Freshening of the Southern Ocean through enhanced sea-ice transport

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Motivation

- The **Southern Ocean** has been significantly **freshening** over recent decades[1-4] (Fig. 1). This signal is among the **strongest global salinity changes**[5].
- The freshening **cannot be explained** purely by observed changes in the **atmospheric freshwater flux**[6] or increased **glacial melt water**[3,7] from Antarctica.
- **Freshwater redistribution** associated with **sea-ice formation, transport, and melt**[8,9] also influences the upper ocean salinity[10] and has **not been quantified** yet[11].

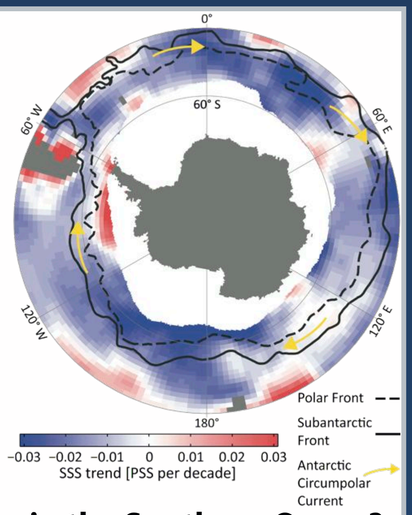

Figure 1: *Observed Southern Ocean salinity trend (1950-2000)[5].*

Research Questions:

1. **How large is the freshwater redistribution by sea ice in the Southern Ocean?**
2. **How did the sea-ice freshwater flux change over recent decades?**
3. **What is the effect of these changes on the Southern Ocean salinity?**

Data & Method

1. **Sea-ice freshwater mass balance (1980 -2008):**
   - Satellite ice concentration[12]
   - Assimilated thickness[13] corrected with laser altimetry data[14]
   - Satellite based drift[15]
   - ⇨ Comparison to evaporation-precipitation (E-P)[16], and land ice melt[17,18].
2. **Trend analysis (1980-2008):** Linear regression analysis based on a least squares method and comparison to changes in E-P[16] and land ice melt[7,18].
3. **Effect on ocean salinity:** Comparison of salinity trend from EN3 Objective Analysis[19] with sea-ice effect using ocean circulation estimates[20,21].

$$F_{ice} = -\frac{\rho_{ice}(1 - S_{ice}/S_{seawater})}{\rho_{freshwater}} \cdot \left(\frac{\partial V_{ice}}{\partial t} + \frac{\partial (u_{ice} \cdot V_{ice})}{\partial x} + \frac{\partial (v_{ice} \cdot V_{ice})}{\partial y} \right)$$

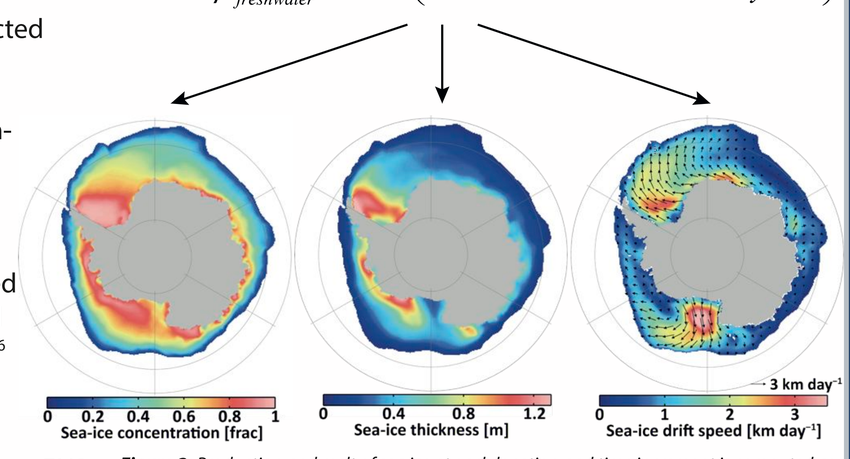

Figure 2: *Production and melt of sea ice at each location and time increment is computed as volume change plus advection. Ice volume (V_{ice}) is the product of grid area, concentration (left), and thickness (middle); u_{ice} and v_{ice} are the components of the ice drift vector (right). The product is then converted to a sea ice-induced freshwater flux (F_{ice}) using sea ice density (ρ_{ice}), freshwater water density (ρ_{water}), sea ice salinity (S_{ice}), seawater salinity ($S_{seawater}$).*

1 Mean net annual sea-ice freshwater flux

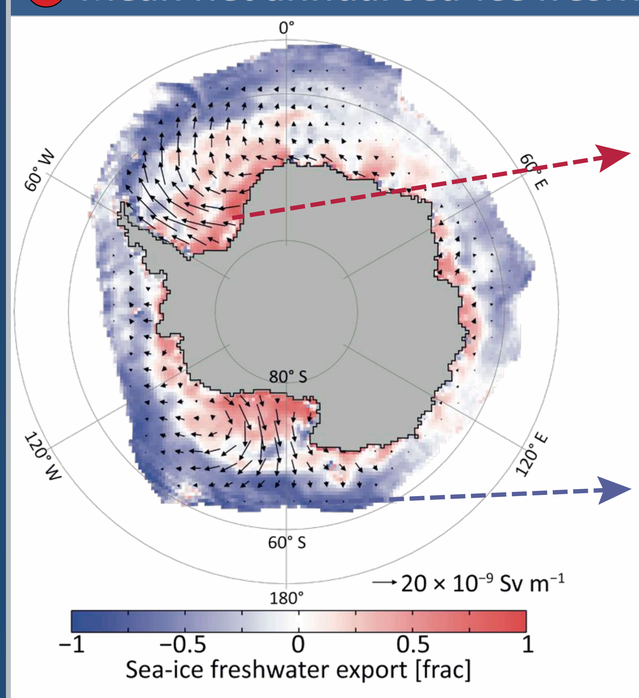

Figure 3: *Mean net annual sea-ice freshwater export fraction (1980-2008). Red: ice exported with respect to local formation; blue: ice imported with respect to local melt; arrows: mean net annual sea-ice freshwater transport.*

1 Results:

- ⇨ **Meridional ice transport** induces net freshwater **extraction at coast** and **input towards ice edge**.
- ⇨ Largest flux in **Ross and Weddell Seas**.

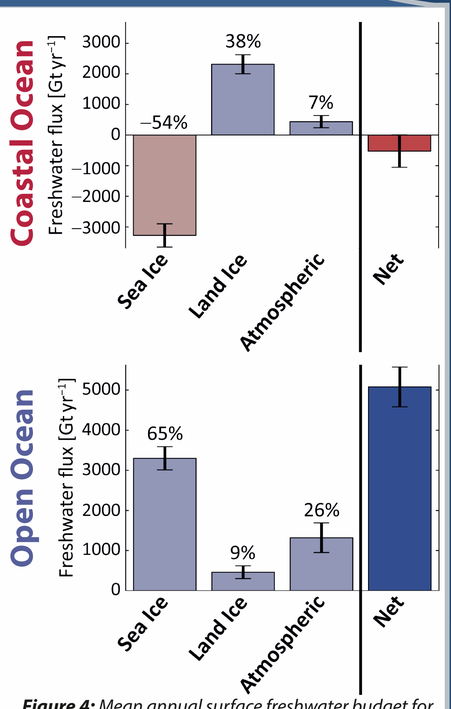

Figure 4: *Mean annual surface freshwater budget for the coastal ocean (upper panel; red in Fig. 3) and the open ocean (lower panel; blue in Fig. 3).*

1 Results:

- ⇨ **Sea ice dominates** surface buget.
- ⇨ **At coast balanced** by land ice and atmospheric flux.

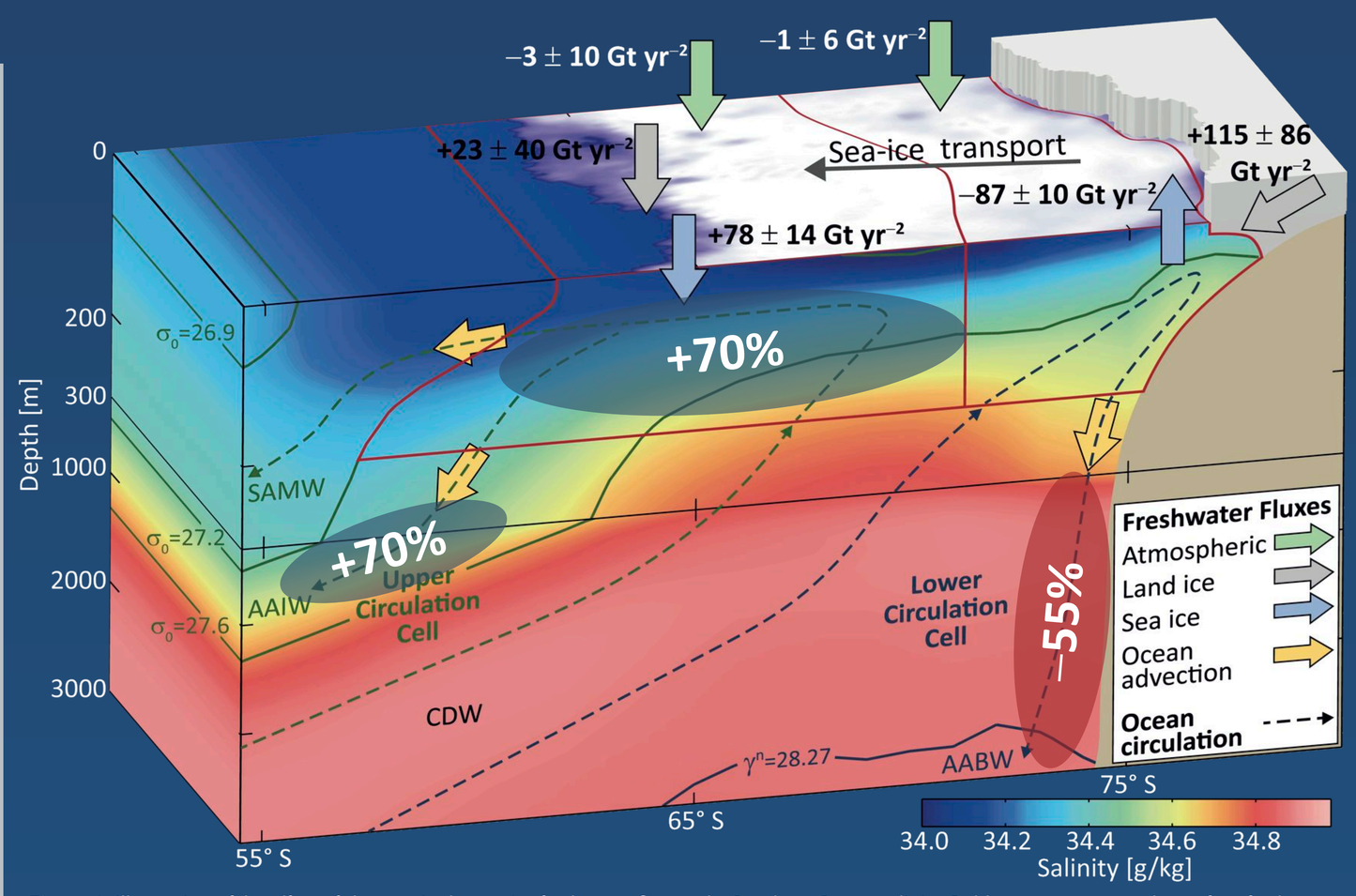

Figure 8: *Illustration of the effect of changes in the sea-ice freshwater flux on the Southern Ocean salinity. Bold arrows represent the surface freshwater fluxes and their changes for the coastal ocean (right) and the open ocean (left). The background shows the ocean circulation (dashed lines), mean salinity (color), and density (solid lines). Ellipses show the percentage of the salinity change explained by changes in sea-ice freshwater flux.*

2 Changing sea-ice freshwater flux

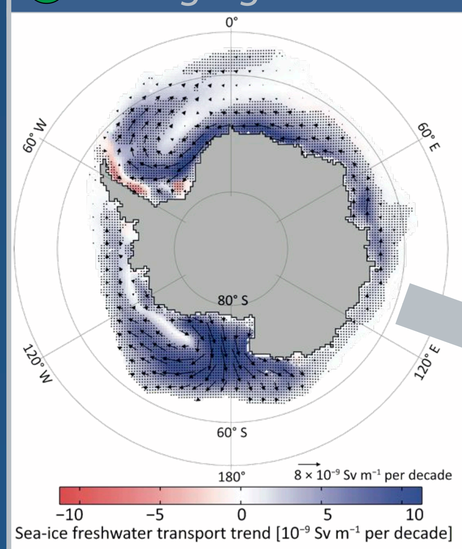

Figure 5: *Trend in sea-ice freshwater transport (1980-2008). Arrows: magnitude and direction of trend; blue: trend in same direction as mean; red: trend in opposite direction as mean; black stippling: significant at a 90% confidence level.*

2 Results:

- ⇨ **Increasing northward transport** of freshwater by sea ice causes **changes** in the surface **freshwater flux balance** between the coastal and open ocean.
- ⇨ Largest changes occur in the **South Pacific** (Ross Sea).

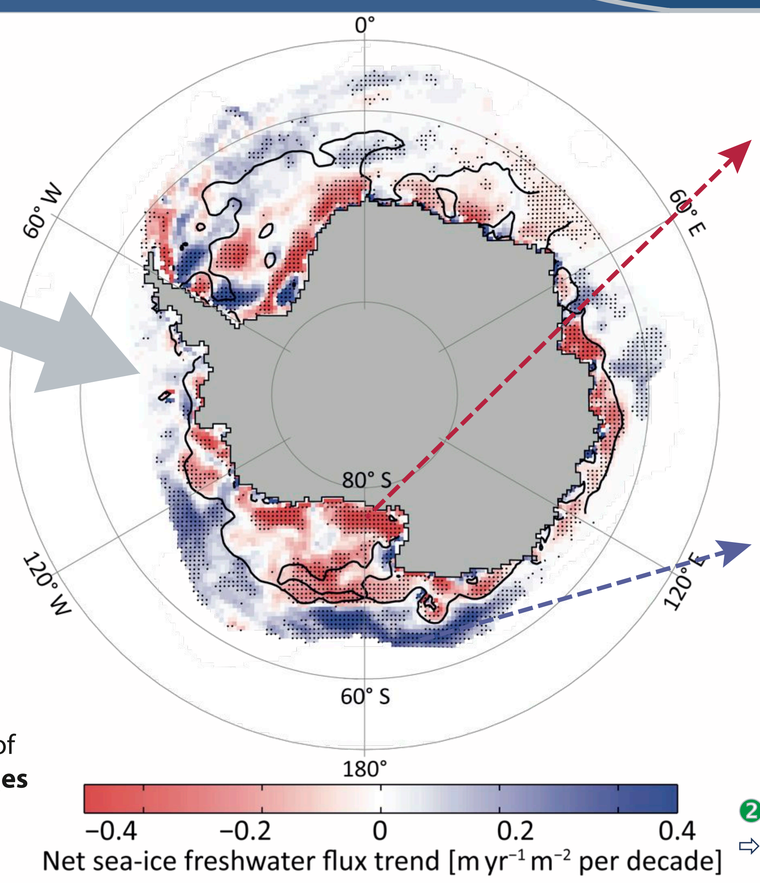

Figure 6: *Trend in net annual sea-ice freshwater flux (1980-2008). Black contour: zero line of the mean state; black stippling: significant at a 90% confidence level.*

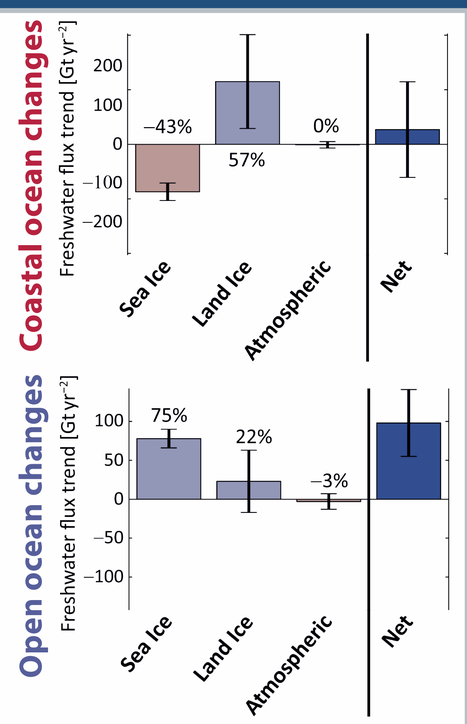

Figure 7: *Trend of annual surface freshwater budget for the coastal ocean (upper panel; red in Fig. 3) and the open ocean (lower panel; blue in Fig. 3).*

2 Results:

- ⇨ At **coast increased sea ice formation reduces freshening** from glacial melt.
- ⇨ Strong **freshening** in the **open ocean** mainly by increased sea ice melt.

3 Effect on ocean salinity changes

3 Results:

- ⇨ Strongest **sea-ice freshwater flux trend** (Fig. 6) in **South Pacific consistent** with pattern of **salinity change** (Fig. 1).
- ⇨ Increased sea-ice freshwater extraction at the **coast reduces the freshening of Antarctic Bottom Water by about 55%** (Fig. 8).
- ⇨ Increased sea-ice freshwater fluxes in the open ocean **explain about 70%** of the freshening observed in the **Antarctic Surface and Antarctic Intermediate Waters** (Fig. 8).

Conclusions

1. ⇨ **Freshwater fluxes associated with sea-ice formation, transport, and melt are the dominant factor in the surface flux balance in the high-latitude Southern Ocean.**
   - ⇨ **They explain up to 65% of the salinity modification of water masses formed in the sea-ice region.**
2. ⇨ **Enhanced sea-ice freshwater flux (+25% per decade) due to increased northward sea-ice transport extracts more freshwater from the coastal ocean and adds it to the open ocean.**
3. ⇨ **Freshening of Antarctic Bottom Water reduced by sea-ice freshwater fluxes by about half.**
   - ⇨ **Freshening of the open ocean mainly caused by changes in the sea-ice freshwater flux (70%).**

Implication:

The high-latitude Southern Ocean density structure is controlled by salinity (Fig. 8). Consequently, changes in the sea-ice freshwater flux have a large potential to alter the stratification, overturning circulation, and surface to deep ocean exchange of heat and carbon. Thus, they could influence long-term changes in global climate[22].

Related manuscript in preparation:
F. A. Haumann, M. Münnich, I. Frenger, N. Gruber (2014): Freshening of the Southern Ocean through enhanced sea-ice transport.

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