



Zonal asymmetries of the Southern Ocean circulation: topography and vorticity & impact on sea ice distribution

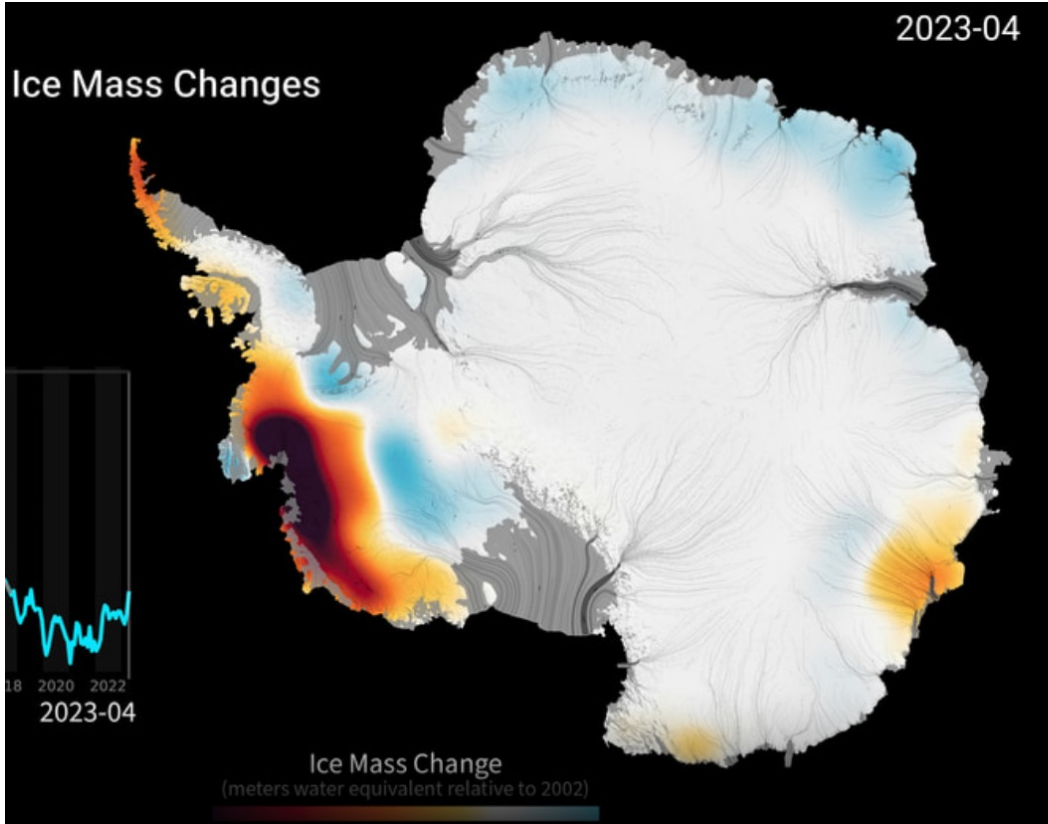
Lynne Talley, Scripps Institution of Oceanography, UCSD

ICTP 7th summer school July 8, 2026

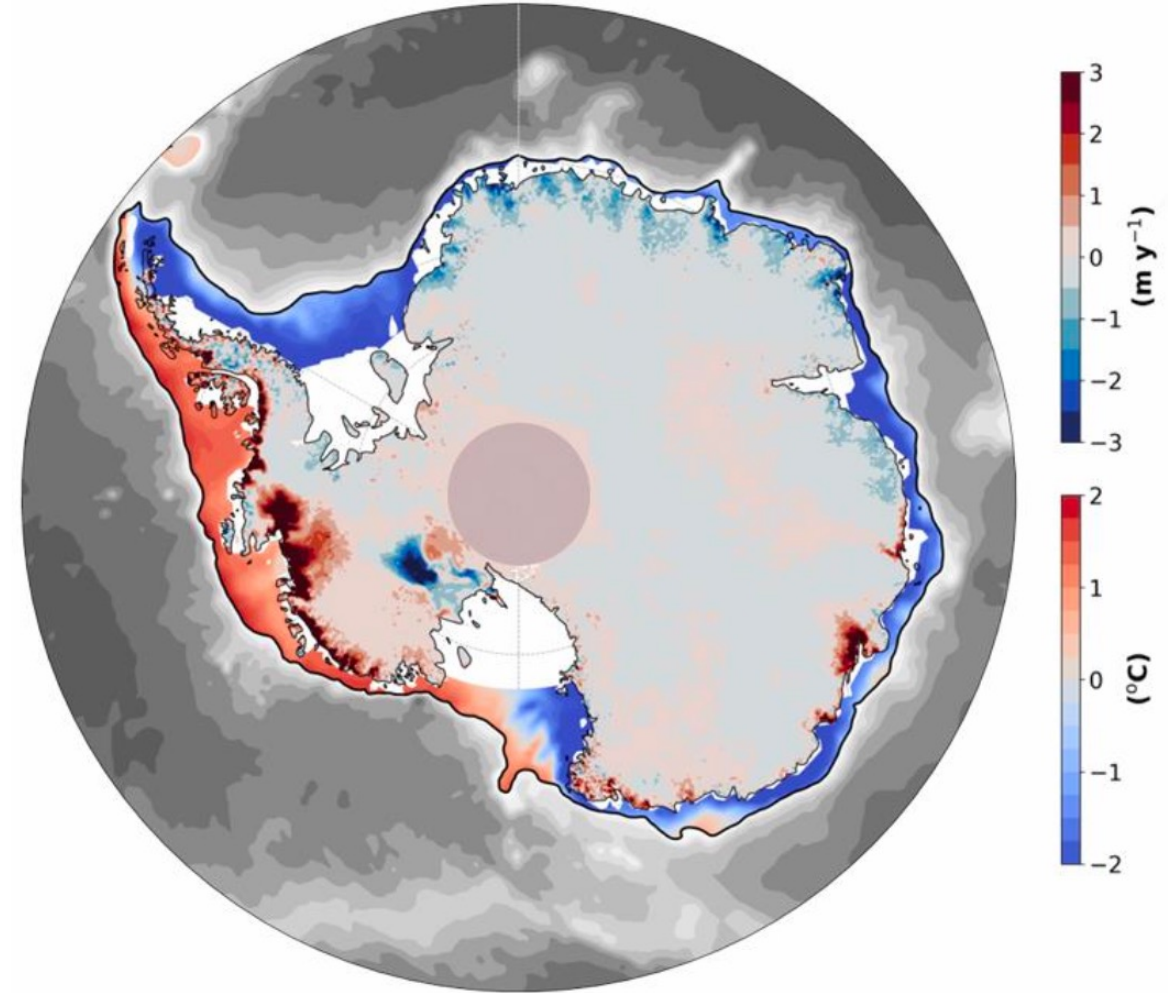


Antarctic ice sheet mass loss

Ice Sheet Mass Change



Cold and warm shelf regimes/ice sheet mass change



<https://climate.nasa.gov/interactives/climate-time-machine/>

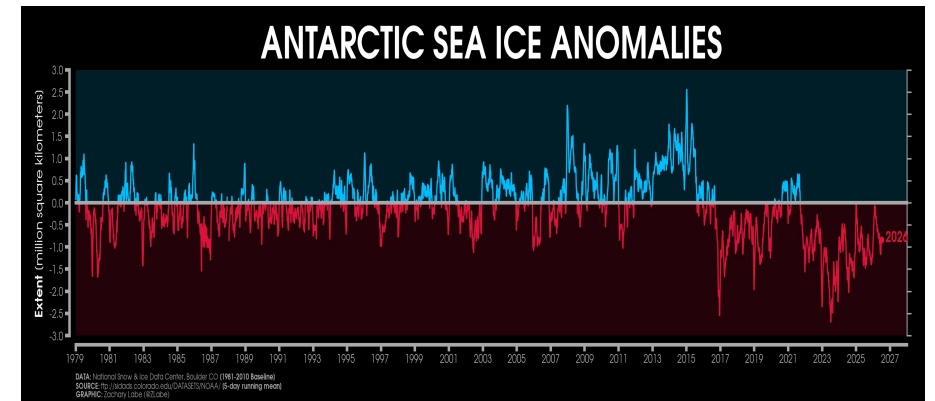
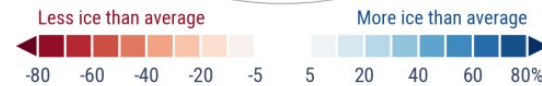
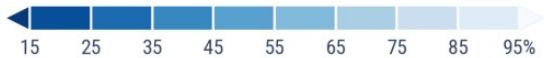
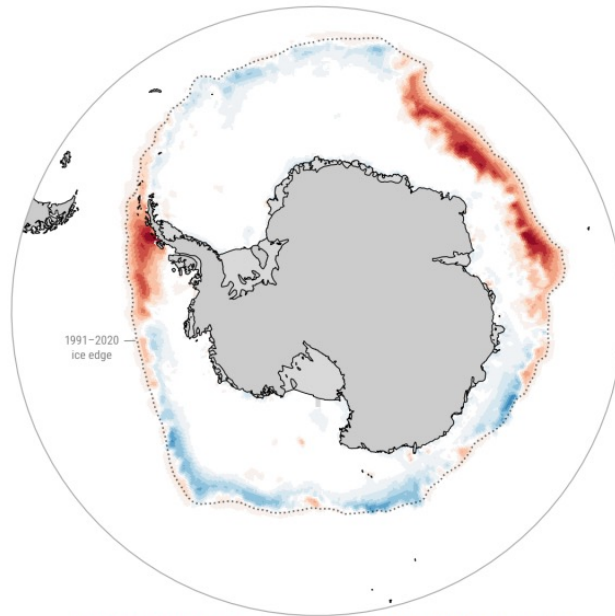
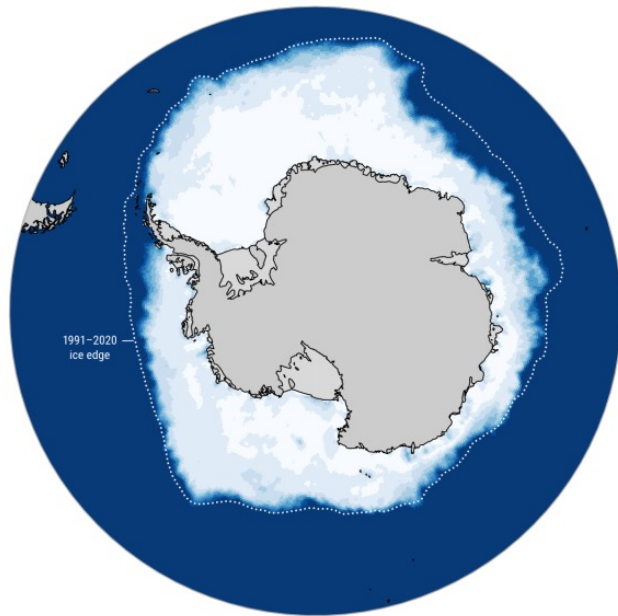
Antarctic sea ice: expanding until 2016, now major decline

Antarctic sea ice cover • September 2025

Data: ERA5 • Reference period: 1991–2020 • Credit: C3S/ECMWF

Sea ice concentration

Sea ice concentration anomaly



1979

2026

<https://zacklabe.com/antarctic-sea-ice-extentconcentration/>



PROGRAMME OF THE EUROPEAN UNION



IMPLEMENTED BY



<https://climate.copernicus.eu/sea-ice-cover-september-2025>

Antarctic sea ice: expanding until 2016, now major decline

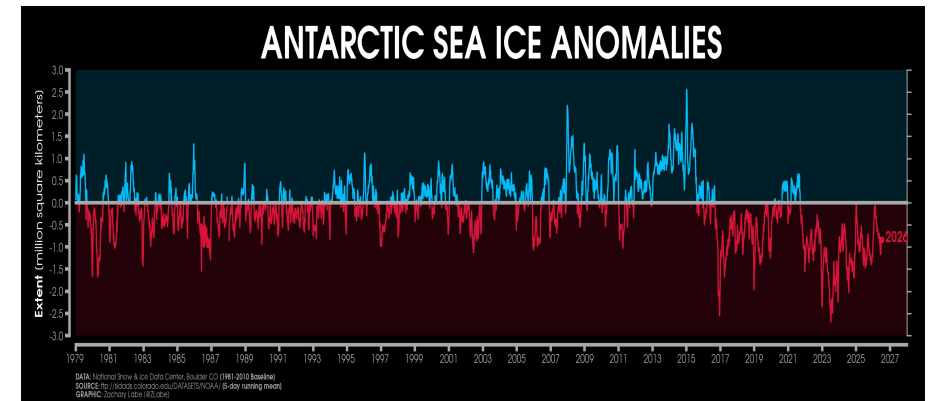
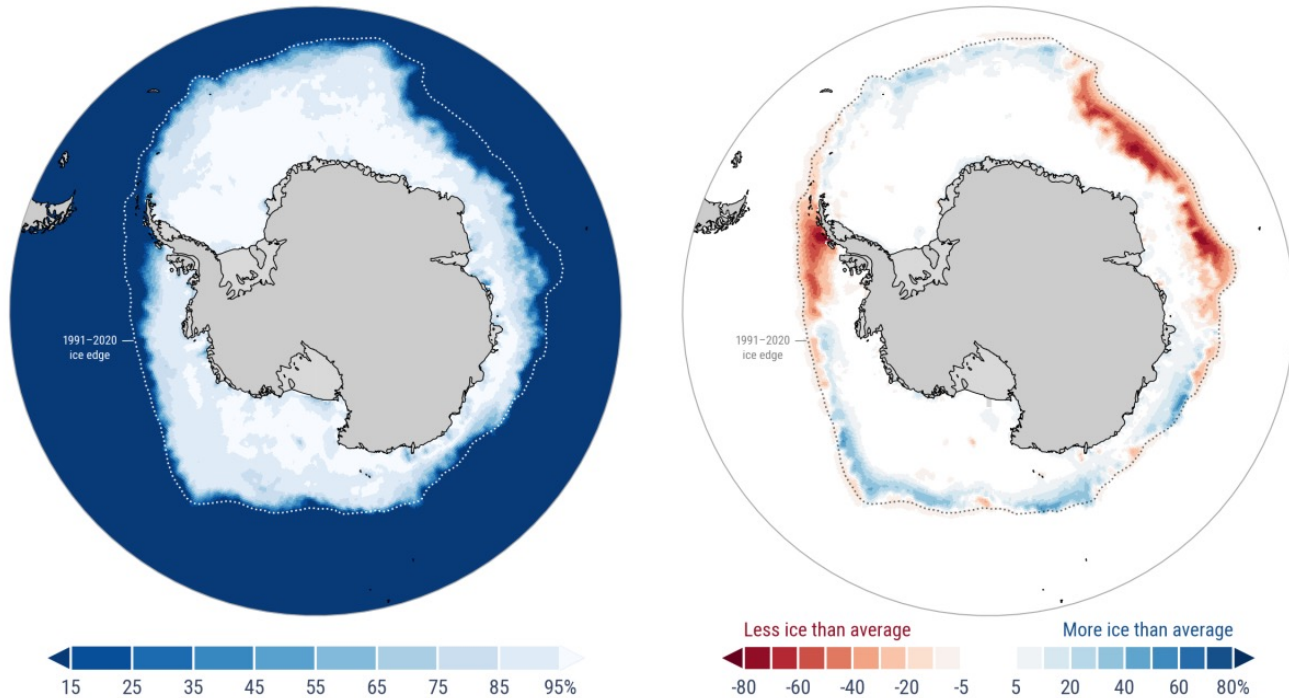
What controls the spatial structure of the mean sea ice distribution?
Answer: ACC fronts (winter ice). What controls the frontal locations?

Antarctic sea ice cover • September 2025

Data: ERA5 • Reference period: 1991–2020 • Credit: C3S/ECMWF

Sea ice concentration

Sea ice concentration anomaly



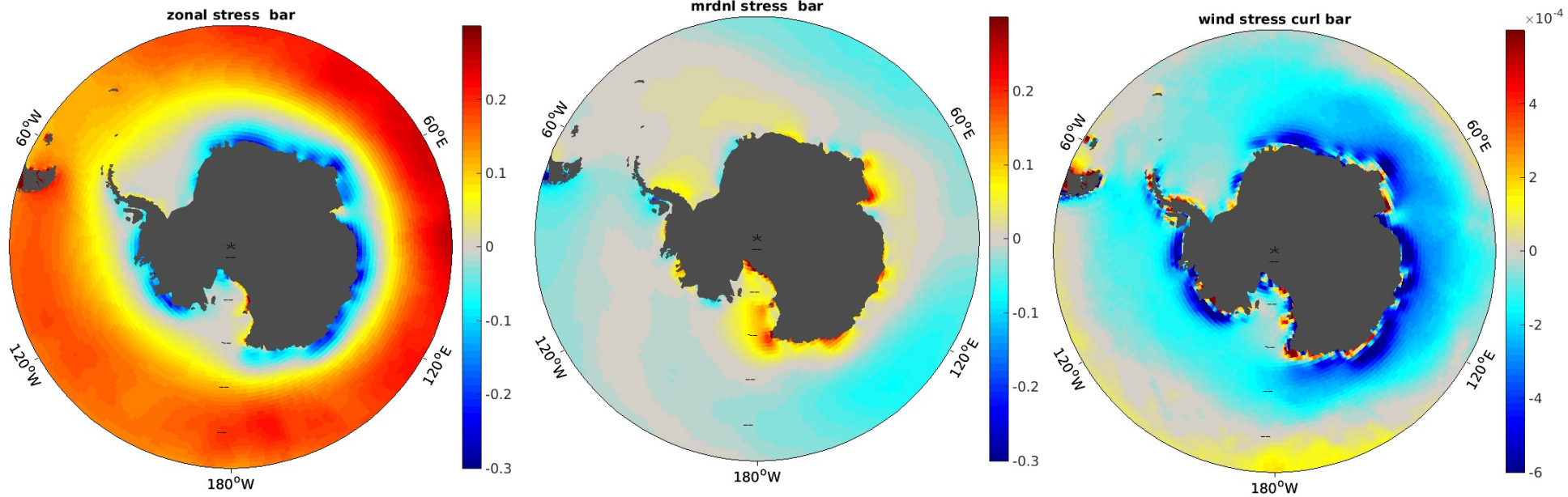
1979

2026

<https://zacklabe.com/antarctic-sea-ice-extentconcentration/>

What drives this pattern of sea ice and circulation?

Wind forcing: Mean wind stress and curl

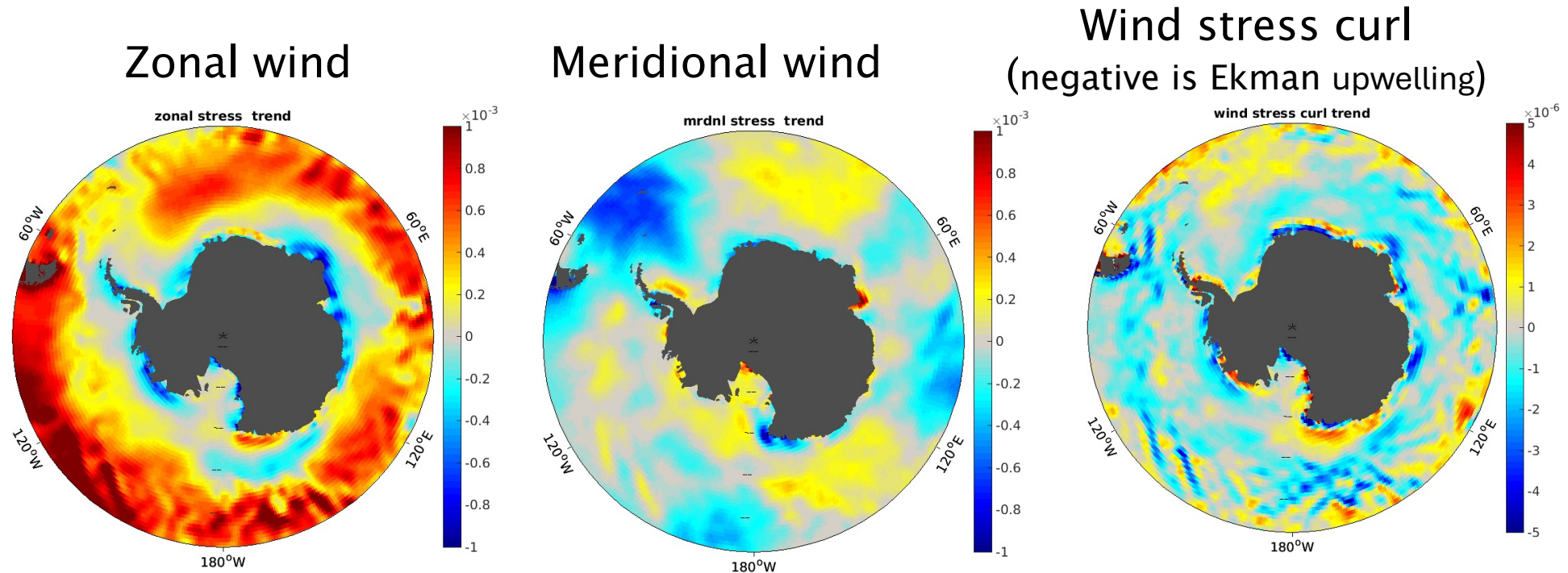


Zonal wind

Meridional wind

Wind stress curl
(blue is Ekman upwelling)

How are the winds changing? Trends over 36 years



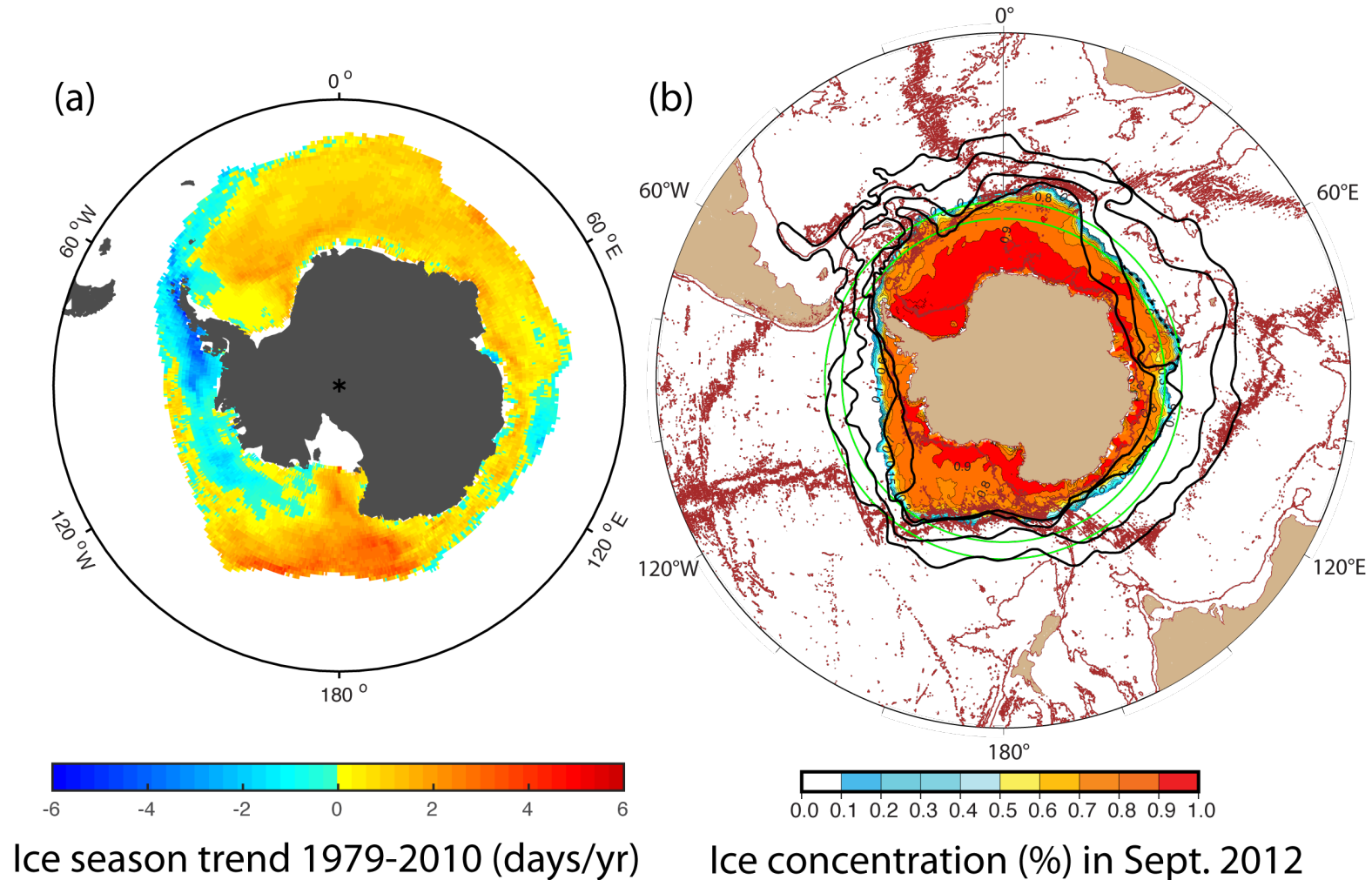
ERA-Interim winds 1979-01-01 to 2015-12-31 (trend per year)

Stronger zonal winds; meridional winds also have interesting pattern
but these do not map directly onto the observed sea ice change.

Why don't sea ice and sea ice trend mirror wind and wind changes?

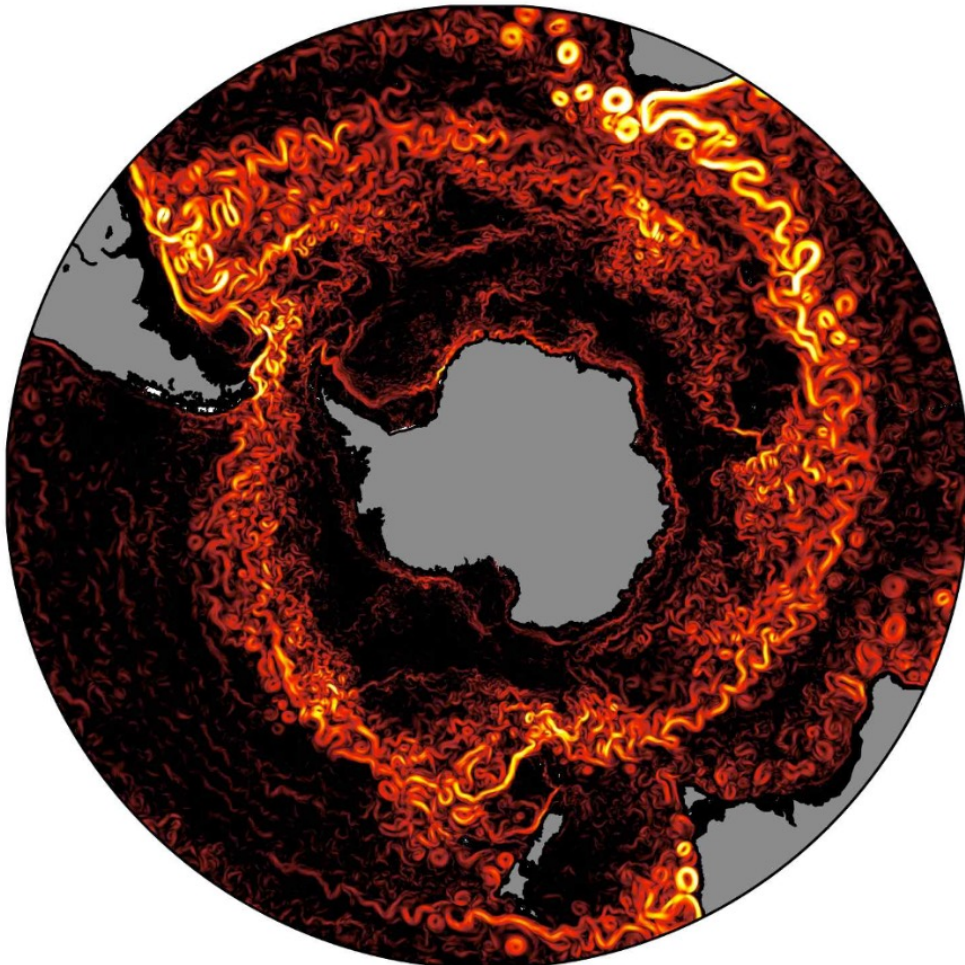
Sea ice season trend and pattern

Why pentagonal shape and why this particular ice trend pattern?
(this map was from the sea ice expansion years)





ACC zonal structure



Two scales of standing meanders:

(1) Full ACC spiral southward from Malvinas/Brazil confluence. Note also Agulhas Return Current and Campbell Plateau (N.Z.)

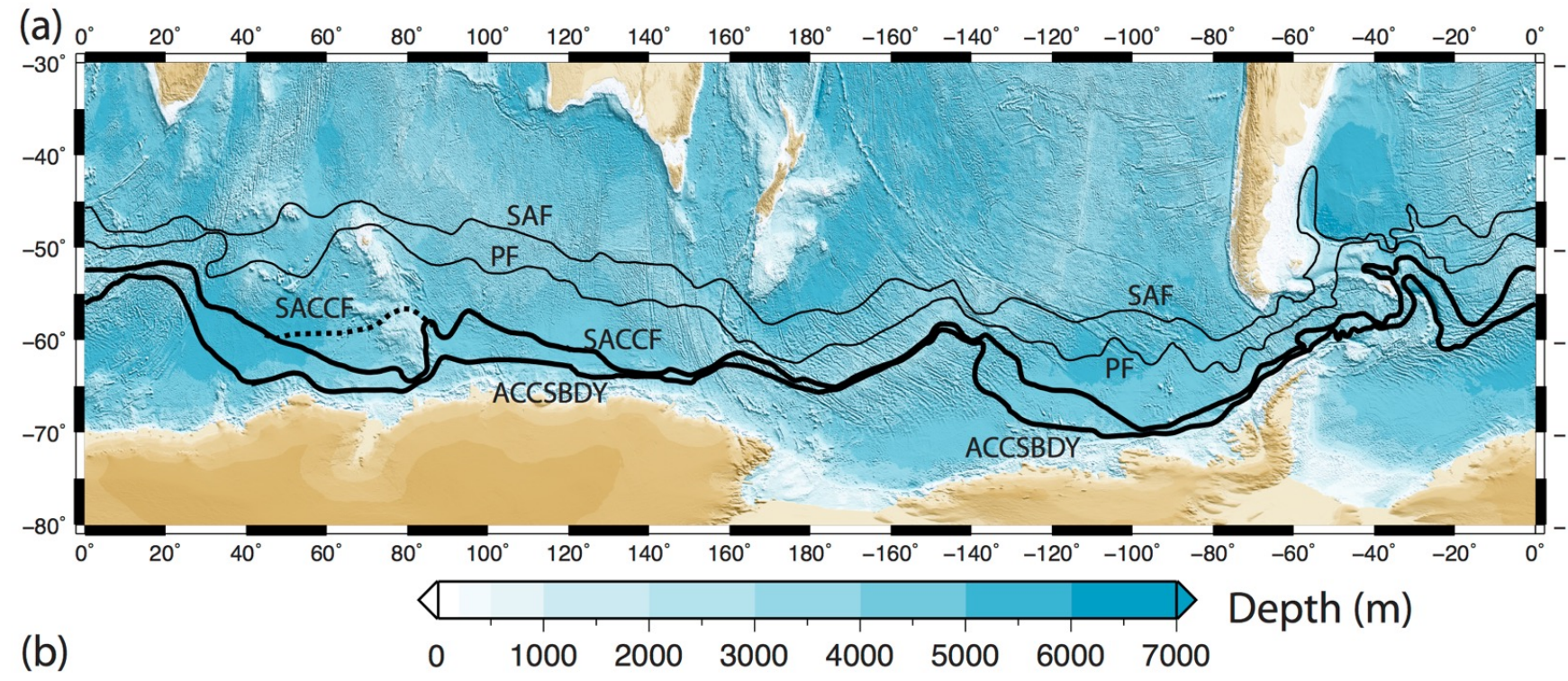
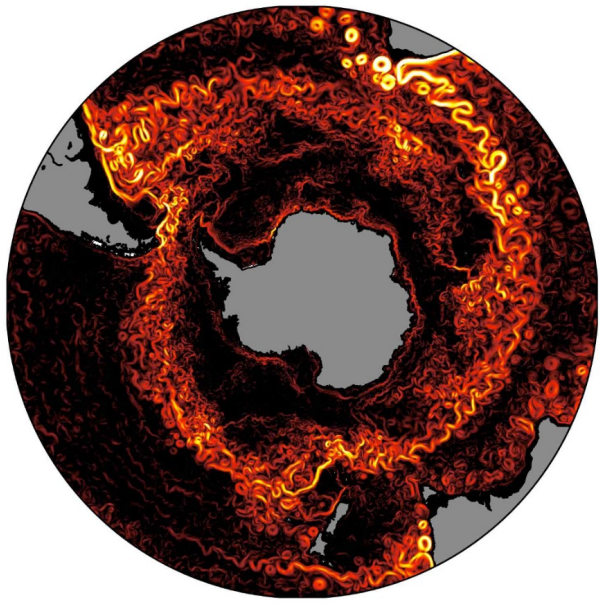
(2) Basin-scale 'scallop' due to geography and topography

Cause?

Wind stress curl and vorticity dynamics with topography

Standing meanders

Wind and topographic controls on circulation



(1) Large-scale meander. The ACC spirals inward: Sverdrup balance?

ACC mass transport: **momentum balance** to diagnose the ACC transport, based on form stress.
Topography is thus central to controlling transport.

However, the PATTERN of southward drift is a **vorticity issue**, little to do with net mass transport.

Stommel (1957)

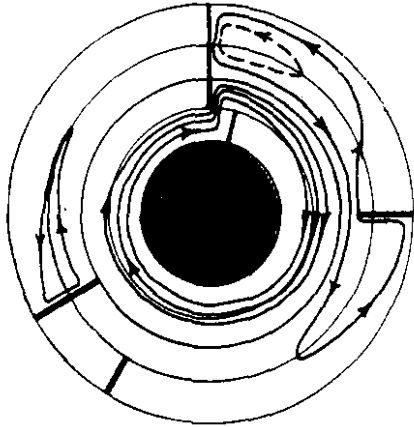


Fig. 26 (d). Hypothetical form of the solution that results from rupturing the American-Antarctic barrier in such a way as to permit water to flow through, but to obstruct all latitude circles.

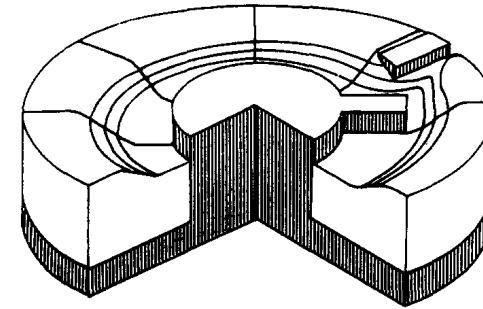


Fig. 27. Surface contours (or isobars) of the hypothetical Circumpolar Current shown in Fig. 26 (d).

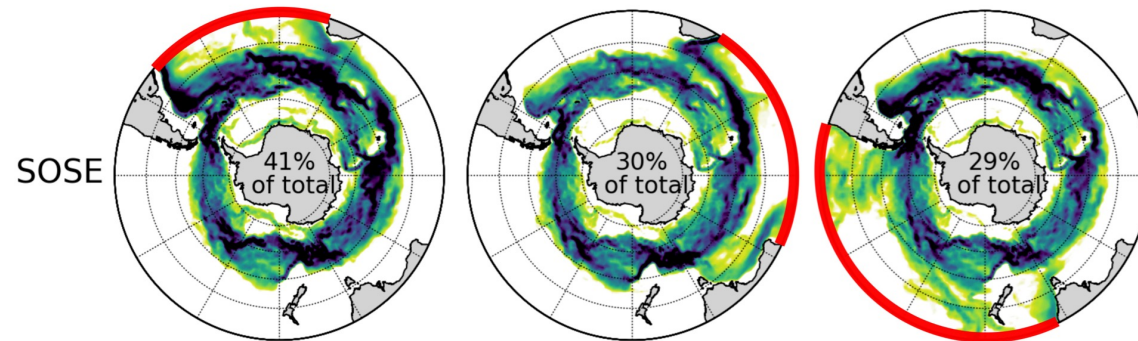
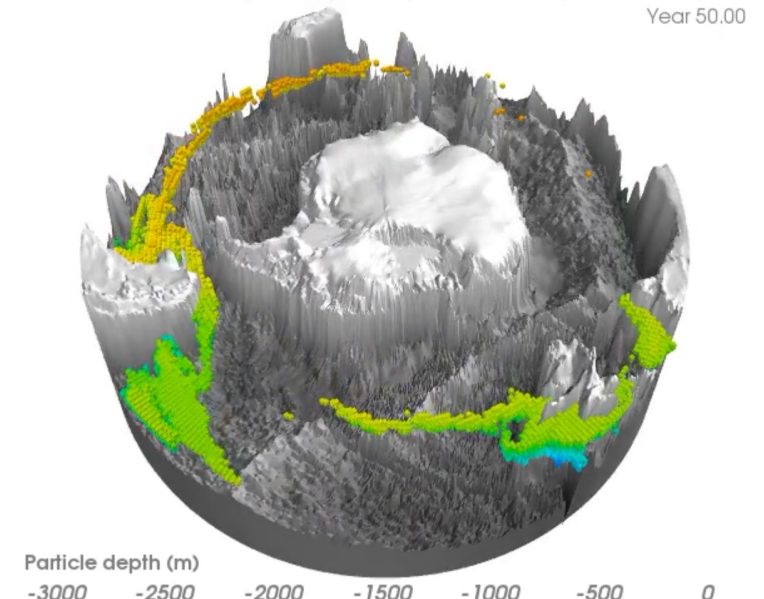
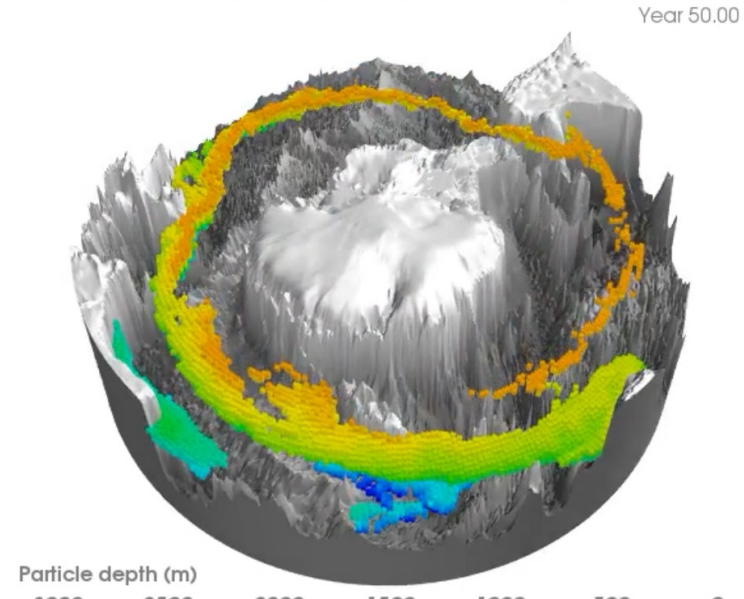
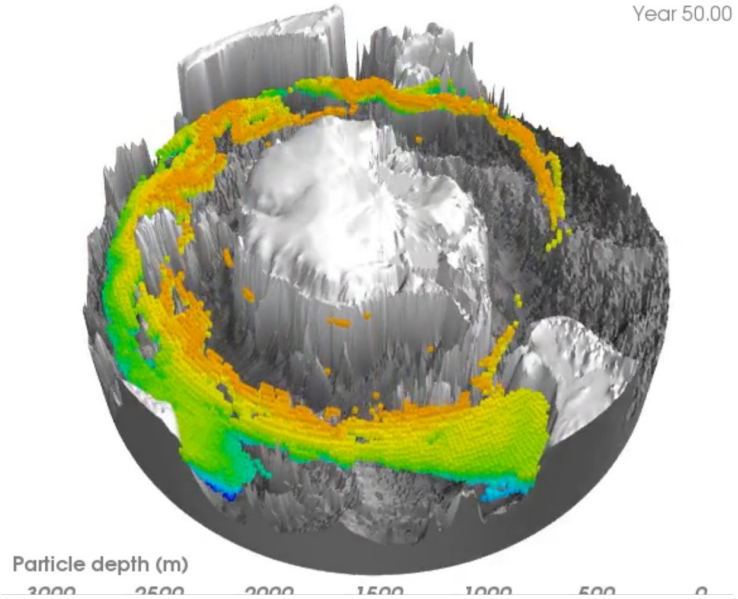
And others:
Warren et al. (JPO, 1996)
inter alia

(1) Large-scale 3-D SOOC: Deep Waters spiralling inwards and upwards

CM2.6 Atlantic Ocean particle pathways with >2.25% particle-transport
Year 50.00

CM2.6 Indian Ocean particle pathways with >2.25% particle-transport
Year 50.00

CM2.6 Pacific Ocean particle pathways with >2.25% particle-transport
Year 50.00

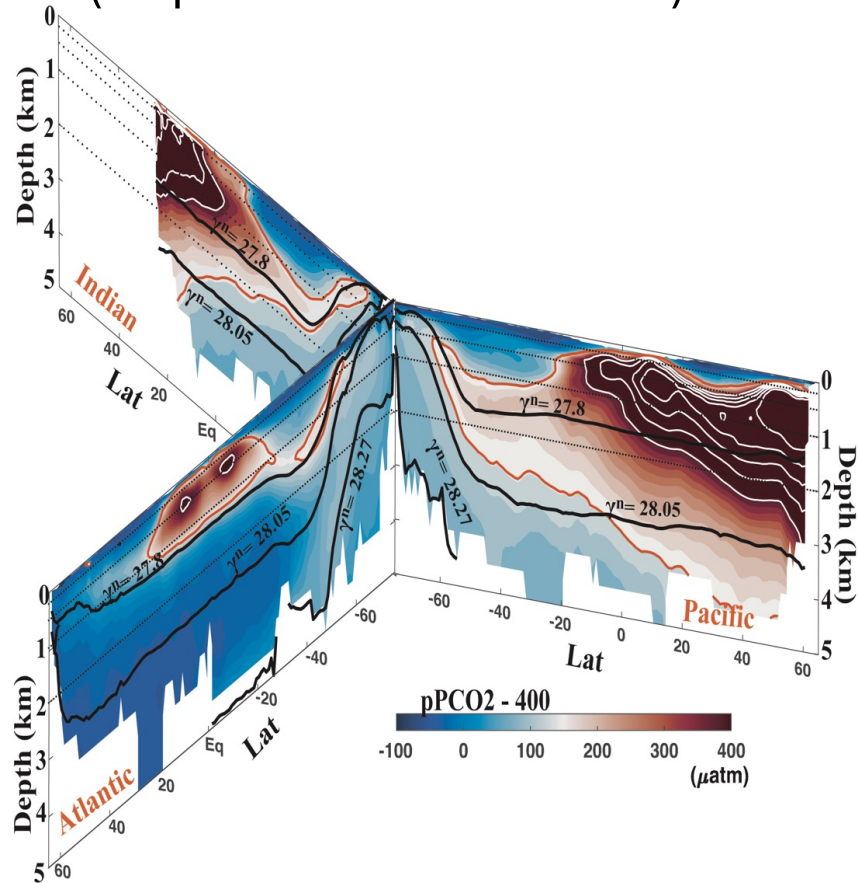


Deep Water particles released in each ocean

Tamsitt et al. (Nat. Comm. 2017, JGR 2018, JGR 2019)

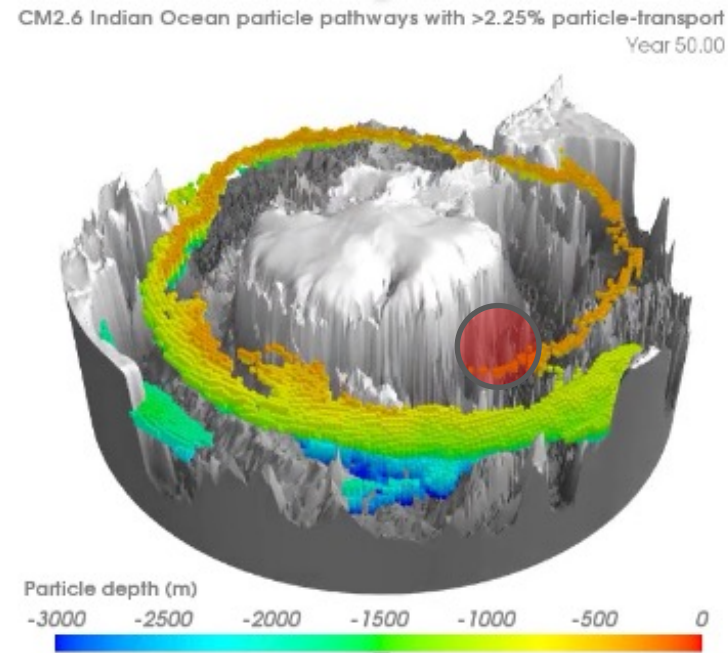
(1) Large-scale: Southern Ocean upwelling of Deep Water to surface, outgassing carbon

High carbon Deep Waters reach surface in Southern Ocean
(ship obs. and BGC floats)



Chen et al. (GBC 2022)

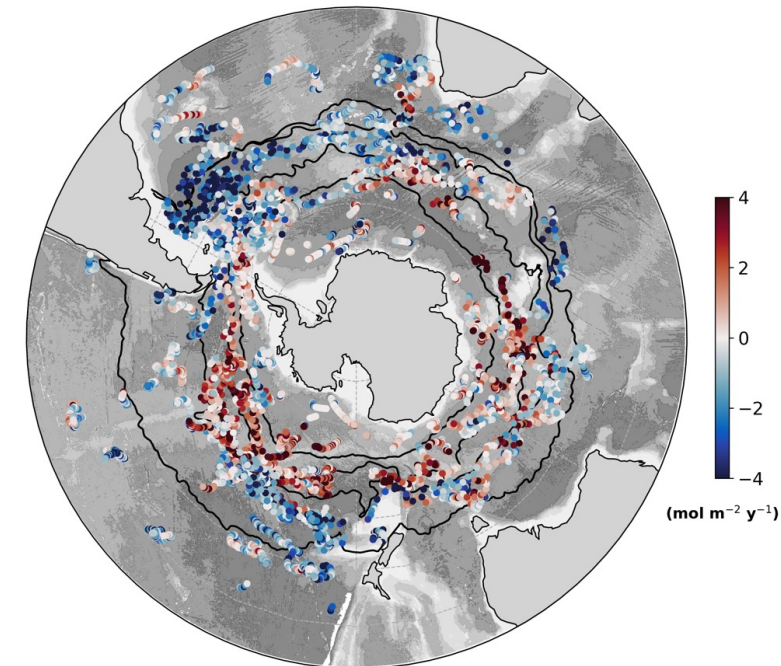
Pathways of high carbon spiral inward and upward
(SOSE, CESM, ESM6, matching hydrographic data)



Tamsitt et al. (Nat. Comm. 2017)

Carbon outgasses in southern ACC
(BGC floats)

Outgas Uptake



Gray et al. (GRL 2018)
Prend et al. (GBC, 2022)

(2) Scalloped sub-basin scale: ACC also controlled by topography

Equivalent barotropic theory, analysis of FRAM model, and process modeling: topographic control where it is strong

Kamenkovich (1962)

Killworth (1992)

Ivchenko et al. (1999)

LaCasce and Isachsen (2010)

Kamenkovich (1962)

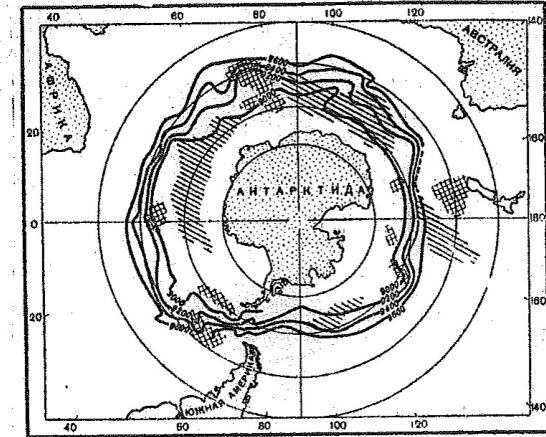


Figure 10. Dynamic chart of the surface of the Antarctic ocean relative to the 3000 db level (after V.G. Neuman). The map shows only individual characteristic isolines. Ridges and deeps are marked in from Fig. 7.

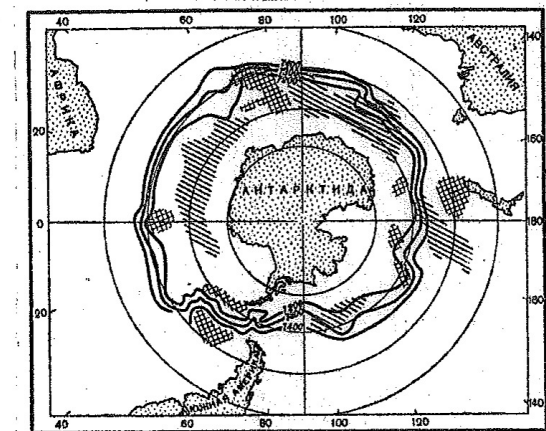
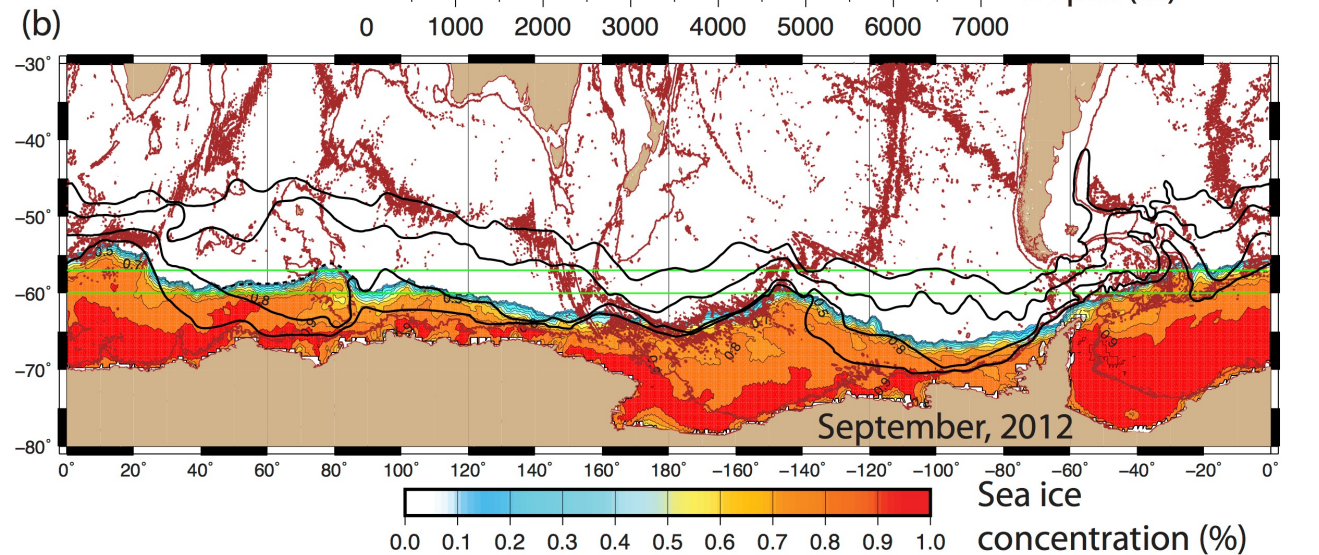
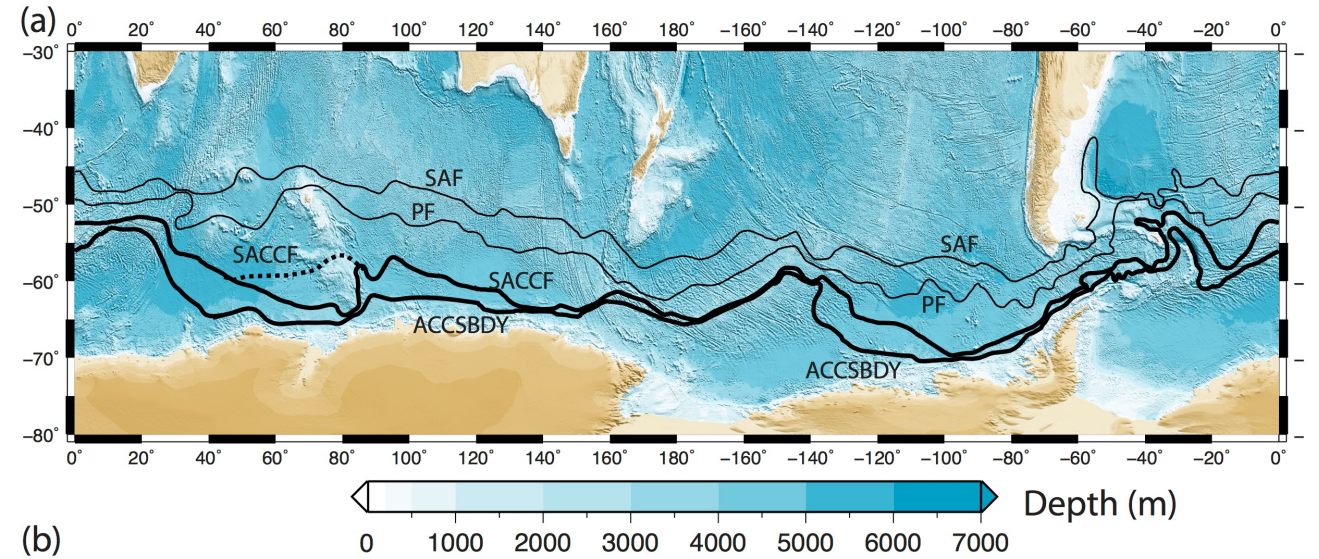
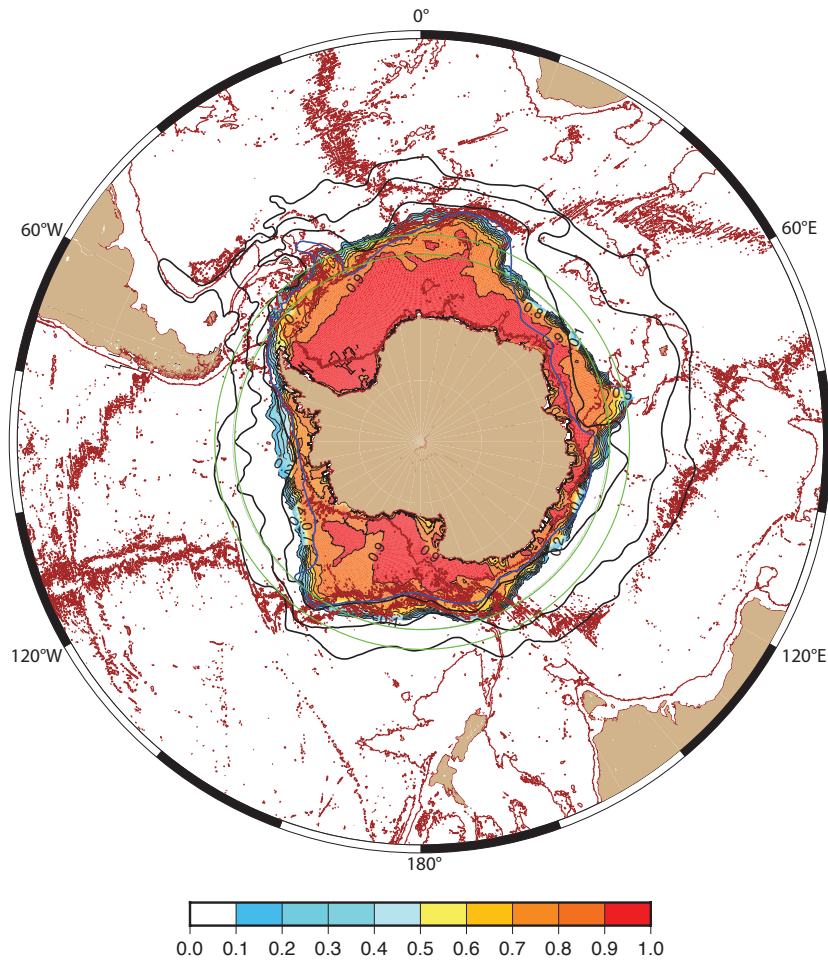


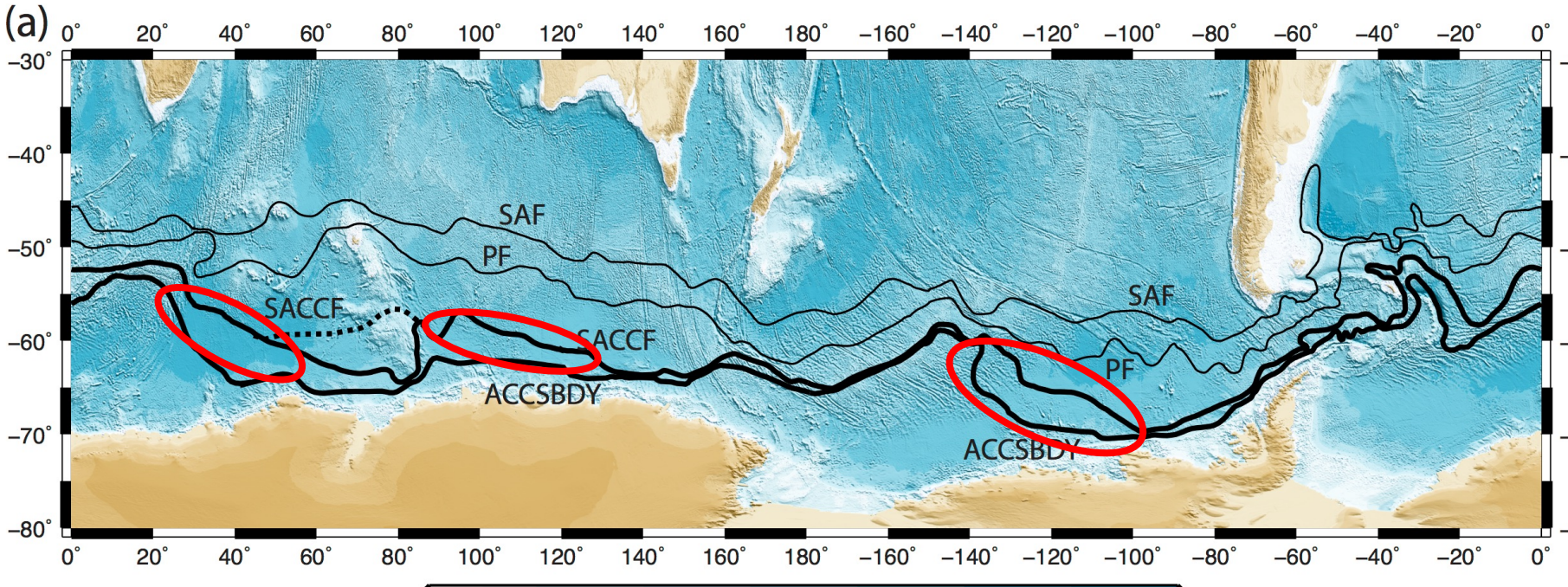
Figure 11. Dynamic chart for the Antarctic for the 600 db level relative to the 3000 db level, as from Fig. 10.

(2) Scalloped basin scale:
 Topography strongly influences ACC southern fronts (very strong temperature gradient),
 hence winter sea ice



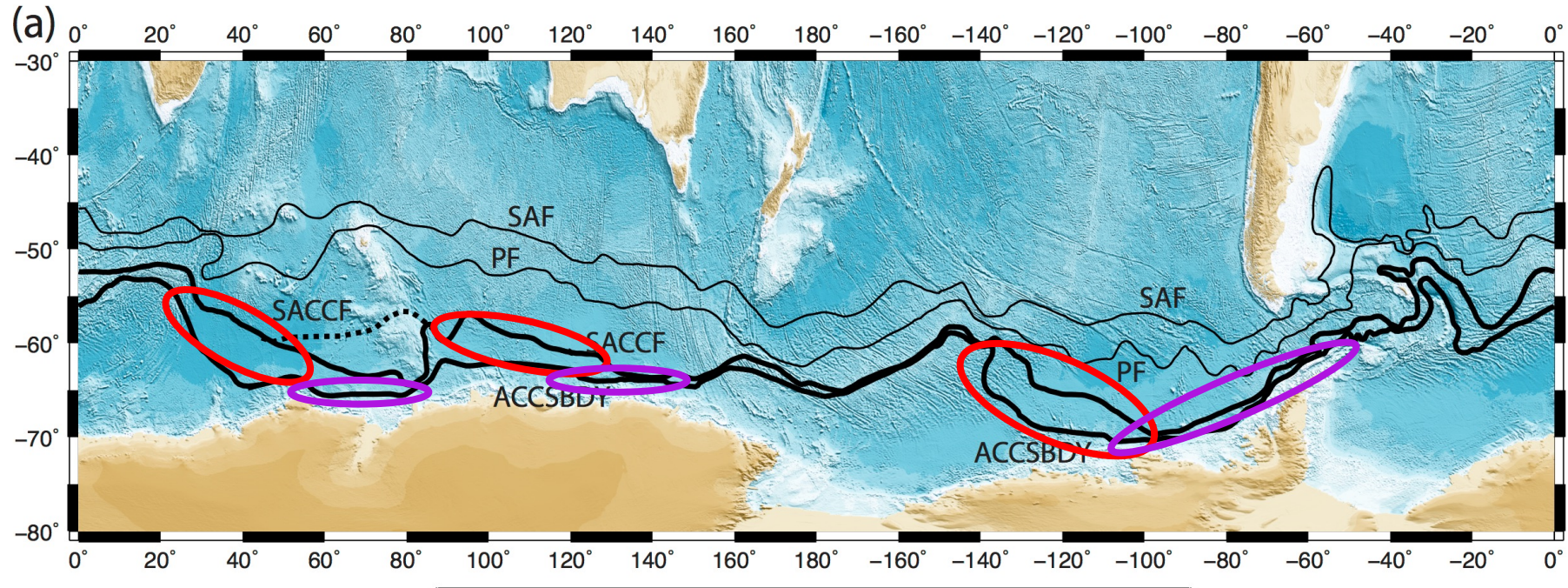
Sea ice edge (winter – September here) strongly associated with southern ACC fronts.

(2) Southward swings of ACC: Warm, saline water southwards



ACC southern boundary **free flow over abyssal plains goes southward towards Antarctica.**
(modified Sverdrup balance under upwelling wind stress curl)

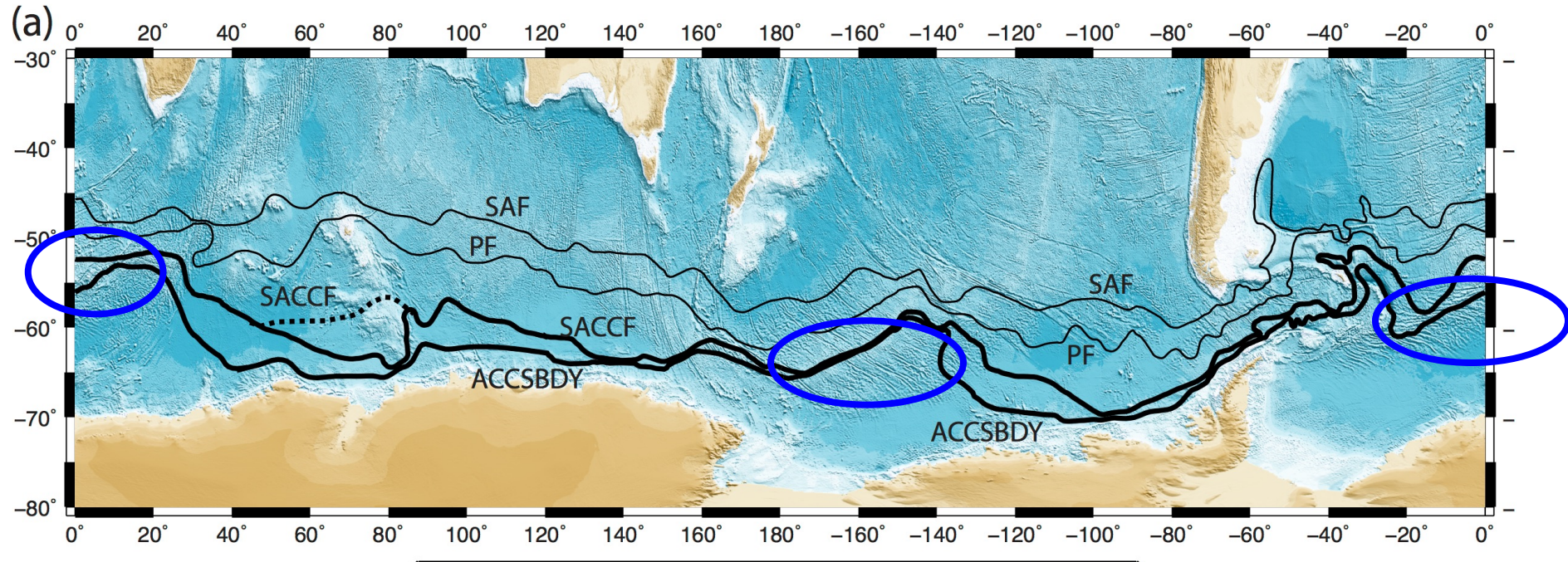
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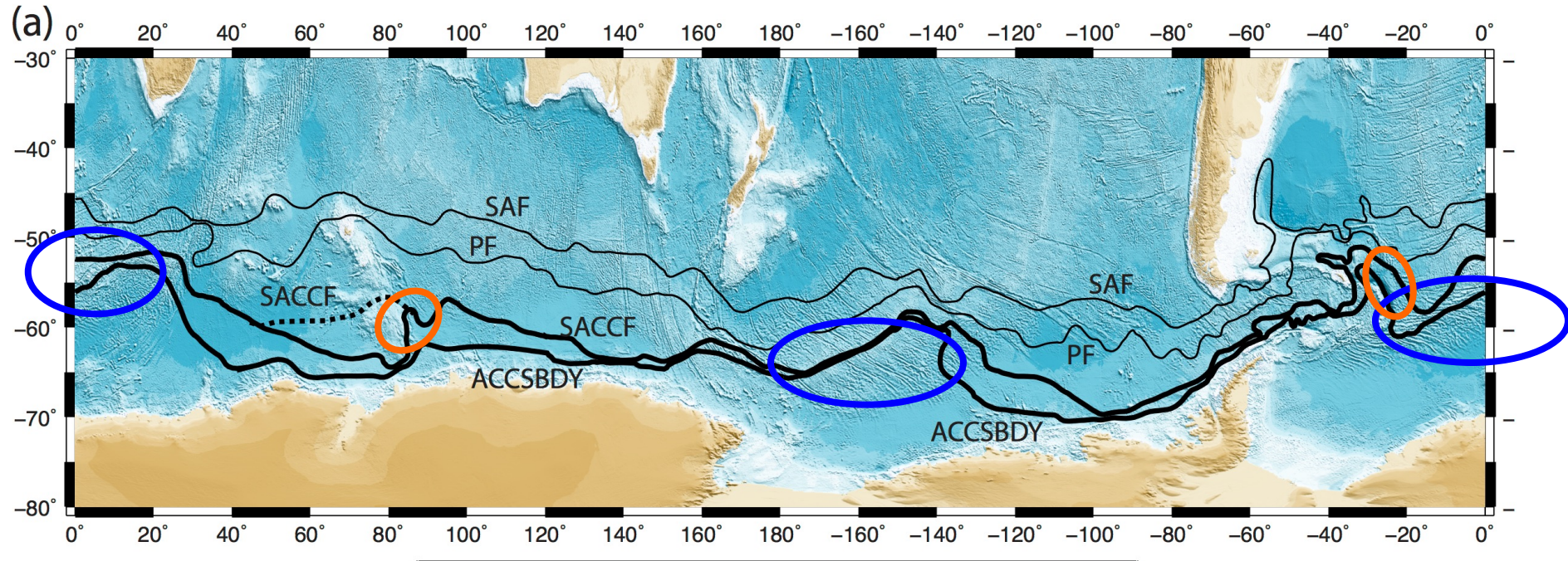
ACC fronts **flow along continental shelf** when they can't go farther south

(2) Northward swings of ACC SBDY: pinned to topography



ACC Southern Boundary (southern edge of UCDW oxygen minimum) driven north along ridges in Pacific and Atlantic
Pacific-Antarctic Ridge
America-Antarctic Ridge and Southwest Indian Ridge

(2) Northward swings of ACC SBDY: pinned to topography and western boundaries

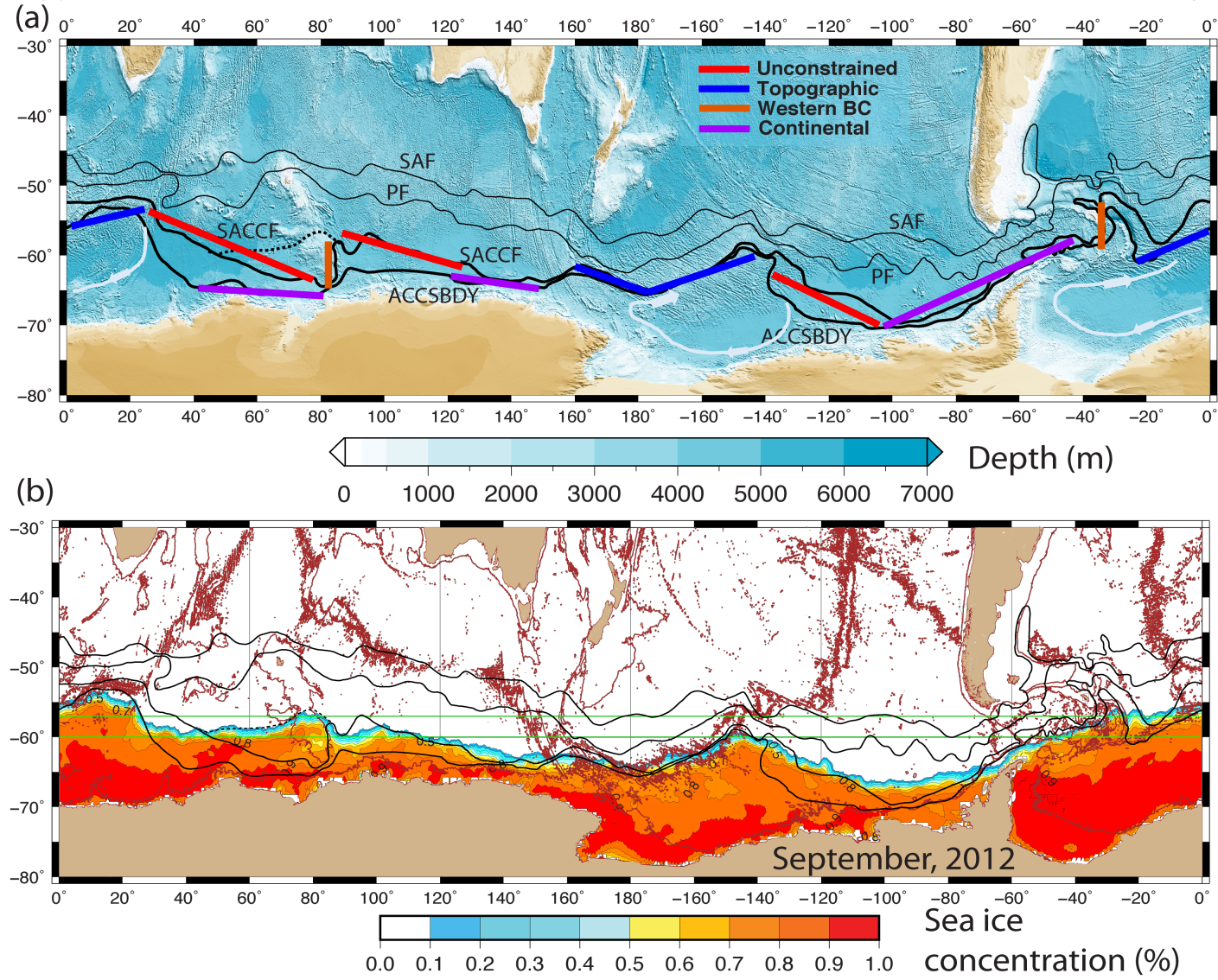


ACC Southern Boundary (southern edge of UCDW oxygen minimum) driven north along ridges in Pacific and Atlantic
Pacific-Antarctic Ridge
America-Antarctic Ridge and Southwest Indian Ridge

And northward as western boundary current at Kerguelen (and southward at South Georgia arc)

(2) Swings of ACC SBDY dictate basin-scale cryosphere patterns

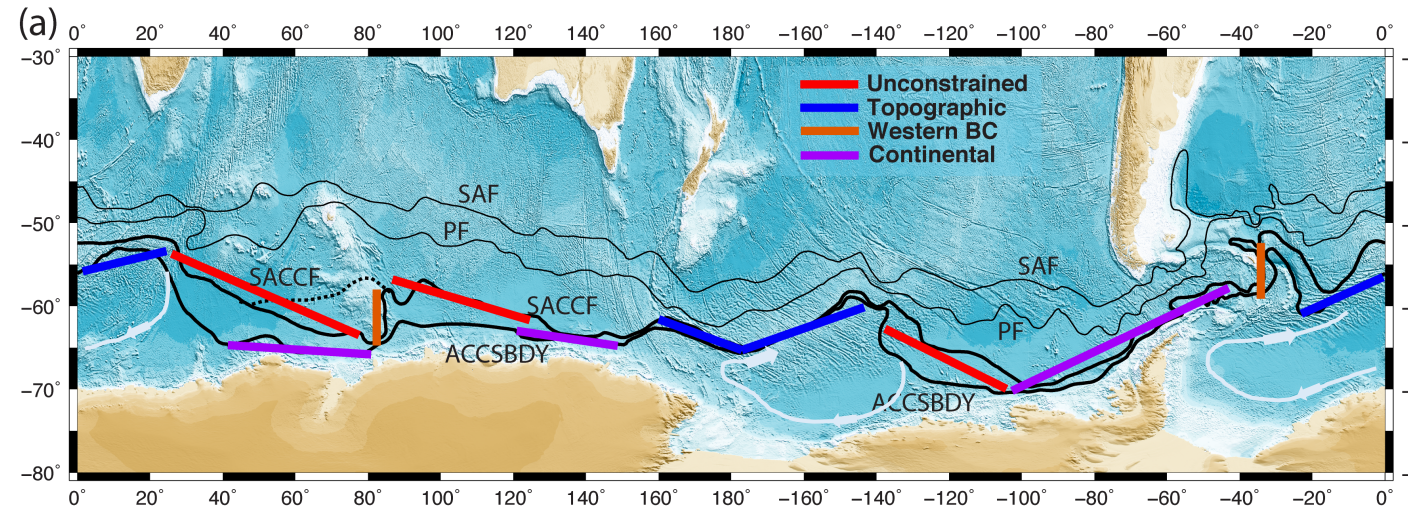
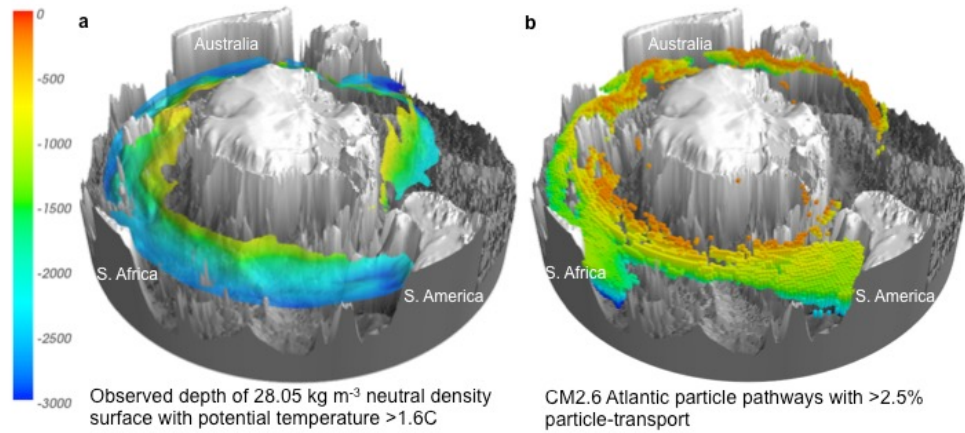
1. Push Warm Deep Waters and ice edge towards shelves
2. Push sea ice far to north (topography, extending way north of any classic Sverdrup gyre with land boundaries; equivalent barotropic flow over topography)



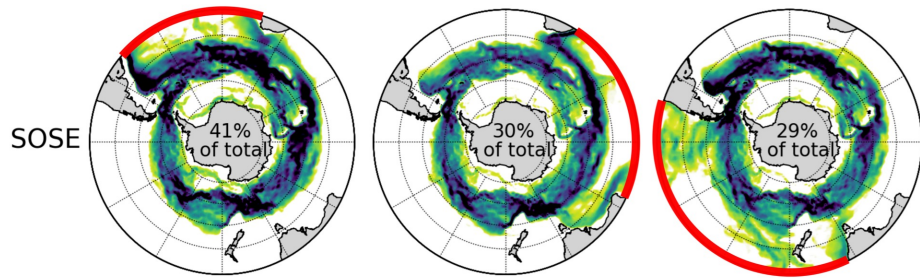
(1) + (2) Zonal asymmetries and Antarctic ice sheet mass



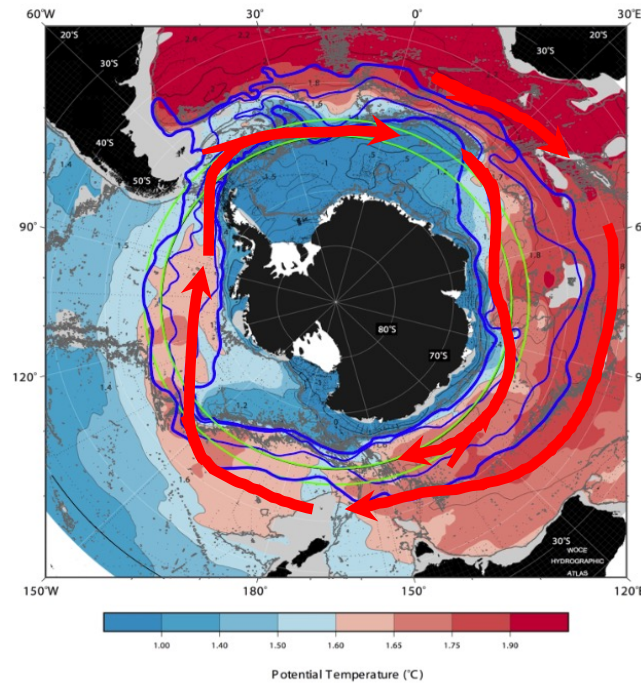
(1) Southward spiral, upwelling Deep Water,
 (2) ACC SBY locally reaching continental shelf ->
 ice sheet mass loss



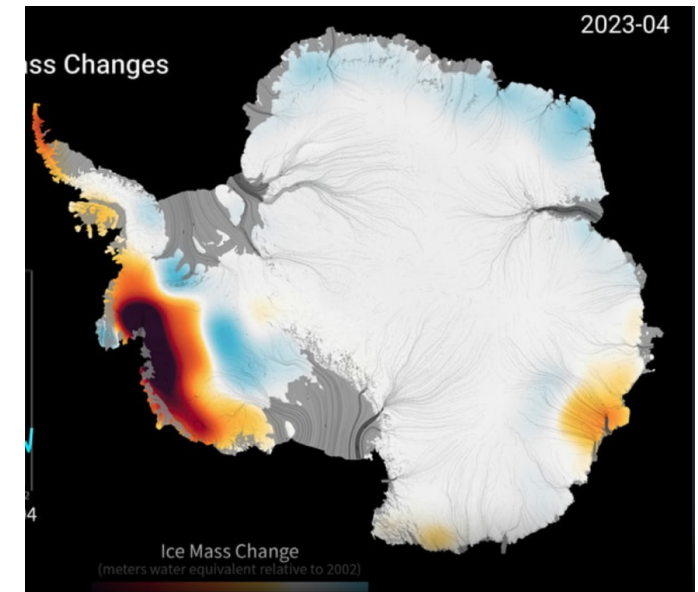
Warm CDW spirals to sea surface
 Moves close to continent with the ACC



Tamsitt et al. (Nat. Comm. 2017)



NADW isopycnal temperature



<https://climate.nasa.gov/interactives>

Dynamics: Vorticity balance in southern ACC?

Basic vorticity models with wind curl:

Marshall et al. (2016), LaCasce & Isachsen (2010), Gill (1978), Stommel (1957)

Topography: Masich et al (2015)

Simplification: Reduced gravity formulation necessary a la Killworth (1992) etc

$$\int \frac{D\zeta}{Dt} dz + \beta V = f(w_{Ek} - w_{bottom}) + \int (diffusion) dz$$

Linear, steady state, non-diffusive
Vertically integrated

$$\beta V = f(w_{Ek} - w_{bottom})$$

Balance over abyssal plains (weak topography)
(Sverdrup balance)

$$\beta V = f w_{Ek}$$

Balance over strong topography (should be modified by the
weak stratification)
(modified Sverdrup balance)

$$f w_{Ek} = f w_{bottom} = f \bar{u}_H \cdot \nabla h$$

Nonlinear, diffusive balance in western boundary currents,
edges of topographic constrictions

$$\int (\bar{u}_H \cdot \nabla \zeta) dz + \beta V = \int (diffusion) dz$$

Relative importance of topography or β in balancing Ekman pumping

Sverdrup balance

$$O[\beta V] = \beta UH$$

Topographic Sverdrup balance

$$O[f\bar{u}_H \cdot \nabla h] = fU |\nabla h|$$

Where U is velocity scale, H is typical depth

Non-dimensional parameter (local) of importance:

B \gg 1 topography important

B \ll 1 β important

$$B = \frac{f |\nabla b|}{\beta H}$$

Typical value for Pacific-Antarctic Ridge with 3000 m drop over 1000 km: B = O(10)

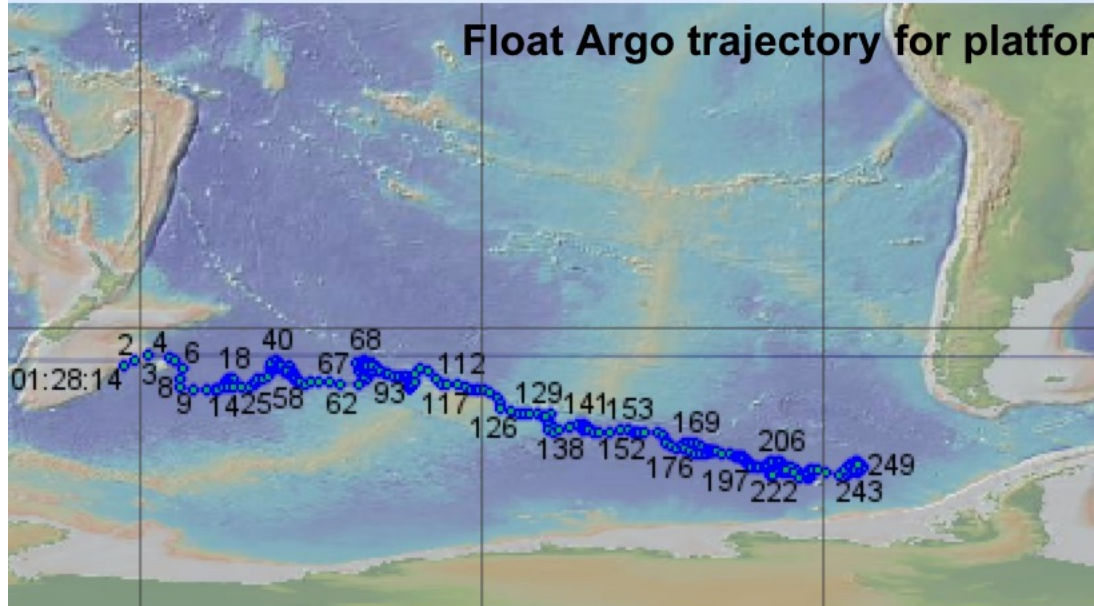
Typical value for Bellingshausen Basin: B < O(1)

Vorticity at ridges and obstructions is more complicated

$$\int (\bar{u}_H \cdot \nabla \zeta) dz + \beta V = \int (\text{diffusion}) dz$$

Sverdrup balance regime over abyssal plains

Float 5903718 2012-03-06 to 2015-09-21



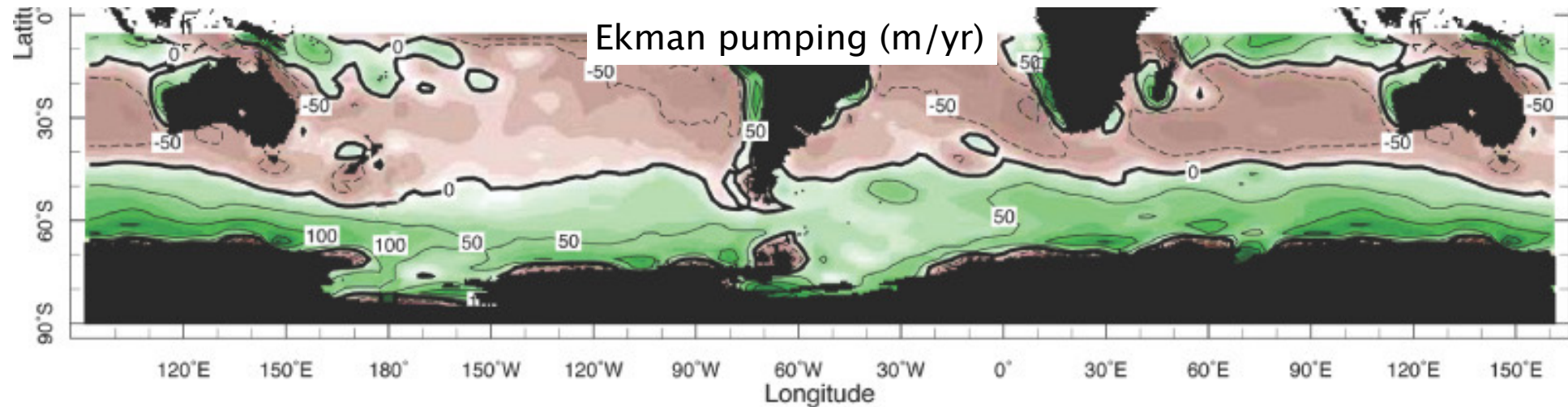
Seems reasonable:

A sample Argo float crossed the SEPacific at an average southward speed at 1000 m

$$V = 0.5 \text{ cm/sec}$$

Sverdrup transport velocity, using pumping from Marshall and Plumb, assuming 4000m layer

$$v = 0.4 \text{ cm/sec}$$



Topographic vorticity regime

Topographic Sverdrup balance

$$f w_{Ek} = f \bar{u}_H \bullet \nabla h$$

$$B = \frac{f |\nabla h|}{\beta H} \gg 1$$

Non-dimensional parameter:
topography/beta

Hypotheses to consider:

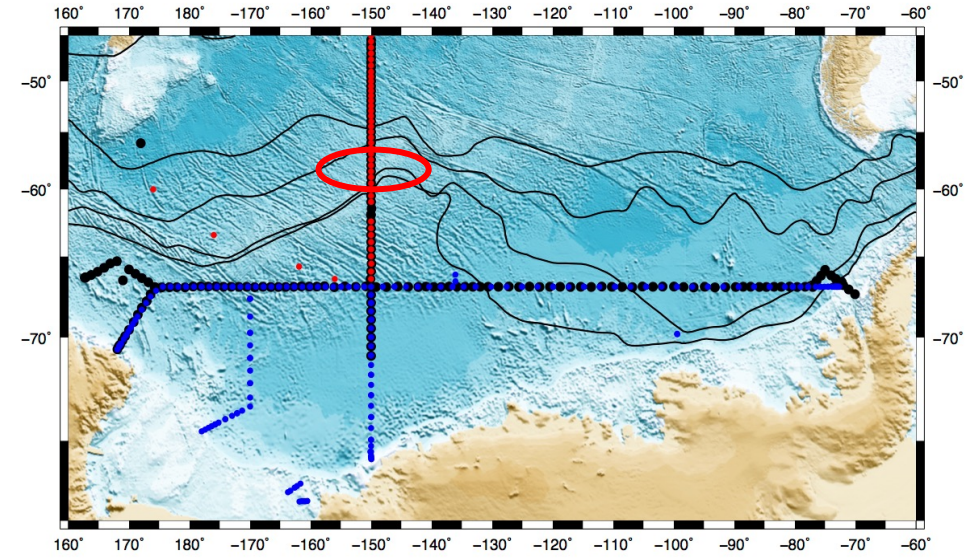
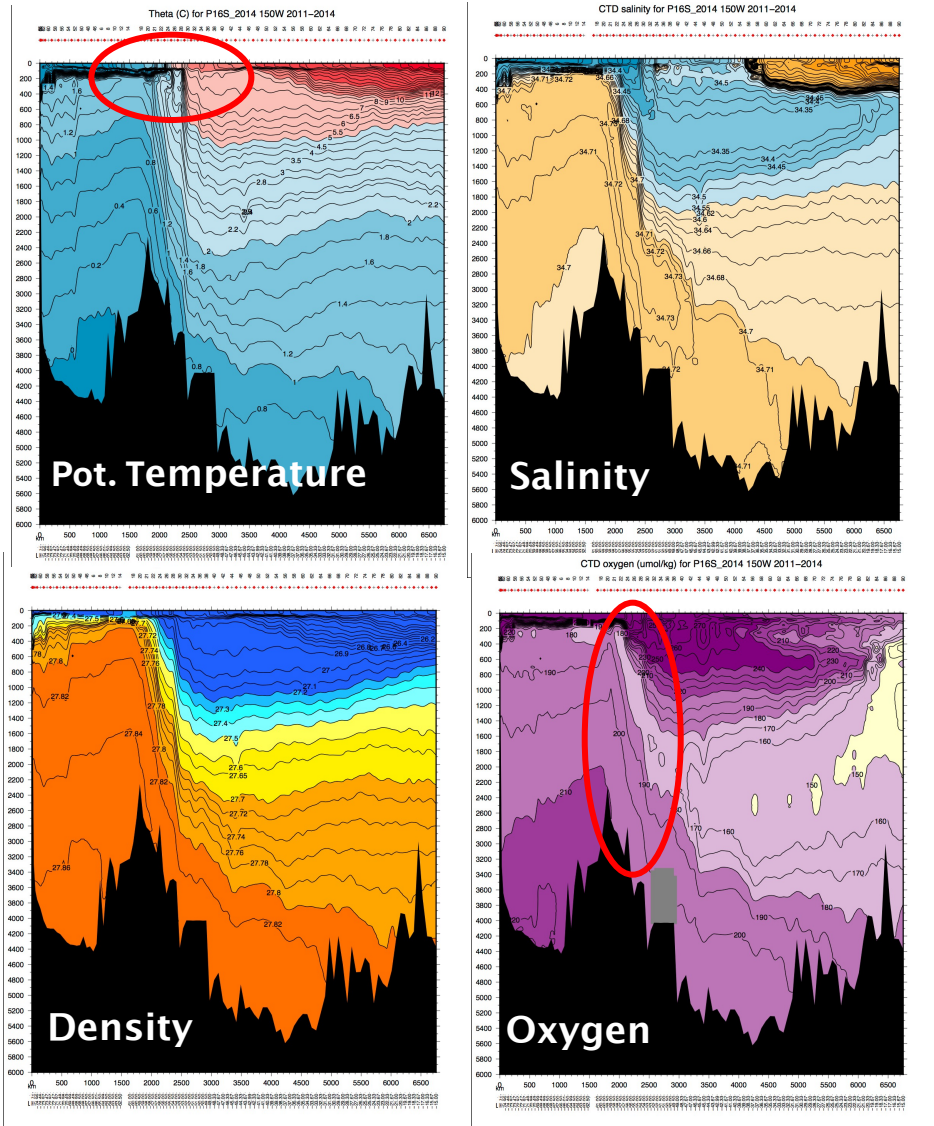
Where $B \gg 1$, strong flow along topography

- steering by f/H contours with strong gradient
- possible frontogenesis along ridges due to converging meridional velocity at ridgetops

Likely **becomes nonlinear**, large eddy field, goes well beyond this balance

Eddy effects create deep water upwelling hotspots at topography (Tamsitt et al., Nat. Comm. 2017)

Topographically controlled, strong southern ACC fronts: Pacific example

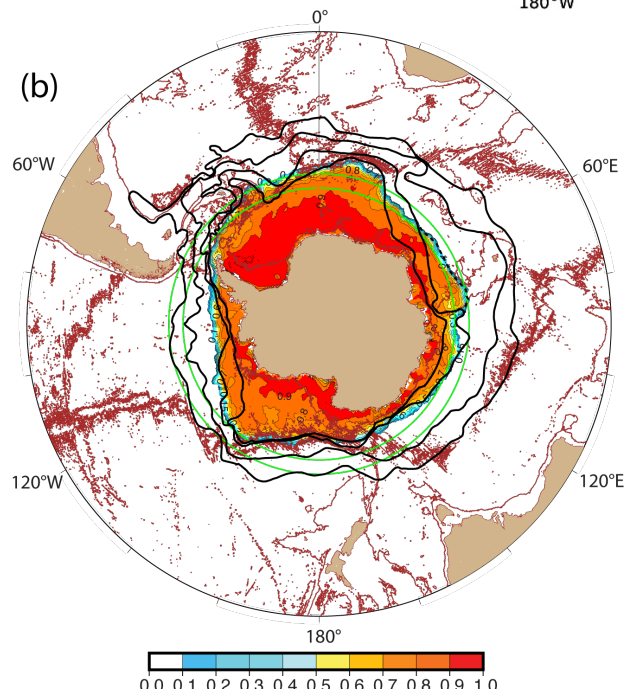
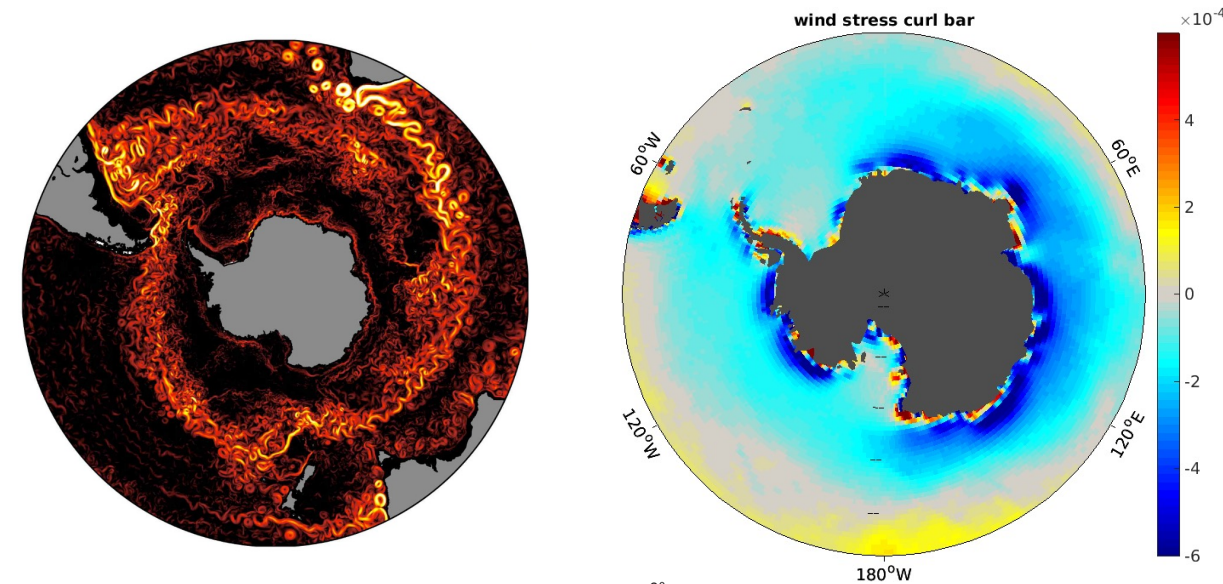


Pacific-Antarctic Ridge: very strong front (topographically controlled, invariant location)

Upwelling of Circumpolar Deep Water far from continent: Guides surface water and sea ice far from Ross Sea

SST/sea ice front: strong feedback on atmosphere, so Amundsen Sea Low perhaps impacted by this topographic constraint

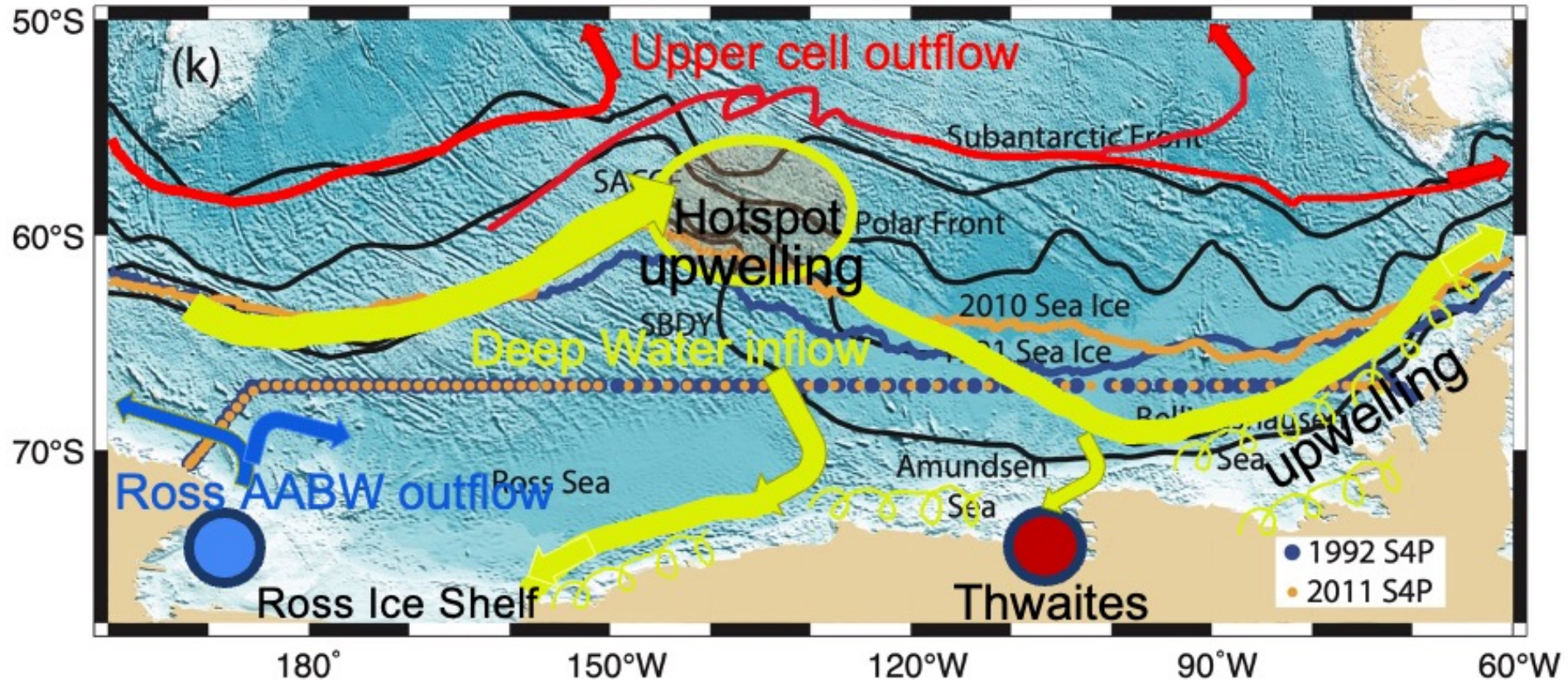
Summary: mean circulation and sea ice



- ACC large-scale spiral southwards with Malvinas as western boundary current: partially Sverdrup dynamics
- ACC southern boundary shape is determined by wind stress curl forcing plus topography or its absence
- ACC is least variable in location where strongly constrained by topography
- ACC southern boundary sets the sea ice edge (plus Ekman transport northward across the front)

Zonal asymmetry of Pacific Southern Ocean overturning cell (very rough schematic)

Ideas from an NSF-sponsored Southern Ocean workshop in 2024. Including A. Thompson, E. Wilson.



Lower cell dominates:
AABW formation

Upper cell dominates:
joining the thermocline

Zonal asymmetry and Southern Ocean overturning cells



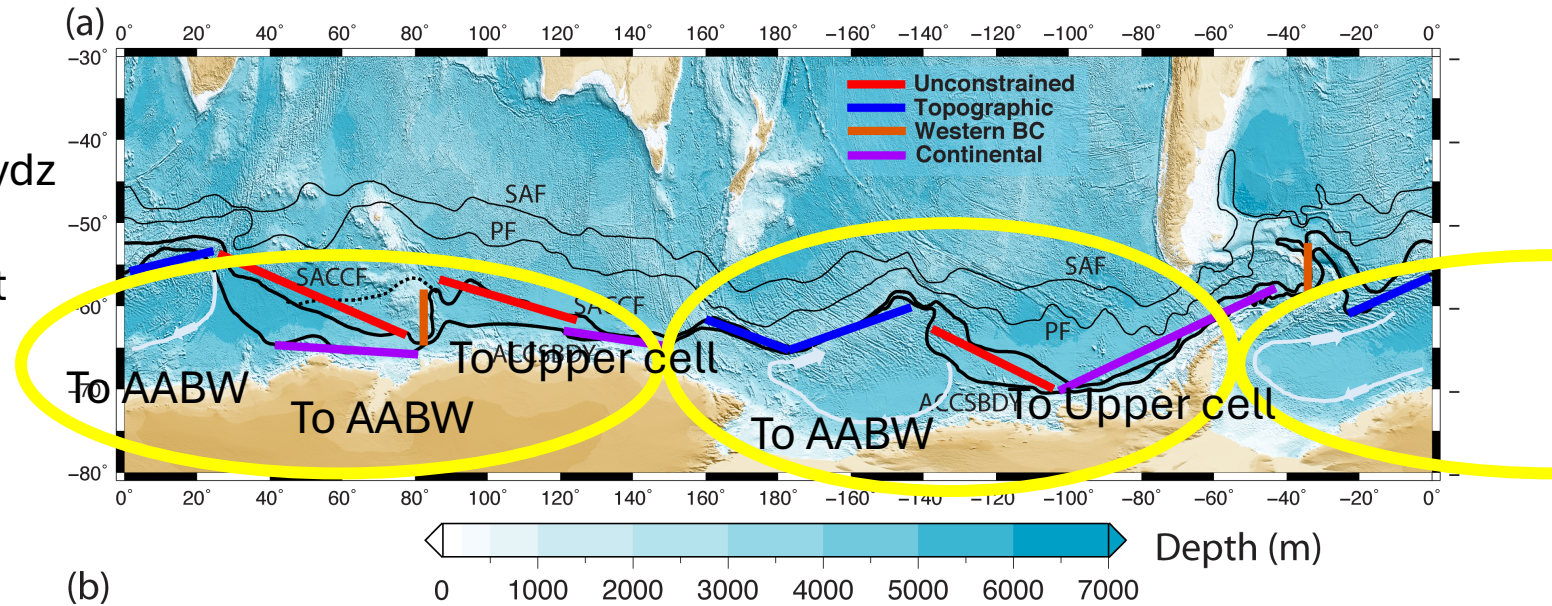
Hypothesis: 2 major zonally separated cells

(a) Pacific sector, with Ross Sea

(b) Atlantic/Indian sector, with Weddell and Prydz

In both cells: export to AABW (dense) is in west and export to Upper cell (light) is in east

Topography is critical for all of these



Lower cell AABW:

Subpolar gyres: Ross, Weddell, (Prydz)

Cold shelf

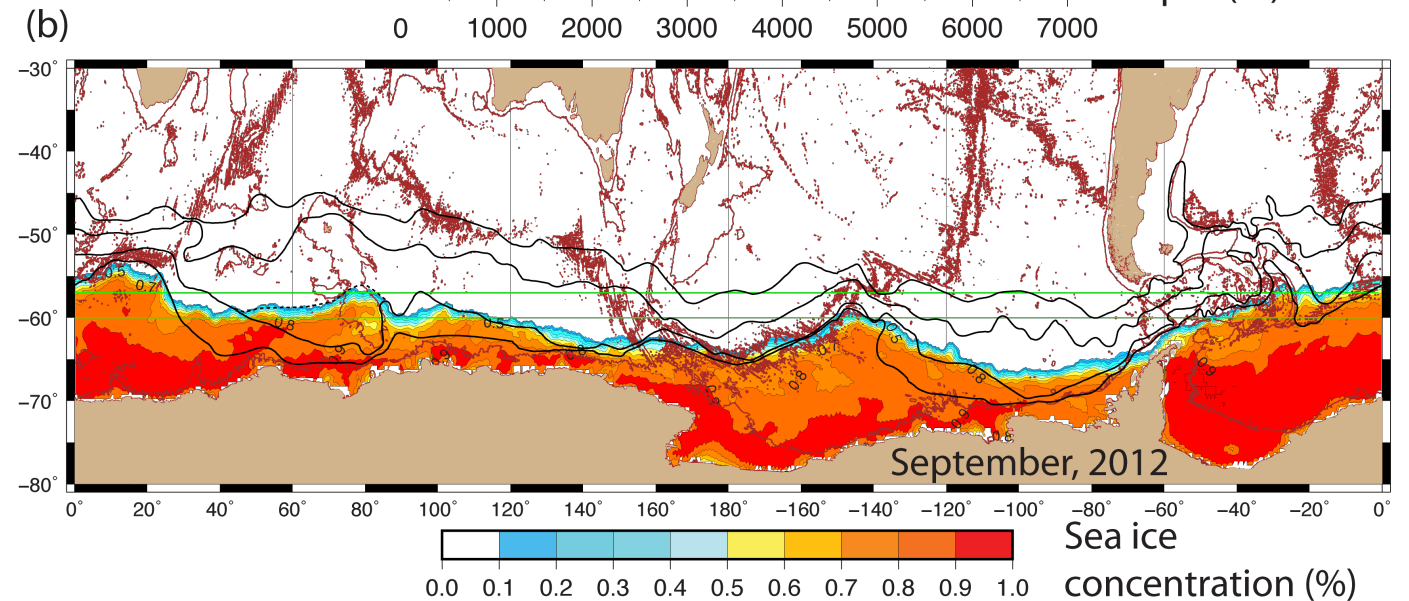
Brine rejection -> dense water formation

Upper cell

ACC approaching shelf

Warm shelf

Buoyancy addition from melting ice -> upper limb

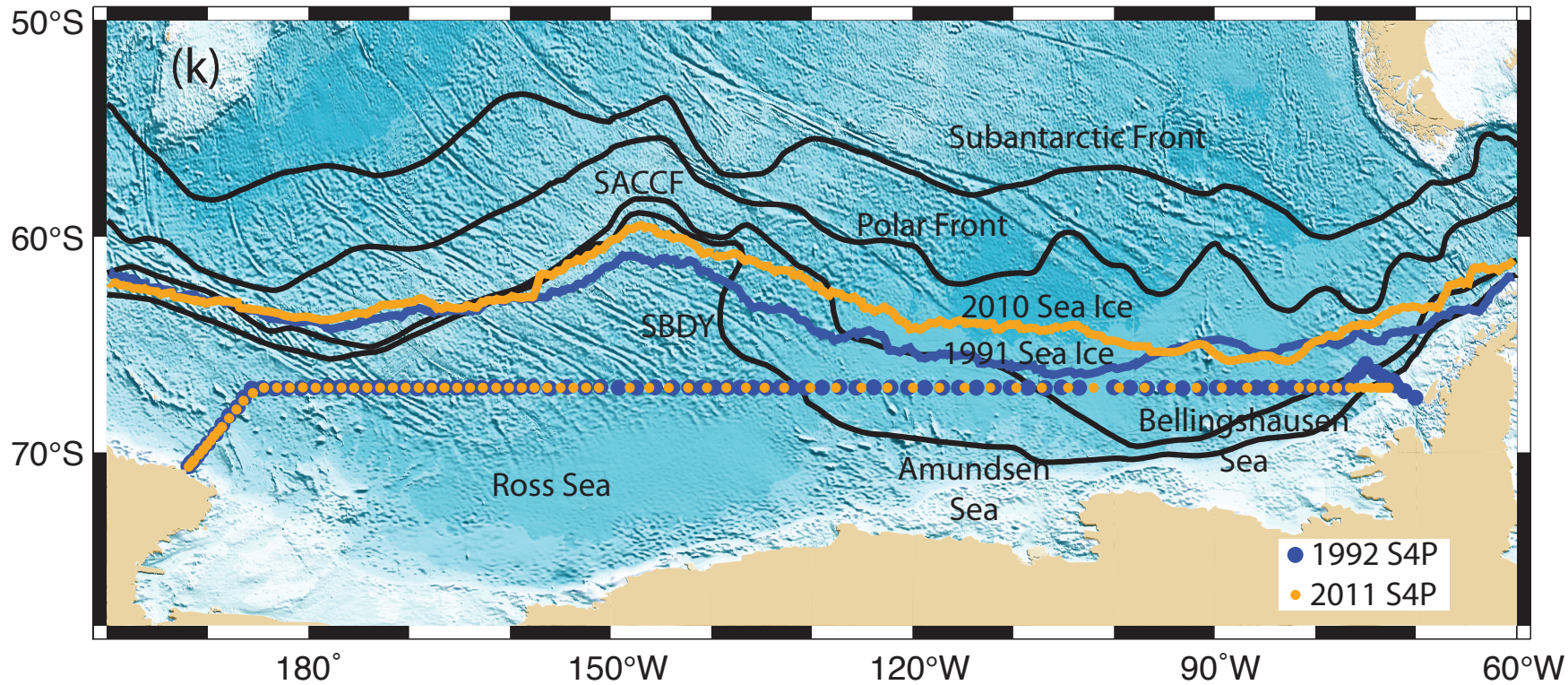


Responses to strengthening westerly winds?

Stronger southward ACC in Bellingshausen (GO-SHIP/WOCE)

Sea ice trends that depend on strength of ACC SBDY front

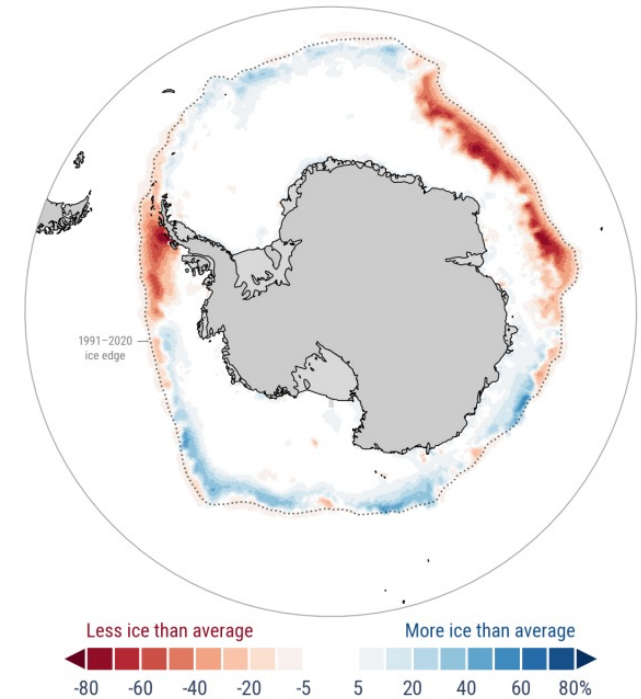
Using GO-SHIP (2011) and WOCE hydrography (1992).
This section was repeated in March-May 2018



er • September 2025

1991-2020 • Credit: C3S/ECMWF

Sea ice concentration anomaly



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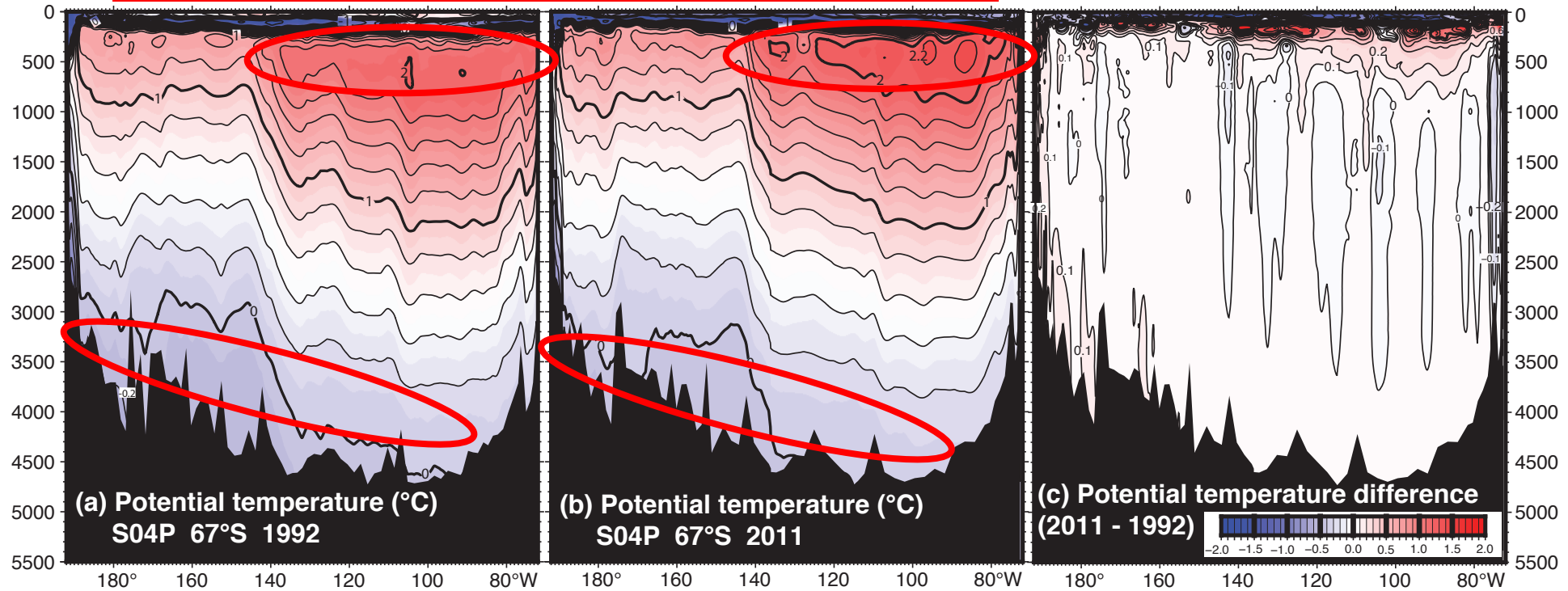


S04P changes are top to bottom

Potential Temperature change 1992 to 2011

Stronger southward transport of ACC, top to bottom consistent with stronger wind stress curl

Warm Upper Circumpolar Deep Water is warmer in 2011

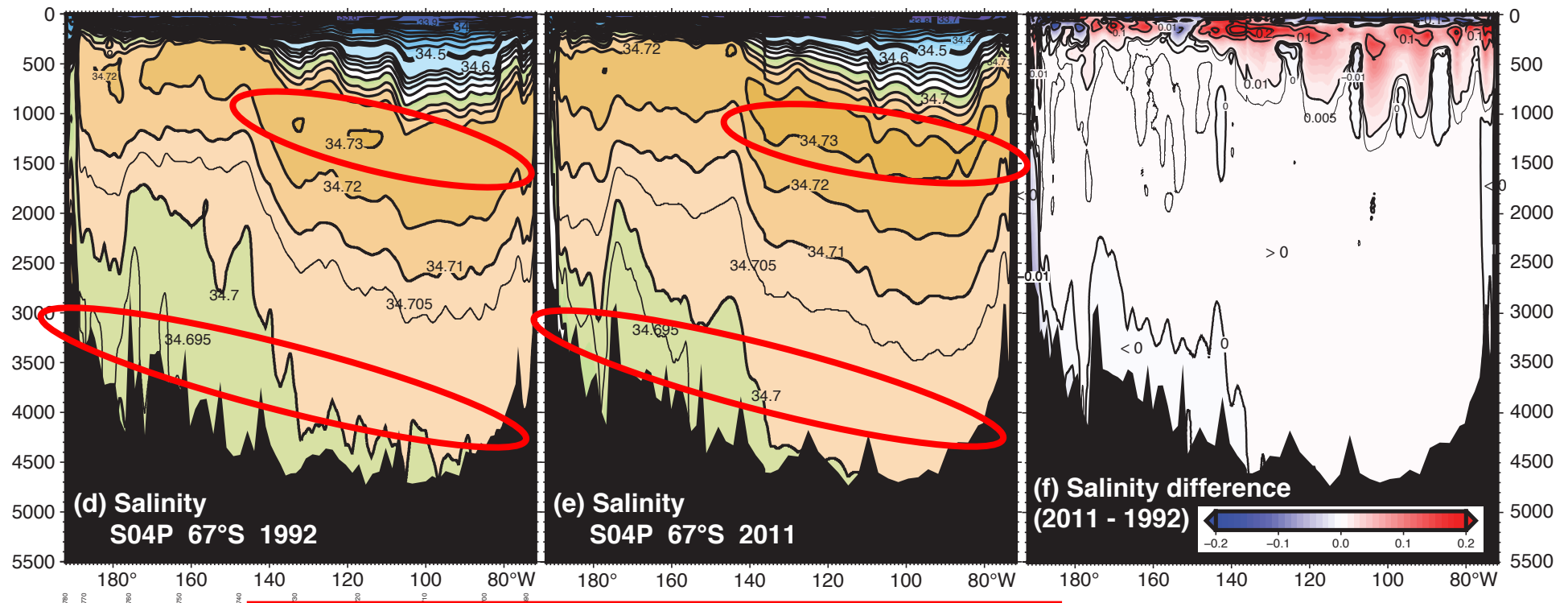


Antarctic Bottom Water is warmer in 2011
(Desbruyeres et al., GRL 2013)

Changes are top to bottom Salinity change 1992 to 2011

Stronger southward transport of ACC, top to bottom consistent with stronger wind stress curl

Salty Lower Circumpolar Deep Water is saltier in 2011



Antarctic Bottom Water is fresher in 2011
(Swift and Orsi, 2012; Purkey and Johnson, 2013)

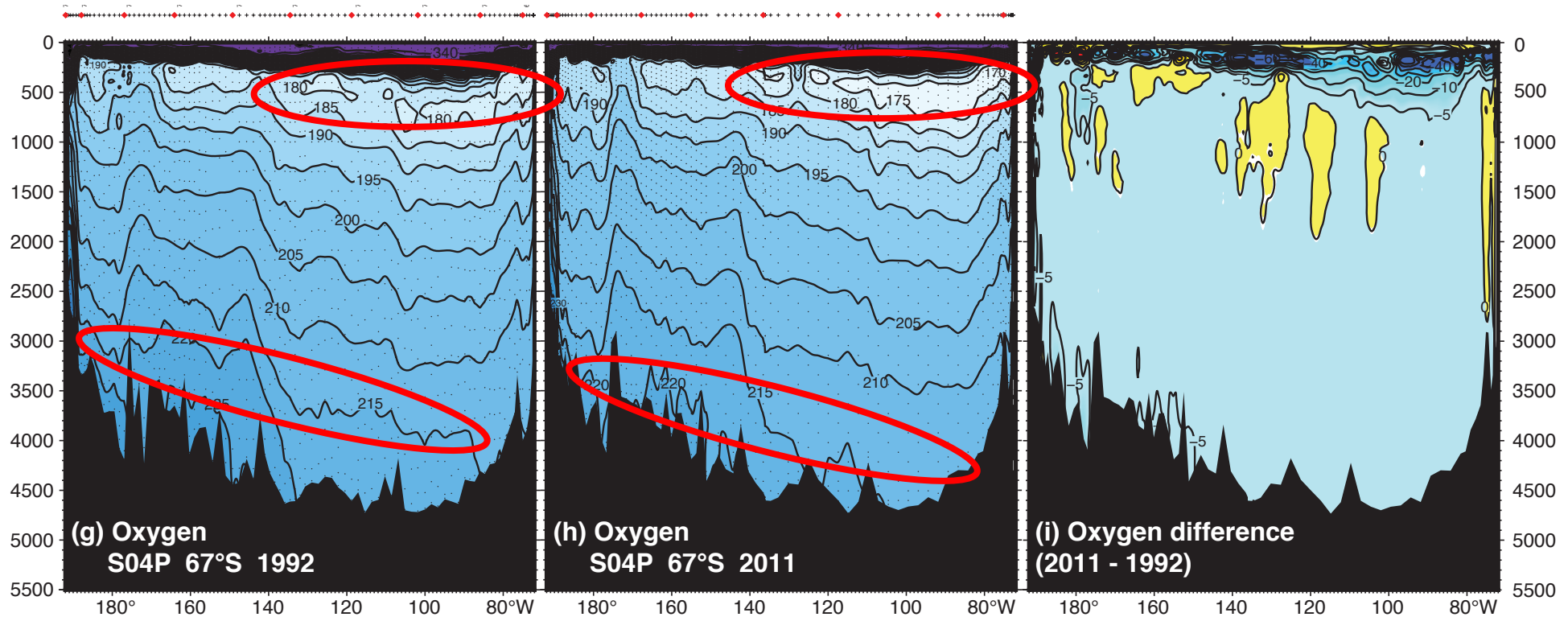
Using GO-SHIP (2011) and WOCE hydrography (1992).

Decadal trends in Pacific sector water properties

Oxygen

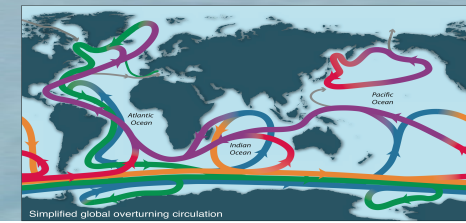
Using GO-SHIP (2011) and WOCE hydrography (1992).

Low O₂ Upper Circumpolar Deep Water is less oxygenated in 2011

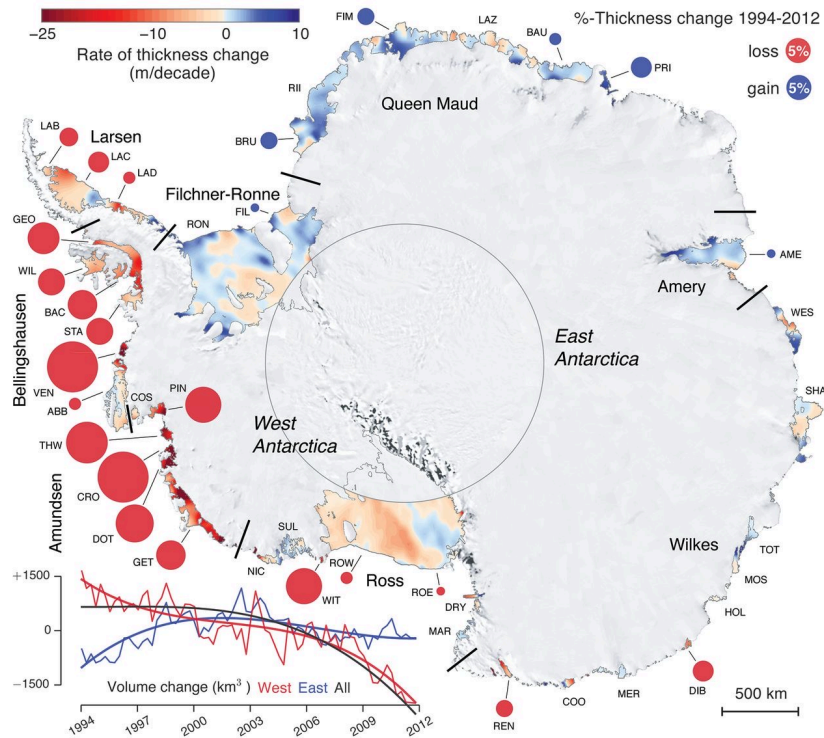


Antarctic Bottom Water is less oxygenated in 2011

Increasing warming from ocean

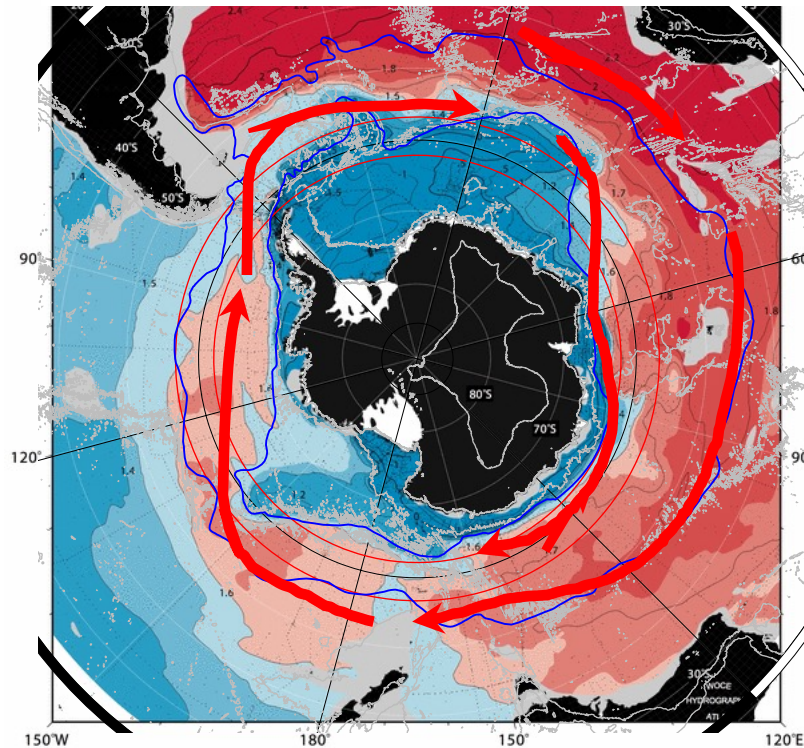


Stronger winds and curl are pushing more warm water to continent, likely contributing to shelf warming and ice melt



Paolo et al. (2015)

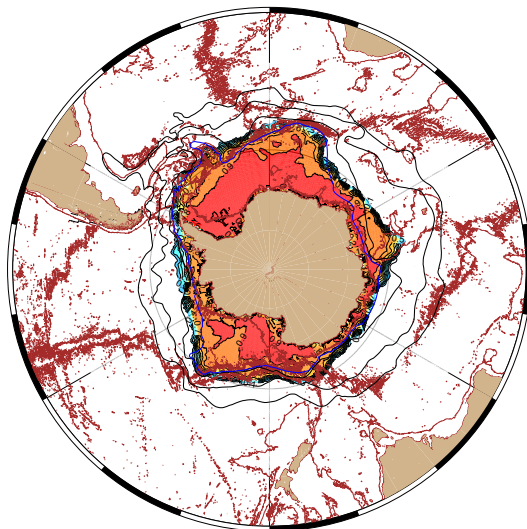
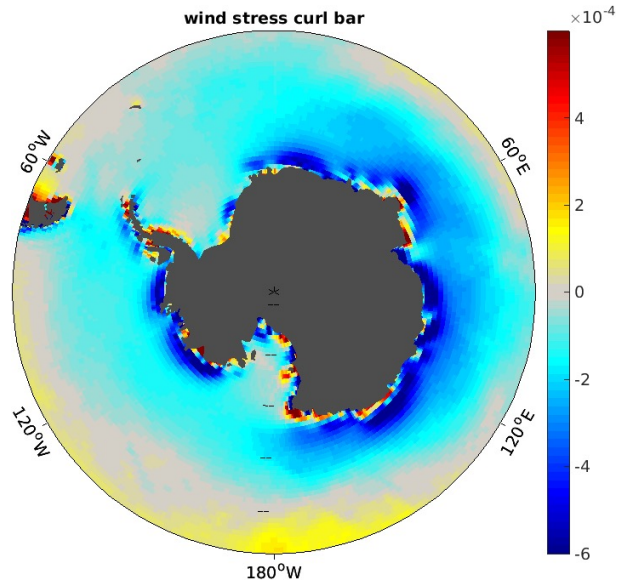
Potential temperature at $\sigma^N = 28.05$
(NADW - LCDW isopycnal)



Orsi and Whitworth (WHP atlas, 2005)



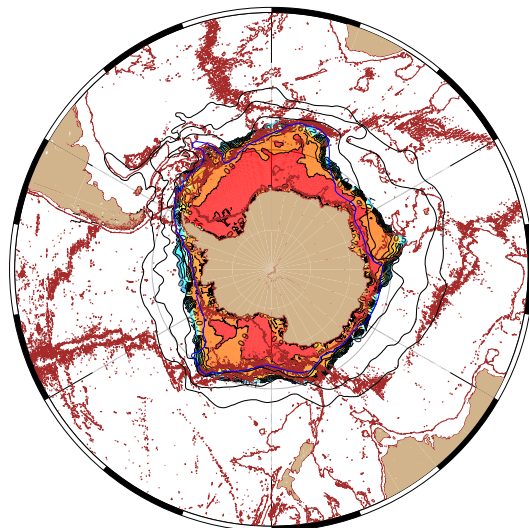
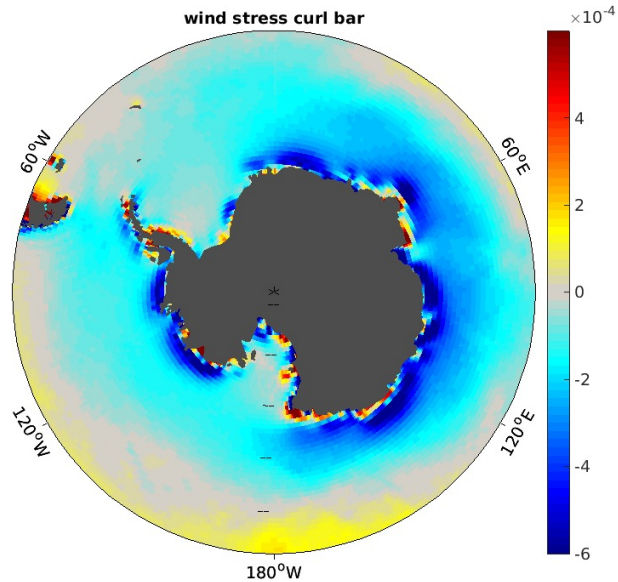
Summary: Wind and topography



- Southern Ocean: vorticity forcing
- Wind stress curl is fundamental to S.O. circulation and climate processes (upwelling, air-sea exchange, southward ACC spiral)
- [Zonal wind important for net transport]

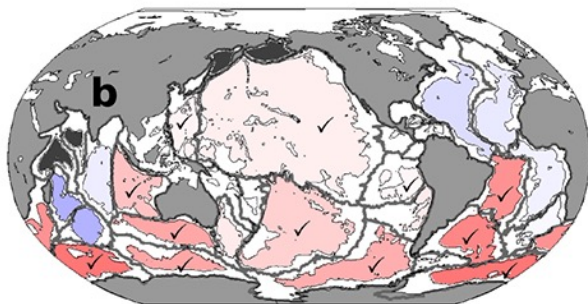
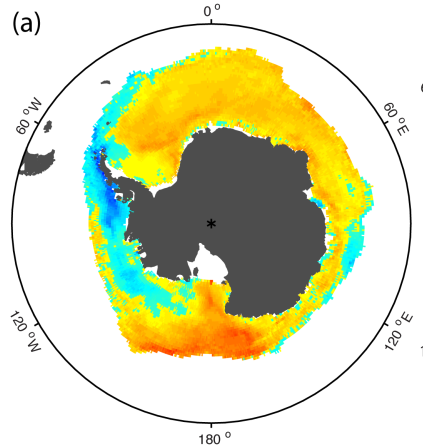
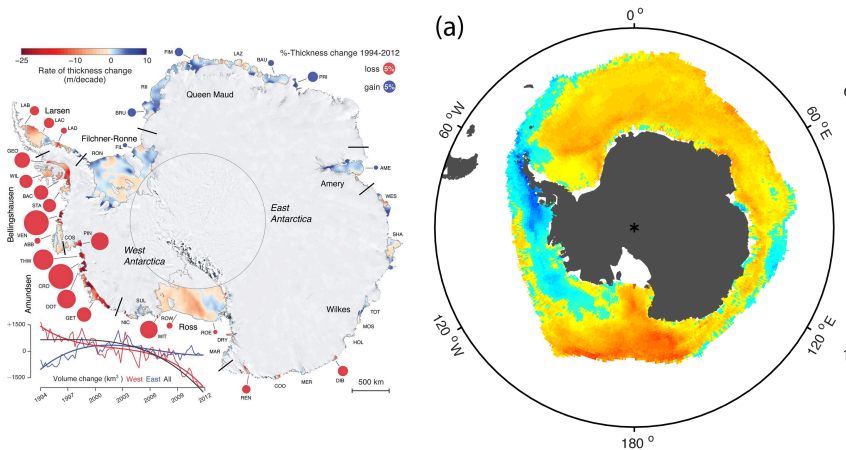
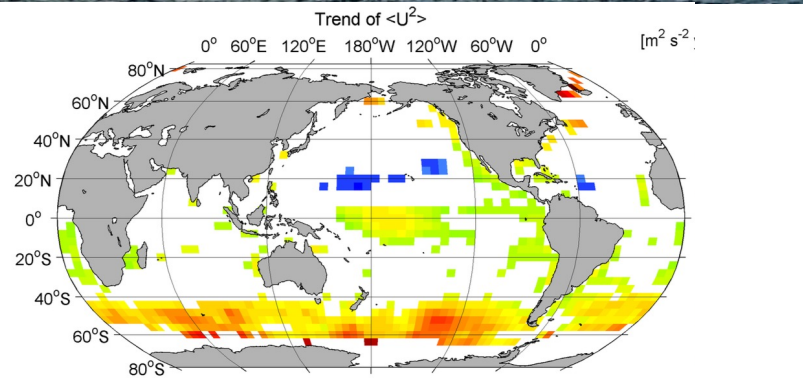


Summary: Wind and topography



- Southern Ocean: geography and topography matter
- ACC has standing meanders
- **One large one**: inward and upward spiral (set by S. America and Ant. Peninsula)
 - Affects where warm water reaches shelves and hence ice shelves
- **Standing meanders on scale of basins** (set by topographic obstructions and ridges)
 - Affects ACC southern front location, upwelling/outgassing, and maximum winter sea ice

Southern Ocean changes



- Climate is changing
- S.O. wind and wind stress curl increasing
- More warm water moving south, more upwelling of warm water to surface to melt sea ice, melt ice shelves; probably more CO_2 outgassing, less uptake*
- Sea ice extent almost neutral as balance of stronger northward Ekman and more heat, but pattern strongly controlled by topography
- More melting sea ice (and some ice shelf) increases freshwater stratification
- Reduces AABW formation so deep Southern Ocean is warming