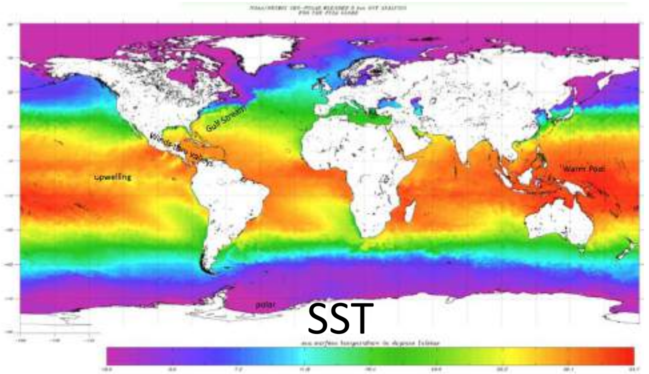
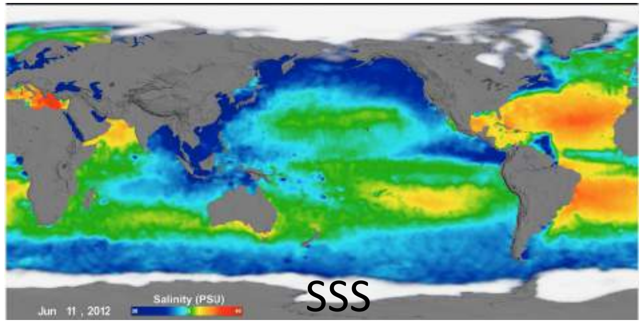
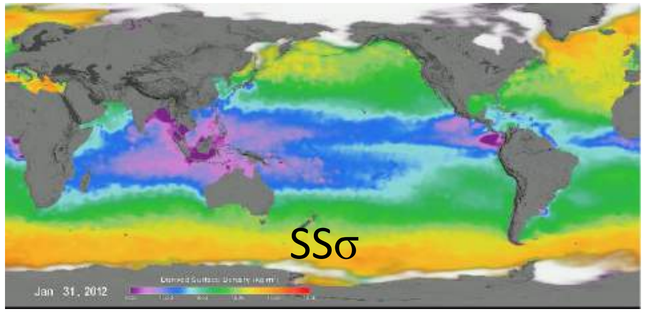
June 2022 Salinity Conference







Warm, salty, denser in reds

Cold, fresher, lighter in blues

Abstract in notes

Changing surface layer salinity, and where it matters most

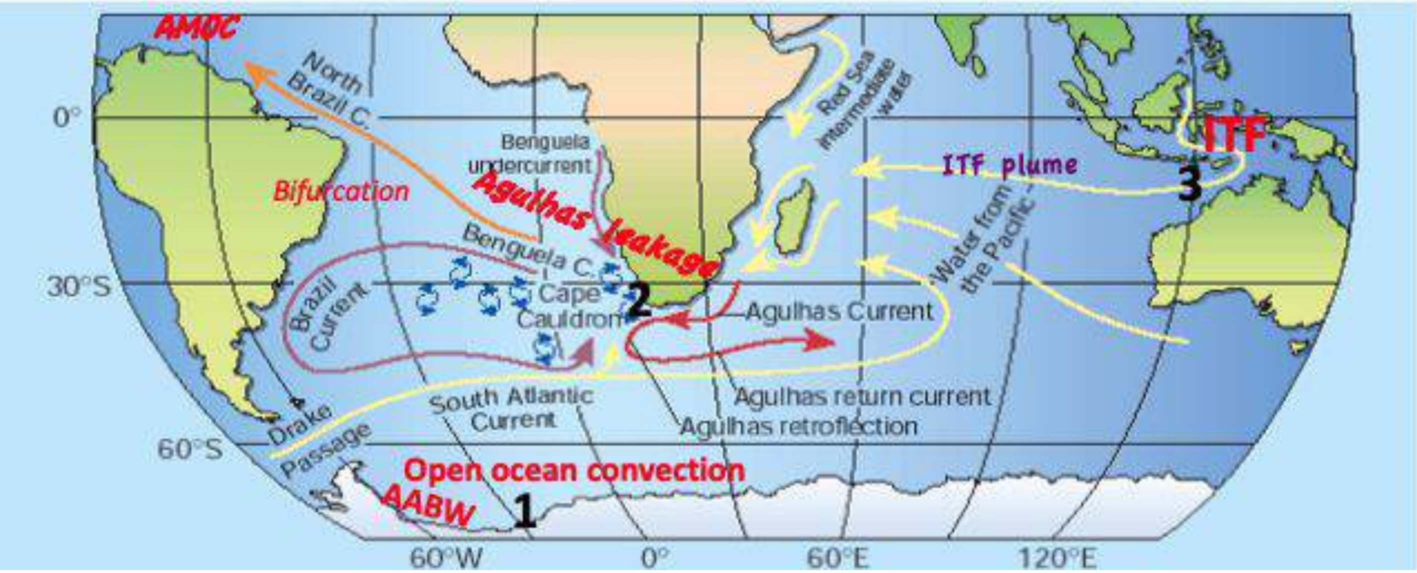
Arnold L. Gordon, Lamont-Doherty Earth Observatory of Columbia University

§ As the Earth's atmosphere warms and the climate patterns shift poleward, the hydrological cycle is energized: the dry becoming drier, the wet, wetter. The ocean stratification and ventilation will respond accordingly, as the convective sites and there T/S properties change.

§ Salinity and temperature (and pressure) determine the sea water density, so salinity is part of the ocean dynamic. But where does salinity matter most in impacting the ocean and climate systems? And how might that change, as the climate changes?

§ Besides the salinity barrier layer of the tropical Pacific across the maritime continent into the Indian Ocean, and interplay between 'fresh' (low SSS) Bay of Bengal and the salty Arabian Sea *(mini-Atlantic/Pacific Oceans)* I focus on 3 places where salinity plays a critical role *(i.e. the ones I research):*

1. **The convective Southern ocean:** two modes of convection (continental margin and open ocean);
2. **The salty Agulhas Leakage:** the Indian Ocean contributes to a salty Atlantic;
3. **The cool Indonesian Throughflow:** warm tropical Pacific surface water is inhibited to enter the Indian Ocean by the maritime continent surface layer 'freshwater plug'.



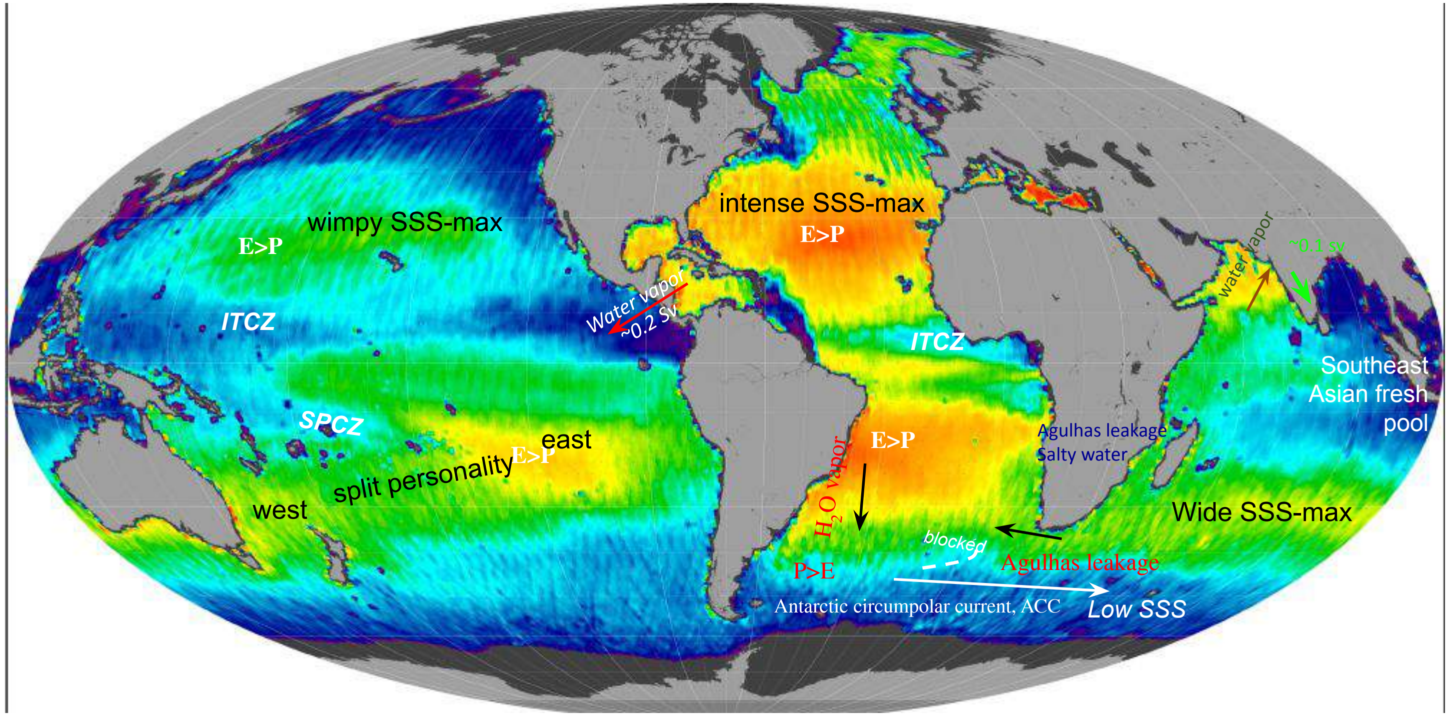
SSS likely to change with invigorated hydrological cycle, *see:*

Durack, P. J. (2015), Ocean salinity and the global water cycle, Oceanography, 28(1), 20–31, doi:10.5670/oceanog.2015.03

Durack, P. J., and S. E. Wijffels (2010), Fifty year trends in global ocean salinities and their relationship to broad-scale warming, J. Clim., 23,
4,342–4,362, doi:10.1175/2010JCLI3377.1.

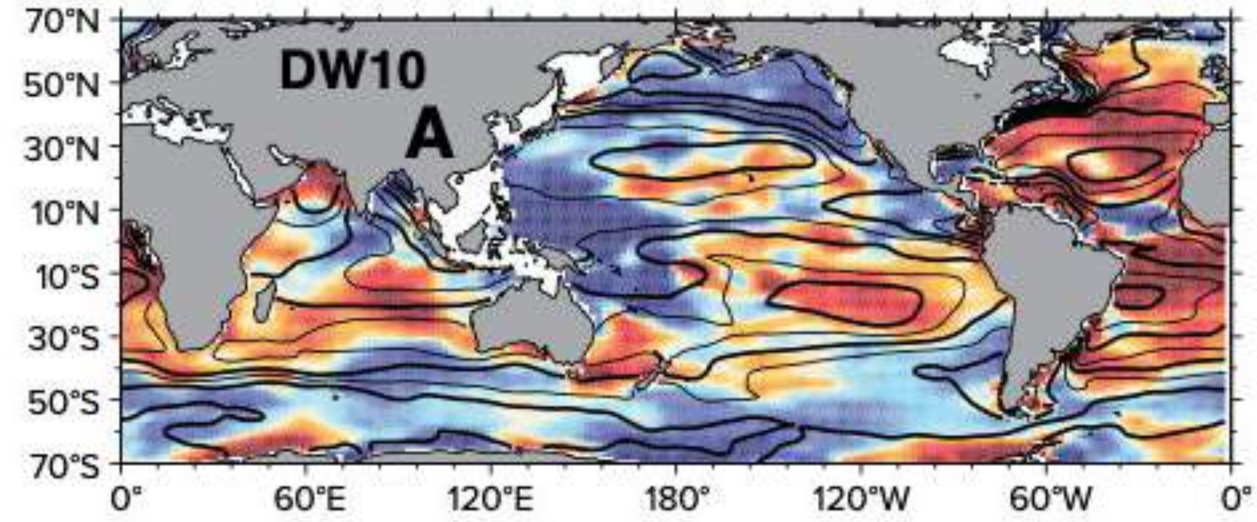
Durack, P. J., S. E. Wijffels, and R. J. Matear (2012), Ocean salinities reveal strong global water cycle intensification during 1950 to 2000, Science, 336(6080), 455–458, doi:10.1126/science.1212222.

Gould, W.J., Cunningham, S.A. Global-scale patterns of observed sea surface salinity intensified since the 1870s. *Commun Earth Environ* **2,** 76 (2021). https://doi.org/10.1038/s43247-021-00161-3



Aquarius Sea Surface Salinity (SSS); June 2014

Gordon, A.L., C.F. Giulivi, J. Busecke, and F.M. Bingham. (2015) 'Differences among subtropical surface salinity patterns. *Oceanography* 28(1):32–39, http://dx.doi.org/ 10.5670/oceanog.2015.02.

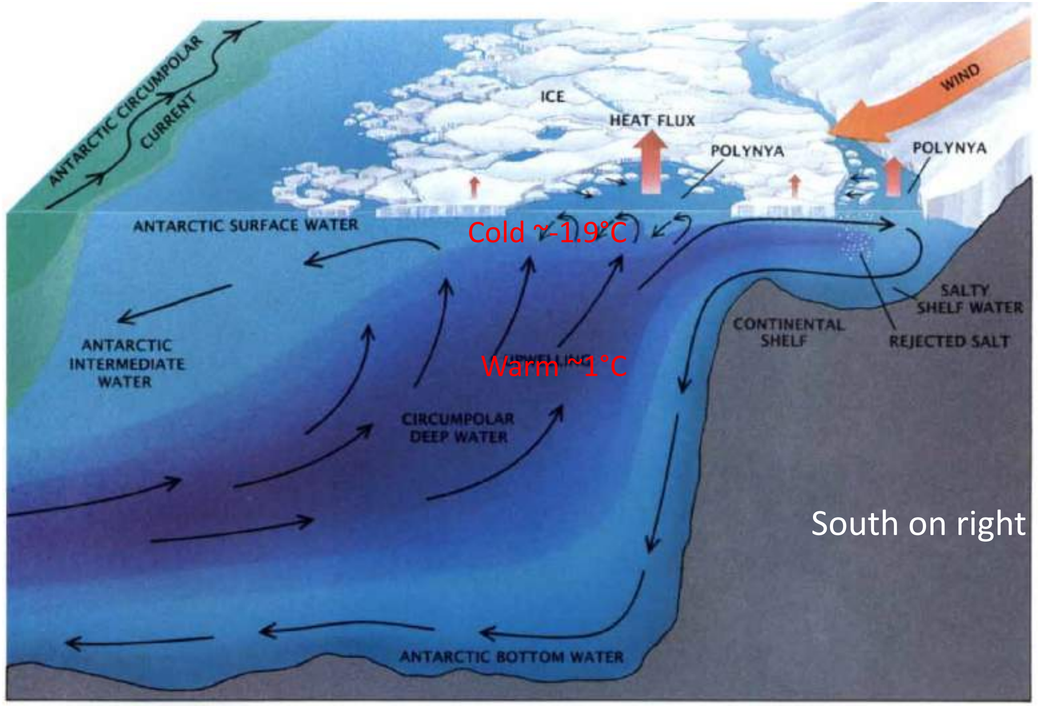


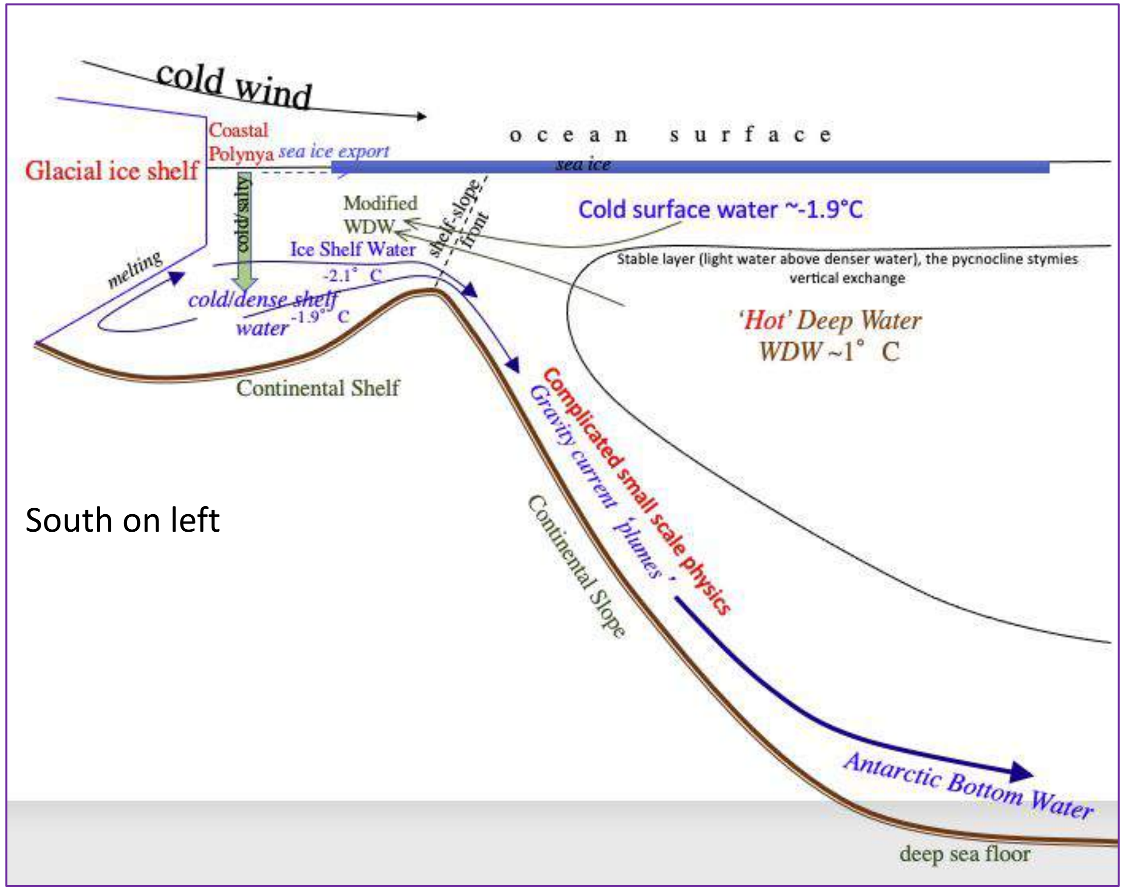
Estimates of global sea surface salinity (SSS) change and the 1950–2000 climatological mean after Durack and Wijffels (2010; analysis period 1950–2008) .Black contours show the associated climatological mean SSS for the analysis period.

Blue denotes freshening regions and red denotes regions with enhanced salinities

1 ***Southern Ocean Meridional Overturning***: Poleward shift of the ACC invigorates the subpolar gyres; increased glacial melt might styme production of dense water along the continental margins. Recent Weddell Sea changes offers a clue of how this might affect the AABW: change in T/S recipe, but not shut down of AABW.

Conventional wisdom: the one and only means of deep ocean ventilation from the Southern Ocean: from the continental margins- *not true, open ocean convection happens!*





Gordon, A.L., and J. C. Comiso (1988) Polynyas in the Southern Ocean. Scientific American, 258(6): 90-97. doi:10.1038/scientificamerican0688-90

The Weddell Polynya discovered when the microwave satellite was turned on in 1973, what a coincidence! Must be there most of the time? ***Wrong***…

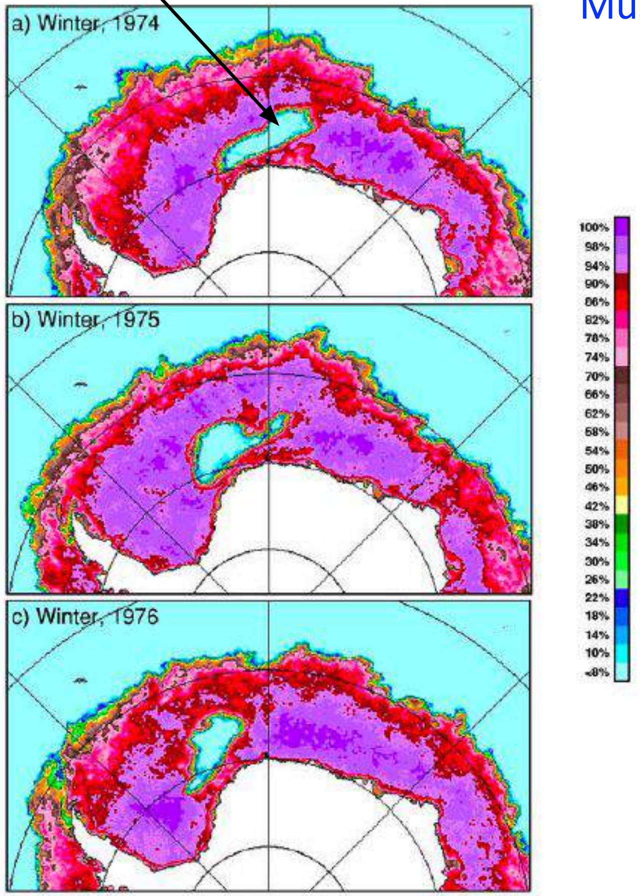


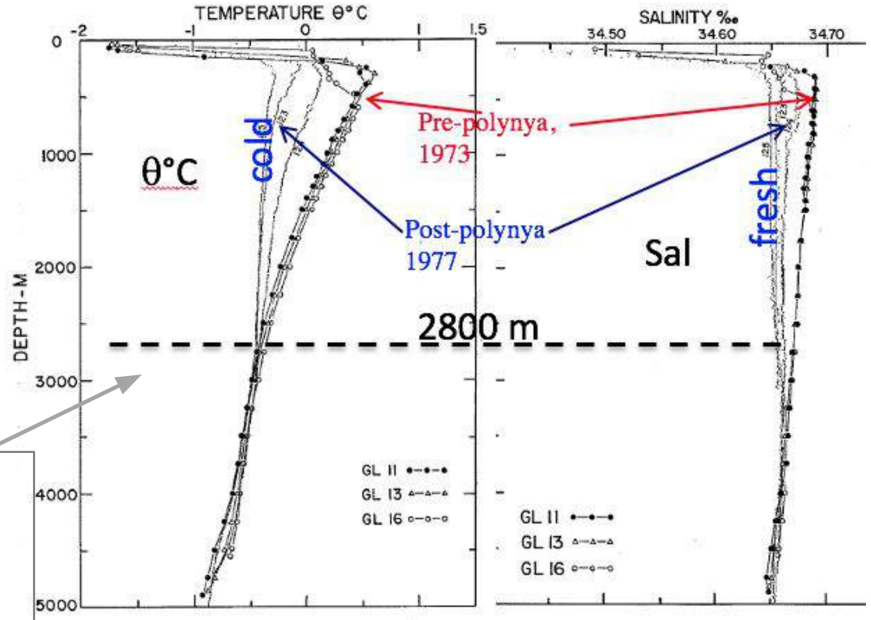
Figure 1. Color coded sea ice concentration maps derived from passive microwave satellite data in the Weddell Sea region during (a) August 30, 1974, (b) August 30, 1975 and (c) August 29, 1976. The Weddell Polynya is the extensive area of open water (in blue) near the Greenwich Meridian roughly between 65°S and 70°S. (Adapted from Gordon and Comiso, 1988).

The Great Weddell Polynya of the mid-1970s:

§ A winter ice free area of 250 10^3 km^2, which drifted westward at 1.3 cm/sec.

§ The persistent Weddell Polynya was a sensible heat polynya in that the heat required to maintain open water came from convection of deep warm water into the surface layer.

[see: Gordon, 1978, 1982, Gordon & Huber 1990; Martinson, Killworth, Gordon, 1981]



Missing heat: cause of the Great Weddell Polynya

Before/after polynya: Altered T/S (colder/fresher) stratification to 2800 m, 'removal' deep water heat;

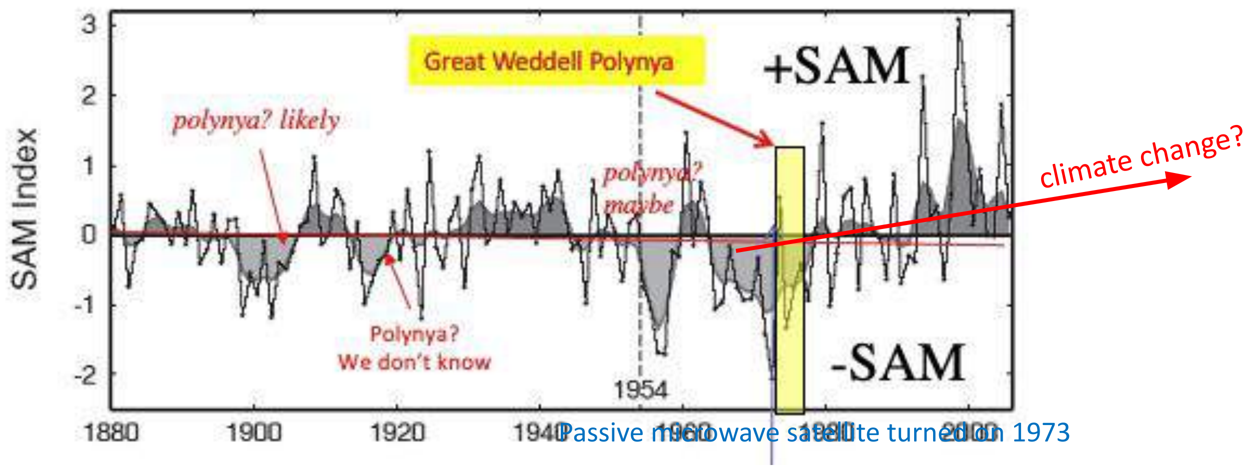
Convection of 1.6 to 3.2 Sv [averaged over the 3 years] **freezing point surface water is required to account for the cooled mass of Weddell Deep water *[Gordon 1978, 1982]***

Enhanced Winter heat loss to atmosphere via the polynya of >130 W/m²

Southern Annular Mode, SAM

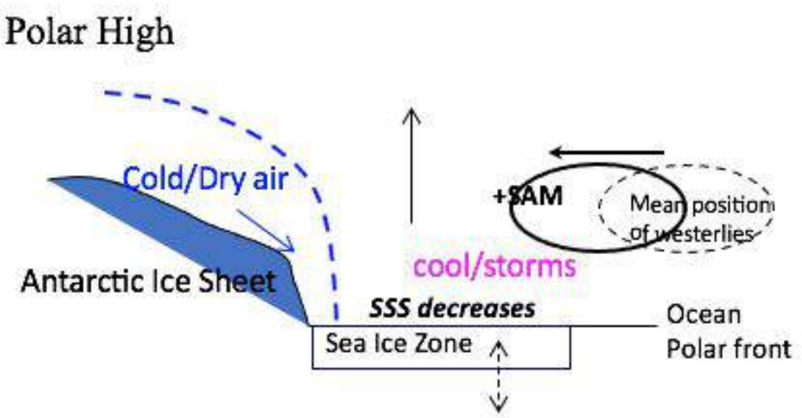
See (Thompson and Wallace (2000); Hall and Visbeck, 2002)

Prolonged (*relative to the <4 year residence time of the surface water in the seasonal sea ice zone*) negative SAM 1954-1960; 1962-1977; 1900-1910; 1914-1920

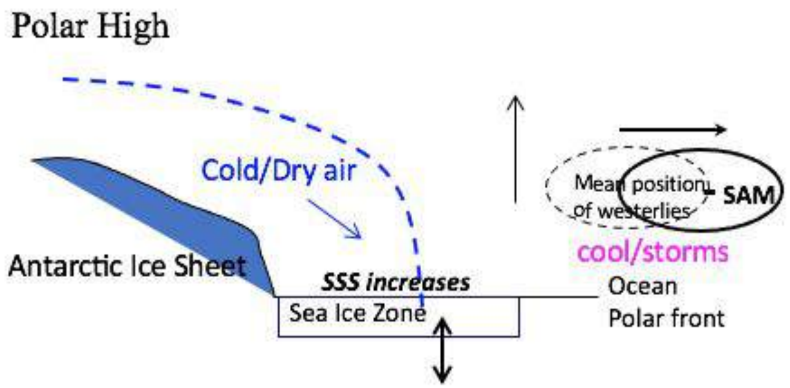


Gordon, A.L., M. Visbeck, J.C. Comiso (2007) "A possible link between the Weddell Polynya and the Southern Annular Mode" J of Climate 20(11) June, 2007, 2558-2571.

***+SAM** more common in warmer climate*



***-SAM** more common in colder climate*

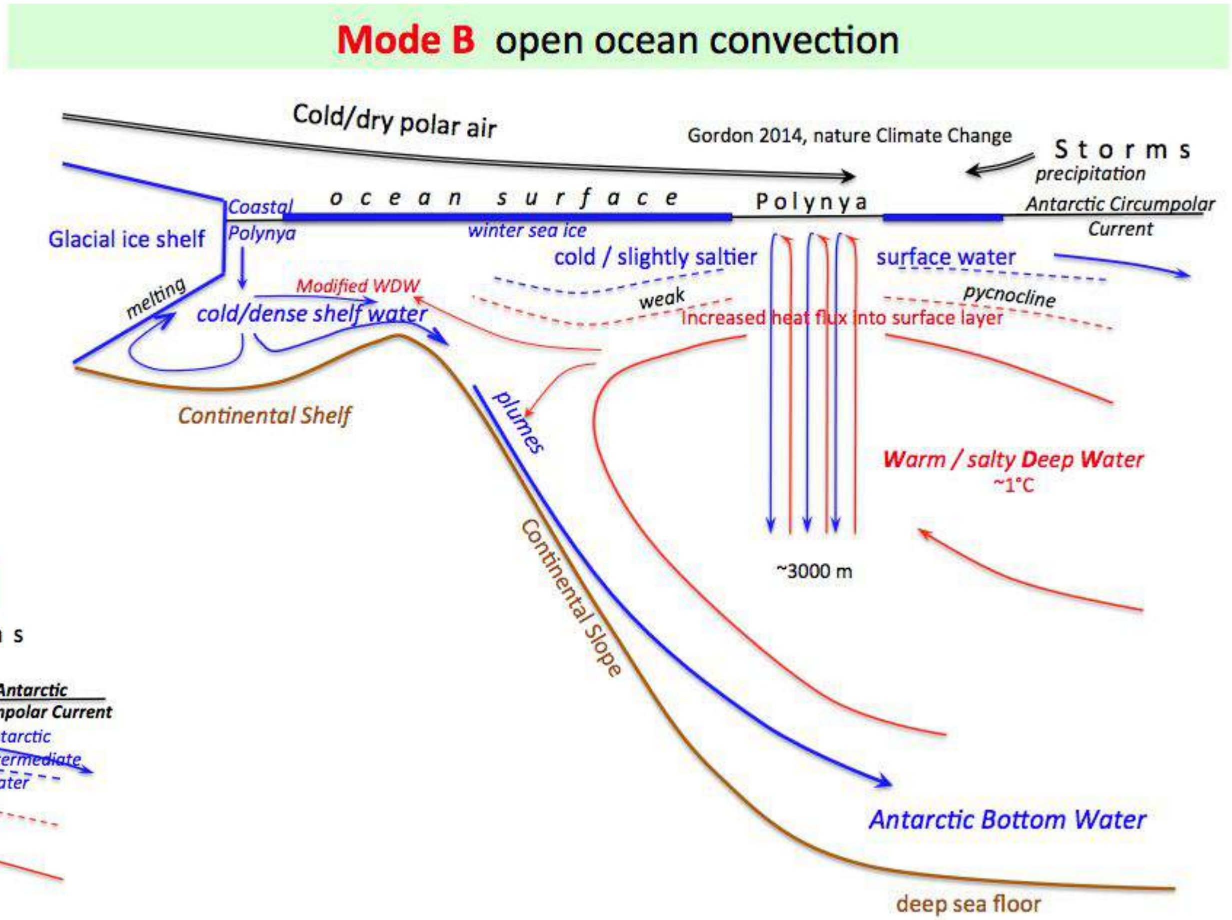


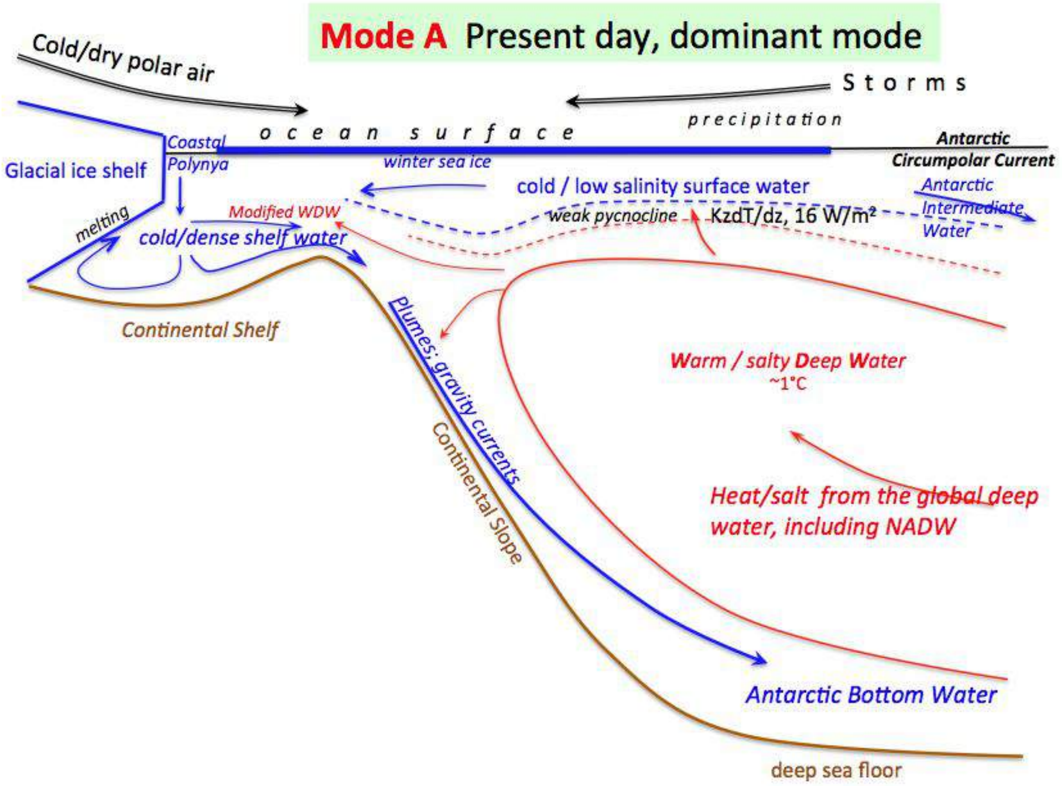
First 20th century decade polynya: Did the Deutschland expedition into the Weddell Sea region of 1912 (Brennecke, 1921) record deep-reaching convection, as Wüst (1928) interpreted the Deutschland data? But with the Discovery data 1930s (+SAM) the view shifted to continental margin processes as the origin of AABW. [assumption of steady state can be misleading.

See: Gordon, A.L. (2012) "Circumpolar View of the Southern Ocean from 1962 to 1992" Oceanography, vol 24(3) 18-23

In a +SAM the SSS within the seasonal sea ice zone is decreased by excess P-E, leading to a more stable surface layer; In a - SAM the surface layer gets saltier, making the sea ice zone more susceptible to vertical exchange processes [maybe a Polynya?]

There are 2 modes of Southern Ocean Ventilation. Under the changing wind conditions over the southern ocean, the Great Weddell Polynya, as last observed in the mid-1970s, will become a 'thing of the past'. It was likely the primary way that the southern ocean ventilated the deep ocean during the glacial ages



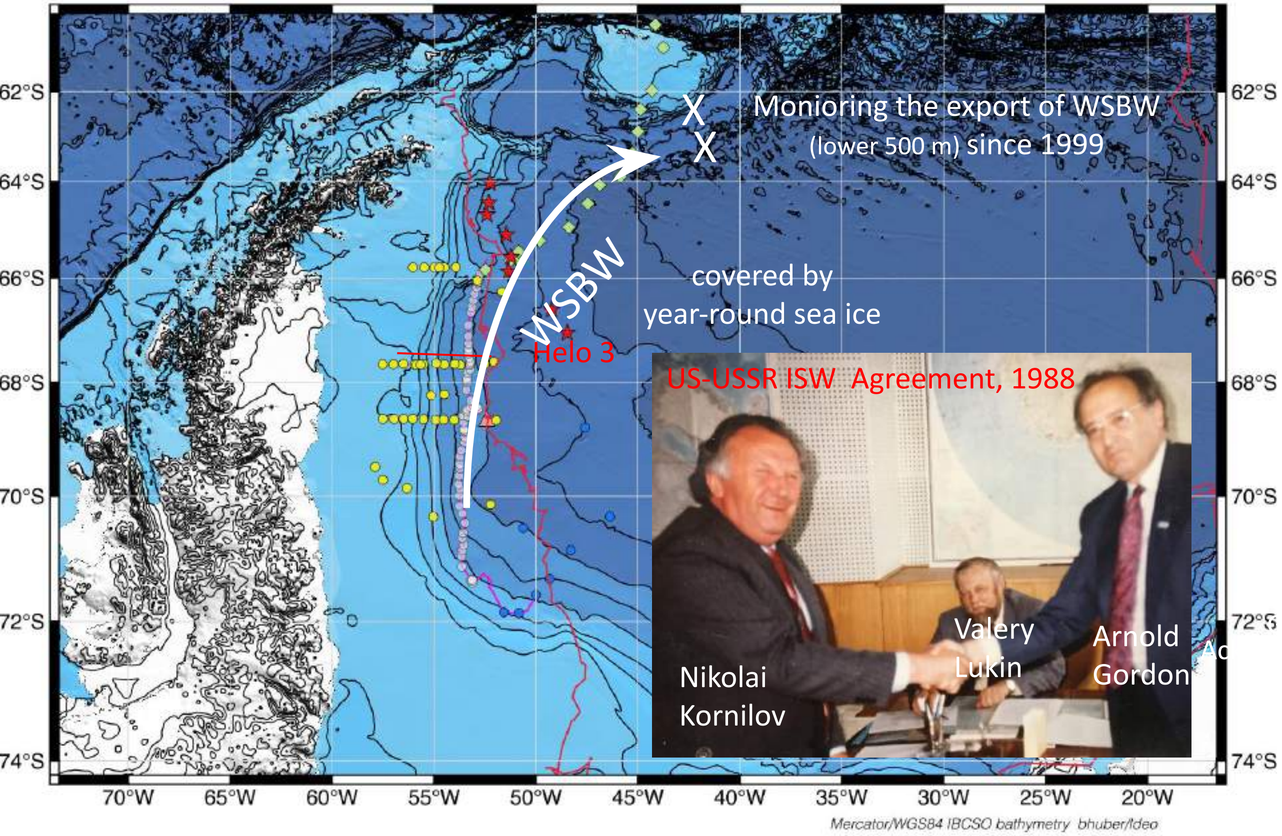


Might Mode B be the standard during the glacial times? Open ocean convection may be a way to store more excess CO_2 in the deep ocean

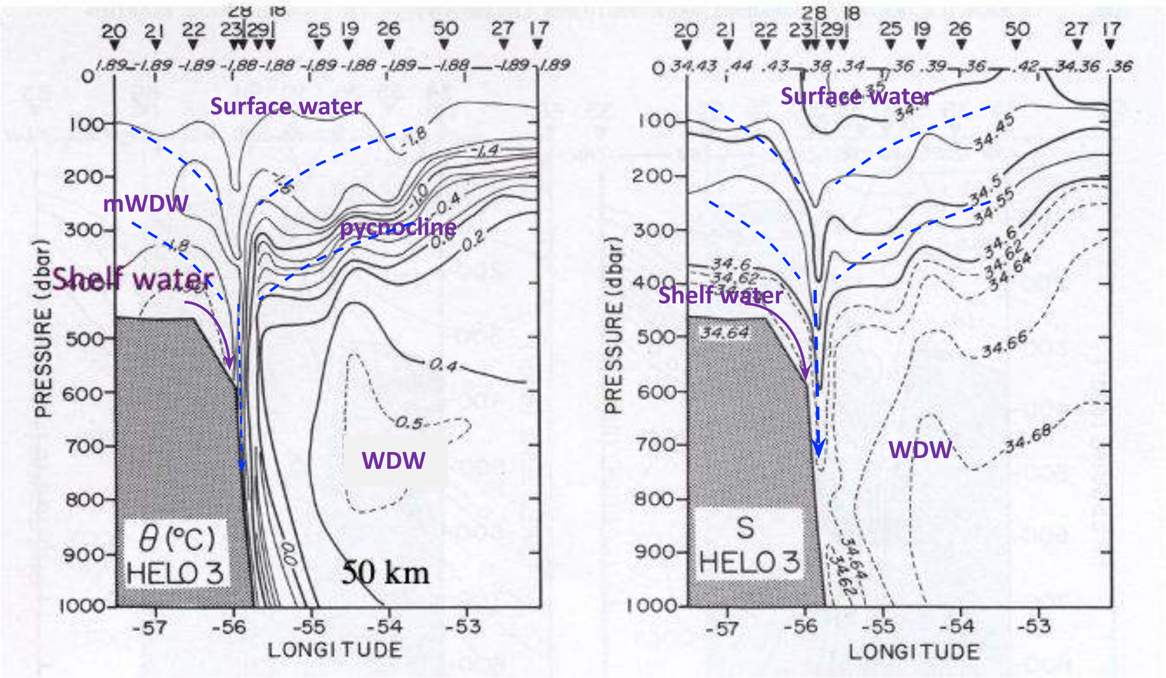
Gordon, A.L., (2014) "Oceanography: Southern Ocean polynya", News and Views for *Nature Climate Change*, vol (4), 249 – 250; doi:10.1038/nclimate2179

Another critical role of salinity in the Southern Ocean bottom water production

Western rim of the Weddell Sea: US-Russia 1992 Ice Station Weddell
(Gordon et al 1993, Science; Gordon, 1998)



ISW Helo 3 @ 67°40'S



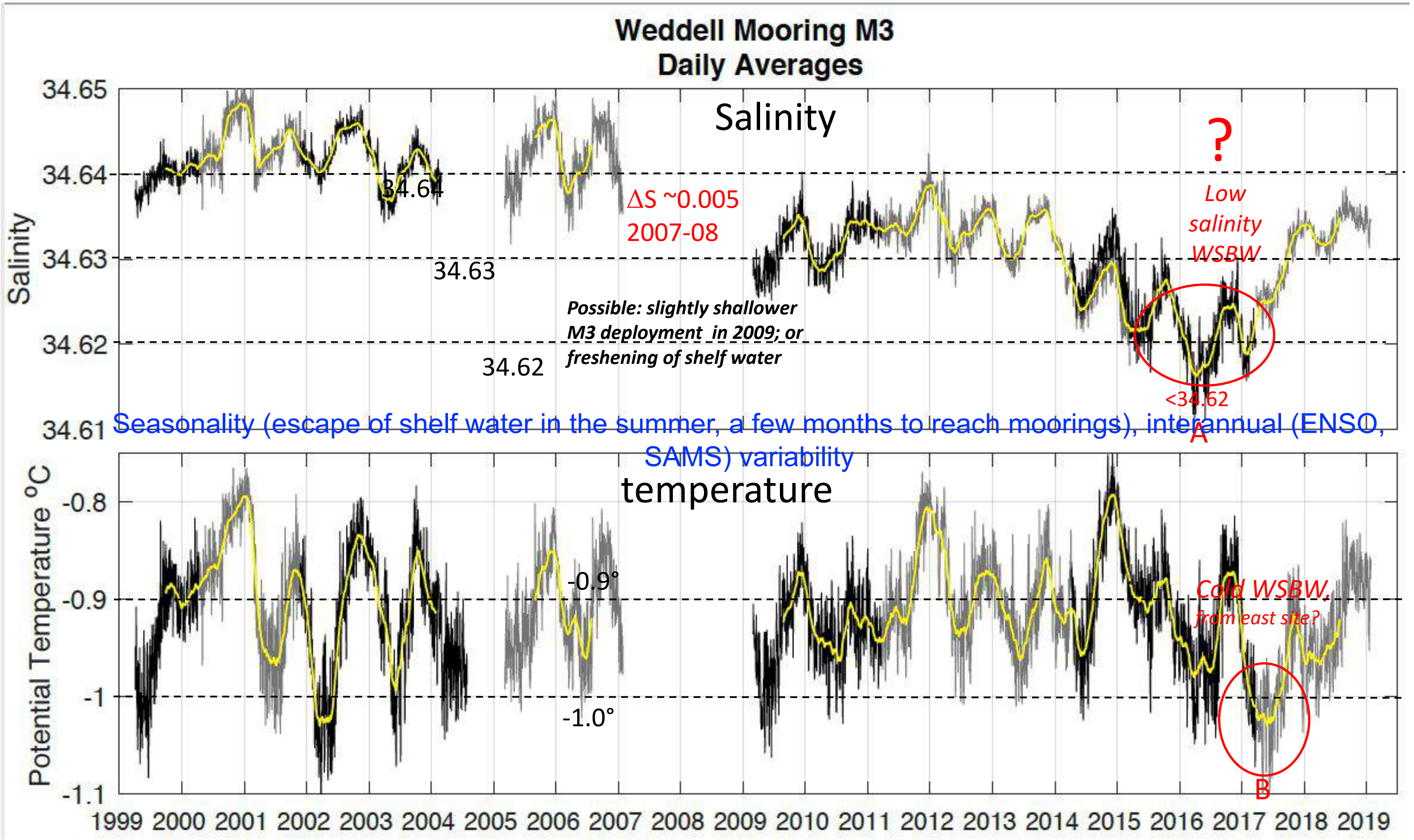
- Convergence of varied water types form shelf/slope fronts,
- Low salinity V-Shaped Trough filled with surface water

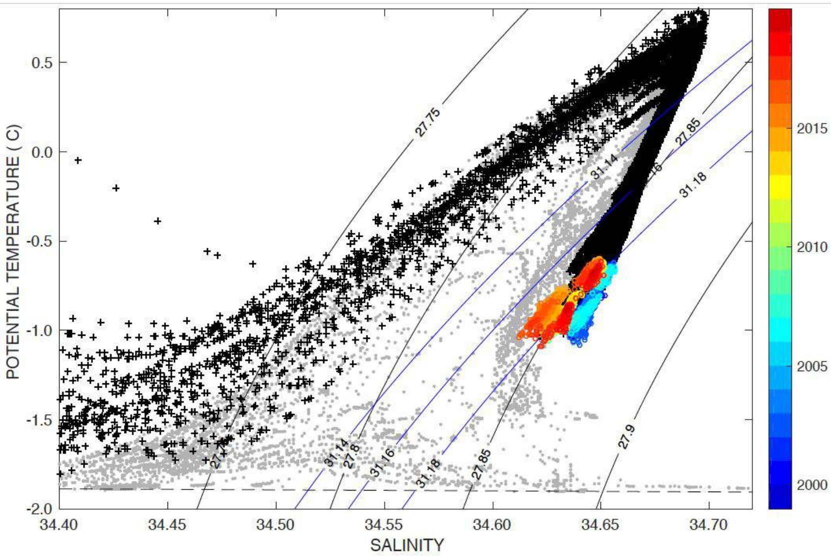
The time series grows, to 2019 ***(next data recovery 2023)***

The 'cold' Weddell Sea Bottom Water (WSBW) Export

WSBW timeseries

T/S (& velocity not shown here)





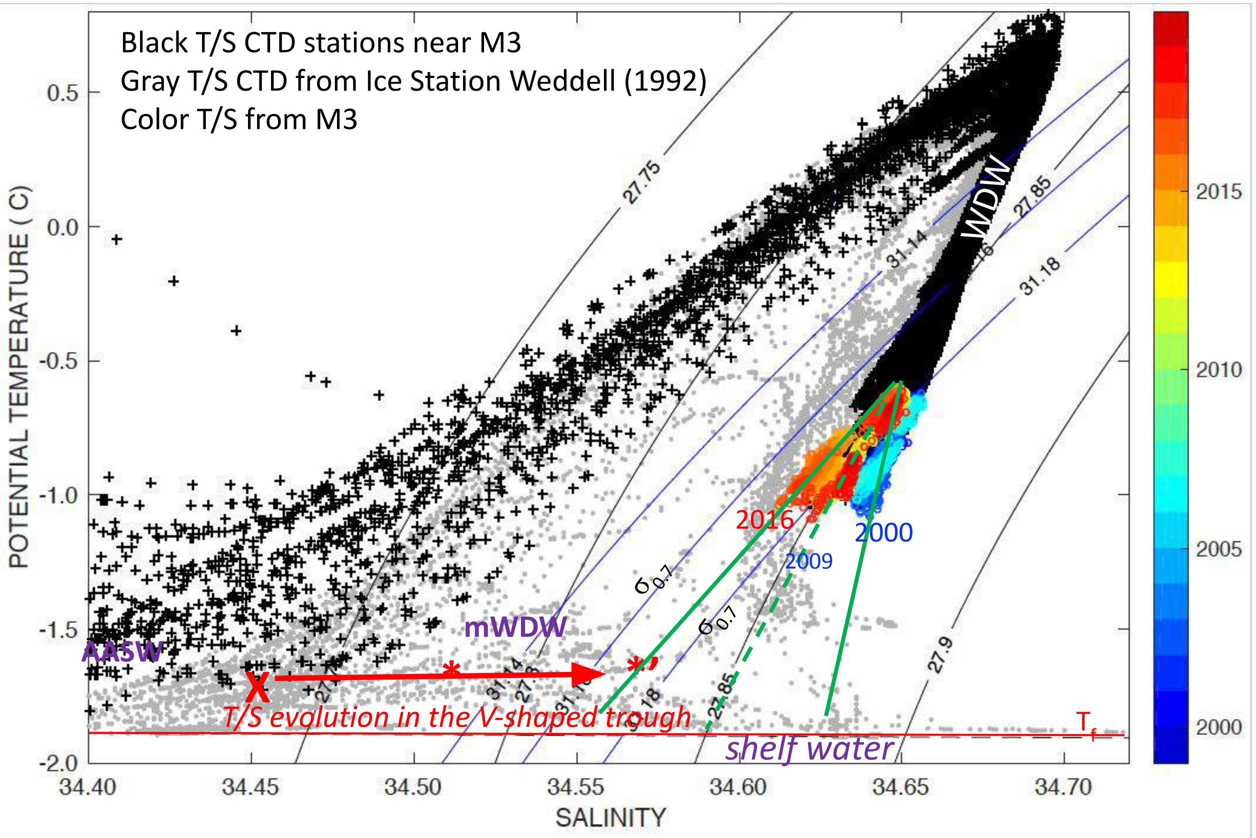
Shifts in salinity of cold end-member

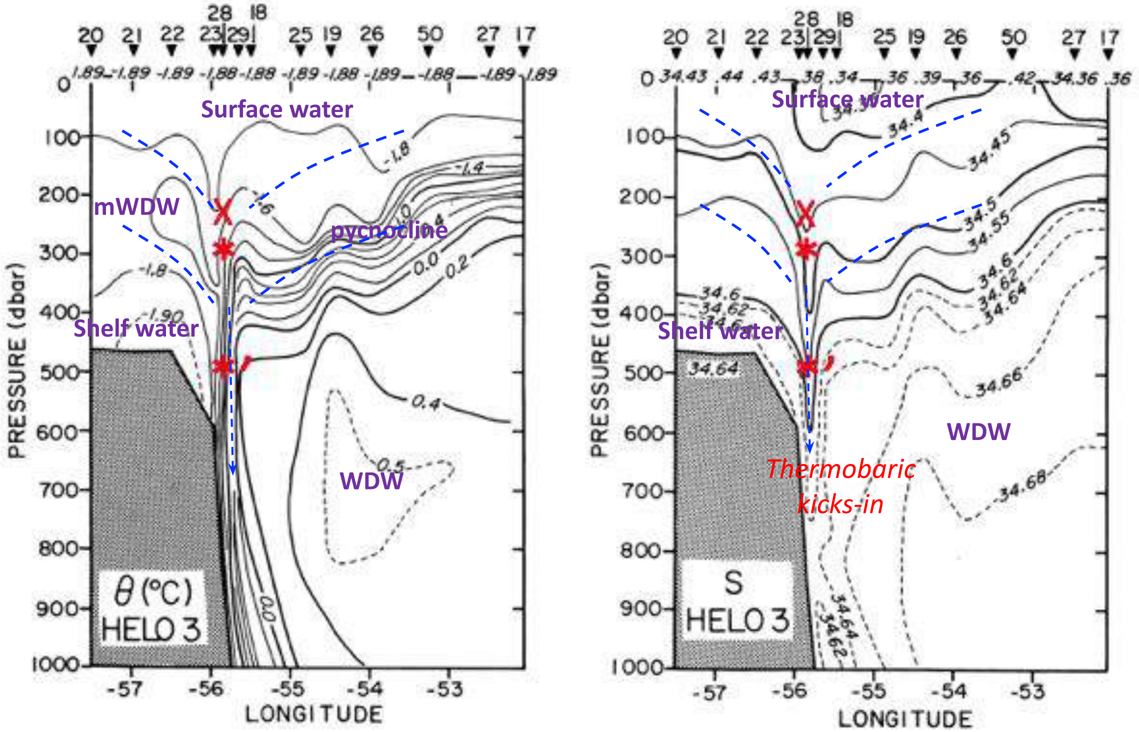
Low salinity Weddell Sea Bottom Water: ~2016, lowest in March/April 2016: ~4 months after maximum cyclonic wind stress over the Weddell Gyre *(see later slide)*

§ Gordon, A.L., Huber, B.A., McKee, D., Visbeck, M.H. (2010) "A seasonal cycle in the export of bottom water from the Weddell Sea" Nature Geoscience: doi:10.1038/ngeo916 vol(3): 551 – 556.

§ McKee, D., Yuan, X., Gordon, A.L., Huber, B.A., Dong, Z. (2011) "Climate Impact on Interannual Variability of Weddell Sea Bottom Water." Journal of Geophysical Research Ocean: doi: 10.1029/2010JC006484 vol(116) C05020

§ Gordon, A. L., Huber, B. A., & Abrahamsen, E. P. (2020). Interannual variability of the outflow of Weddell Sea Bottom Water. *Geophysical Research Letters*, 47, e2020GL087014. https://doi.org/10.1029/2020GL087014



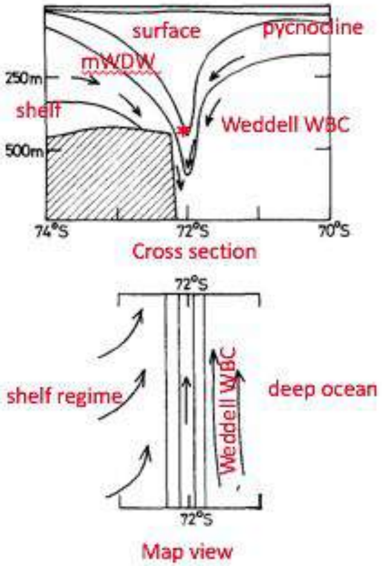


Ice Station Weddell Helo CTD across western boundary

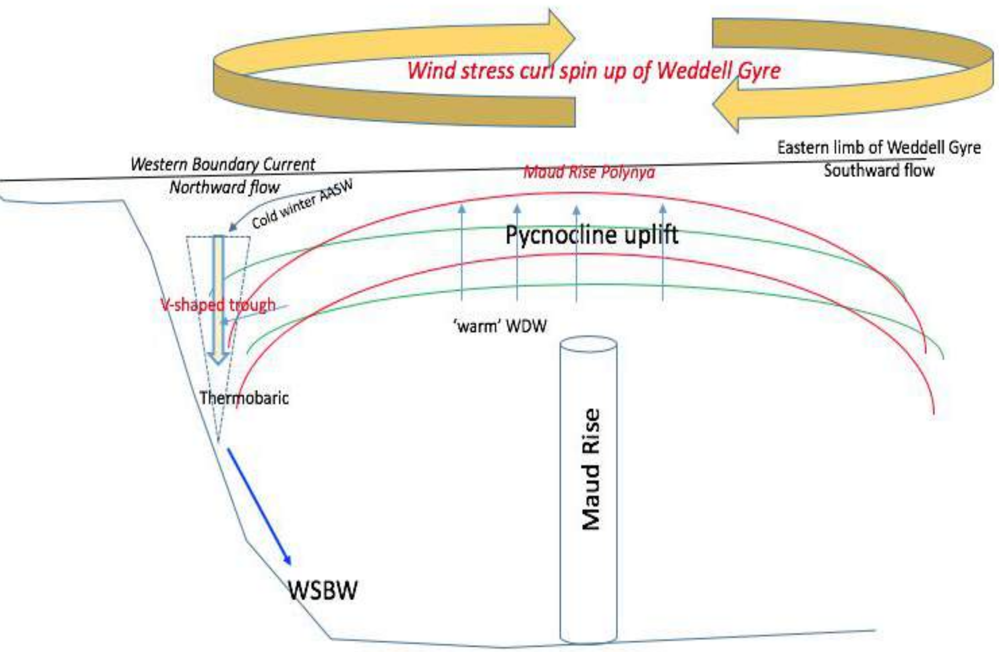
§ Might deepening of the apex of the V-shaped trough enable AASW and/or modified WDW *', to replace the freezing point, salty shelf water as the source of cold water feeding in the Weddell Sea Bottom Water (WSBW)?

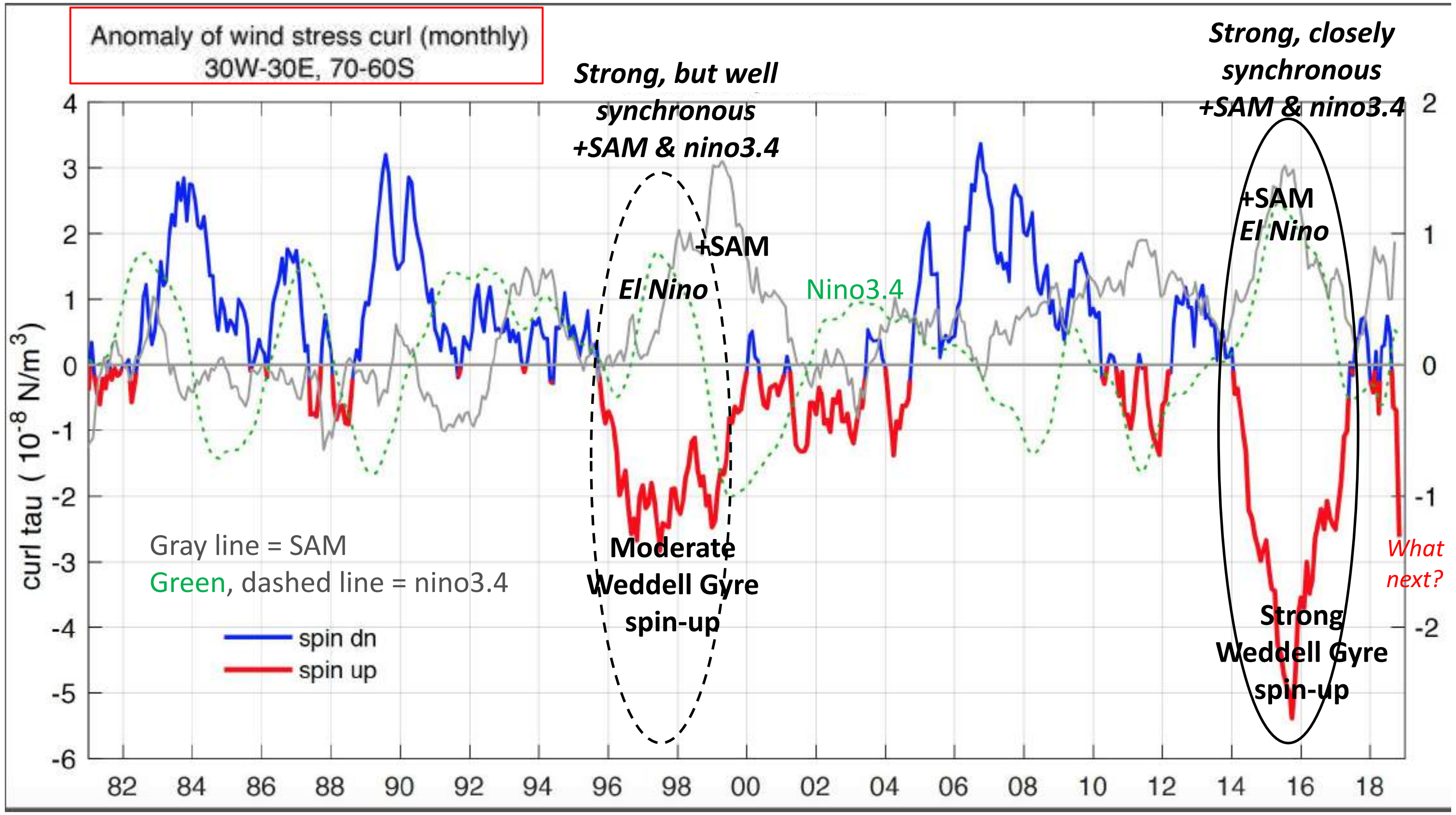
§ If the Apex deepens enough (~700 m) the <u>thermobaric</u> effect may enable the AASW, and/or mWDW, to descend to the sea floor to contribute to WSBW?

Gill 1973 *"At the edge of the shelf in the western Weddell Sea, there is a V-shaped double front, above which lies the cold fresh water from the coastal current. The descending cold salty water from the shelf meets the warmer fresher water of the open-ocean pycnocline at the base of the V and the two waters mix to form bottom water which then runs down the continental slope."*

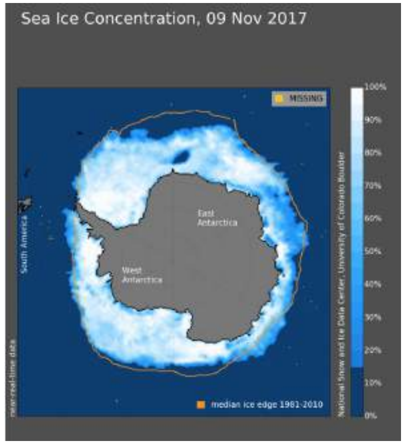


Gill 1973, fig 7 *[red words added]*



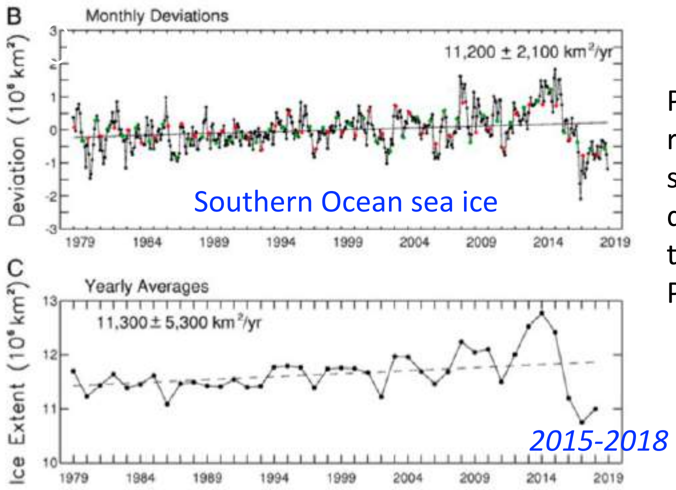


Gordon, A. L., Huber, B. A., & Abrahamsen, E. P. (2020). Interannual variability of the outflow of Weddell Sea Bottom Water. *Geophysical Research Letters*, 47, e2020GL087014. https://doi.org/10.1029/2020GL087014

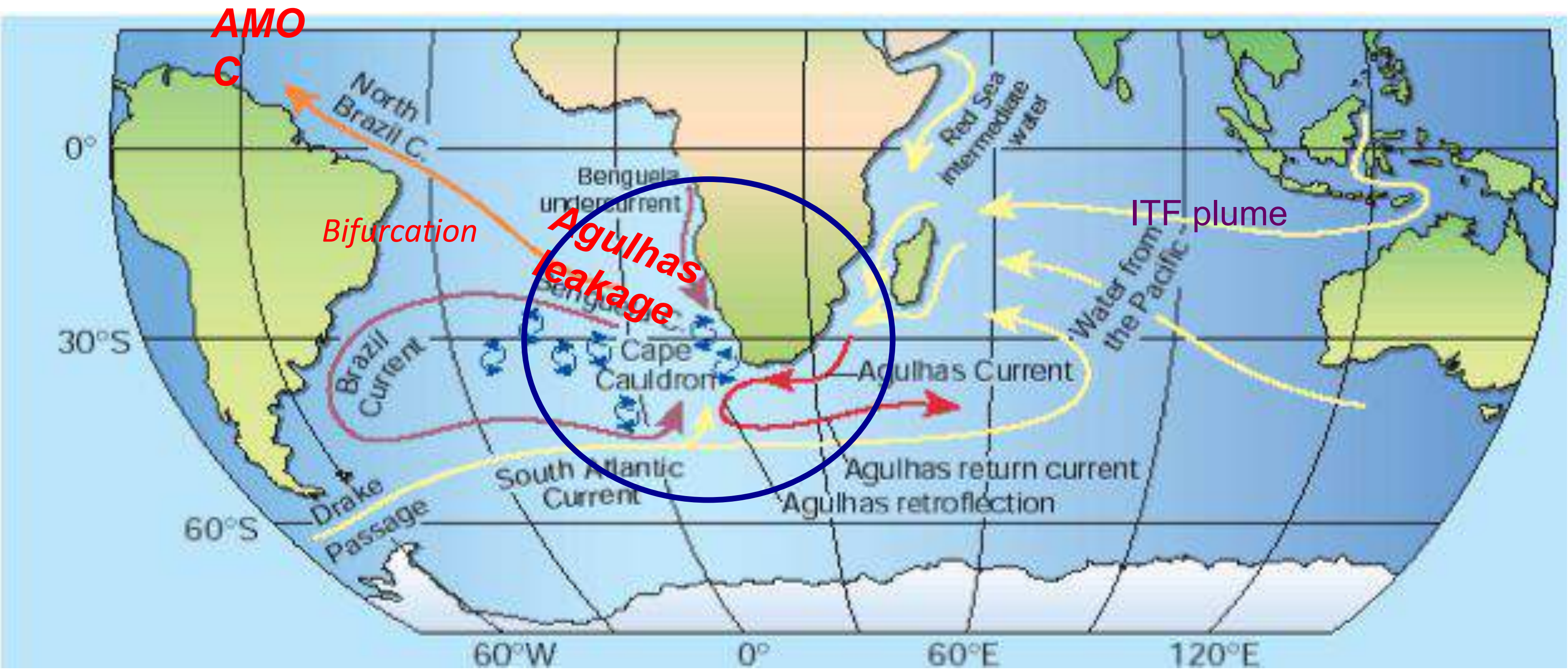


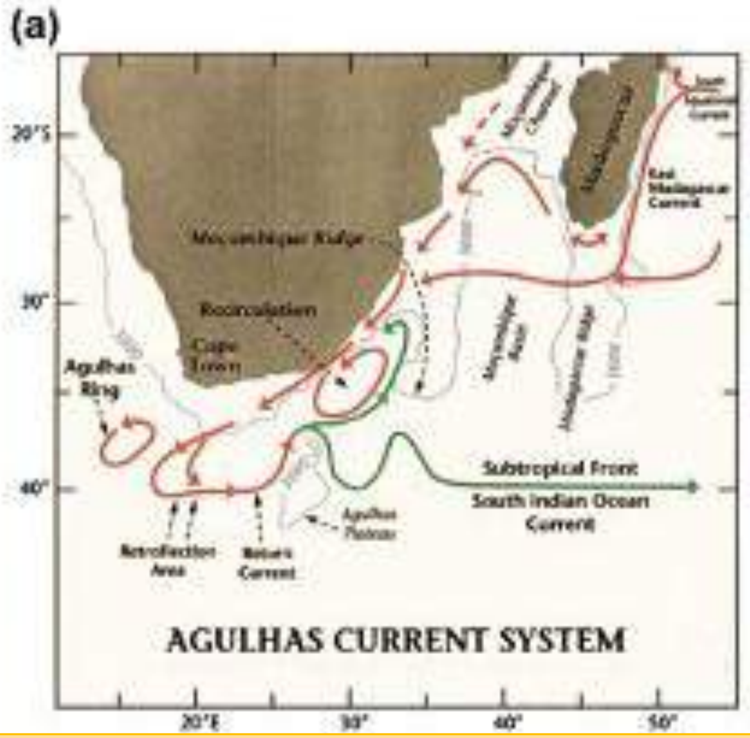
Weddell Gyre spin-up may explain:

- **change in WSBW T/S.**
- **The Maud Rise Polynya;**
- **decreased Antarctic sea ice cover in 2015/18.**



Parkinson, C. 2019 A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic . PNAS 116(26)





to warmer water ***2. Agulhas Leakage The Aguhas is leaking Indian Ocean water into the Atlantic!***

Agulhas Leakage makes for a saltier Benguela Current, than if the S. Atlantic subtropical gyre were closed by the cooler, fresher South Atlantic Current. This [along with the export of North Atlantic subtropical derived water vapor across Central America] **conspire to make for a salty Atlantic, conditioning it for deep ocean overturning, the AMOC**

Agulhas leakage maybe closely linked to the AMOC decadal to glacial;/interglacial scales variability.

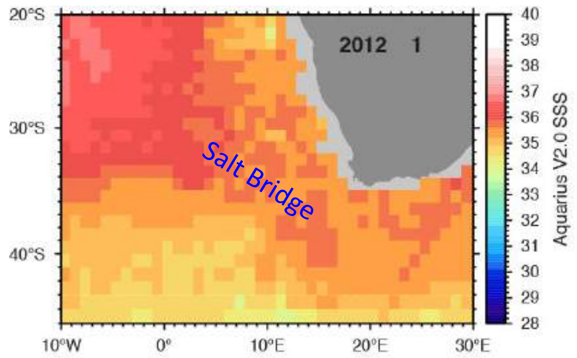
The subpolar North Atlantic will receive more freshwater from Greenland glacial melt and increased precipitation, attenuating AMOC. However, might this be offset by increased Agulhas leakage that injects Indian Ocean into the South Atlantic, which decades later spreads into the North Atlantic?

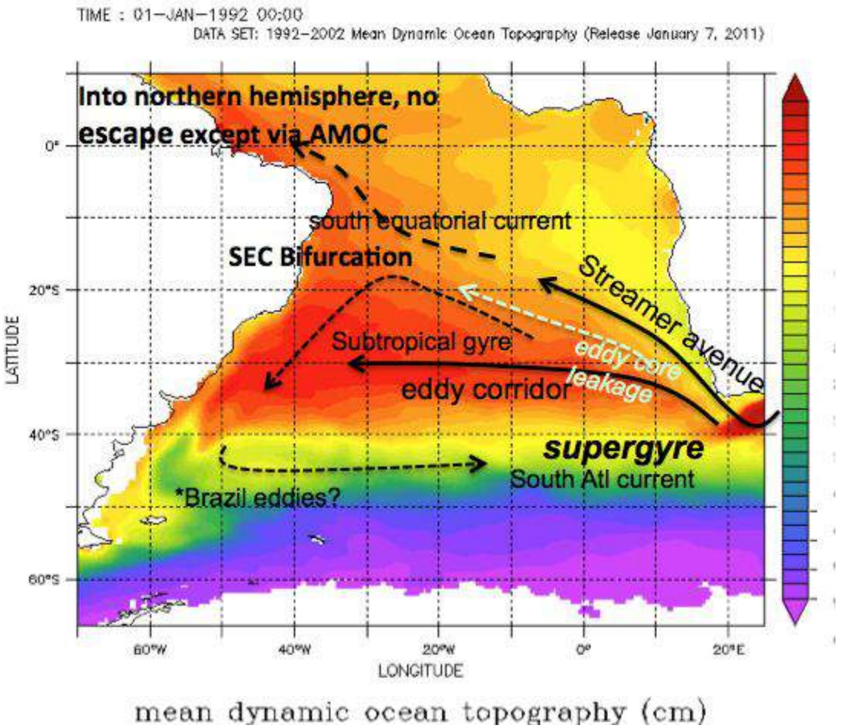
Transport weighted temperature/salinity for a 10 Sv Agulhas leakage profile, 0-1000 m:

100% Agulhas: 14.91°C; 35.22; 100% South Atlantic Current: 9.29°C, 34.64;

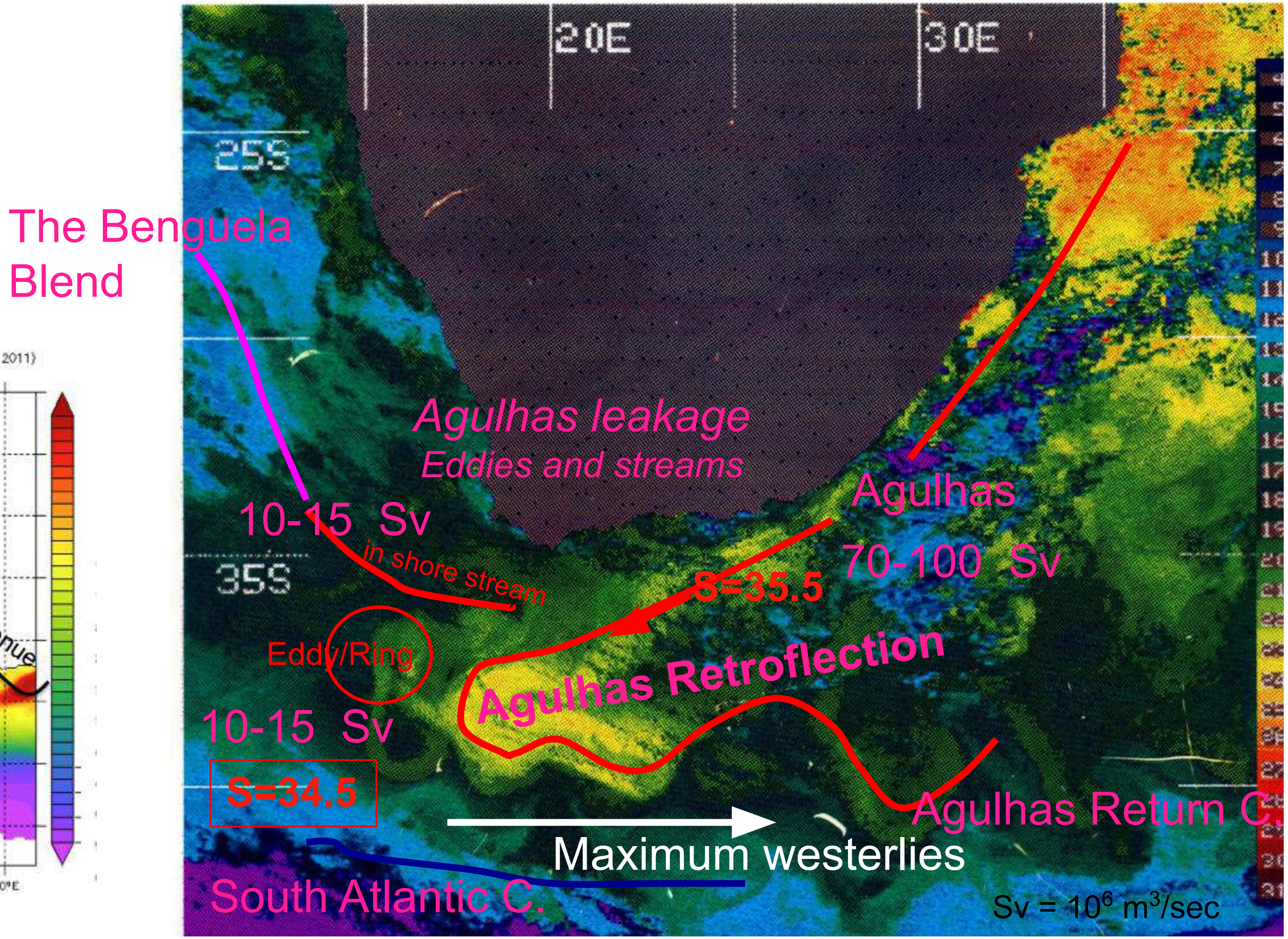
50:50 mix: 12.10°C, 34.93: $\Delta T/\Delta S$ boost of 3°/0.3 over no leakage

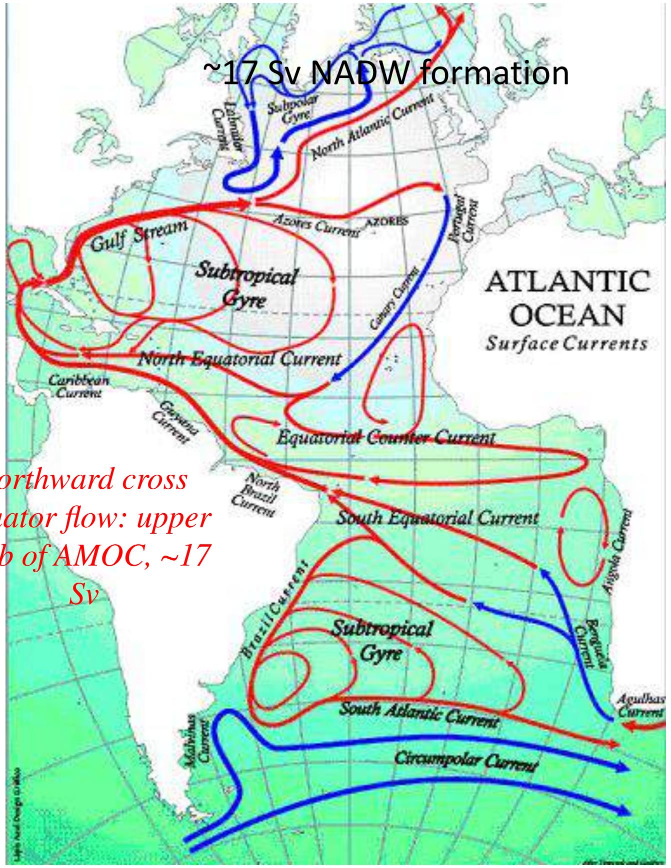
Lee et al (2011), What caused the significant increase in Atlantic Ocean heat content since the mid-20th century?, Geophys. Res. Lett., 38, L17607, doi:10.1029/2011GL048856.

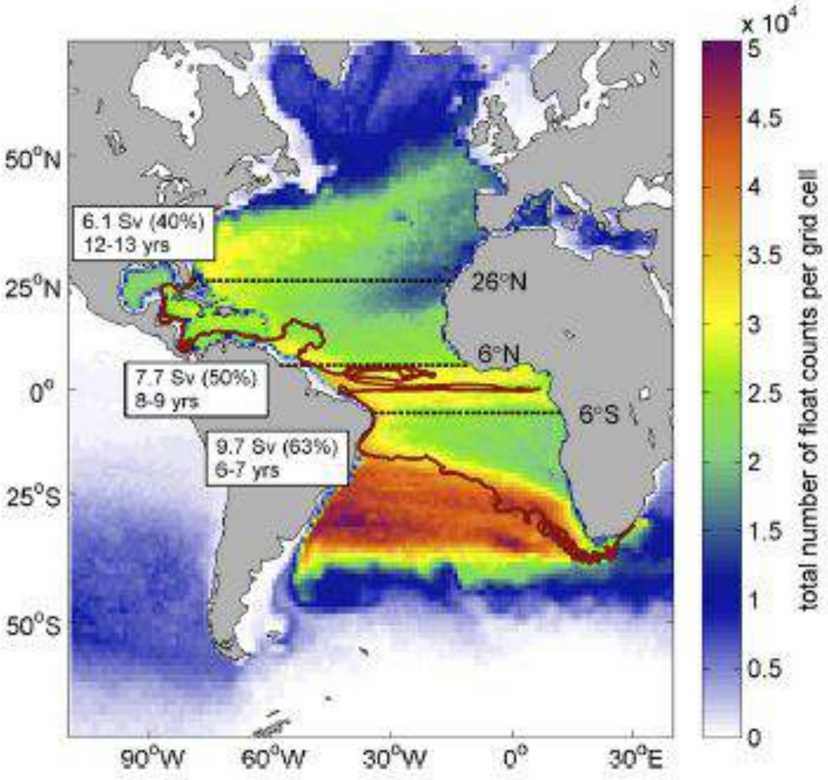




Latitudal shifts in Maximum westerlies can alter the leakage







Rühs, S., J. V. Durgadoo, E. Behrens, and A. Biastoch (2013), Advective timescales and pathways of Agulhas leakage, Geophys. Res. Lett., 40, doi:10.1002/grl.50782.

A considerable fraction of Agulhas leakage reached the subtropical North Atlantic: of a mean Agulhas leakage transport of 15.3 Sv entering the South Atlantic, 9.7, 7.7, and 6.1 Sv crossed sections at 6°S, 6°N, and 26°N, respectively. The most probable transit time of leakage to reach the respective latitudes is one to two decades. We suggest that changes in Agulhas leakage could manifest in the Gulf Stream regime most probably within two decades.

http://oceancurrents.rsmas.miami.edu/atlantic/

The Agulhas is injecting Indian Ocean water into the Atlantic!

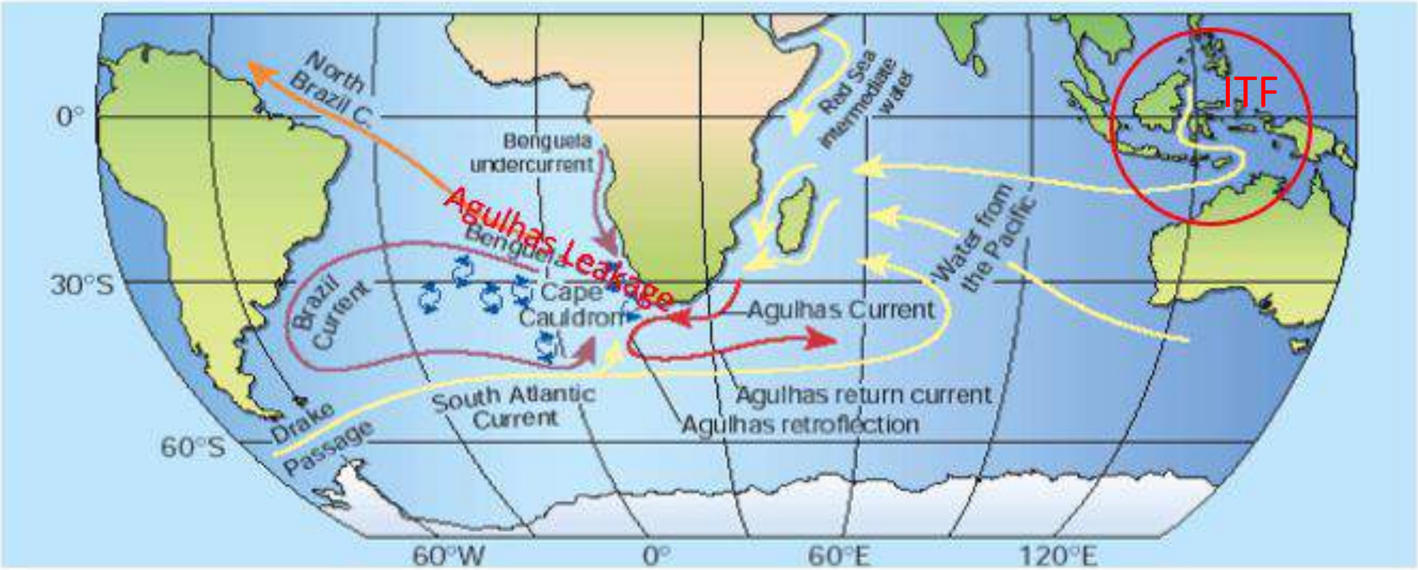
A major factor in making for a salty Atlantic, prone to formation of convection in the northern North Atlantic and establishment of the Atlantic Meridional Overturning Circulation [AMOC], a key global climate feature, which delivers lots of heat into the North Atlantic.

Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies, by A. Biastoch, C. W. Boning, F. U. Schwarzkopf, J. R. E. Lutjeharms [2009]

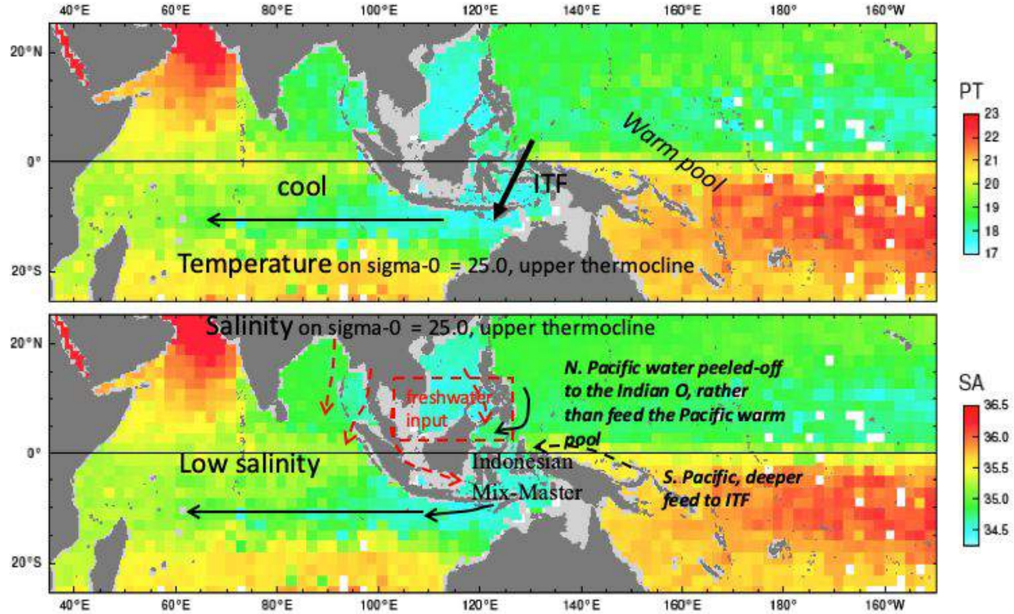
Might increased Agulhas salty leakage, offset freshening in the northern North Atlantic, to counter AMOC shutdown?

3. The ‘cool’ Indonesian Throughflow (ITF): warm tropical Pacific surface water is inhibited from entering the Indian Ocean by the maritime continent ‘freshwater plug’.

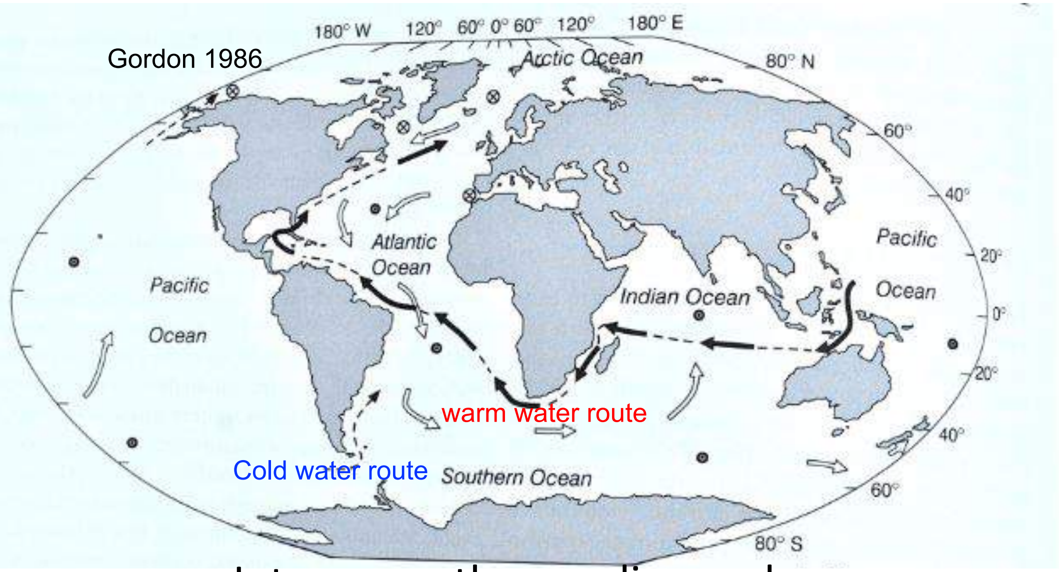
1983 Discovery of Agulhas leakage led me to the Indonesian Throughflow, which serve as the source- both ~15 Sv



A cool/ low salinity plume across the tropical Indian Ocean



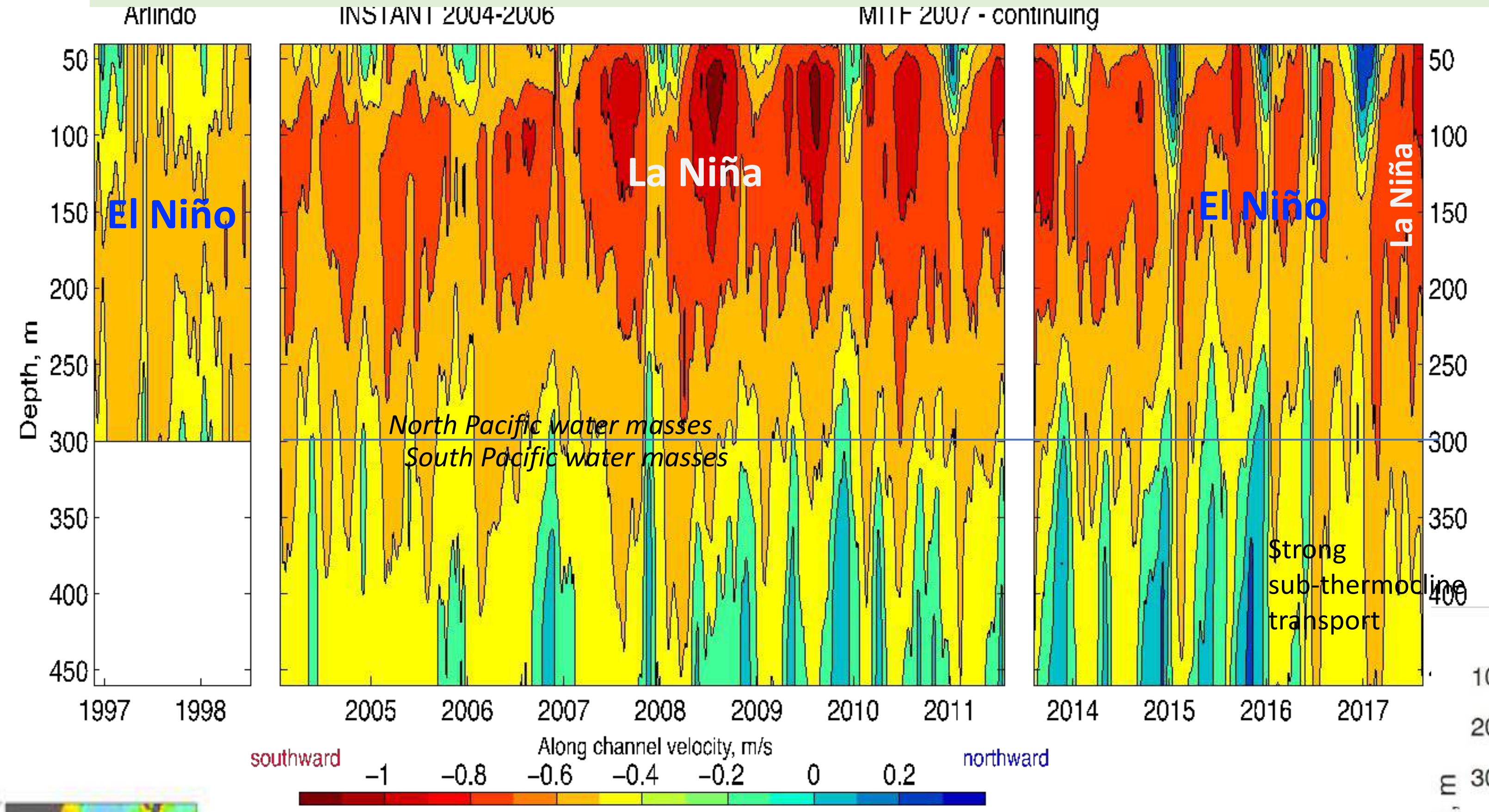
Gordon, A.L. (1986) Inter-Ocean Exchange of Thermocline Water. J. Geophys. Res., 91(C4): 5037-5046

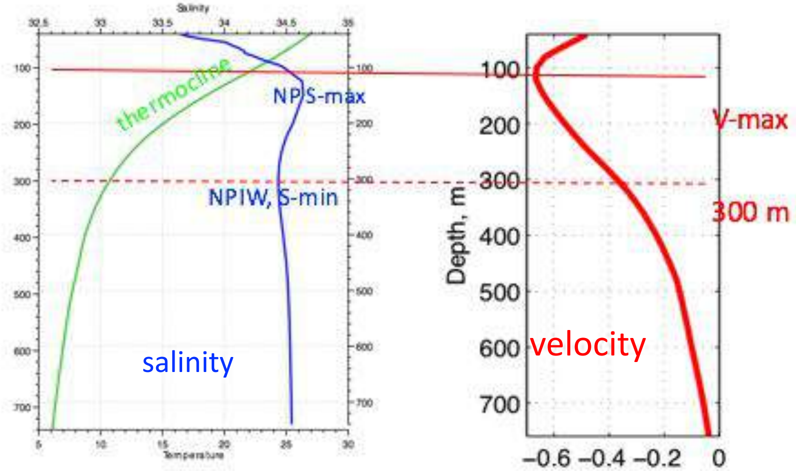


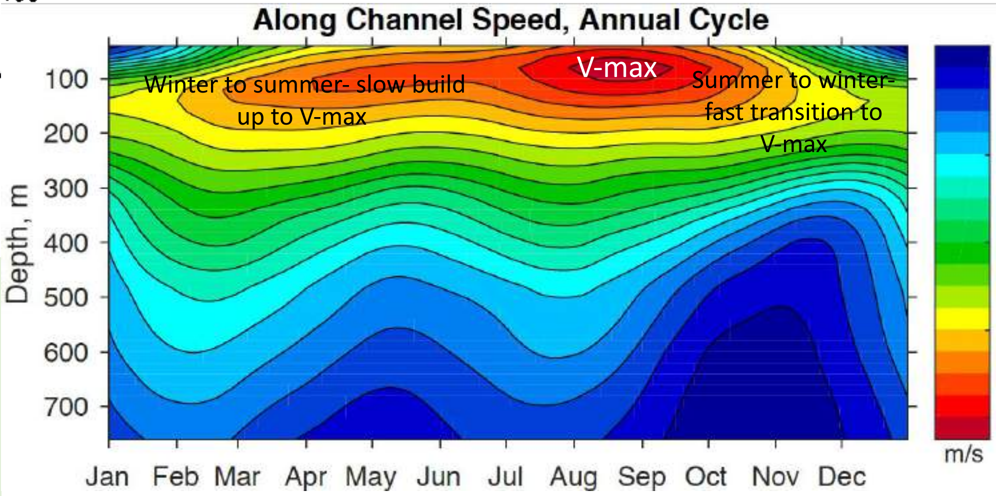
Interocean thermocline exchange

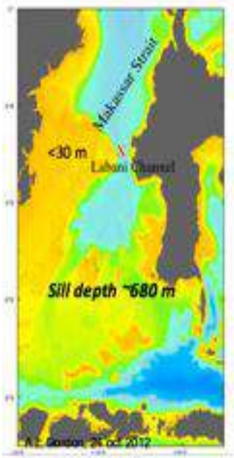
Gordon, A.L. (1985) Indian-Atlantic Transfer of Thermocline Water at Agulhas Retroflection. Science, 227(4690): 1030-1033.
Gordon, A.L. (1986) Inter-Ocean Exchange of Thermocline Water. J. Geophys. Res., 91(C4): 5037-5046.

We now have 13.3 years of Makassar throughflow: November 1996 - early July 1998; January 2004 - August 2011; August 2013 - August 2017





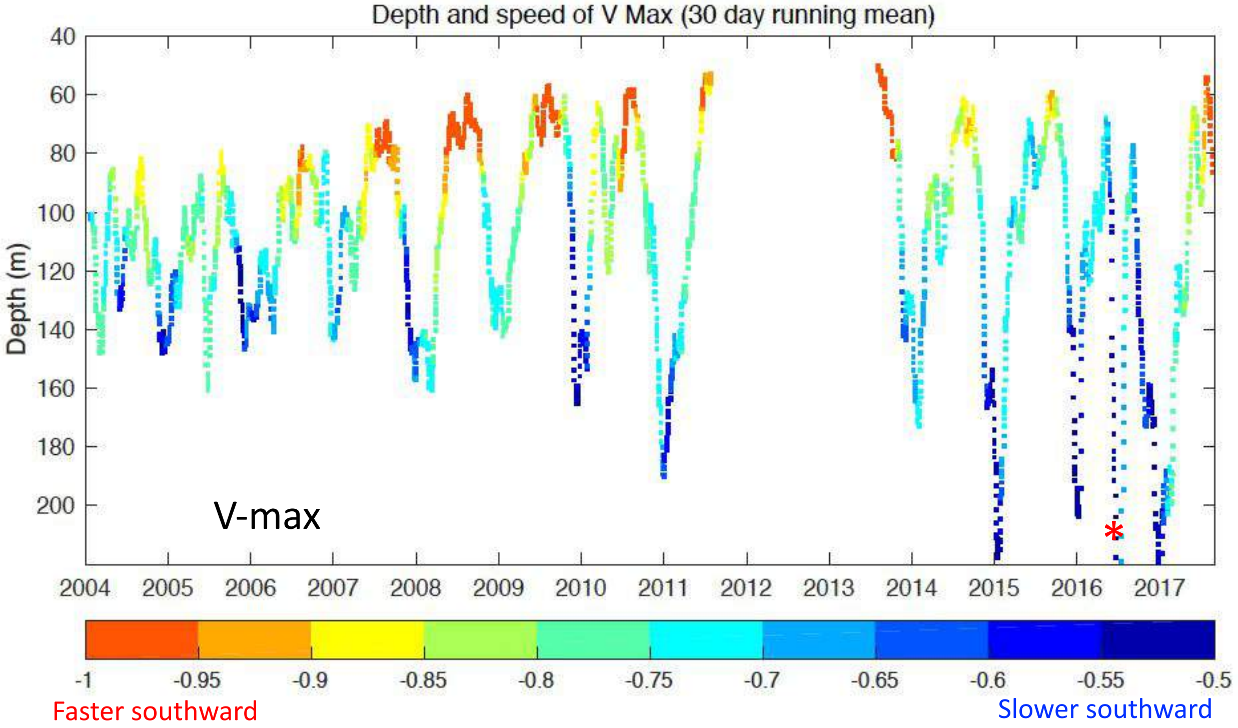


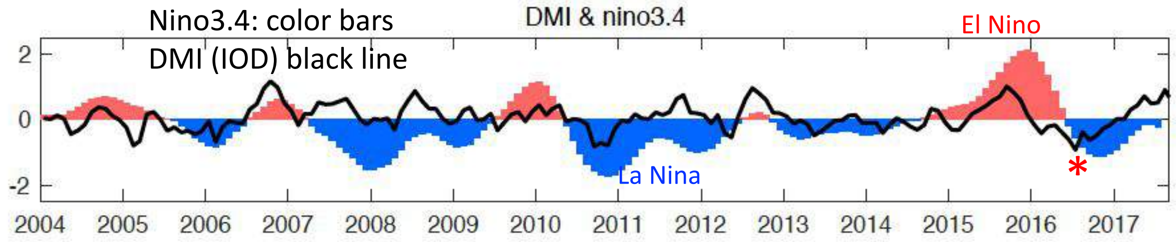


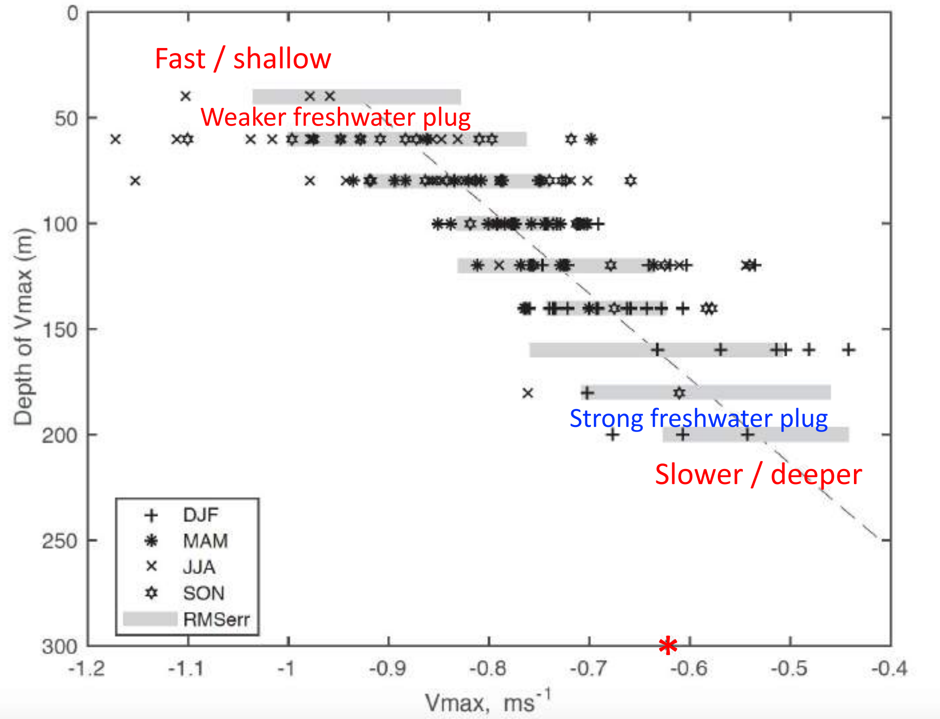
The Makassar Strait throughflow ~12 Sv, representing ~80% of the total ITF, displays fluctuations over a broad range of time scales, from intraseasonal; to seasonal and interannual, reflecting the ITF connectivity to the larger scale ocean and climate systems.

Strong southward transport during boreal summer, modulated by ENSO interannual signal: weaker southward surface layer flow, mainly in winter; a deeper subsurface velocity maximum (V-max) weaker/deeper during El Niño; stronger/shallower during La Niña: modulates ITF heat flux into the Indian Ocean.

Gordon et al, 2019, JGR







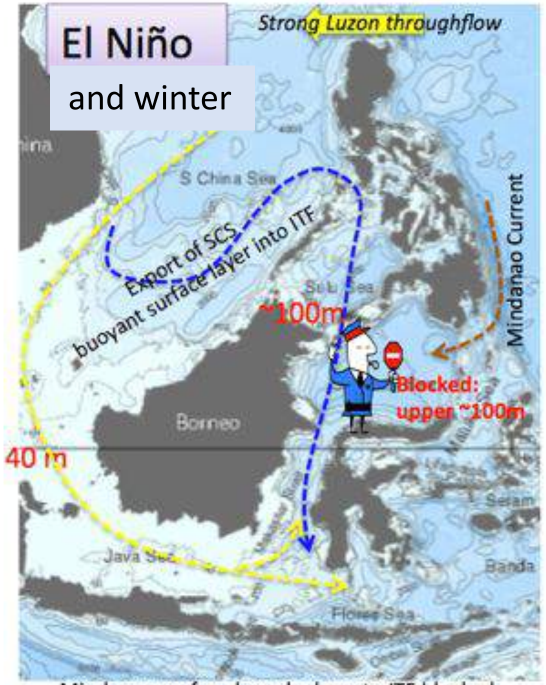
**** the strange summer 2016 relaxation of the throughflow; happened during strong negative IOD (coastal kelvin water issue), see:*** Pujiana, Kandaga,et al (2019) Unprecedented response of Indonesian throughflow to anomalous Indo-Pacific climatic forcing in 2016. JGR *Oceans: 124*, 3737–3754. https://doi.org/10.1029/2018JC014574.

Depth of the v-max, color coded for speed: shallower (warmer water) linked to stronger V-max. Scales to ENSO (NEC Bifurcation): faster/warmer in La Niña with more northern NEC bifurcation latitude

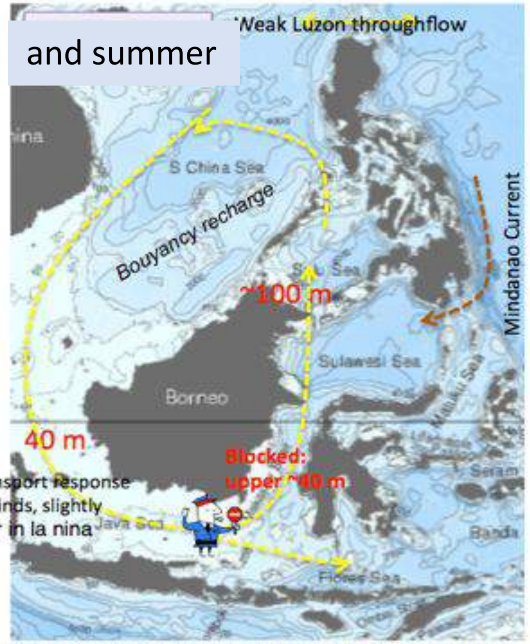
Gruenburg, L.K., and A.L. Gordon (2018) Variability in Makassar Strait heat flux and its effect on the eastern tropical Indian Ocean. *Oceanography* 31(2), https://doi.org/10.5670/oceanog.2018.220

Freshwater Plug

On to the Indian Ocean [and beyond]

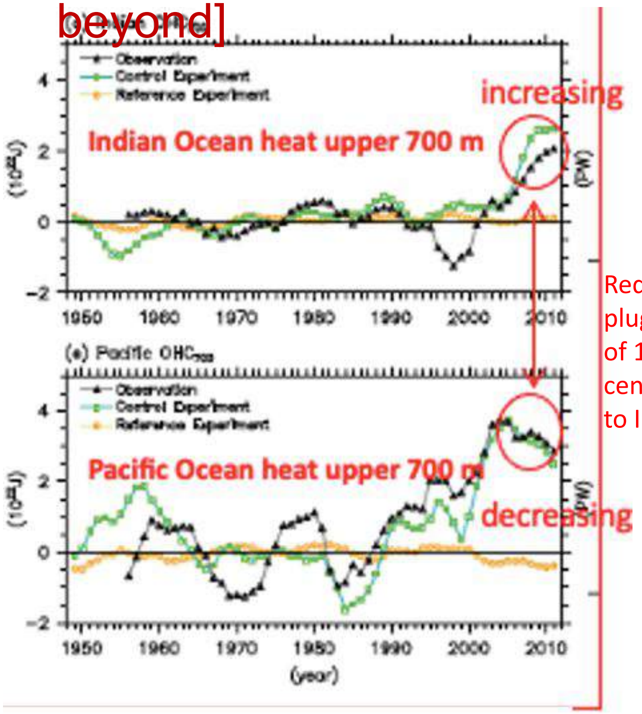


Mindanao surface layer leakage to ITF blocked upper ~100 m



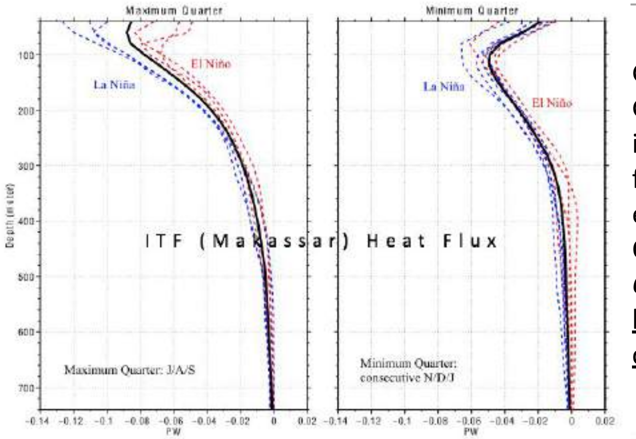
Karimata transport response to local winds, slightly stronger in la nina

Gordon, A.L., Huber, B.A., Metzger, E.J., Susanto, R.D., Hurlburt, H.E., Adi, T.R. (2012) South China Sea Throughflow Impact on the Indonesian Throughflow" Geophysical Research Letters: doi:10.1029/2012GL052021 vol (39) L11602

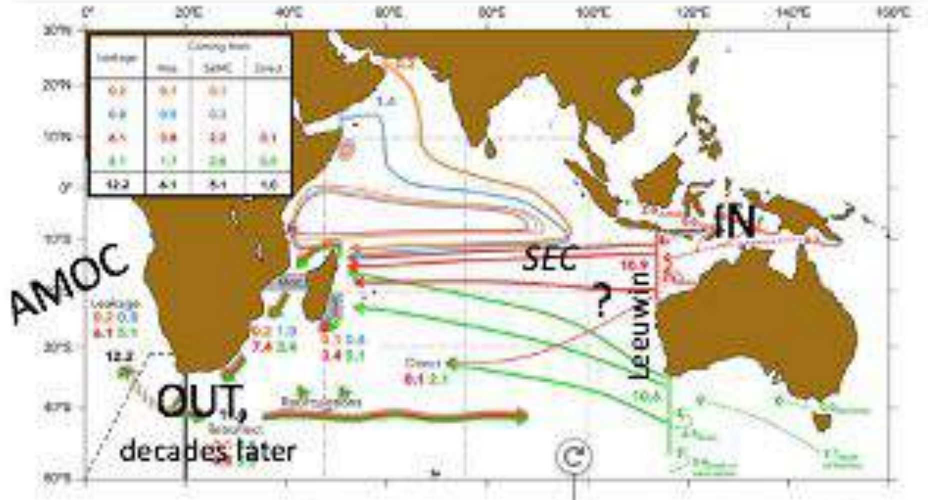


Reduced freshwater plug during La Nina, of 1st decade of 21st century: more pacific to Indian heat flux.

Lee, S.-K., W. Park, M. O. Baringer, A. L. Gordon, B. Huber, and Y. Liu (2015), Pacific origin of the abrupt increase in Indian Ocean heat content during the warming hiatus, *Nature Geosci*, 8(6), 445-449, doi:10.1038/ngeo2438



Gruenburg, L.K., and A.L. Gordon (2018) Variability in Makassar Strait heat flux and its effect on the eastern tropical Indian Ocean. *Oceanography* 31(2), https://doi.org/10.5670/oceanog.2018.220.



Durgadoo, J. V., S. Rühs, A. Biastoch, and C. W. B. Böning (2017), Indian Ocean sources of Agulhas leakage, J. Geophys. Res. Oceans, 122, doi:10.1002/2016JC012676

ENSO induced change of the South China Sea (SCS) throughflow: increased when westward Luzon Strait throughflow during El Niño forces buoyant SCS surface water into the Sulawesi Sea, inhibiting tropical Pacific surface water injection into the ITF; During La Niña, when the Luzon Strait transport is reduced, the SCS freshwater inventory is recharged.

Concluding message to the Salinity Conference:

Ocean salinity is important driver of the climate system, from polar to the tropics!