean T, S and basal melt

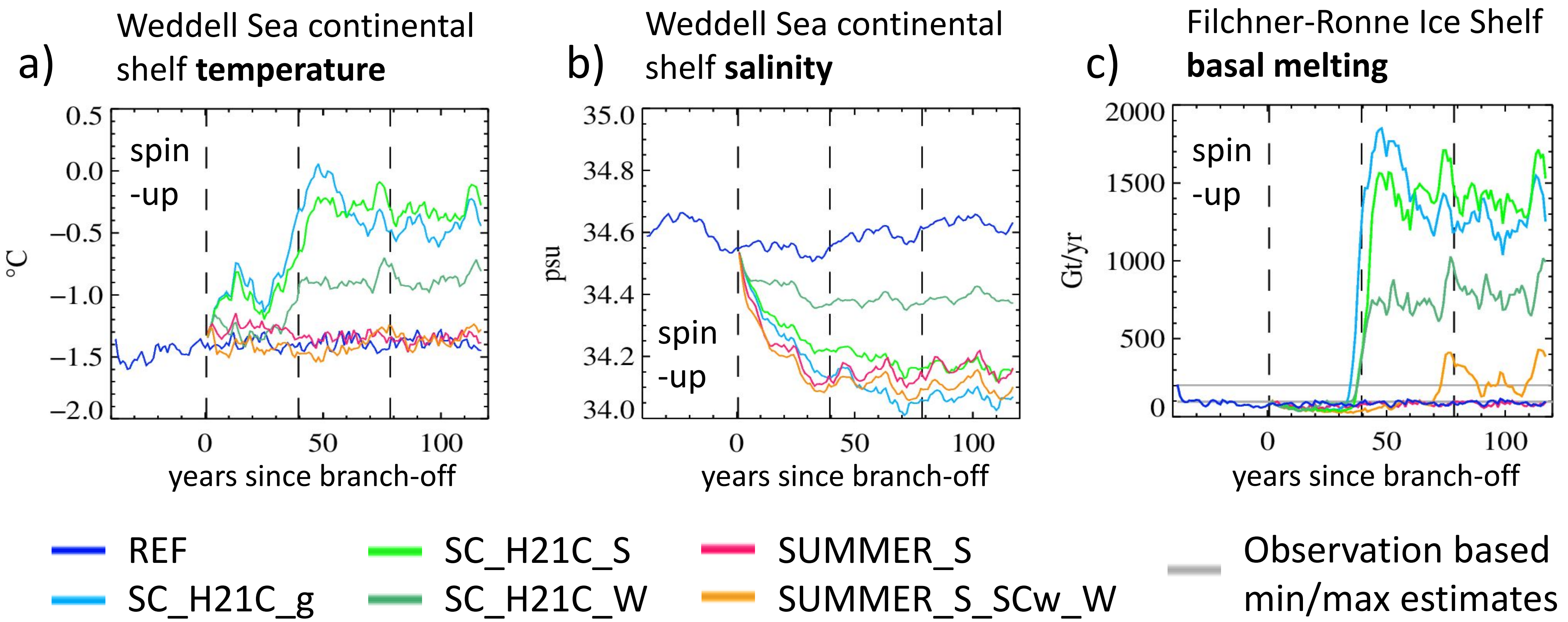


Figure 3: mean on-shelf a) temperature and b) salinity (excluding upper 200 m) and c) mean basal melt of FRIS

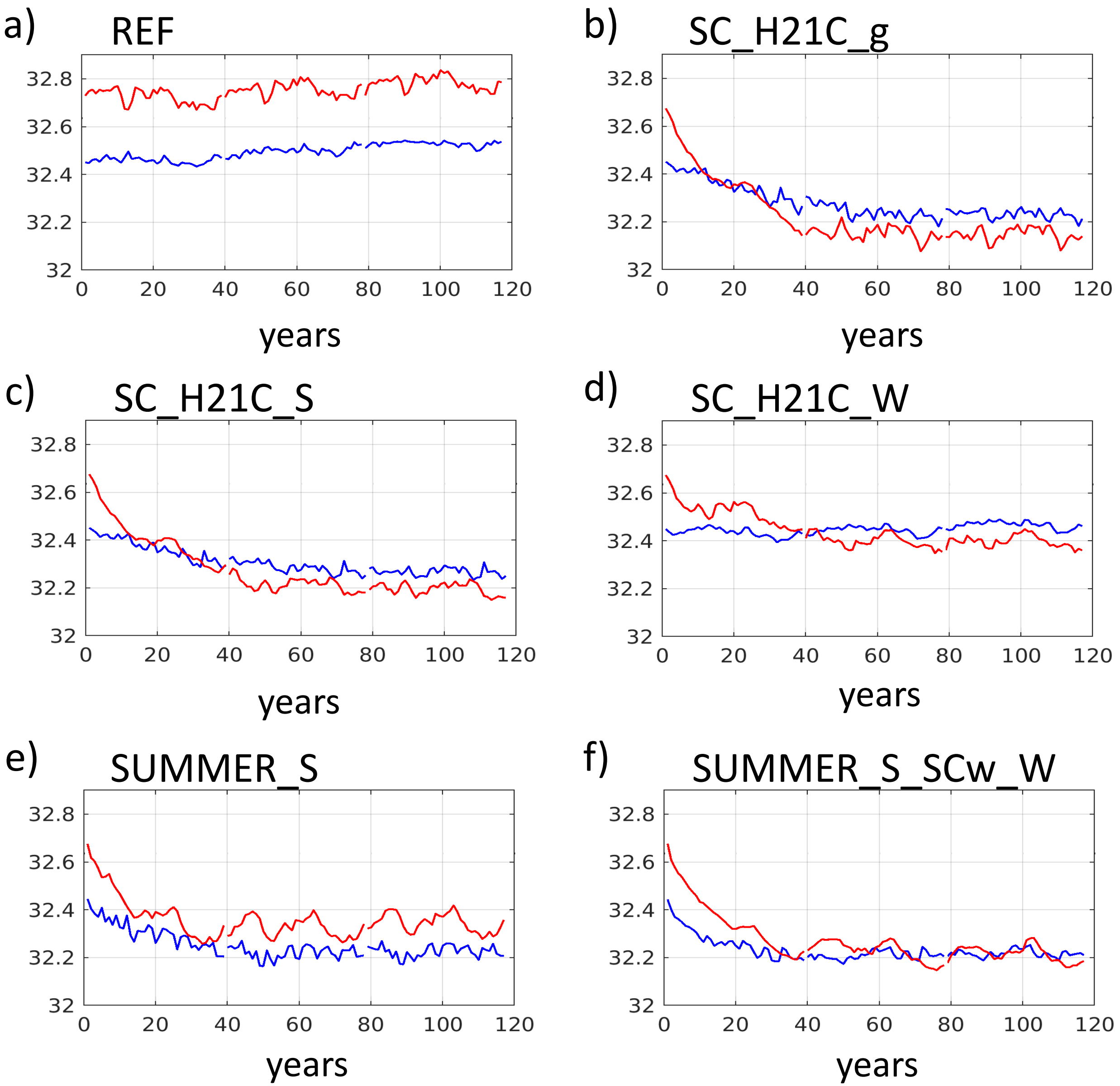
Note that the increase in melt rates is generally preceded by a drop in basal melt as the old source of dense water (HSSW) loses density and the circulation in the cavity slows down, until it is replaced by the inflowing off-shelf waters.

Mean T, S and basal melt

While all experiments feature a strong freshening of the continental shelf compared to REF, the mean on-shelf temperature is only substantially increased in the SC_H21C_* family of experiments. Again, we see the difference in impact between regional manipulation and circumpolar or global application. For these experiments the **basal melt** of the Filchner Ronne Ice Shelf (FRIS) features a **sudden increase by a factor O(10)** in year 36 or 37. After this, the mean **basal melt correlates well with the on-shelf temperature** and seems controlled by it.

Although SUMMER_S features a substantial freshening on the continental shelf and during the first 40 years even a slight warming compared to REF, FRIS basal melt remains low on the same level as in REF. The additional wind manipulation in SUMMER_S_SCw_W increases on-shelf freshening a little further and thereby seems to cross a threshold, and FRIS basal melt increases substantially after year 70, but fitting the relative stability of the on-shelf temperatures this increase remains moderate compared to SC_H21C_*.

Density balance



Density
sigma1-1000 kg m^{-3}

Maximum at Ronne ice shelf front

Upstream at approx. sill depth

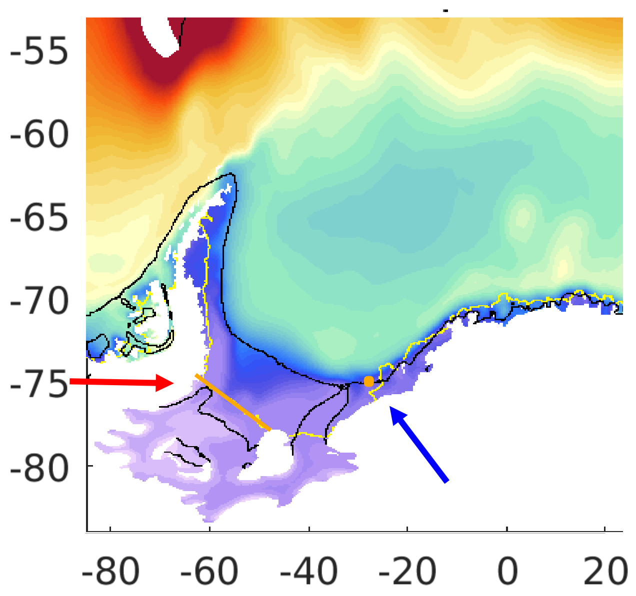


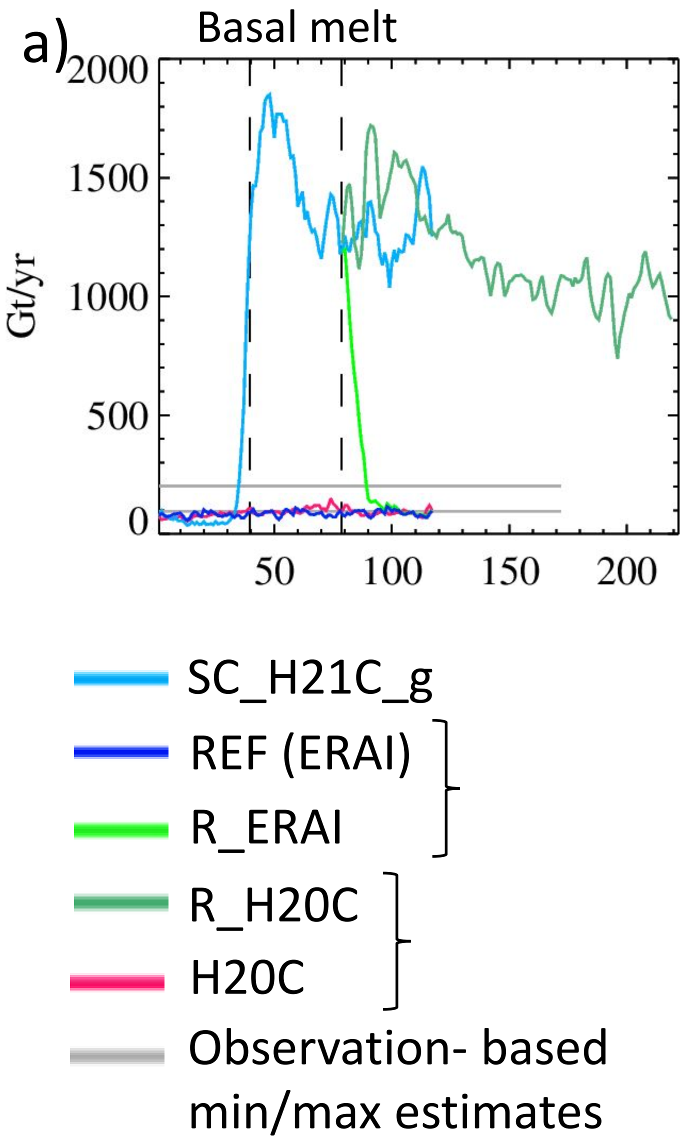
Figure 4: annual mean density evolution at Ronne Ice front and off the continental shelf at approximately sill depth.

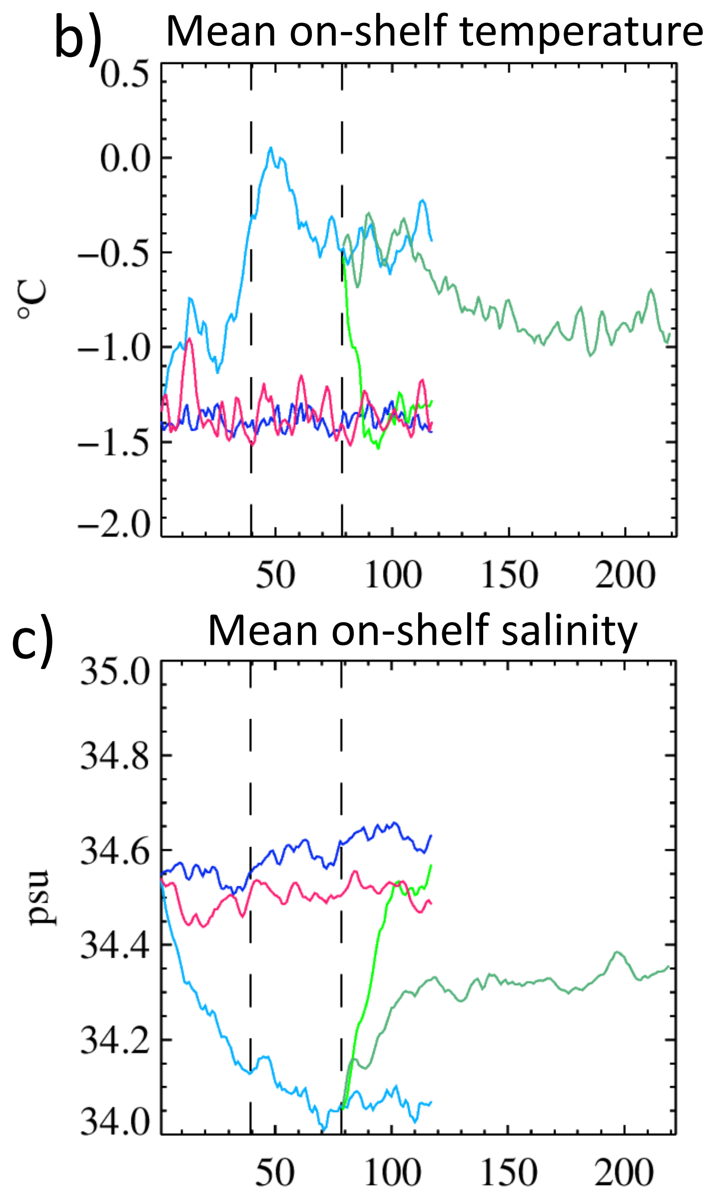
Note that the graph shows annual mean values and temporary intrusions of warm water can occur before the curves cross.

Density balance

The critical factor if (and when) the continental shelf will take on a ‚warm' state with off-shelf water freely entering the ice shelf cavities is the evolution and **balance of the density** of the densest water produced **on the continental shelf** and the density of the water found **off-shelf at sill depth**.
In our experiments (and as can be assumed for any future scenario) both decrease over time as warming and freshening continue. The continental shelf remains stable until the dense shelf water density decreases below that off the off-shelf water at sill depth. Then the inflow occurs and quickly changes the state of the continental shelf, leading to a strong increase of basal melt under the ice shelf. Since the warm water inflow is accompanied by **positive feedbacks**, this process is one of several **tipping points** in the climate system.
While SUMMER_S never reaches this point, the slightly more decreased on-shelf density in SUMMER_S_SCw_W is enough to tip the balance at least temporarily and the **maximum density** found at the Ronne ice front **controls** the inflow and the mean FRIS **meltrate** after year 70 (cf. Fig. 3c and Fig 4f).

Hysteresis behaviour





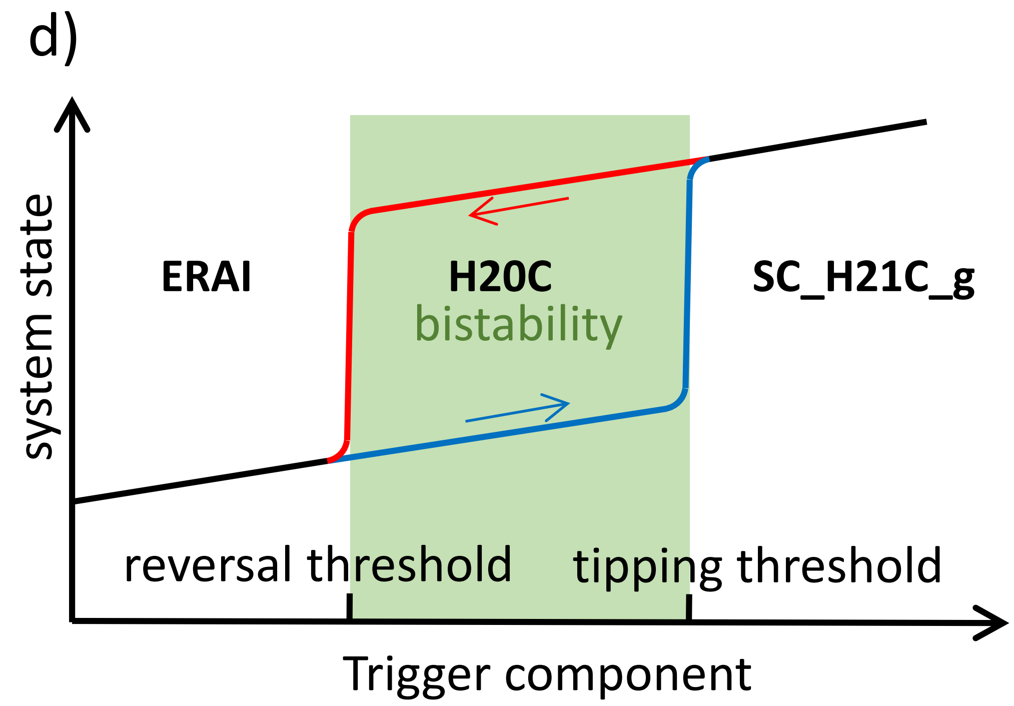


Figure 5: a) mean basal melt of FRIS and mean on-shelf b) temperature and c) salinity (excluding upper 200 m) d) schematic of hysteresis behaviour of tipping point

Hysteresis behaviour

A quick test on **reversibility** on the cold-to-warm switch of the continental shelf based on our experiment SC_H21C_g shows **hysteresis behaviour**.
While a **return to ERA Interim** forcing (R_ERAI) brings the system back across both the tipping and the reversal threshold and quickly **re-establishes a cold state** comparable to REF, the **H20C forcing** hits the sweet spot between the thresholds, where the **resulting state** of the system **depends on the previous state** (compare H20C starting from a cold state and R_H20C starting from a warm state).

Conclusions

- The Weddell Sea continental shelf is very vulnerable to tipping due to it‘s comparatively deep sill depth
- The tipping is controlled by the density balance of the densest water produced on the shelf and the water off-shelf at sill depth
- If this balance is fragile and just on the brink, the density found on the shelf controls the amount of basal melt (for FRIS)
- For more intense inflow, the amount of melt correlates well with the mean temperature on the continental shelf
- The hysteresis behaviour of the tipping of the continental shelf can be shown in our experiments.

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Thank you for your attention!

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