The suppression of Southern Ocean deep convection under anthropogenic climate change

Impacts on future ocean carbon and heat storage

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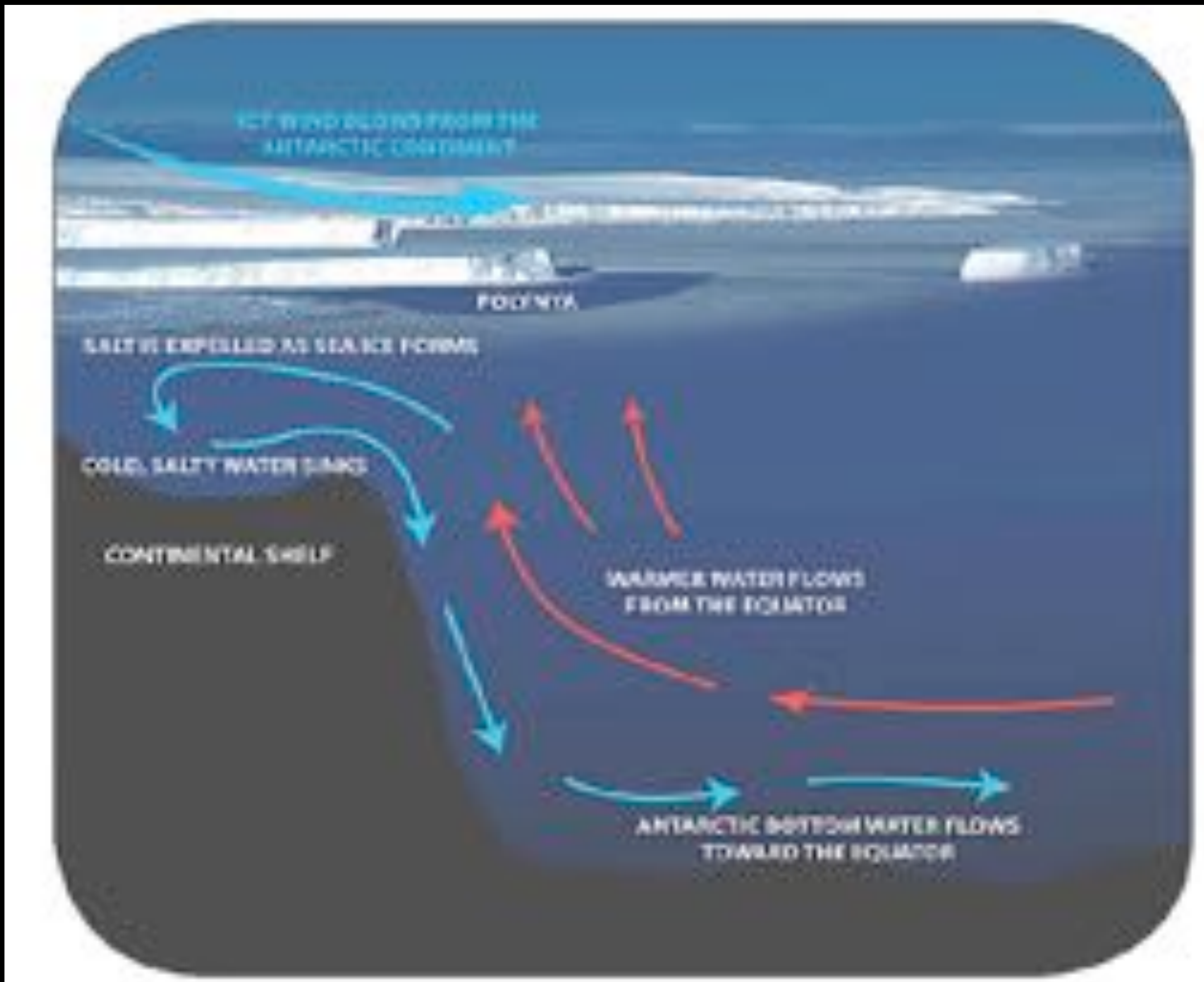
Conclusions

I. The Weddell Sea was once a site of deep convection, but has been quiet for almost 40 years
II. Freshening and stratification of the polar Southern Ocean has been observed over that time period
III. CMIP5 models suggest that the observed degree of freshening is associated with anthropogenic climate change and is sufficient to suppress open ocean convection

Implications

I. CARBON – the suppression of S. Ocean deep convection allows the ocean to store more natural CO_2, but suppresses the uptake of anthropogenic CO_2, with the net impact evolving over time
II. HEAT – the suppression of convection may allow for increased deep ocean heat uptake

AABW is presently produced on the shelves



Near-boundary convection and downslope flow. Now the only mode of AABW formation. Schematic from M. England's web page.

Wüst (1928) hypothesized that some AABW must be formed in the open ocean waters of the Weddell Sea

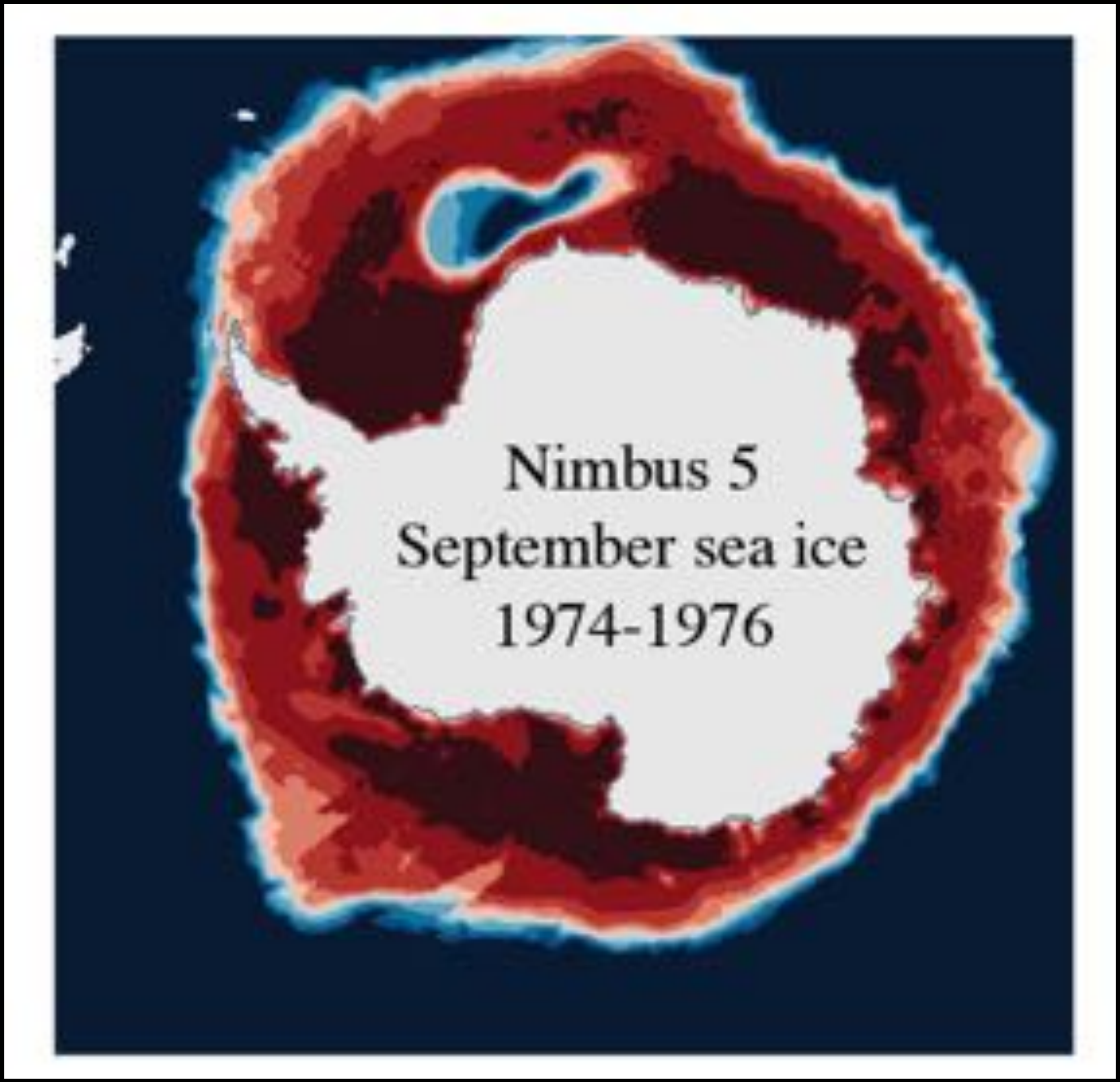
DER URSPRUNG DER ATLANTISCHEN TIEFENWÄSSER

(Aus den Ergebnissen der Deutschen Atlantischen Expedition)

VON GEORG WÜST, BERLIN

Mit 1 Abbildung und 3 Tafeln

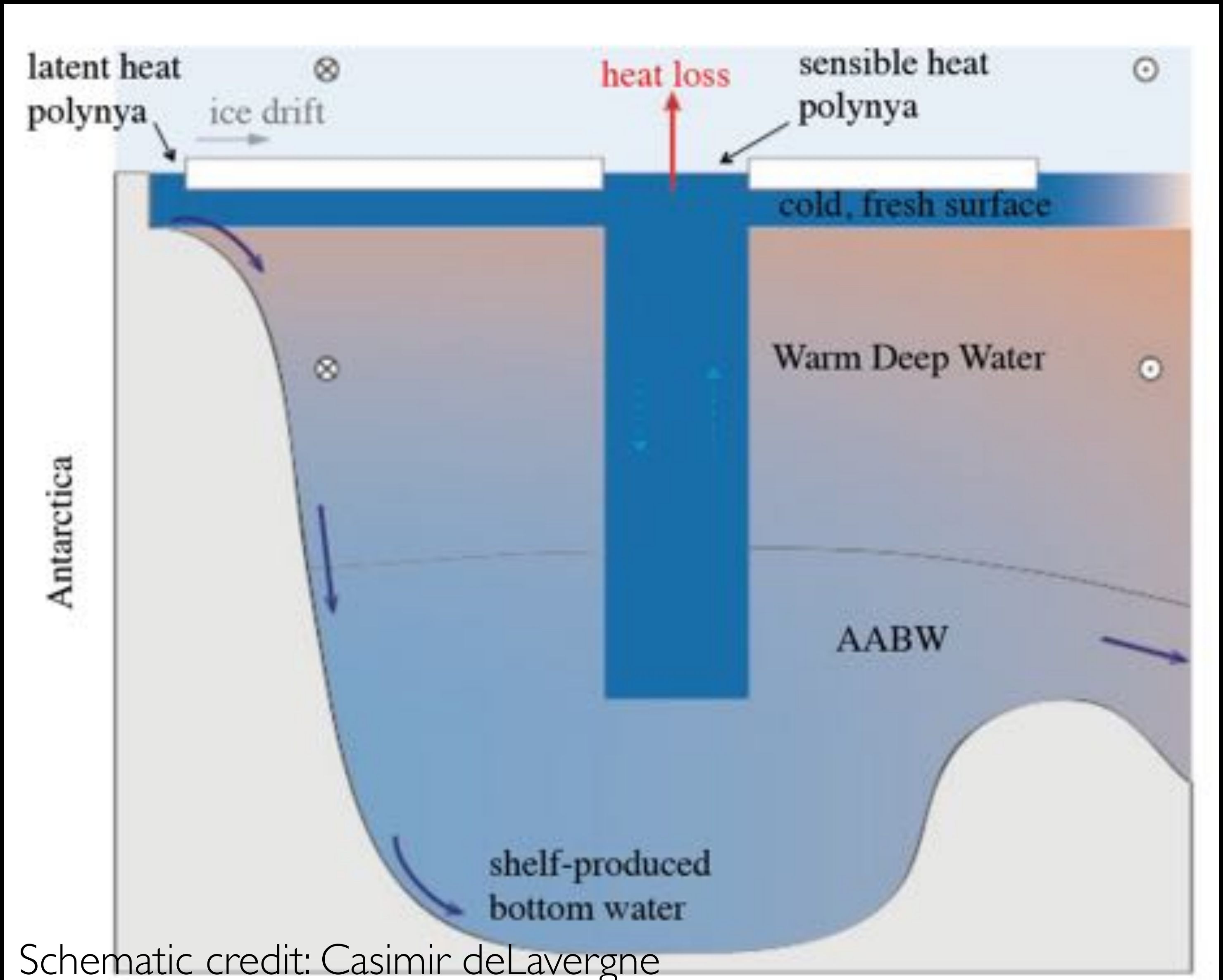
When the first microwave satellite launched almost 50 years later, Wüst appeared to be right!



A giant polynya appeared for 3 straight years over Maud Rise in the Weddell Sea (Carsey et al., 1979).

5 times as big as the Labrador Sea Water formation region!

Polynya kept open by mixing with relatively Warm Deep Water



Schematic credit: Casimir deLavergne

The Weddell Polynya was a monstrous climate phenomenon, considered for many years to be a leading source of AABW

From 1974-1976, the heat released from the polynya was estimated at 1.2×10^{21} J (Gordon 1982)

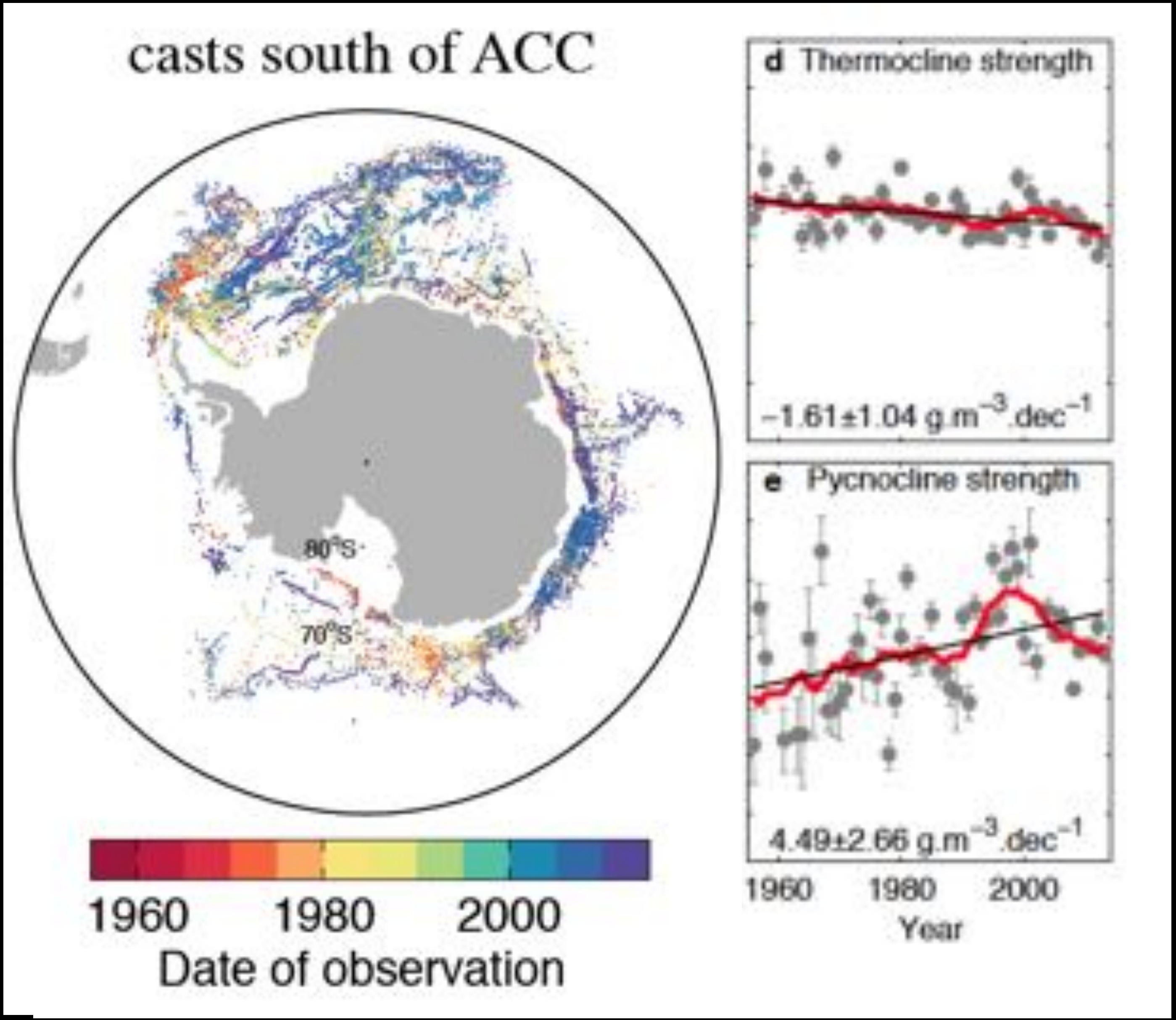
Table 2. The Earth's Heat Budget[a] $\times 10^{21}$ J

Component	1972–2008	1993–2008
Shallow ocean (0–700m)	112.6	45.9
Deep ocean (700–3000m)	49.7	20.7
Abyssal ocean (3000m-bottom)	30.7	12.8
Total ocean storage	**193.0**[b]	**79.4**
Glaciers (Latent only)	3.0	1.7
Antarctica (Latent only)	1.4	0.8
Greenland (Latent only)	0.7	0.6
Sea ice	2.5	1.0
Continents	4.7	2.0
Atmosphere	2.0	1.2
Total other storage	**14.2**	**7.3**
Total storage	**207.2**	**86.7**

From Church et al., 2010

But since 1976, no Weddell Polynya has been seen again …

The polar Southern Ocean has freshened, stratified and stabilized, despite the subsurface accumulation of heat



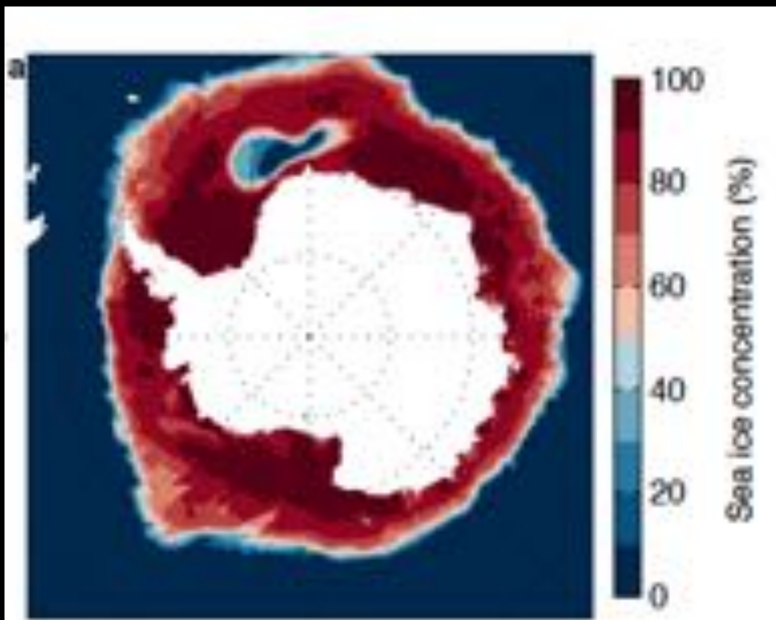
From de Lavergne et al., 2014. Nature Climate Change

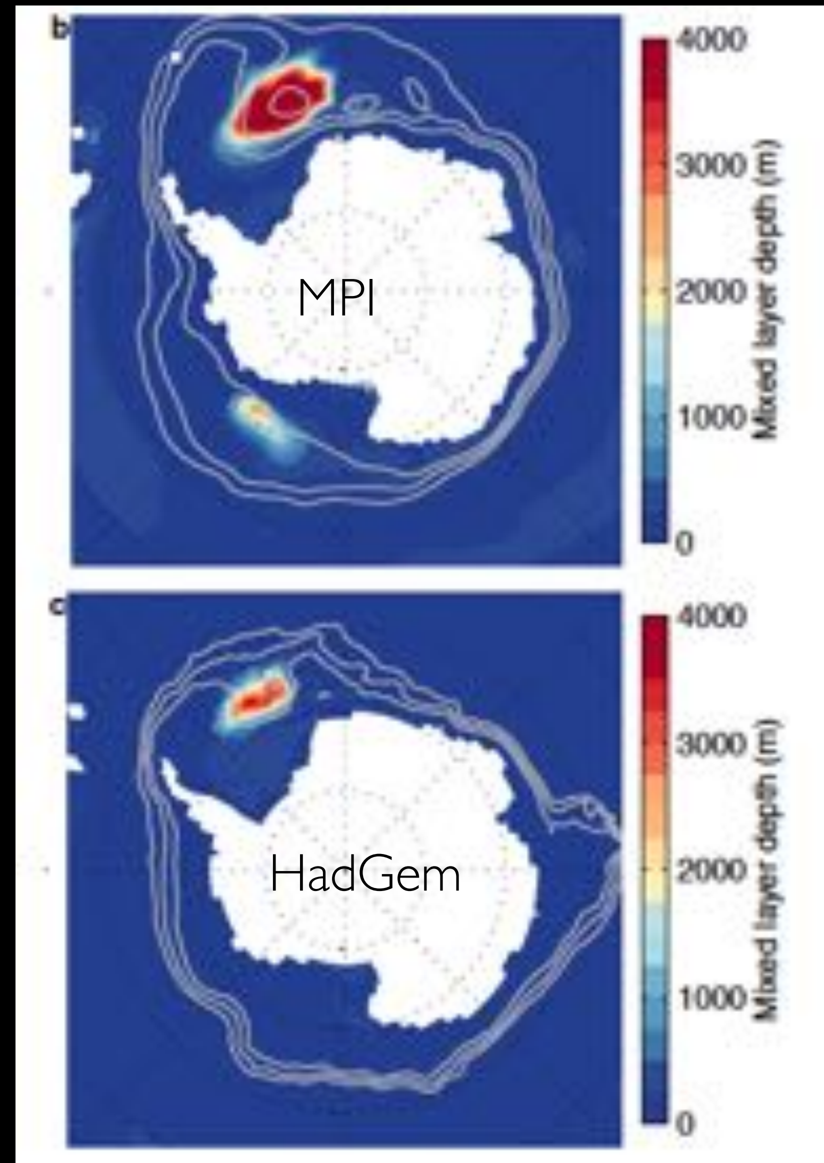
Is this degree of freshening sufficient to suppress convection?

- CMIP5 tremendously helpful in evaluating this question
- 25 of 36 CMIP5 models simulate open S.O. ocean convection under preindustrial forcing
- Some caveats
  - Climate models generally do not properly represent shelf processes, so the deep ocean is too poorly stratified and open ocean convection is favored
  - Convection is parameterized, introducing additional uncertainties

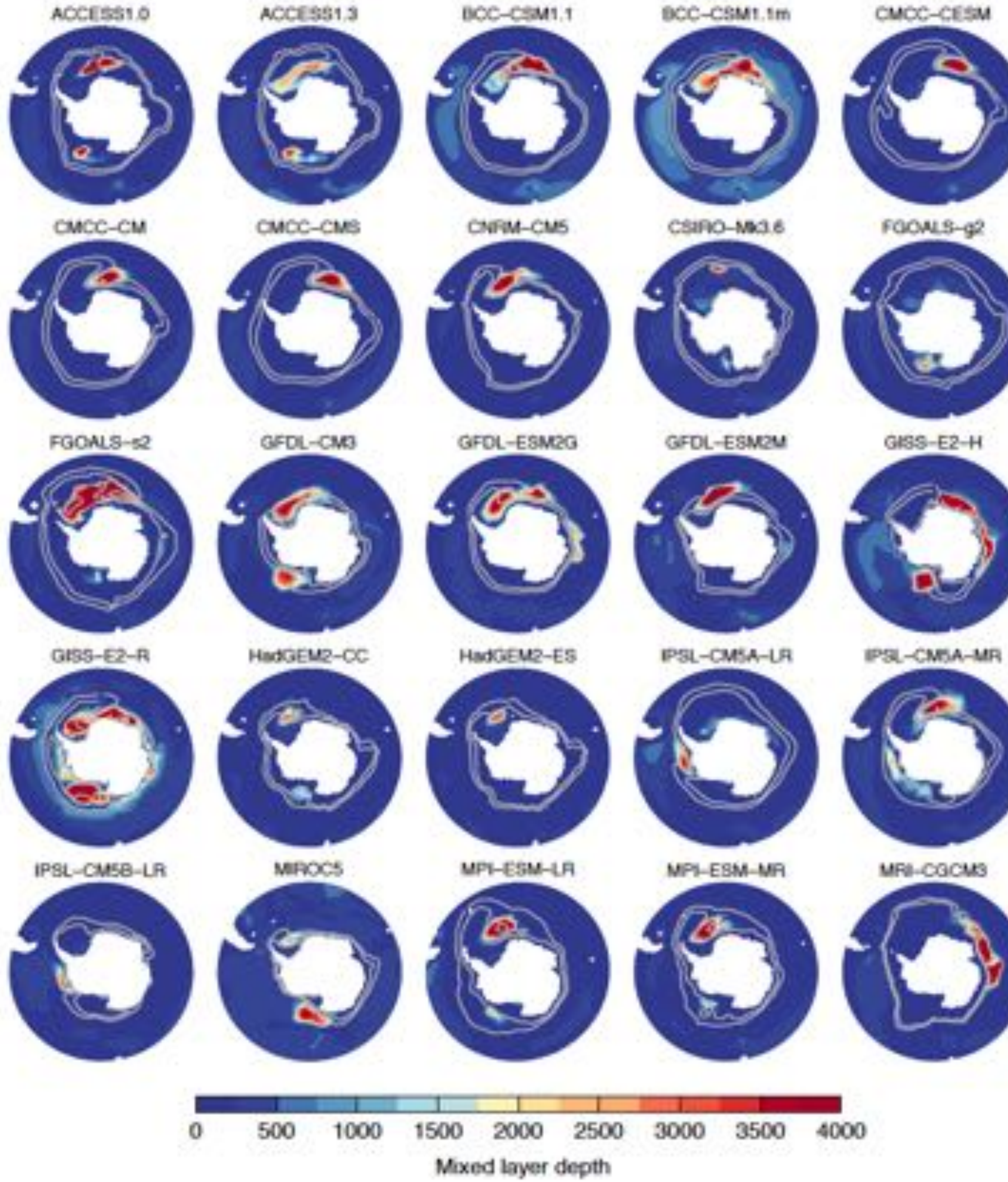
Preindustrial model convection compared with satellite observations

Satellite observations

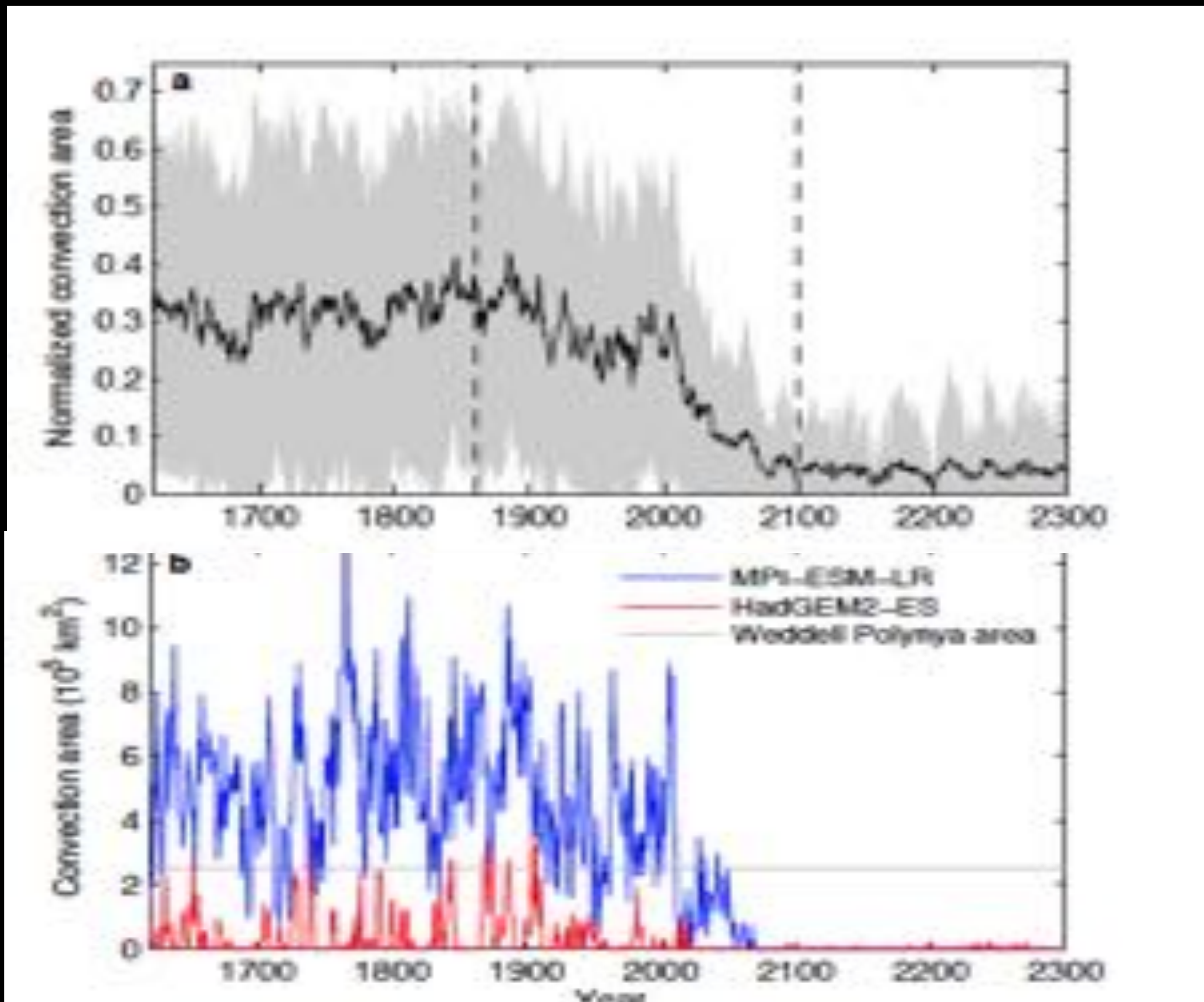




Mixed layer depth in two models with extended simulations, good AABW properties, and realistic-looking Weddell Polynya. Germany's MPI (top) and UK's HadGem (bottom).


ACCESS1.0
ACCESS1.3
BCC-CSM1.1
BCC-CSM1.1m
CMCC-CESM
CMCC-CM
CMCC-CMS
CNRM-CM5
CSIRO-Mk3.6
FGOALS-g2
FGOALS-s2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-H
GISS-E2-R
HadGEM2-CC
HadGEM2-ES
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MRI-CGCM3
0
500
1000
1500
2000
2500
3000
3500
4000
Mixed layer depth

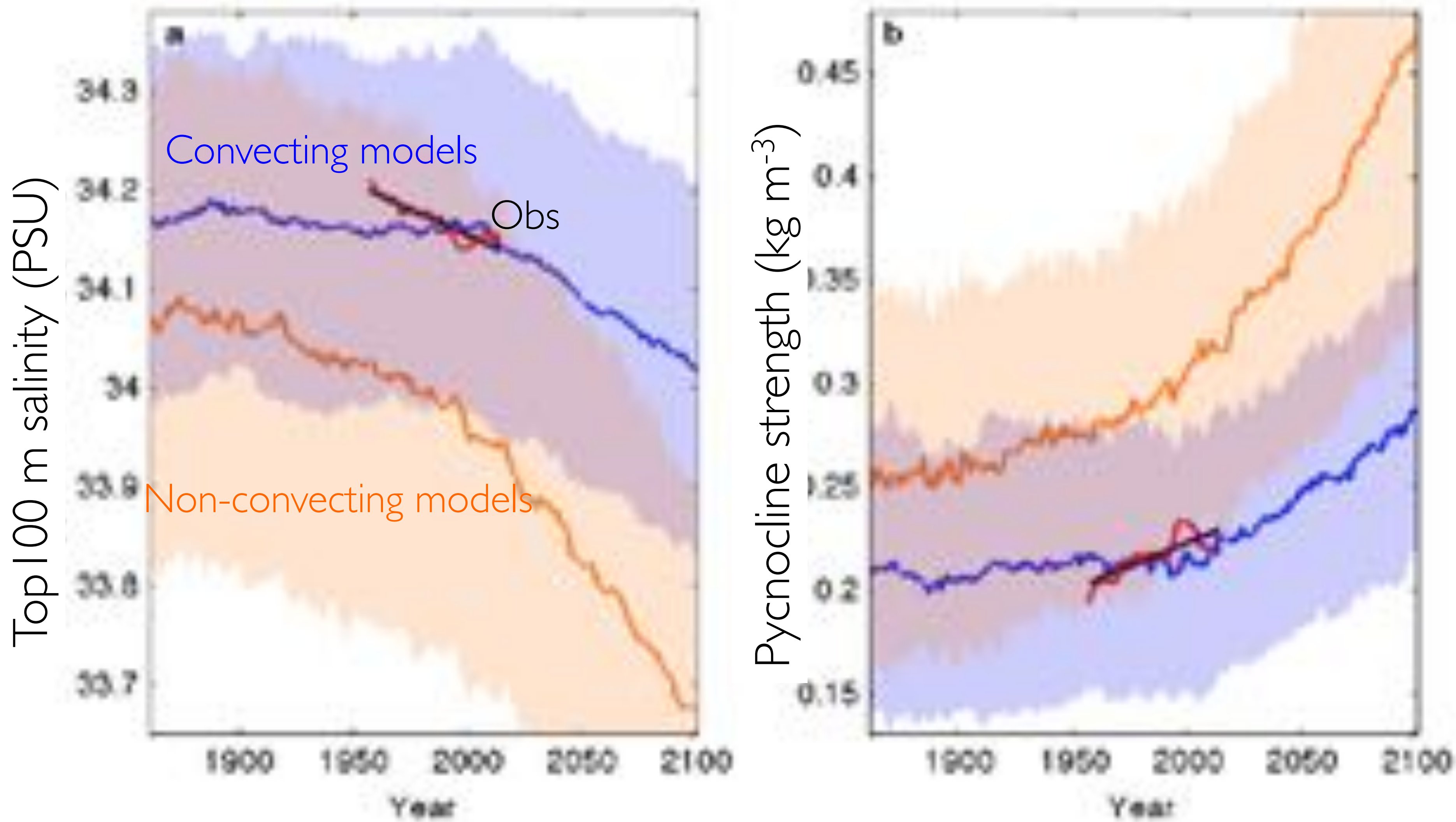
Under anthropogenic (historical + RCP8.5) forcing, convection slows and ceases



Normalized convection area, vs. time. Normalization is done by dividing by each simulation's maximum convective area.
7 models completely cease convecting by 2030.

Convection area for MPI and HadGem models.

Starting approximately this decade, the simulated Southern Ocean freshens and stratifies to a similar degree to that already observed, *just as simulated convective overturning completely collapses.*



How does the suppression of Weddell Sea convection influence ocean heat and carbon uptake?

Geophysical Research Letters

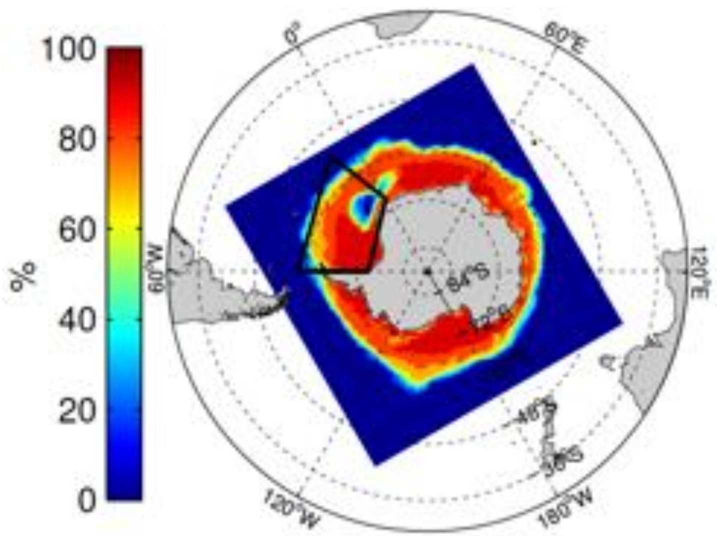
RESEARCH LETTER
10.1002/2014GL061313

Impact of Weddell Sea deep convection on natural and anthropogenic carbon in a climate model

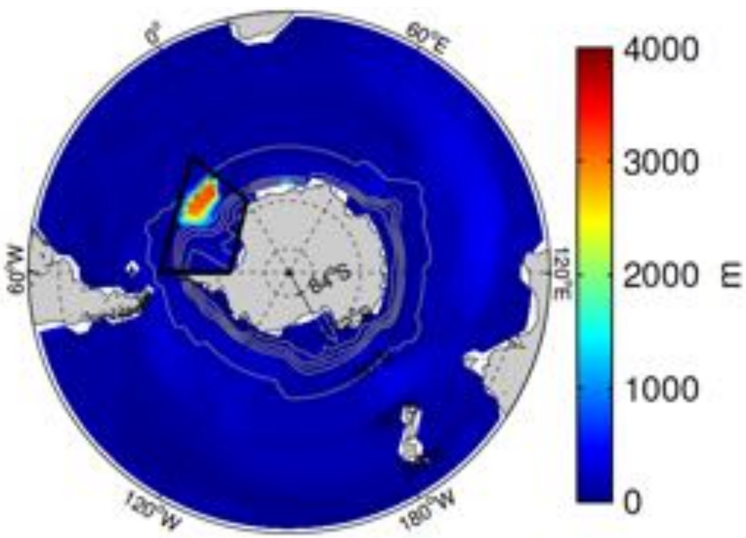
Raffaele Bernardello[1], Irina Marinov[1], Jaime B. Palter[2], Eric D. Galbraith[3], and Jorge L. Sarmiento[4]

Key Points:

Satellite Sept Sea Ice (1974-1976)



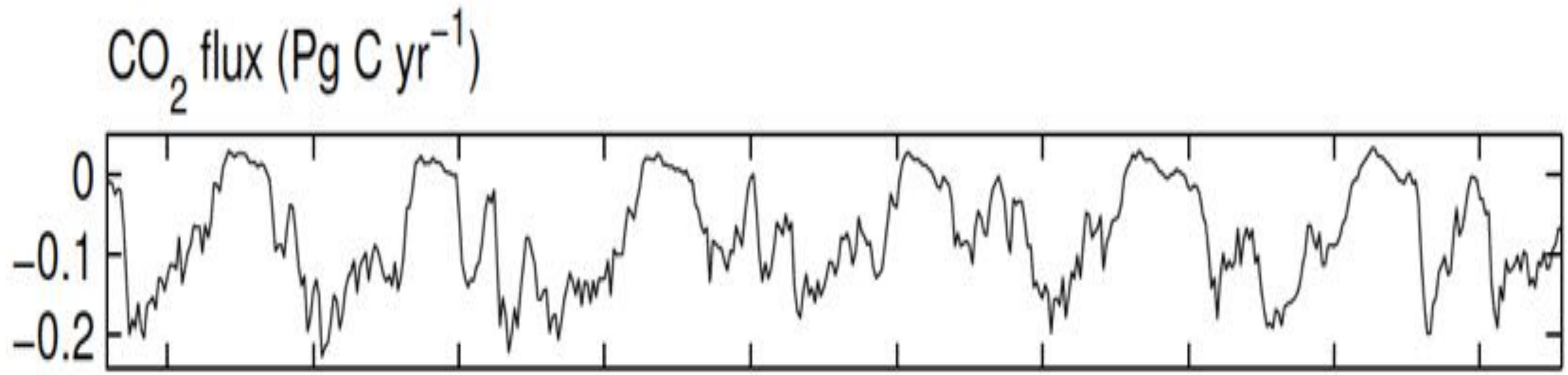
Model Sept. MLD (3 convective winters)



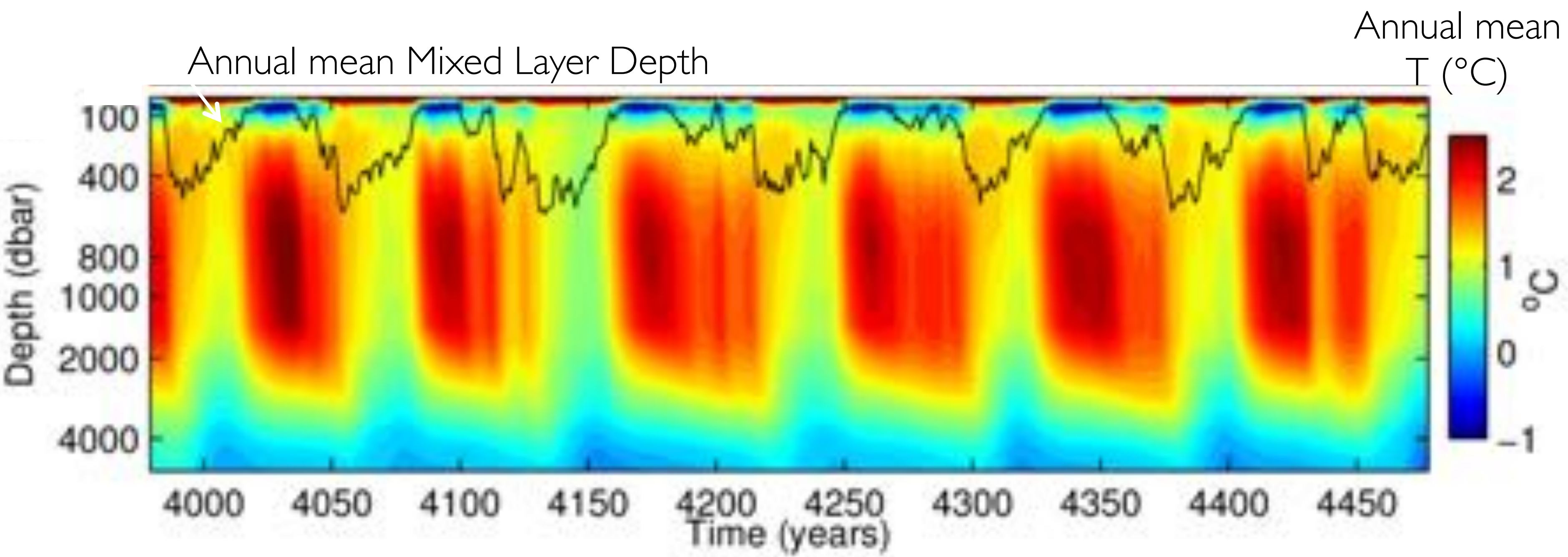
- Periodic deep convection in the Weddell Sea occurs regularly throughout the long preindustrial spin-up
- Model: CM2Mc, a coarse resolution version of GFDL's CM2.1 (Galbraith et al., 2011) with BLING (Biogeochemistry, Light, Iron Nutrients, Gas) model (Galbraith et al. 2010)

Penn
University of Pennsylvania

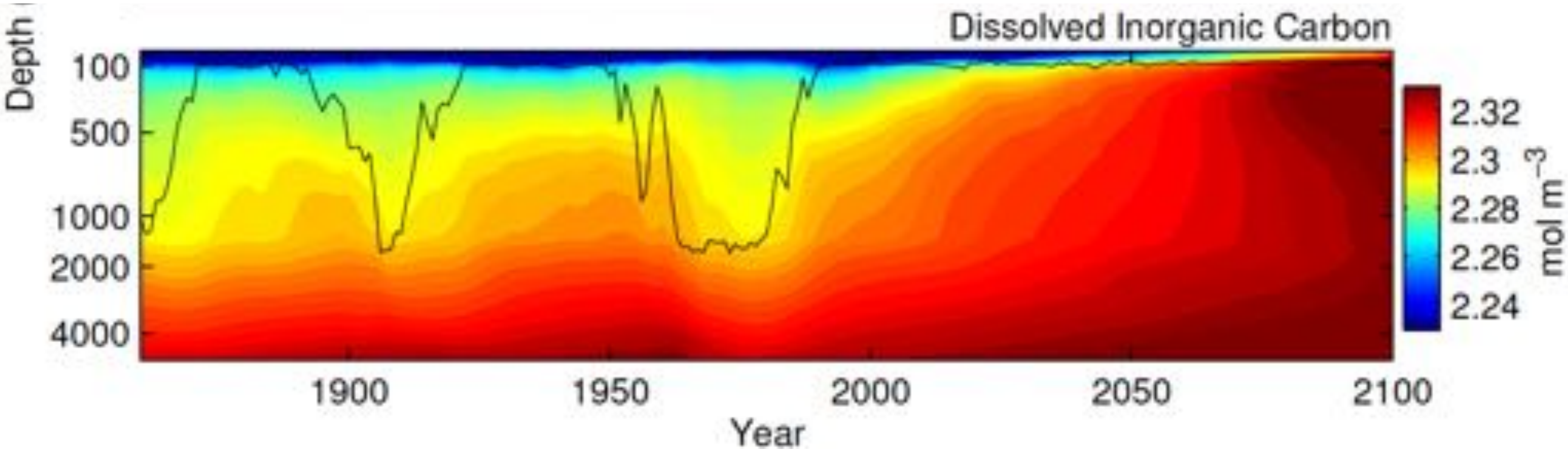
Periodic deep convection in the Weddell Sea occurs regularly throughout the long preindustrial spin-up



Each convection event outgasses deep remineralized carbon

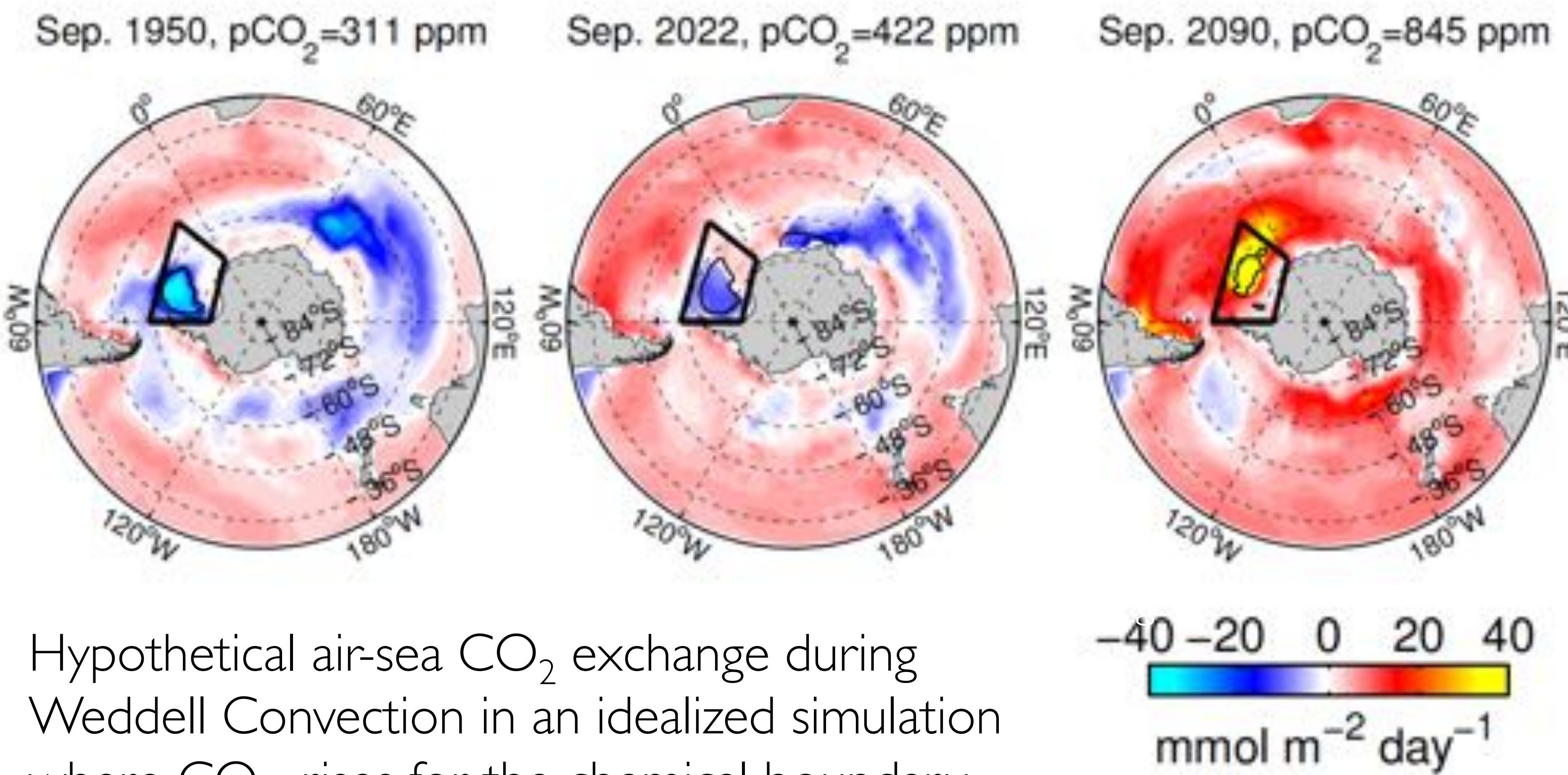


Convection collapses during historical forcing in all 3 ensemble members (mean year of last convective winter: 1981)



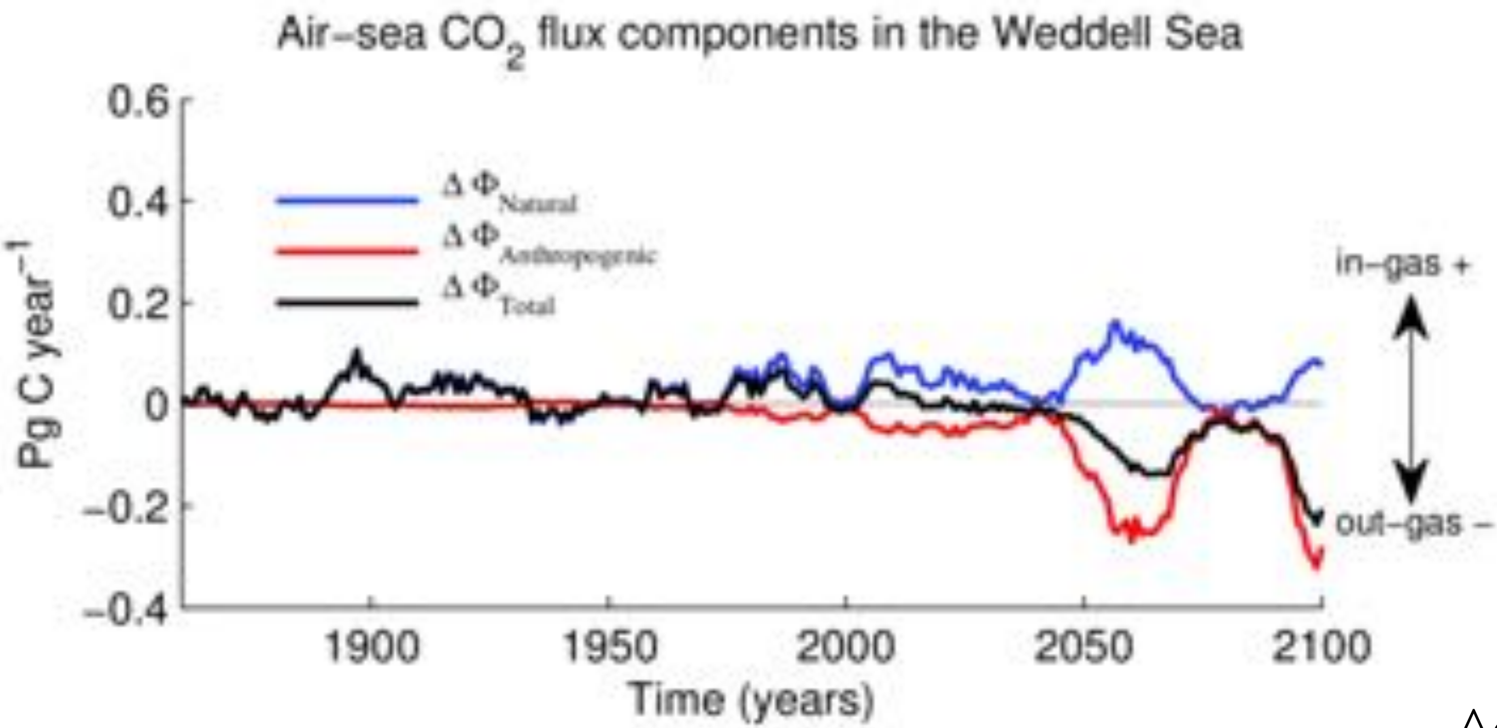
Following collapse remineralized, carbon steadily fills the deep Weddell Sea and AABW generally.

Anthropogenic emissions gradually raise atmospheric pCO_2, so deep convection events gradually transition from outgassing to ingassing



Hypothetical air-sea CO_2 exchange during Weddell Convection in an idealized simulation where CO_2 rises for the chemical boundary condition with the ocean only, but the radiative forcing is held constant.

Effect of cessation of convection on air-sea CO_2 flux components



Effect of climate change on cumulative ocean CO_2 uptake (Pg C)

	Weddell Sea	Southern Ocean	Global Ocean
$\Delta\Phi_{Natural}$	+5.8	-0.0	-24.1
$\Delta\Phi_{Anthropogenic}$	-10.1	-19.3	-55.1
$\Delta\Phi_{Total}$	-4.3	-19.3	-79.2

Accumulated air-sea flux of CO_2 in Weddell Sea compared to the Southern and Global Oceans from 1982 - 2100

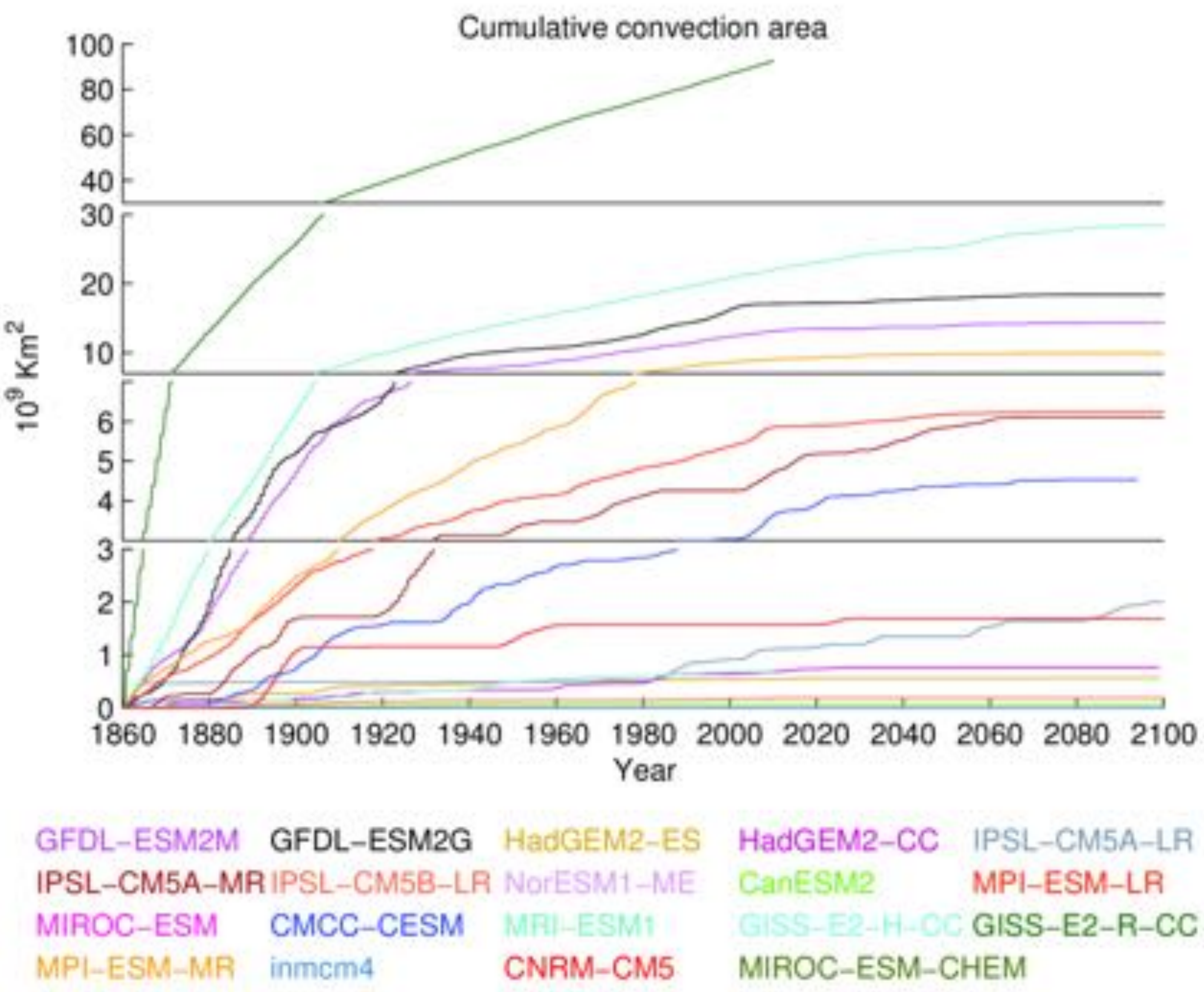
CO_2nclusions

- In our coupled model, the cessation of open ocean deep convection in the Weddell Sea causes a reduction of CO_2 uptake of 4.3 Pg C by 2100.

- This is the result of an increase in natural carbon storage (+6.2 Pg C) and a negative stronger decrease in anthropogenic carbon uptake (-10.5 Pg C).

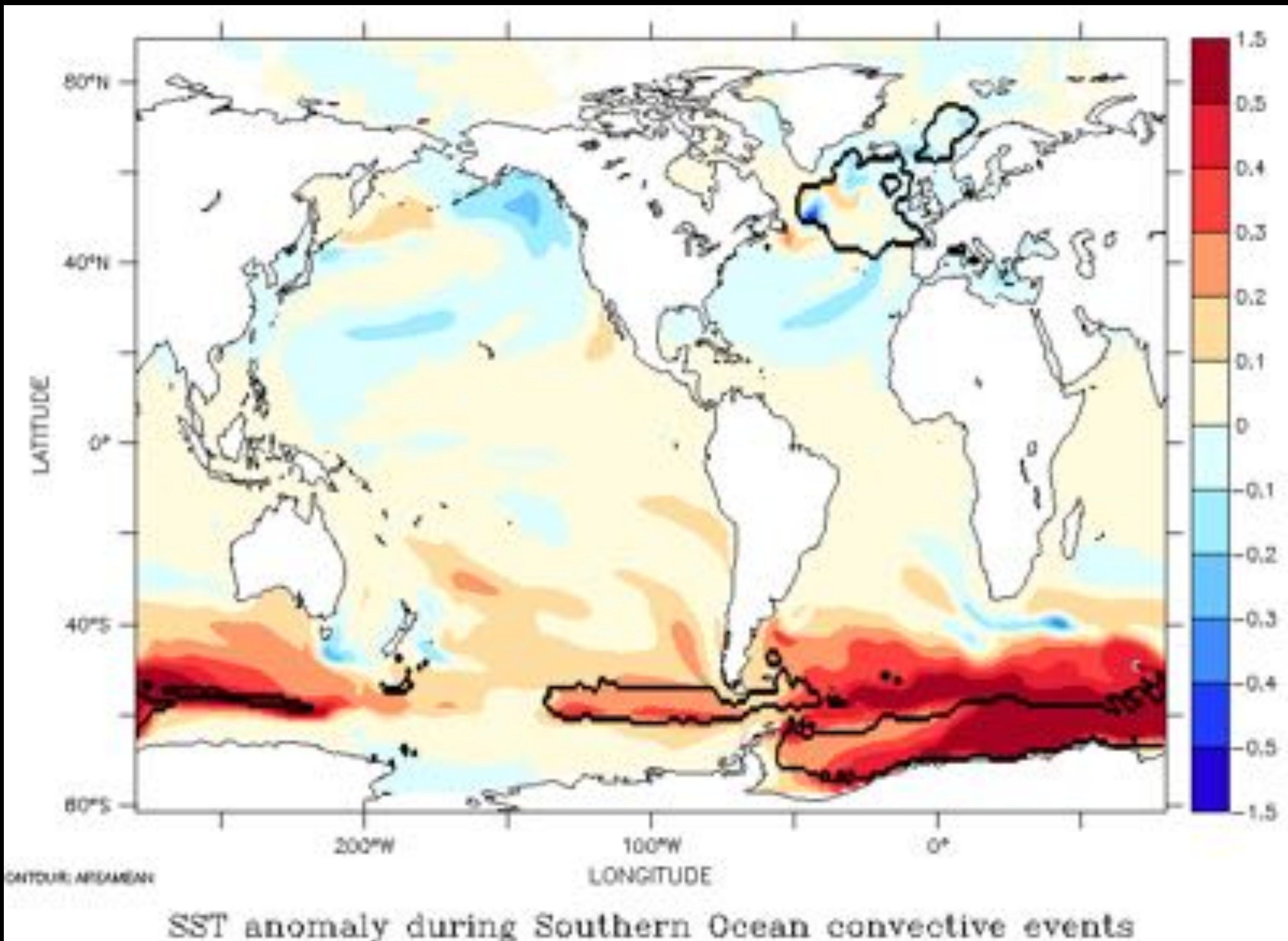
- Despite representing only 1% of the Global Ocean surface, the Weddell Sea is responsible for 20% of the climate-driven slowing of ocean anthropogenic carbon uptake.

Hypothesis: CMIP5 variability in convection and the timing of its shutdown contribute to uncertainty in carbon storage and heat uptake



- Models convecting longer in the 21st century will expose more of their interior volume to increasing atmospheric CO_2.
- The influence on total CO_2 will be set by the preindustrial DIC concentration in AABW, its air-sea gas exchange during exposure to the atmosphere, and the timing of convective shutdown.

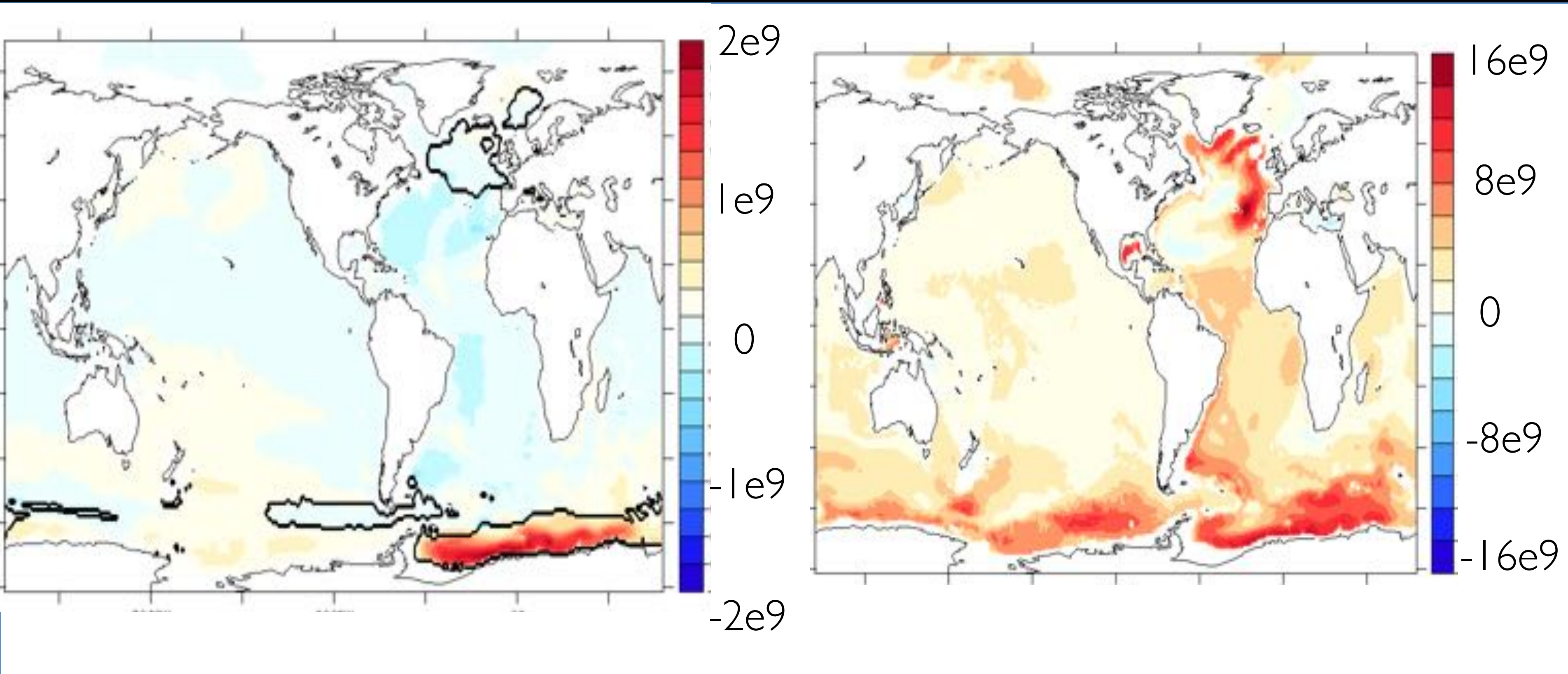
Possible implications for ocean heat uptake and transient climate change



SST anomaly during an average convection event in the Chinese model BCC-CSM11m. Global average: 0.1°C above average. Dark contour is average convective area.

Figure credit: Sarah Marcil.

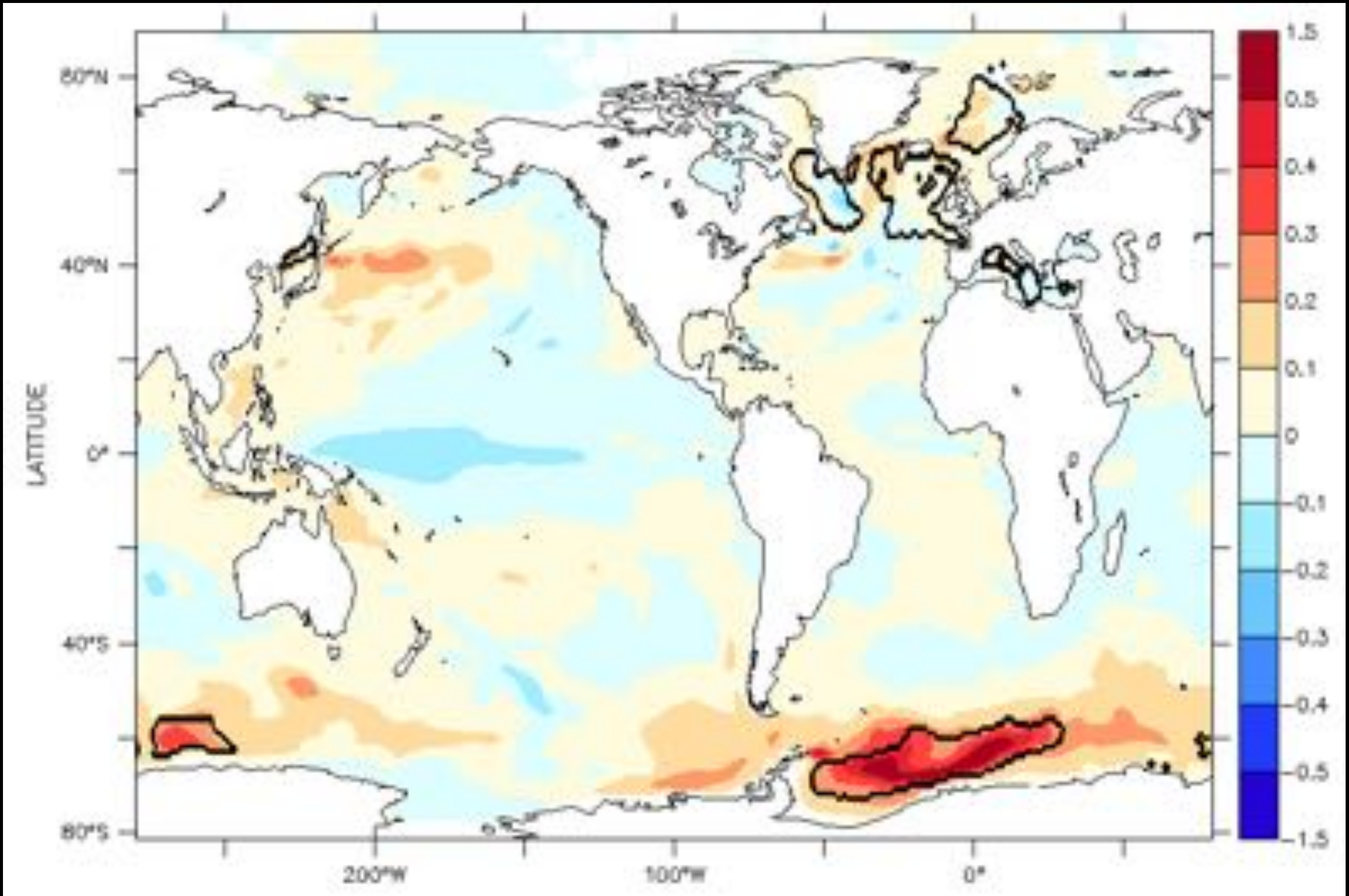
Deep (>1000 m) uptake of heat during the average PI non-convective event and following the last convective event in RCP8.5



Average NON-convective period in the preindustrial (J m^{-2})

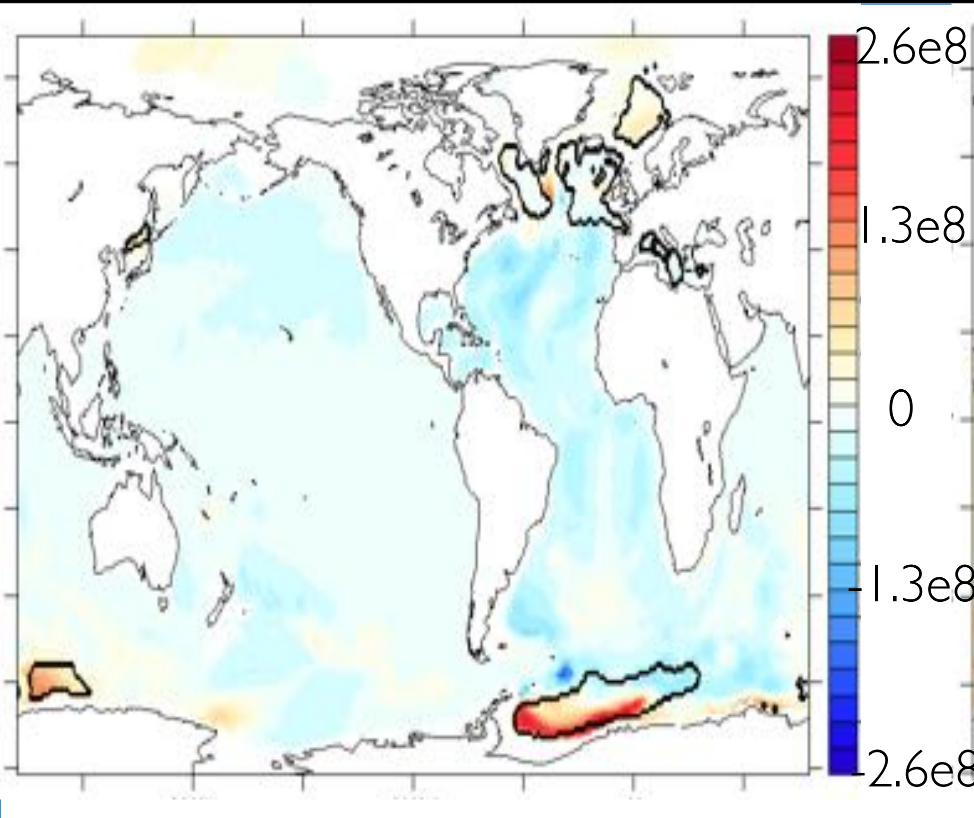
Following the last convective in RCP8.5, 2087 (J m^{-2}). Note that the volume of convected water shrinks before convection completely ceases.

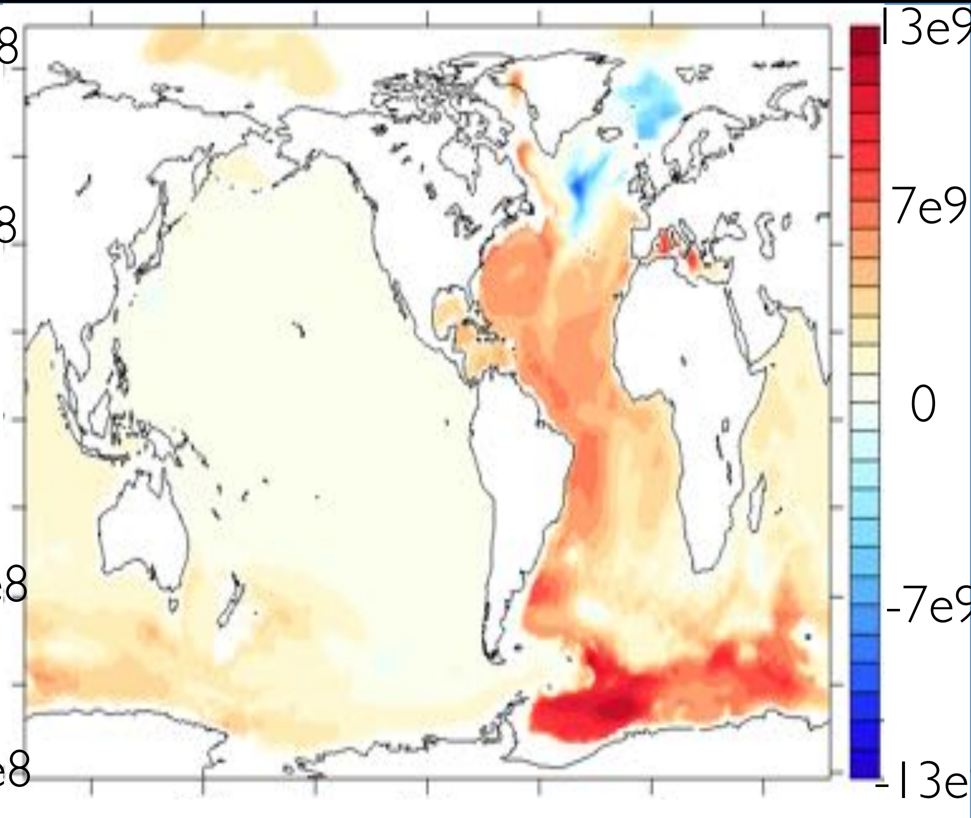
Features are much the same in many models, but the magnitude of the signal varies



SST anomaly during average convection event GFDL-ESM2M. Global SST anomaly = 0.03°C.

Ocean heat content anomaly beneath 1000 m during NON-convective periods





Average NON-convective period in the preindustrial (J m^{-2}).

Following the last convective in RCP8.5, 2017 (J m^{-2})

Climate implications

- Surface warming during convective events (cooling during non-convective periods)
- OHC loss during convective events
- After convective shutdown, OHC accumulates in deep Southern Ocean, hiding heat from the atmosphere/surface ocean
- Though the winds might be propping one door open, the "door to the deep ocean" due to convection is slamming shut, limiting exposure to anthropogenic CO_2, but allowing the deep accumulation of heat in many CMIP5 models.

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Sarah Marcil, McGill University