Sea ice and the ocean mixed layer over the Antarctic shelf seas

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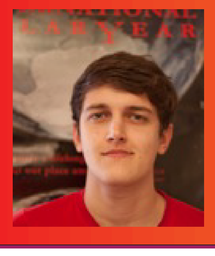

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The aim of this study is to understand the mean state and recent/future trends in the surface driven formation of Antarctic shelf sea waters. A mixed layer model has been incorporated into the CICE sea ice model, forced by both ERA-I and HadGEM2-ES atmospheric data. The model results provide further evidence of the bimodal nature of the Antarctic shelf seas, and demonstrates sea ice growth/melt dominating the mixed layer evolution. The ERA-I simulation shows mainly insignificant trends compared to the long-term HadGEM2-ES simulation.

1. The Antarctic Shelf Seas

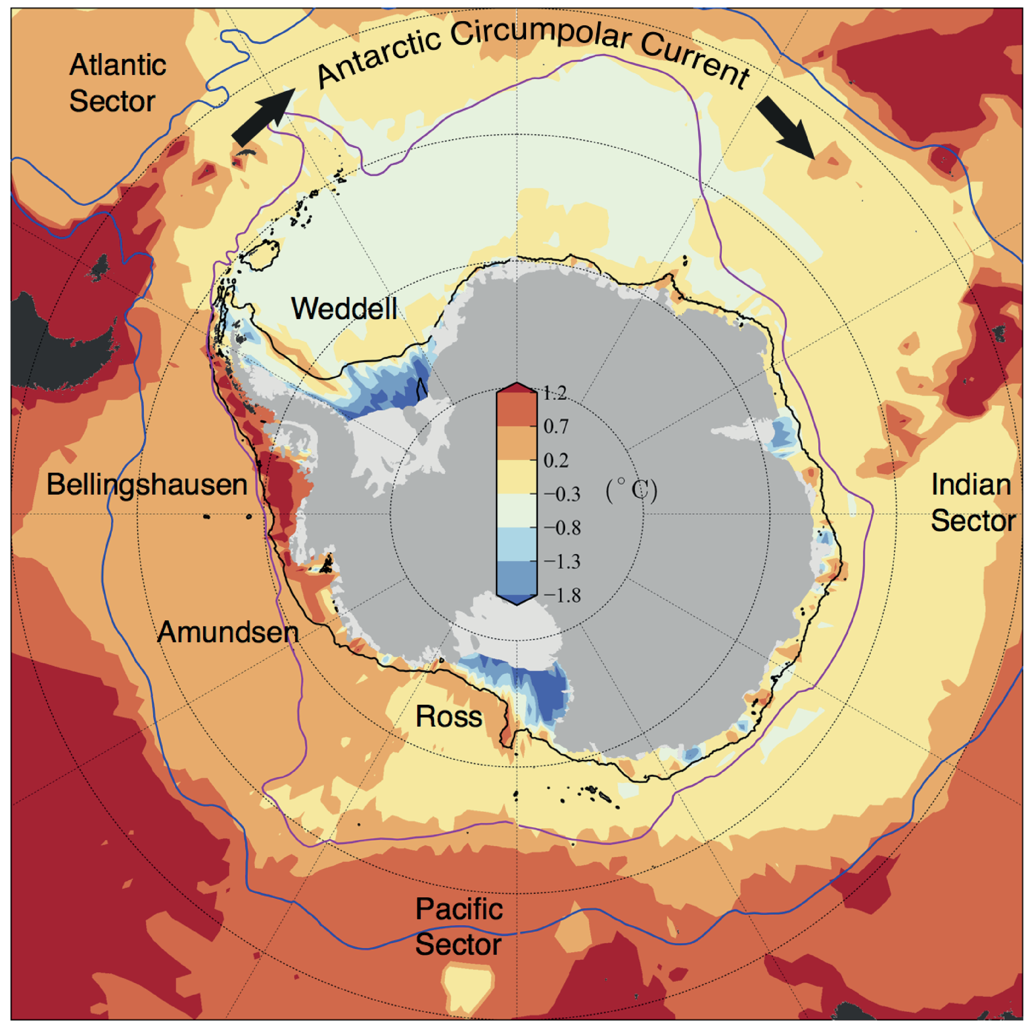


Figure 1: Southern Ocean bottom temperature (from WOA09). The 1000m isobath (dark blue) and the Antarctic landmask are taken from the RTOPO dataset (Timmermann et al., 2010, E.Syst). The blue and magneta lines indicate the northern and southern ACC boundary (Orsi et al., 1995, DSR).

The Antarctic shelf seas are a crucial component of the Earth's climate system. The Amundsen and Bellingshausen shelf seas are flooded with warm (+1 °C) Circumpolar Deep Water, which is implicit in the recent ocean-driven erosion of the Antarctic Ice Sheet. In contrast, the Weddell and Ross shelf seas are filled with cold, saline waters (around the surface freezing temperature of -1.9 °C), which feed the global thermohaline circulation through HSSW/AABW formation.

It was demonstrated, using a highly idealised model, that this bimodal distribution (Fig 1) could be be driven purely by atmospheric differences between the two regimes (Petty et al., 2013, JPO).

The main aims of the work presented here are (i) to accurately quantify the cause of regional variations in the surface driven formation of Antarctic shelf sea waters and (ii) to investigate the recent and future evolution of the sea ice and the surface inputs of salt/freshwater and heat over the Antarctic continental shelf .

A key theme throughout this study is the focus on surface processes (e.g. sea ice) over variable ocean dynamics.

2. CICE-Mixed Layer Modelling

An ocean mixed layer model has been incorporated into the CICE sea ice model (Fig. 2) to investigate regional variations in the sea ice and surface driven formation of shelf waters around Antarctica (Petty et al., 2013, TCD).

The model is forced with ERA-I (1985-2011) atmospheric data to accurately quantify recent behaviour (mean state and trends). HadGEM2-ES forcing data (1985-2099) are used to investigate long-term trends.

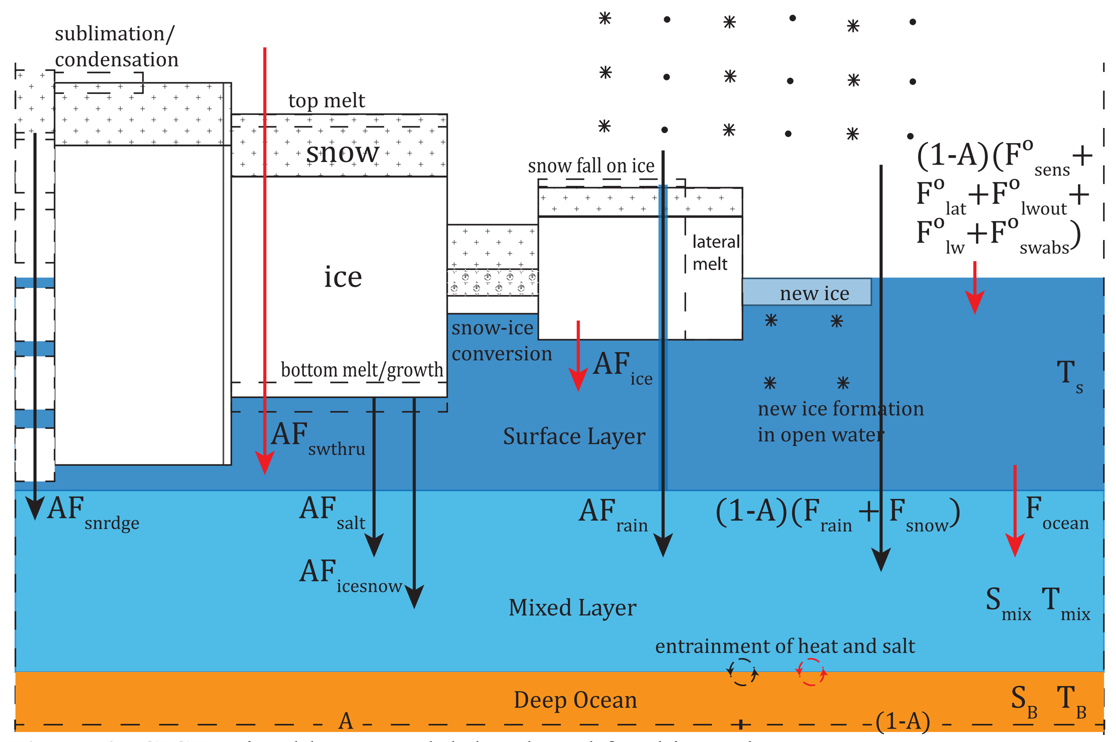


Figure 2: CICE-mixed layer model developed for this study.

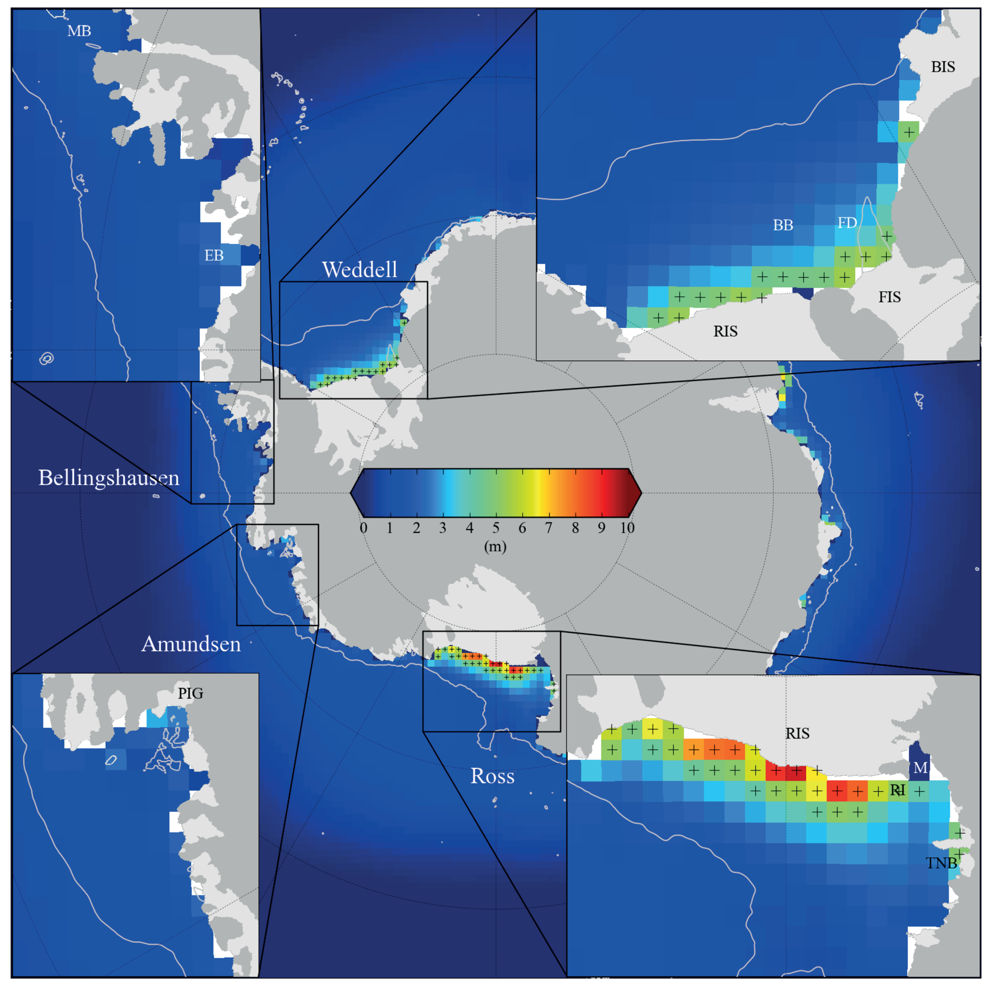


Figure 3: Mean annual ice growth from the ERA-I simulation (1985-2011). Crosses indicate high (>4 m) growth 'polynya' regions.

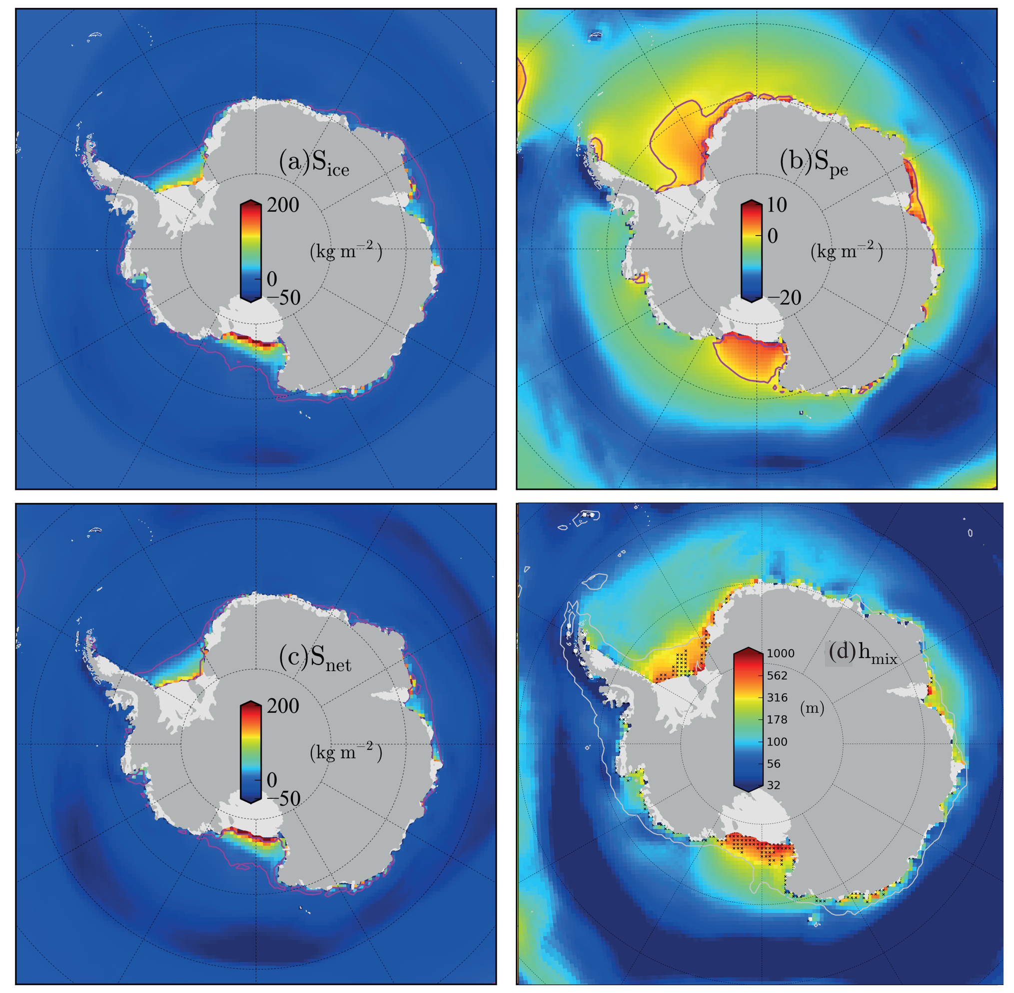
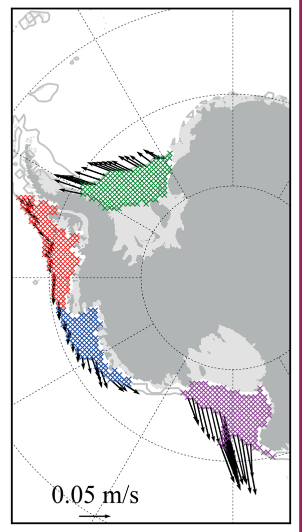


Figure 4: Mean annual effective salt input from (a) ice growth/melt, (b) P-E, (c) total. (d) Mean maximum mixed layer depth. Crosses = destratification.

Figs. 3 and 4 show the mean (1985-2011) results from the ERA-I simulation. Significantly more sea ice is grown in the Ross and Weddell seas, especially along both coastal ice fronts. This results in a mixed layer that deepens and destratifies large regions of both shelf seas each winter. Sea ice dominates the annual effective salt input over the Antarctic continental shelf compared to net precipitation (P-E). The Weddell and Ross seas receive a net annual input of effective salt over virtually the enitre shelf sea region.

3. Sea Ice Mass Balance Trends



The Weddell and Ross shelf seas experience the highest annual ice growth, with a large fraction exported northwards each year, whereas the Bellingshausen shelf sea experiences the highest annual ice melt, driven by the advection of ice into the shelf sea from the northeast.

The ERA-I simulation shows a significant decrease in the annual Weddell shelf sea ice melt, but weak, insignificant trends in the annual ice growth, melt and export, across the remaining shelf seas. The HadGEM2-ES simulation shows more significant (although not necessarily stronger) trends across all shelf-sea regions, due to the moderate climate warming signal and extended time-period. However, the accuracy and validity of the HadGEM2-ES results (forcing from a free-running GCM) are highly uncertain .

ERA-I	Weddell	B'hausen	Amundsen	Ross
G_i (km^3 dec^{-1})	-4.84	-9.81	0.40	6.56
G_i (m dec^{-1})	-0.01	-0.02	0.002	0.01
M_i (km^3 dec^{-1})	**-44.1**	-5.09	-14.9 (90)	17.4
M_i (m dec^{-1})	**-0.10**	-0.01	-0.06 (90)	0.04
E_i (km^3 dec^{-1})	27.3	-28.4	4.82	1.30
E_i (m dec^{-1})	0.06	-0.07	0.02	0.003
'Polynya' area (10^3 km^2)	55.1	-	-	96.9
G_i^p (km^3 dec^{-1})	1.90	-	-	-10.4
G_i^p (m dec^{-1})	0.03	-	-	-0.10
M_i^p (km^3 dec^{-1})	-4.43 (93)	-	-	2.22
M_i^p (m dec^{-1})	-0.08 (93)	-	-	0.02
E_i^p (km^3 dec^{-1})	3.57	-	-	-10.9
E_i^p (m dec^{-1})	0.07	-	-	-0.11
HadGEM2-ES				
G_i (km^3 dec^{-1})	-6.05 (97.3)	**-22.1**	**-10.6**	-2.94
G_i (m dec^{-1})	-0.01 (97.3)	**-0.055**	**-0.041**	-0.01
M_i (km^{3}dec^{-1})	**6.25**	**-11.0**	**-5.28**	0.84
M_i (m dec^{-1})	**0.01**	**-0.03**	**-0.02**	0.002
E_i (km^3 dec^{-1})	**-12.0**	**-11.9**	**-5.60**	-3.90 (94.9)
E_i (m dec^{-1})	**-0.03**	**-0.03**	**-0.02**	-0.01 (94.9)
'Polynya' area (10^3 km^2)	76.5	-	-	93.9
G_i^p (km^3 dec^{-1})	**-3.16**	-	-	**-3.57**
G_i^p (m dec^{-1})	**-0.04**	-	-	**-0.04**
M_i^p (km^3 dec^{-1})	0.55	-	-	-0.27
M_i^p (m dec^{-1})	0.01	-	-	-0.003
E_i^p (km^3 dec^{-1})	**-3.67**	-	-	**-3.29**
E_i^p (m dec^{-1})	**-0.05**	-	-	**-0.04**
Shelf sea area (10^3 km^2)	433	398	261	459

Table 1: Trends in the sea ice mass balance (for regions shown in the top right map). 'Polynya' trends are denoted by the p superscript. Bold values indicate the trend is significant at 90%

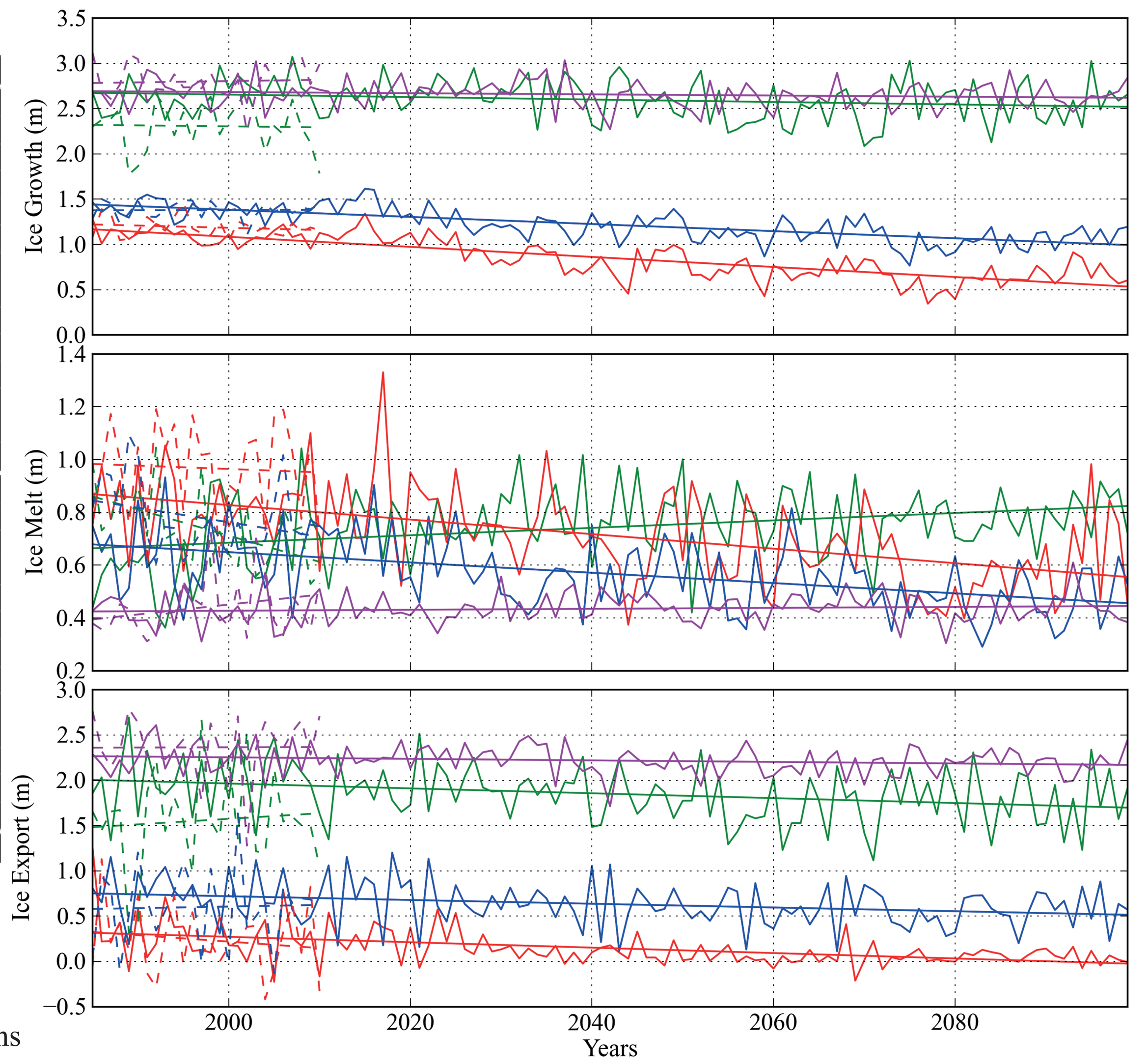


Figure 5: Sea ice mass balance trends for the ERA-I (1985-2011 - dashed lines) and HadGEM2-ES (1985-2099 - solid lines) simulations

4. Ice Thickness Trends

The ERA-I simulation captures much of the recently observed regional trends in concentration and ice motion. The simulation also shows strong spatially variable trends in ice thickness, especially along the Antarctic coastline within the shelf seas (top row - Fig. 6). This agrees well with the magnitude and regional variability of other recent modelling studies.

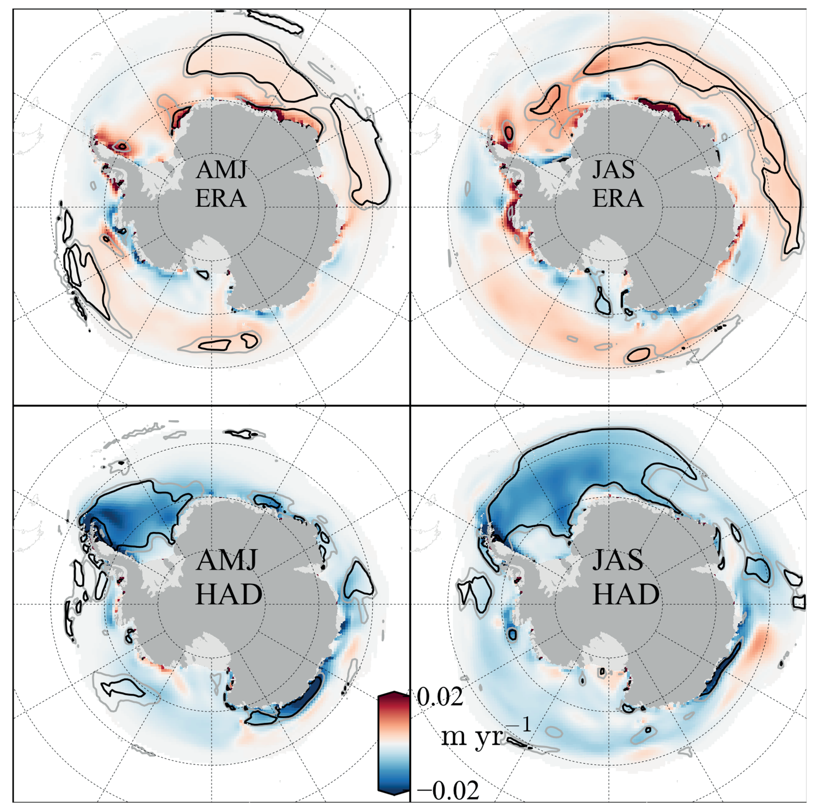


Figure 6: Ice thickness trends over 1985-2011 for the ERA-I (top row) and HadGEM2-ES (bottom row) simulations.

The HadGEM2-ES simulation shows a more consistent thinning trend, although there are some regions of thickening along the coast in the recent, short-term analysis (bottom row - Fig. 6), highlighting the important role of dynamical trends in ice motion.

5. Salt/Freshwater and Temperature Trends

The decrease in the annual ERA-I Weddell ice melt leads to a near-significant increase in the annual effective salt input over the Weddell shelf, along with a moderate estimated freshening of the winter mixed layer. A near-significant decrease in the annual effective salt input under the Ross polynya is simulated, driven primarily by sea ice changes. The HadGEM2-ES simulation shows stronger and more significant trends in the annual effective salt input at the surface, as expected from the regional sea ice trends.

The freshening signals were placed in context of the rapid thinning and acceleration of the West Antarctic ice shelves. This demonstrates that the large input of fresh glacial meltwater dominates over changes in freshwater from sea ice/precipitation trends. However, strong freshening is estimated in localised regions (e.g. polynyas) of a similar order of magnitude to the recently observed freshening (0.03 dec^{-1} in the Ross). More research is needed to understand the potential pathway of increased fresh glacial meltwater, to fully understand the impact on the shelf seas and regions of HSSW formation.

ERA-I	Weddell	B'hausen	Amundsen	Ross
Shelf sea area (10^3 km^2)	433	398	261	459
$\overline{h}_{max}$ (m)	340	50	110	360
S_{ice} (kg m^{-2}dec^{-1})	3.60 (95)	0.33	2.16	-0.61
S_{pe} (kg m^{-2}dec^{-1})	-0.16	0.36	0.63 (93)	-0.03
S_{net} (kg m^{-2}dec^{-1})	3.50 (92)	0.70	2.78 (92)	-0.63
FWE_{net} (gt dec^{-1})	-43.1 (92)	-7.91	-20.6 (92)	8.20
$\widehat{S}_{net}$ (dec^{-1})	0.01 (92)	0.01	0.02 (92)	-0.002
Shelf sea salinity (dec^{-1})	2e-4 (97)	-1e-4 (92)	1e-4	2e-5
'Polynya' area (10^3 km^2)	55.1	-	-	96.9
$\overline{h}^p_{max}$ (m)	520	-	-	590
S^p_{net} (kg m^{-2}dec^{-1})	4.75	-	-	-5.70 (91)
FWE^p_{net} (gt dec^{-1})	-7.46	-	-	15.7 (91)
$\widehat{S}^p_{net}$ (dec^{-1})	0.01	-	-	-0.01 (91)
HadGEM2-ES				
$\overline{h}_{max}$ (m)	350	30	90	350
S_{ice} (kg m^{-2}dec^{-1})	**-1.14**	-0.32 (96)	**-0.43**	-0.010
S_{pe} (kg m^{-2}dec^{-1})	-0.04 (93)	**-1.29**	**-0.93**	-0.020
S_{net} (kg m^{-2}dec^{-1})	**-1.18**	**-1.60**	**-1.37**	-0.040
FWE_{net} (gt dec^{-1})	**14.5**	**18.1**	**10.1**	0.48
$\widehat{S}_{net}$ (dec^{-1})	**-0.003**	**-0.05**	**-0.01**	-1e-4
Shelf sea salinity (dec^{-1})	**-4e-5**	**5e-5**	**-5e-5**	6e-6
'Polynya' area (10^3 km^2)	76.5	-	-	93.9
$\overline{h}^p_{max}$ (m)	550	-	-	590
S^p_{net} (kg m^{-2}dec^{-1})	**-1.79**	-	-	-0.69 (98)
FWE^p_{net} (gt dec^{-1})	**3.88**	-	-	1.84 (98)
$\widehat{S}^p_{net}$ (dec^{-1})	**-0.003**	-	-	-0.001 (98)

Table 2: Effective salt input, equivalent freshwater input, estimated water column freshening and shelf sea salinity trends for the ERA-I (1985-2011) and HadGES2-ES (1985-2099) simulations.

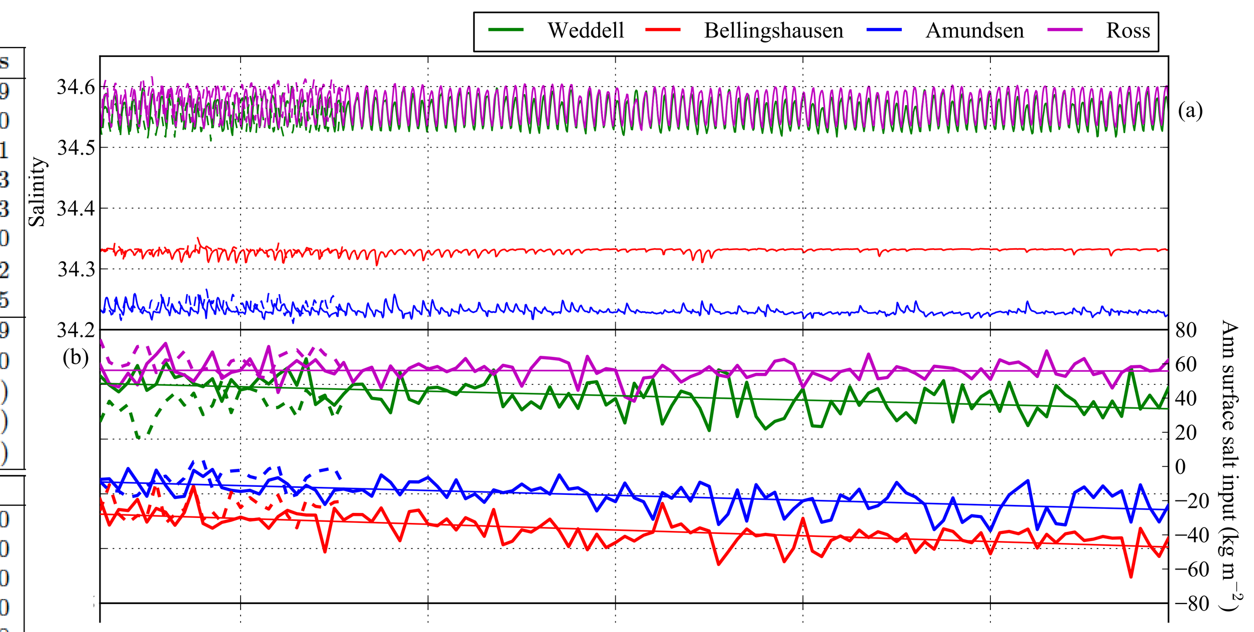


Figure 7: Direct shelf sea salinity (top row) and net annual effective salt input (bottom row) for the ERA-I (dashed) and HadGEM2-ES (solid) simulations.

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