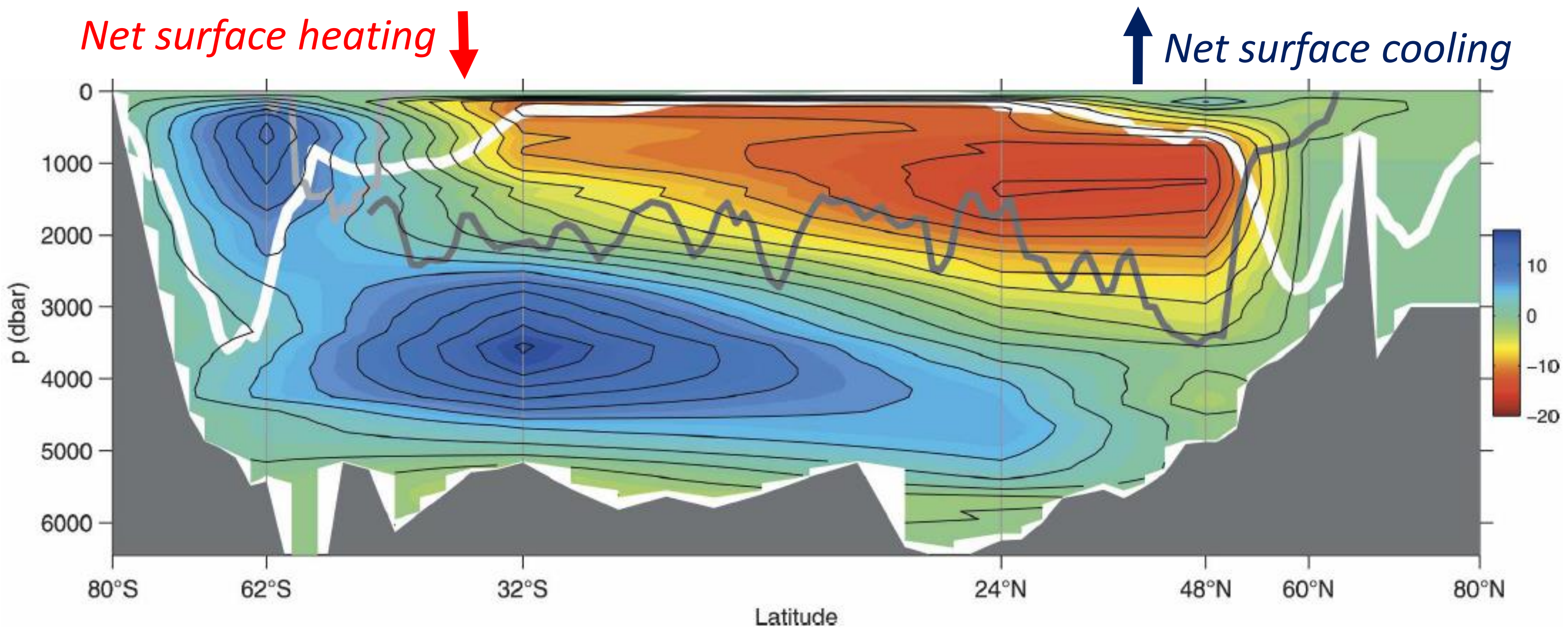
Decoupling of oceanic and atmospheric heat transports over the ACC?

Arnaud Czaja (Imperial College), Ute Hausmann (WHOI) & John Marshall (MIT)

Outline

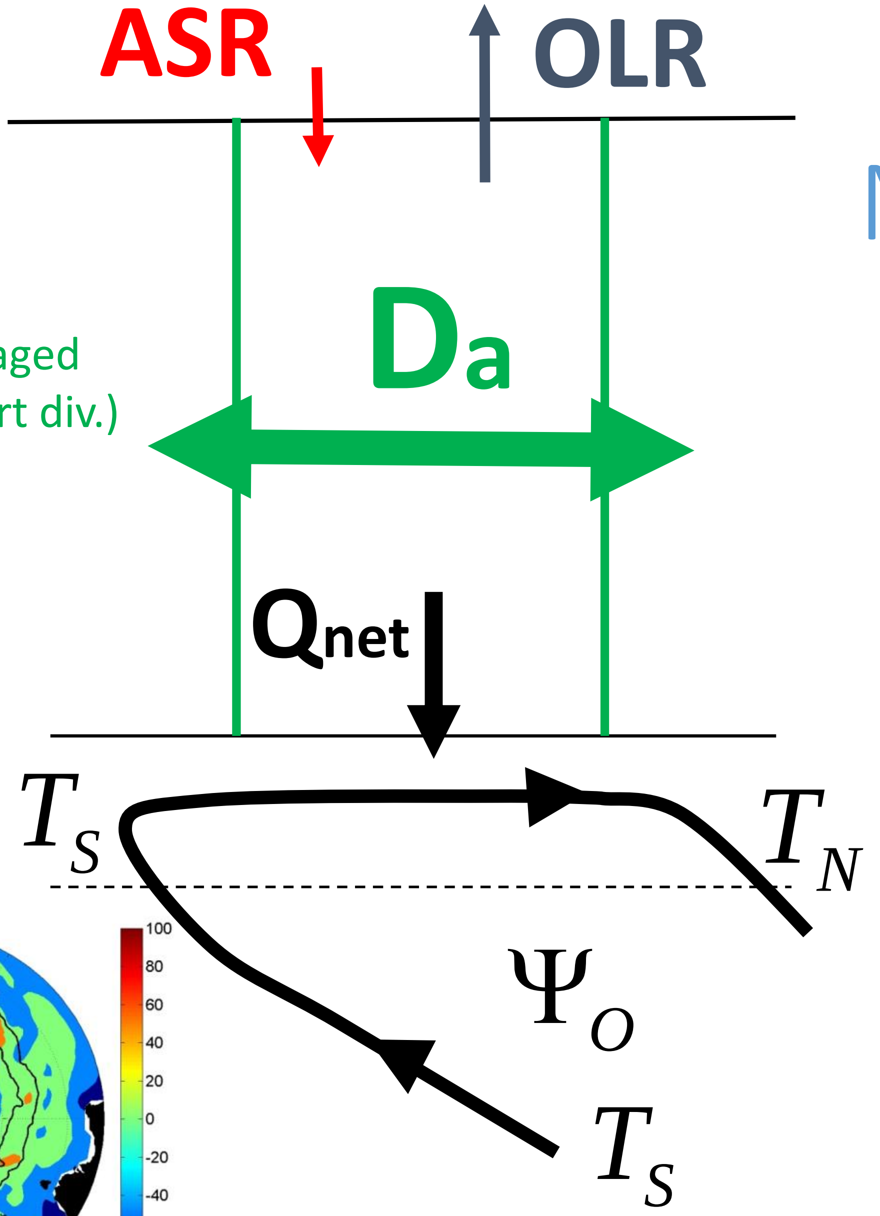
- A minimal model for heating/cooling of the upper thermohaline cell
- Feedback analysis
- Summary and implications for heat uptake by the Southern Ocean

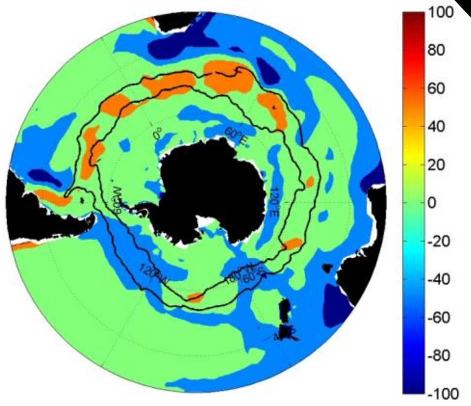


Global ocean overturning from Speer and Rintoul (2007)

A minimal model for heating/cooling of the upper thermohaline cell

Minimal model for surface *heating* of the upper cell





Czaja & Marshall (2015)

$$OLR_O = A + \gamma_{rad}(T_S + T_N)/2$$

$$Q_{net} = (ASR_O - OLR_O) - D_a$$

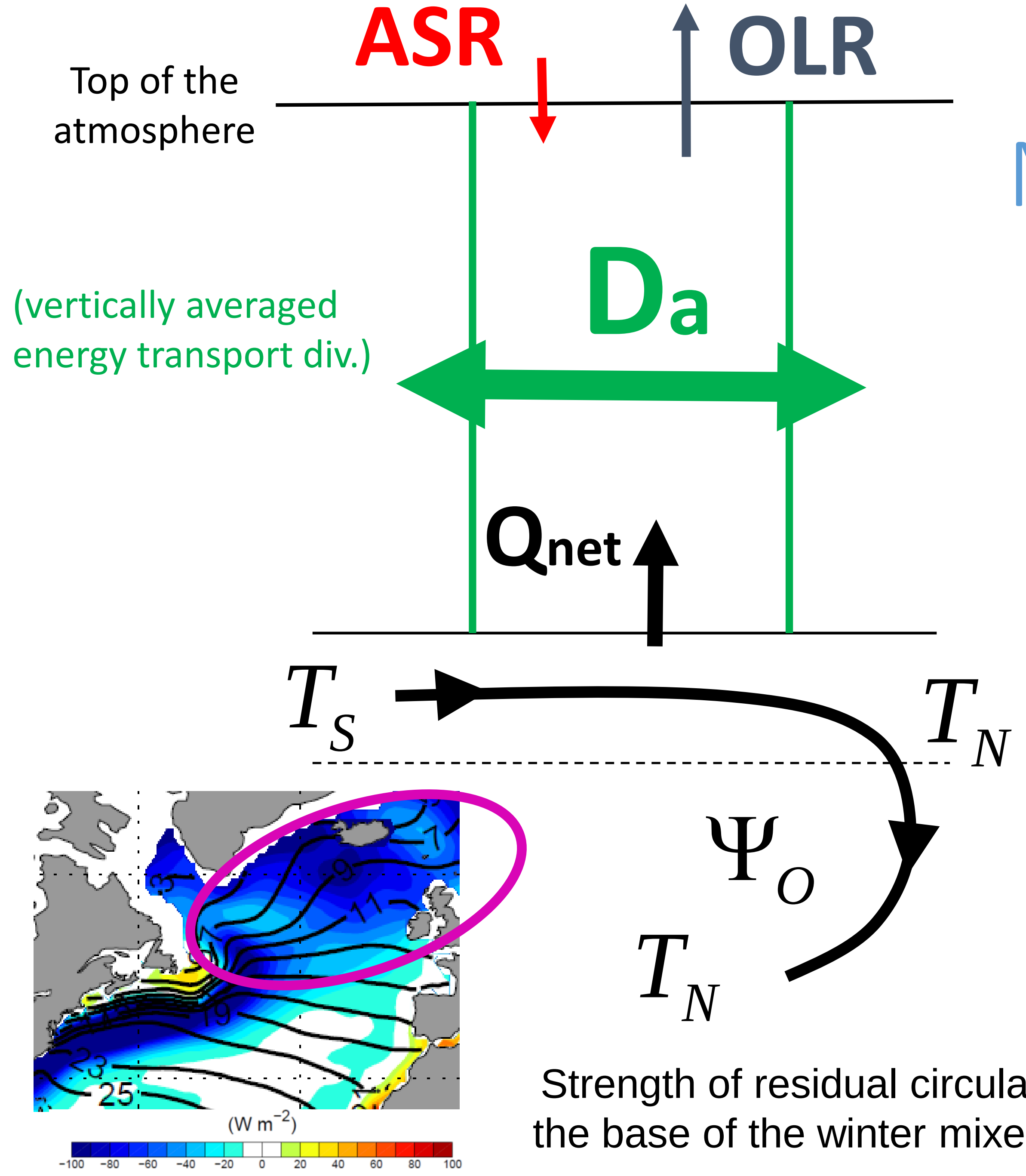
$$C_O \Psi_O (T_N - T_S) = A_O Q_{net}$$

Strength of residual circulation at the base of the winter mixed layer

Temperature of upwelled water

Surface area covered by the cell

Minimal model for surface *cooling* of the upper cell



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Strength of residual circulation at the base of the winter mixed layer

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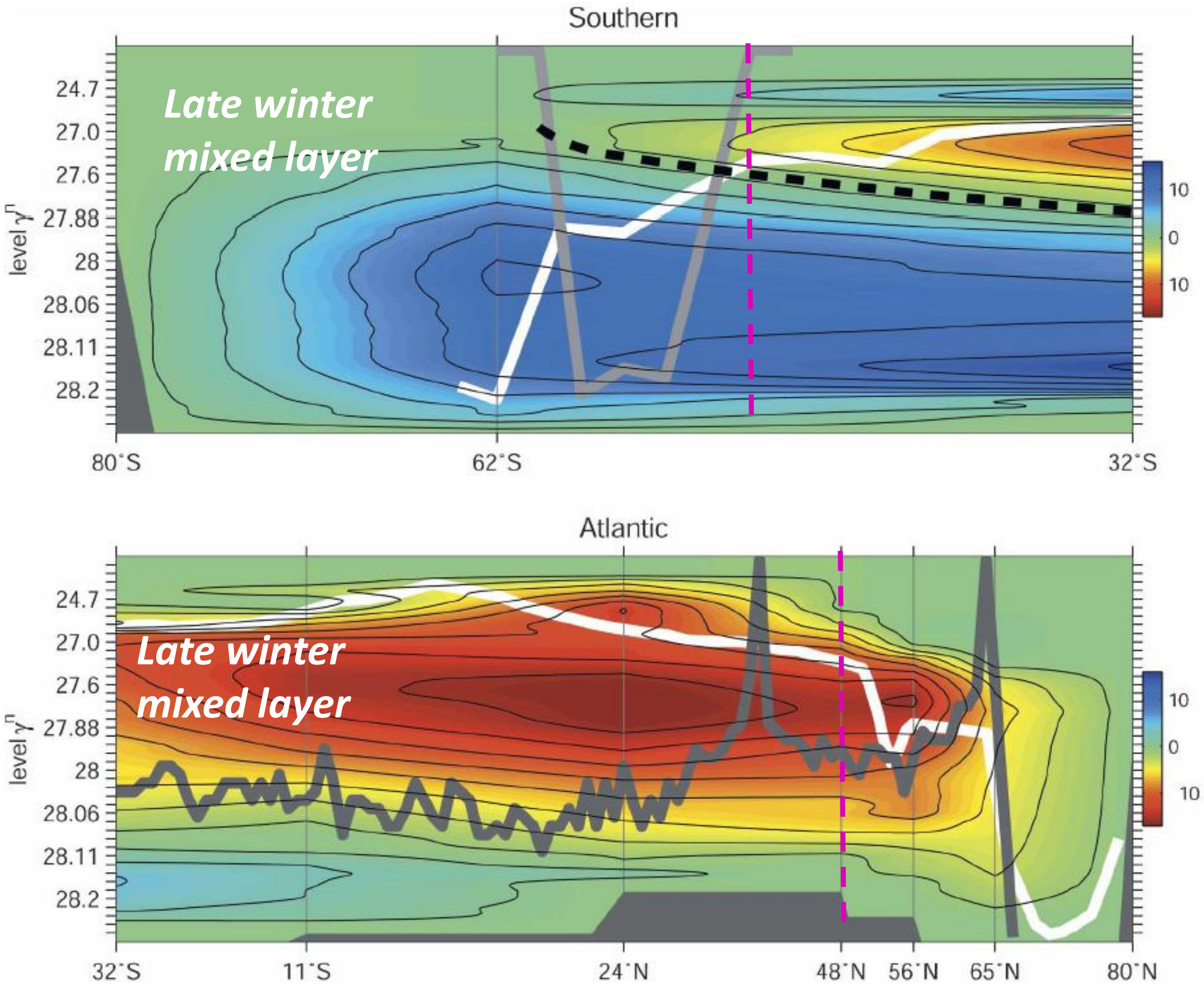
Surface area covered by the cell

Overturning circulations (Speer & Rintoul, 2007)

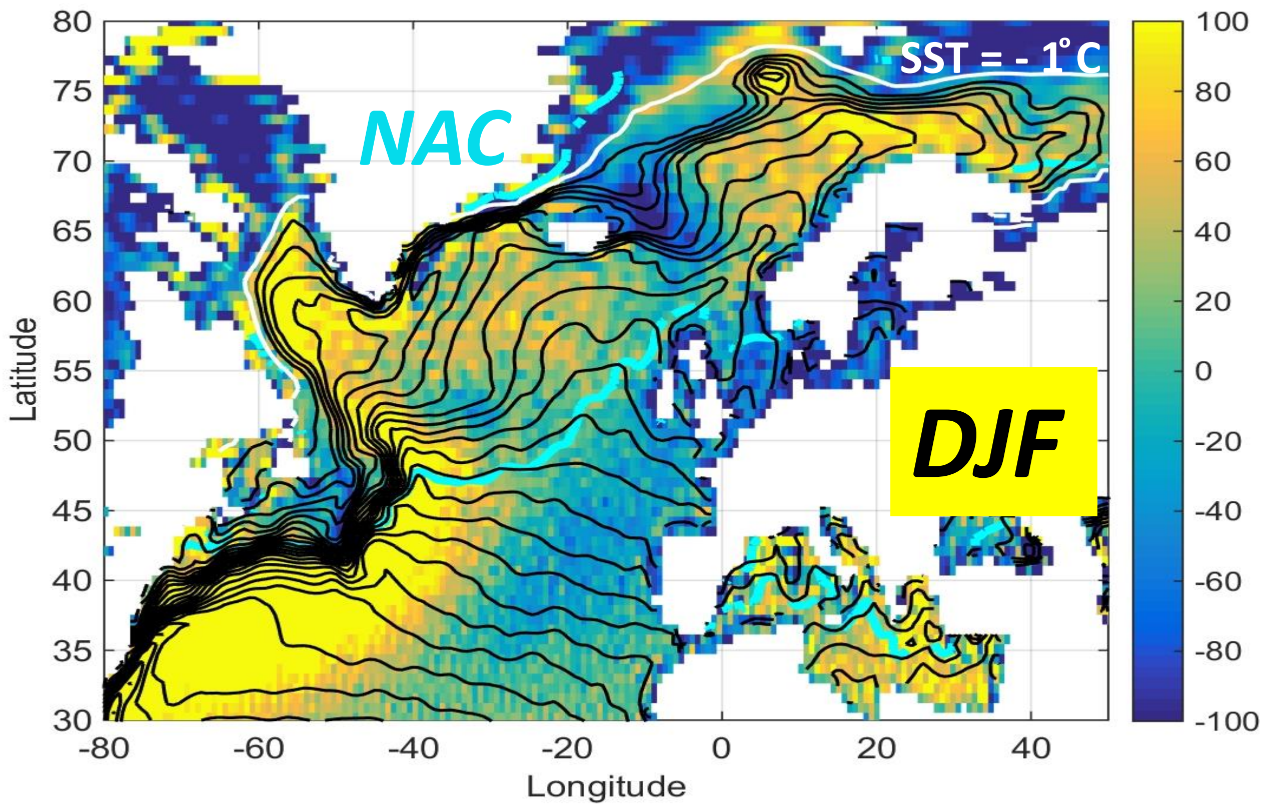


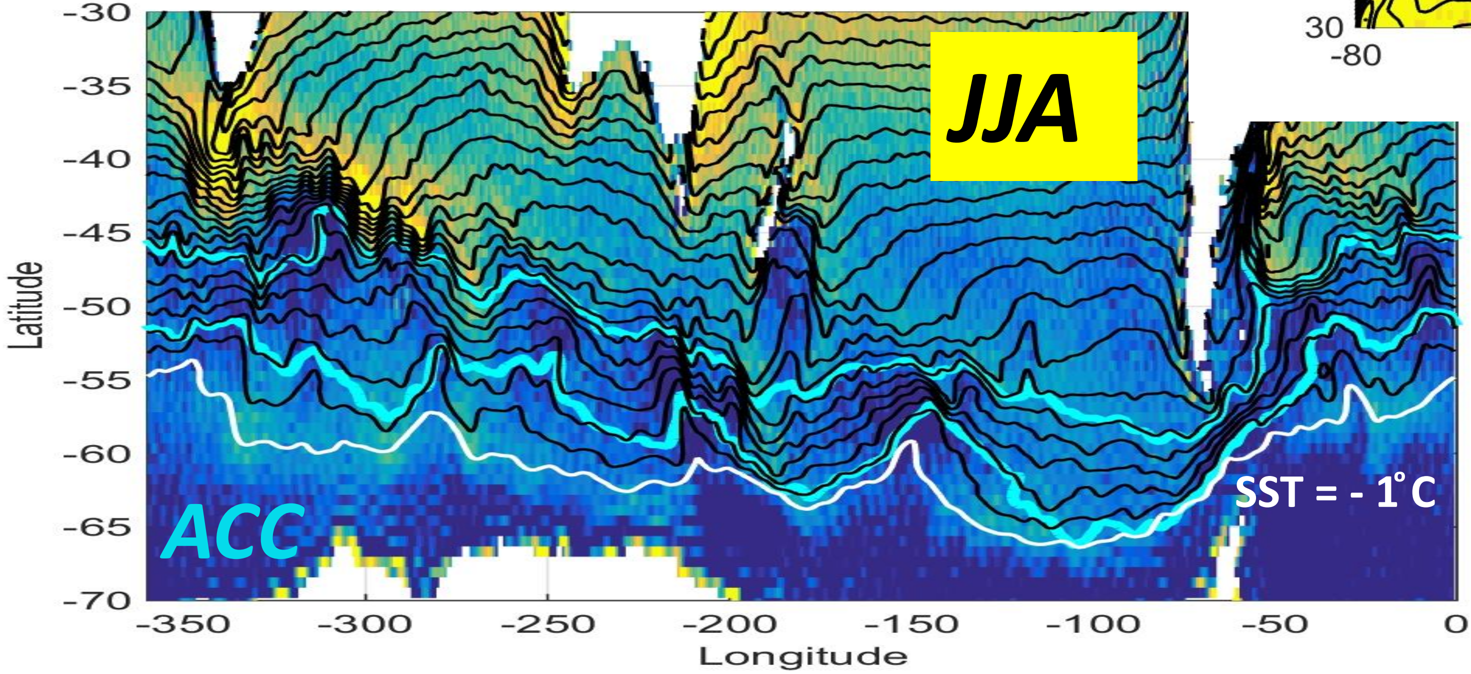
- Ψo~5Sv for the Southern Ocean
- ψo~10Sv for the North Atlantic

Observations

-Atmospheric heat transport divergence and SST from ERAinterim (2002-2008, shown here in colour and contour with a ci=1K)

-TOA fluxes from CERES-EBAF (2001-2008)

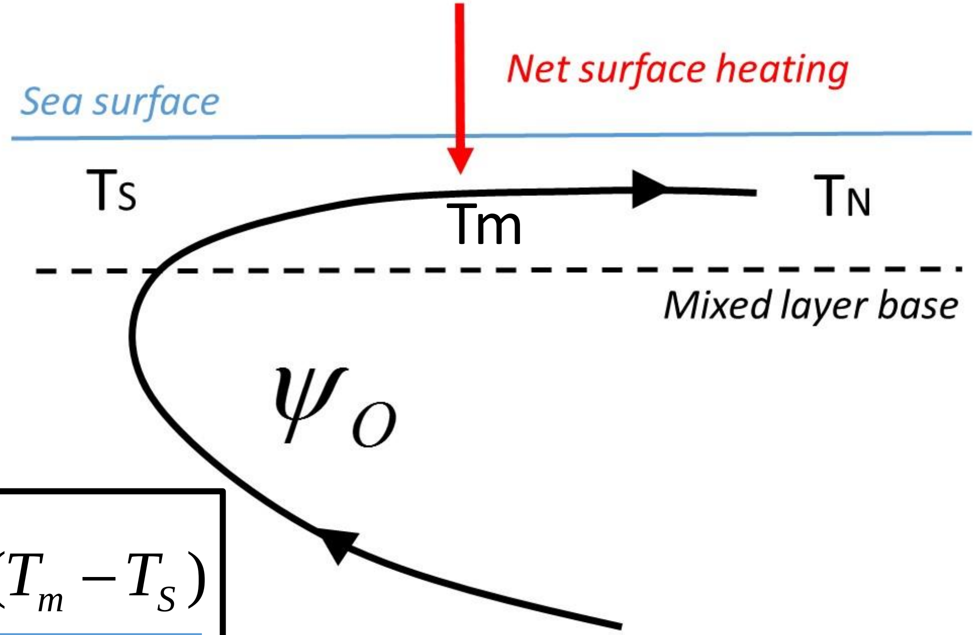




NB: Ao(acc)/Ao(nac)~4

Dynamic topography from Maximenko et al. (2009)

Model parameters



- Model equation for Tm=(Ts+TN)/2

$$\rho_o h_o c_o \frac{\partial T_m}{\partial t} = [ASR - (A + D_A)] - \gamma_{rad} T_m - \gamma_{adv}(T_m - T_S)$$

net air-sea heat flux — ocean advection

- Radiative feedback $\gamma_{rad} \approx 2Wm^{-2}K^{-1}$

- Advective feedback $\gamma_{adv} \equiv \frac{2c_o\psi_o}{A_o} \approx 2.5Wm^{-2}K^{-1}(SO) \,\&\, 20Wm^{-2}K^{-1}(NA)$

Input: Ts, DA, ψo → **Output**: Tm, TN, Qnet, OLR, etc.

Key model prediction: critical Da for net surface heating (Southern Ocean)

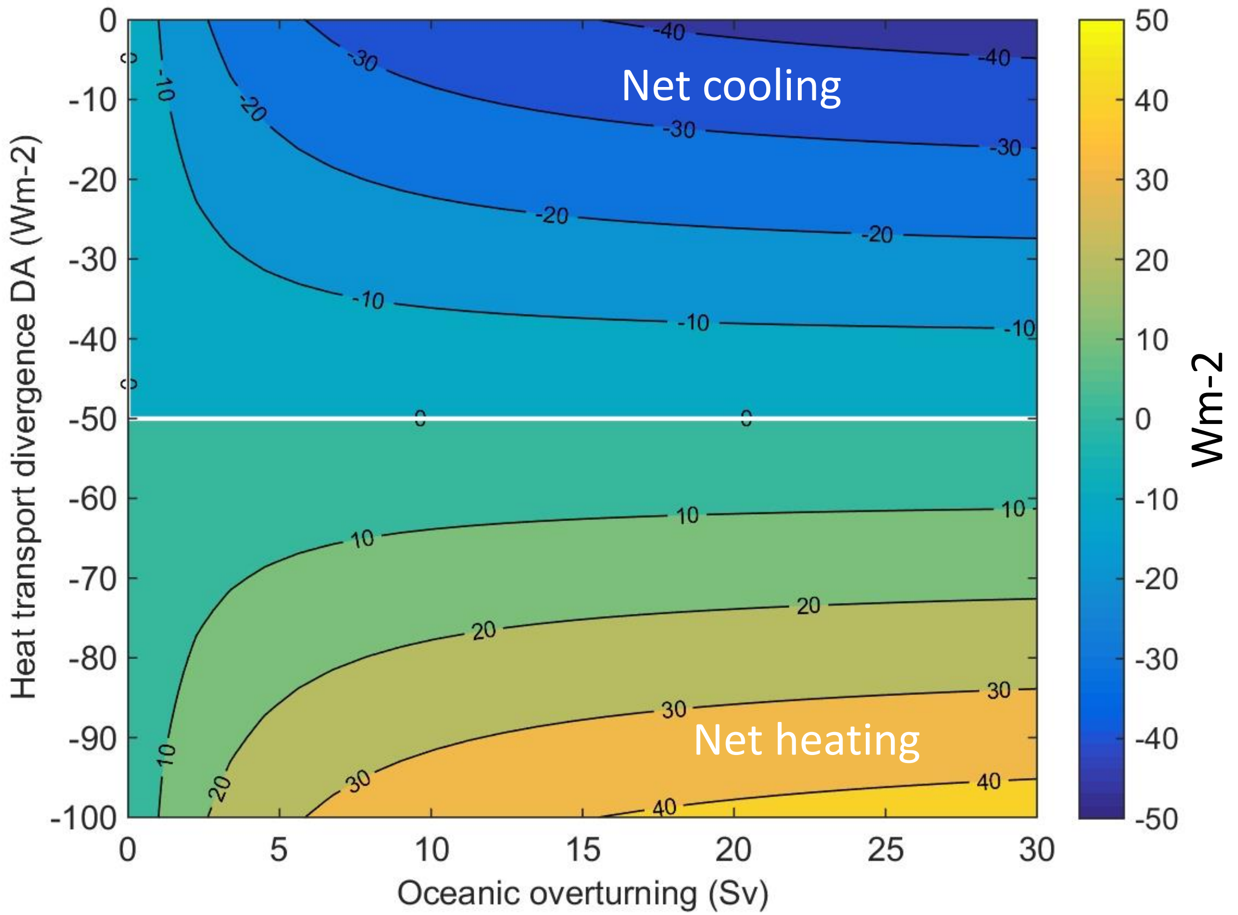
- Atmospheric heat transport convergence must be large enough to sustain net surface heating
- The "threshold value" is a simple function of TOA parameters and is independent of ψo:

$$D_a^* = ASR_O - OLR_S$$

ASR averaged over surface cell

OLR at the southern boundary of the cell

Qnet for Ts = 1.1 deg C



Key model prediction: critical Da for net surface cooling (North Atlantic)

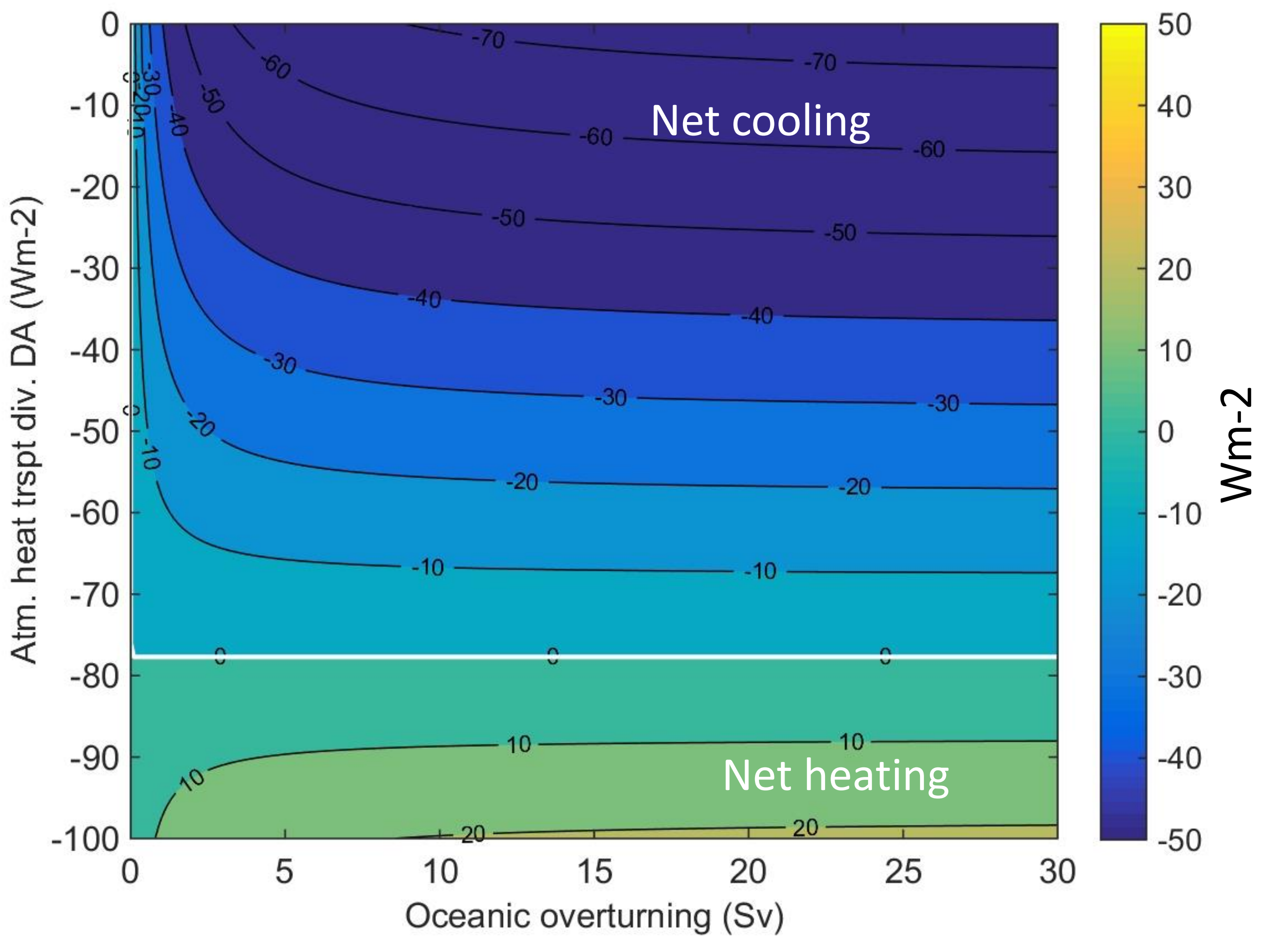
- Atmospheric heat transport convergence must not be too large to sustain net surface cooling
- The "threshold value" is a simple function of TOA parameters and is independent of ψo:

$$D_a^* = ASR_O - OLR_S$$

ASR averaged over surface cell

OLR at the southern boundary of the cell

Qnet for Ts = 12 deg C



Comparison with observations (2002-2008)

Southern Ocean

- CERES-EBAF data suggests:

$$ASR_O = 156Wm^{-2}$$
$$OLR_S = 206Wm^{-2}$$
$$\therefore D_A^* = -50Wm^{-2}$$

- ERAint data suggests:

$$D_A = -67Wm^{-2}$$

North Atlantic

- CERES-EBAF data suggests:

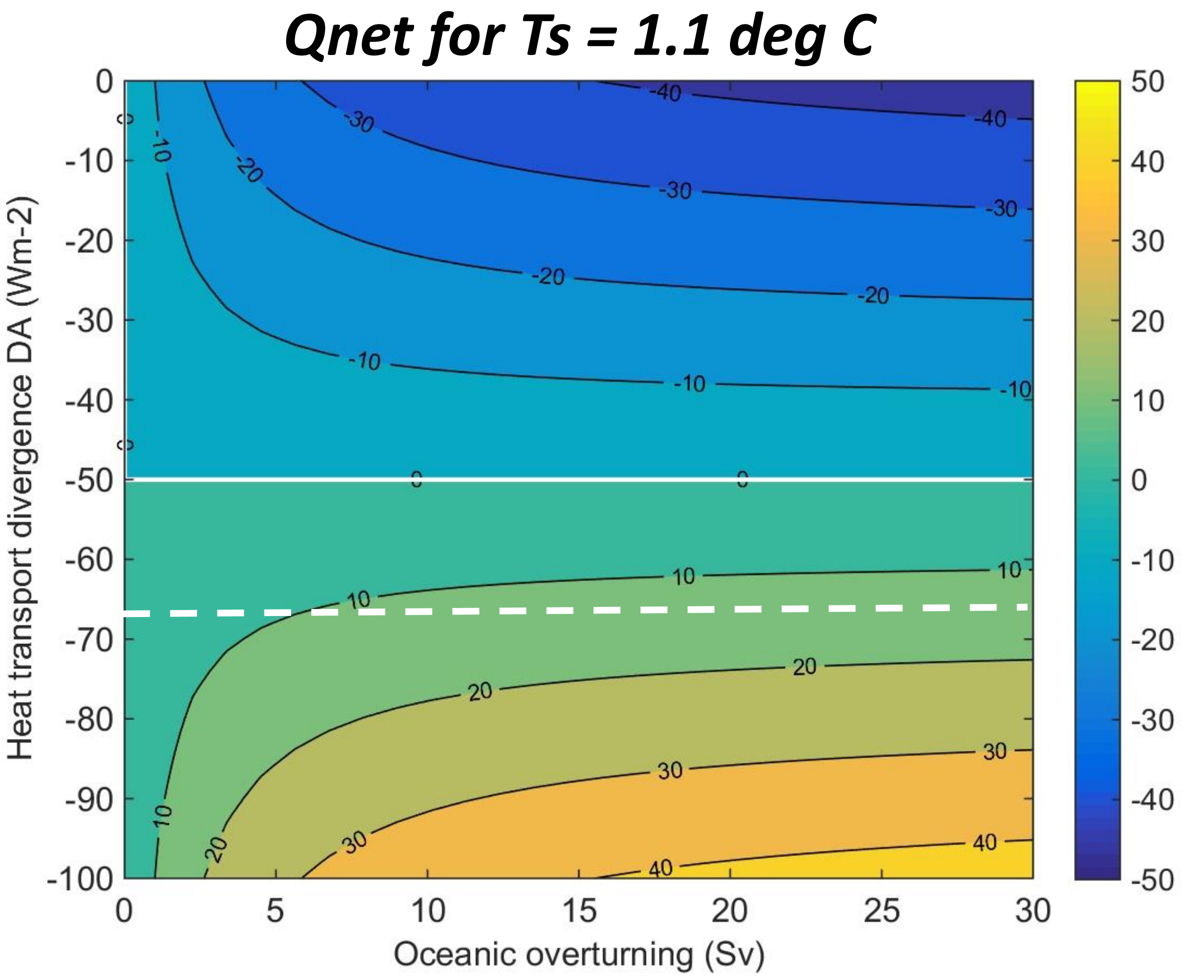
$$ASR_O = 145Wm^{-2}$$
$$OLR_S = 223Wm^{-2}$$
$$\therefore D_A^* = -78Wm^{-2}$$

- ERAint data suggests:

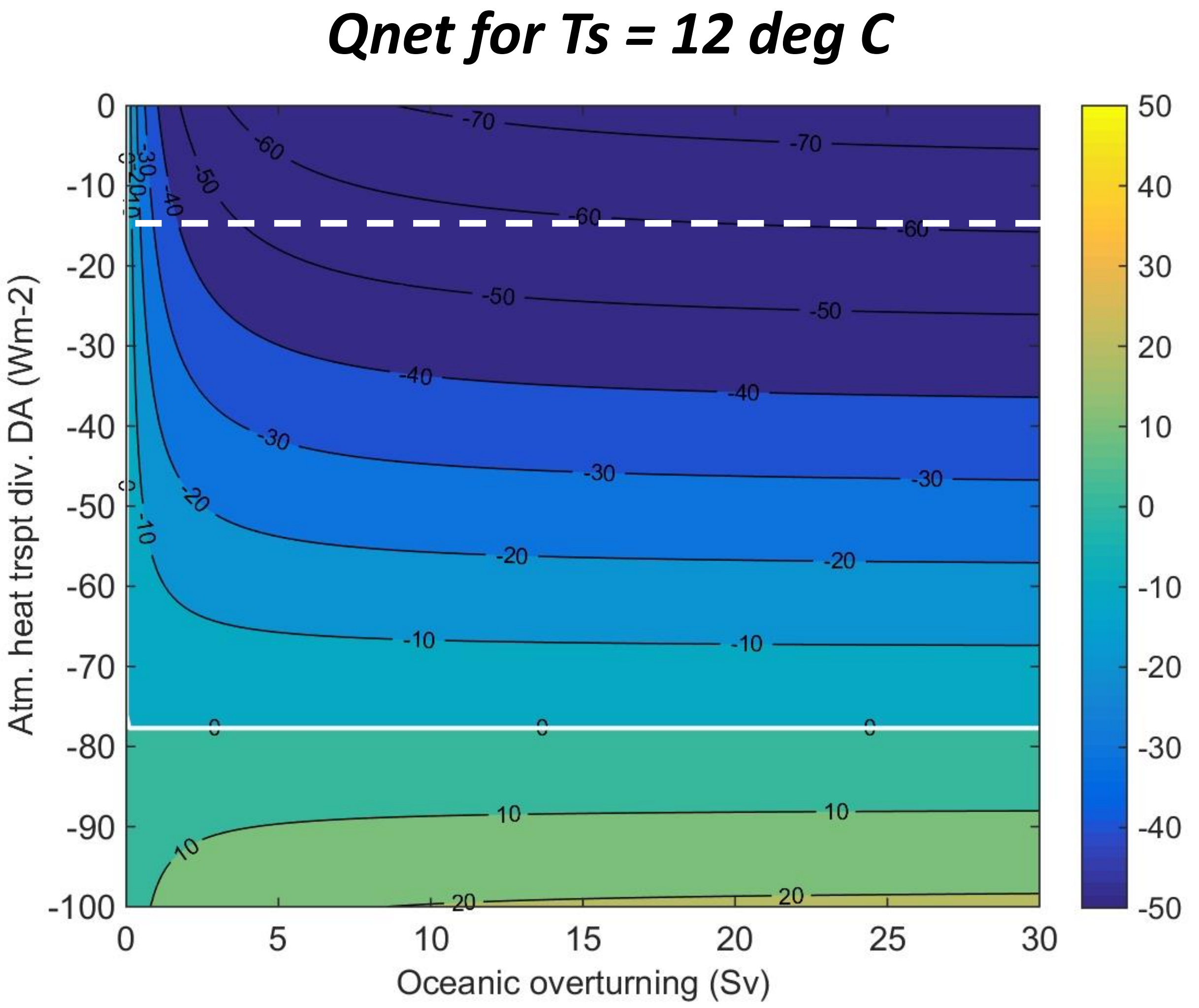
$$D_A = -13.6Wm^{-2}$$

Comparison with observations (2002-2008)

Southern Ocean



North Atlantic



Comparison with observations (2002-2008)

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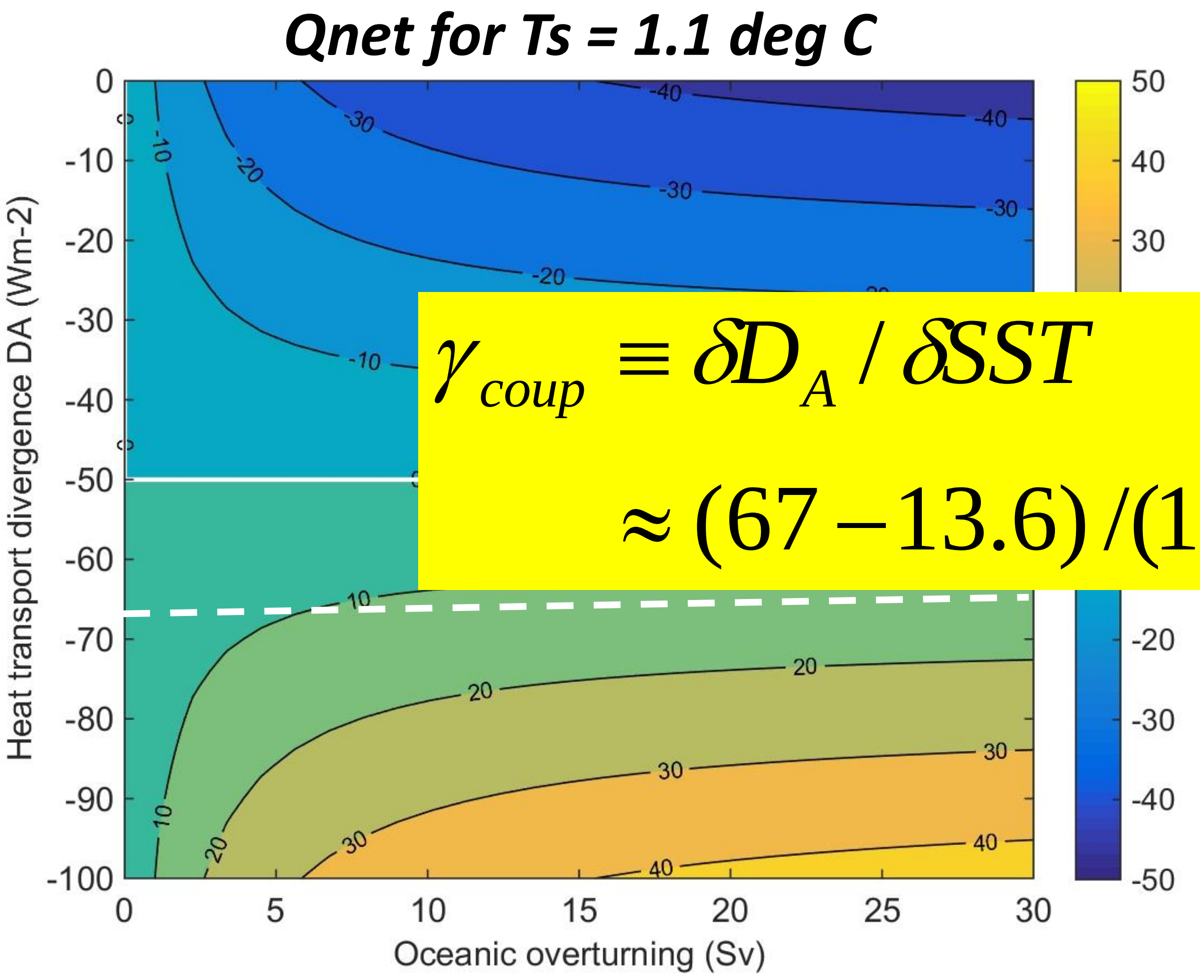
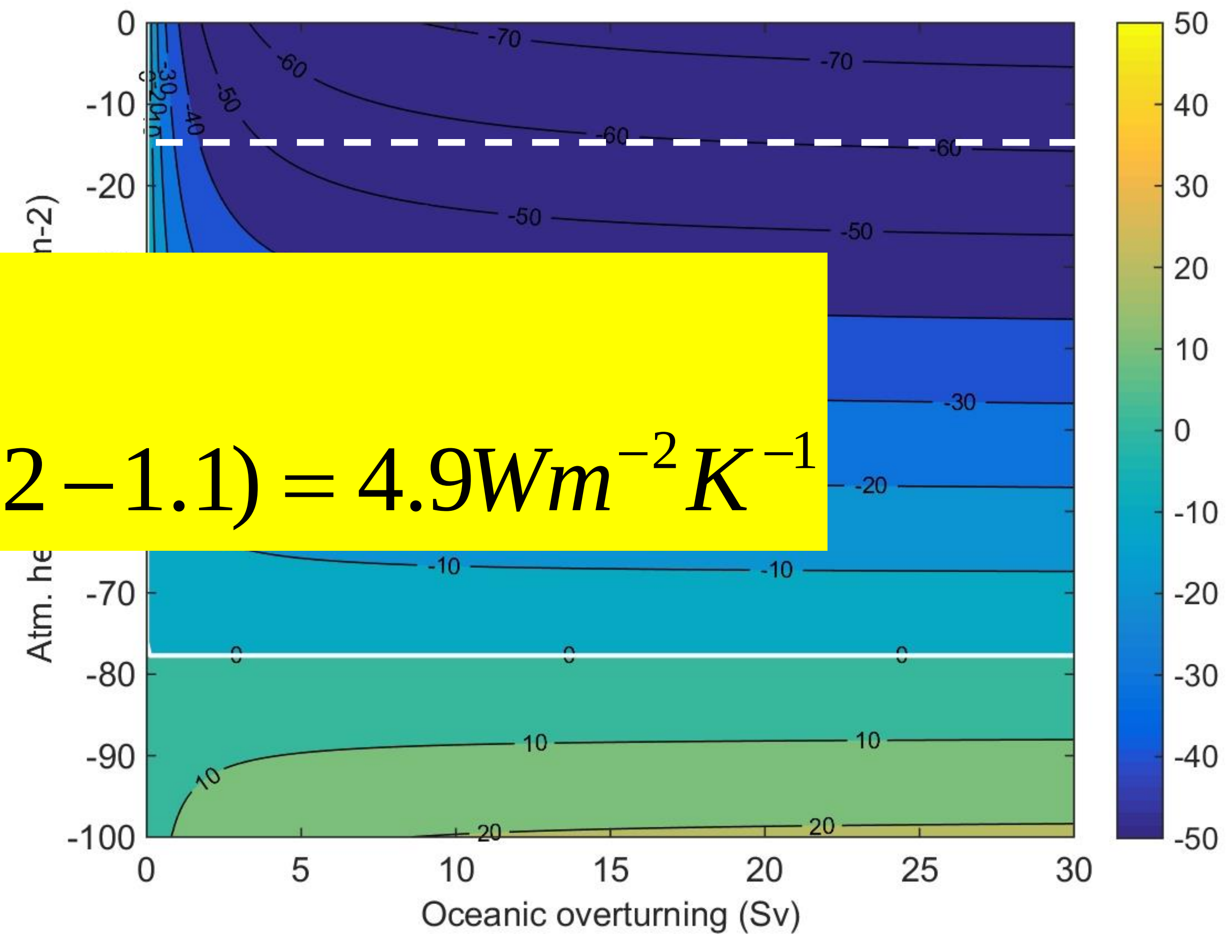


North Atlantic

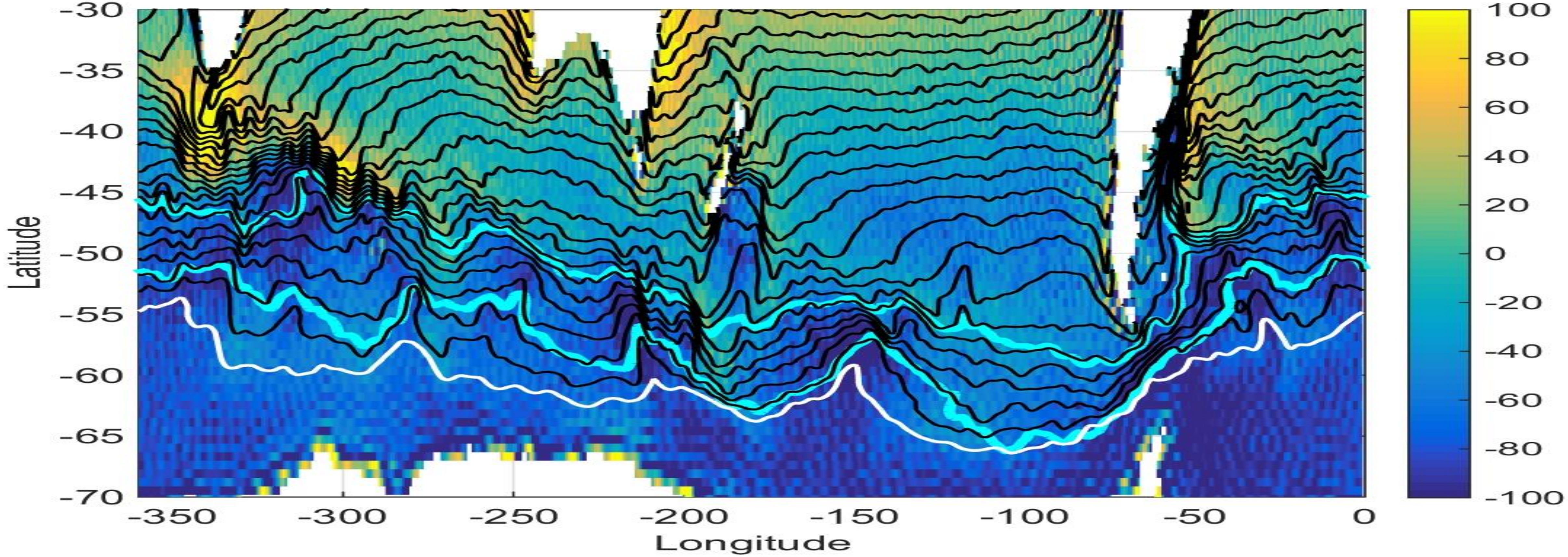


$$\gamma_{coup} \equiv \delta D_A / \delta SST$$

$$\approx (67 - 13.6)/(12 - 1.1) = 4.9 Wm^{-2} K^{-1}$$

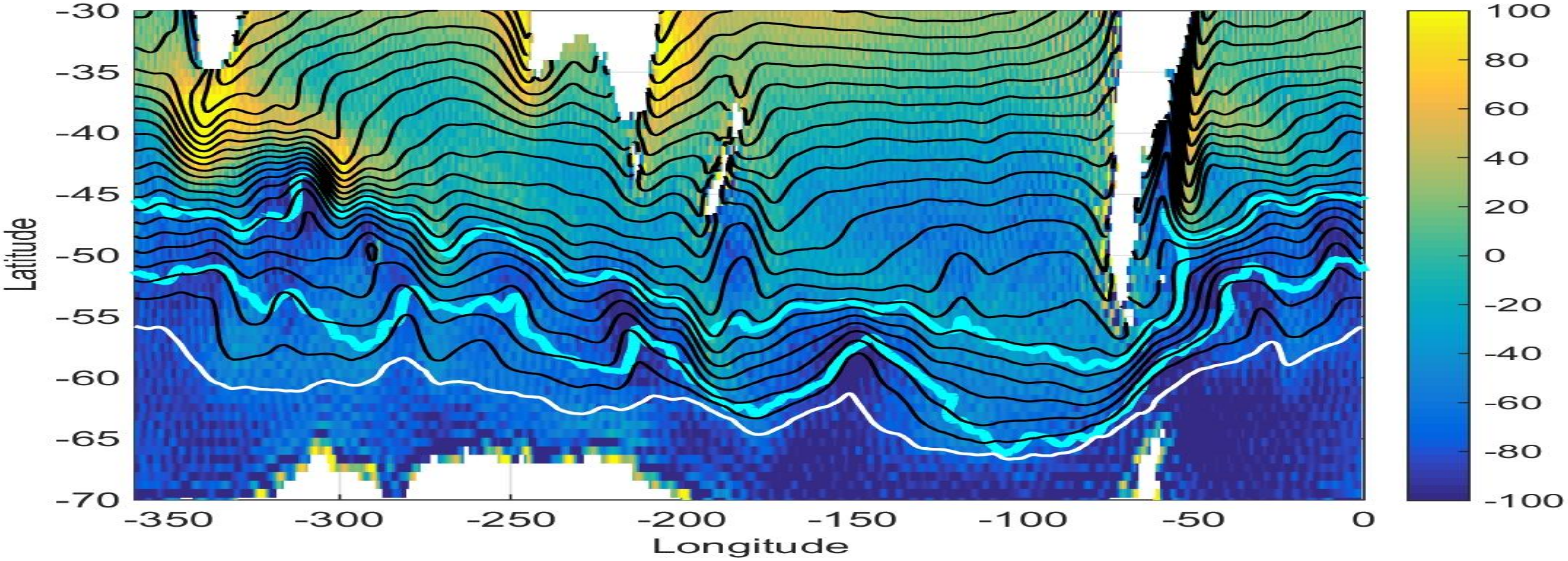
Feedback analysis

Take advantage of change in SST resolution after 2002 in ERAinterim…



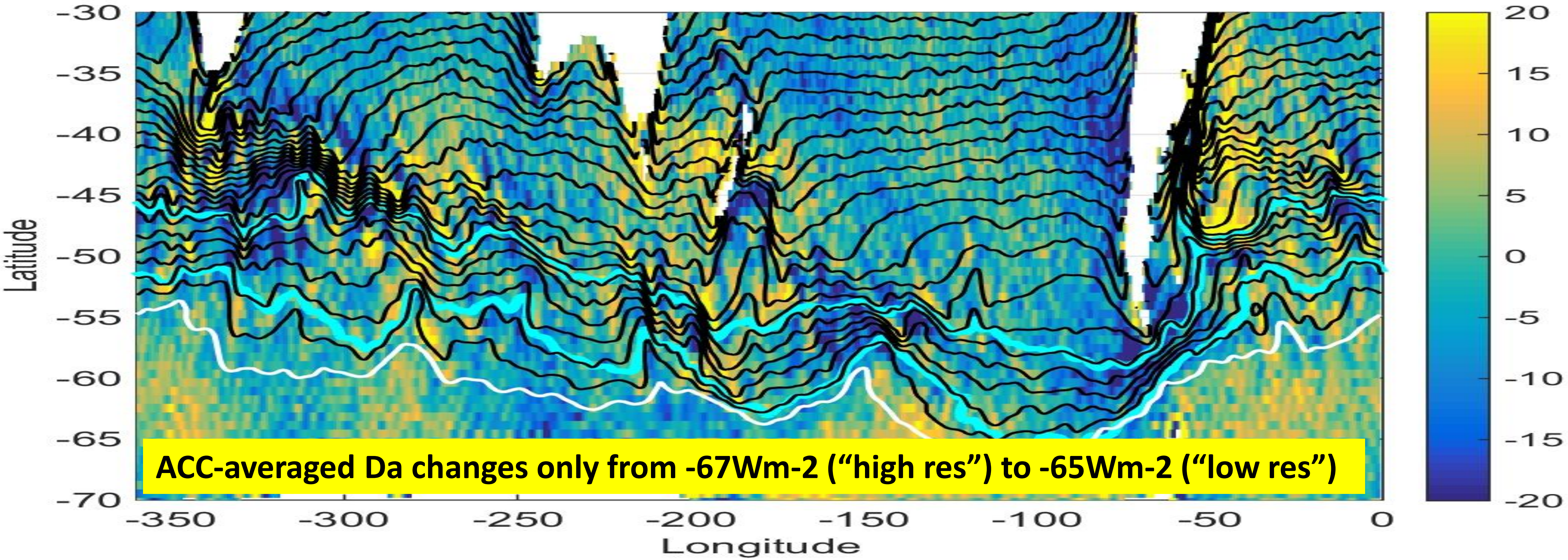
2002-2008: Annual mean Da & JJA SST

Take advantage of change in SST resolution after 2002 in ERAinterim…



1989-2001: Annual mean Da & JJA SST

Take advantage of change in SST resolution after 2002 in ERAinterim…

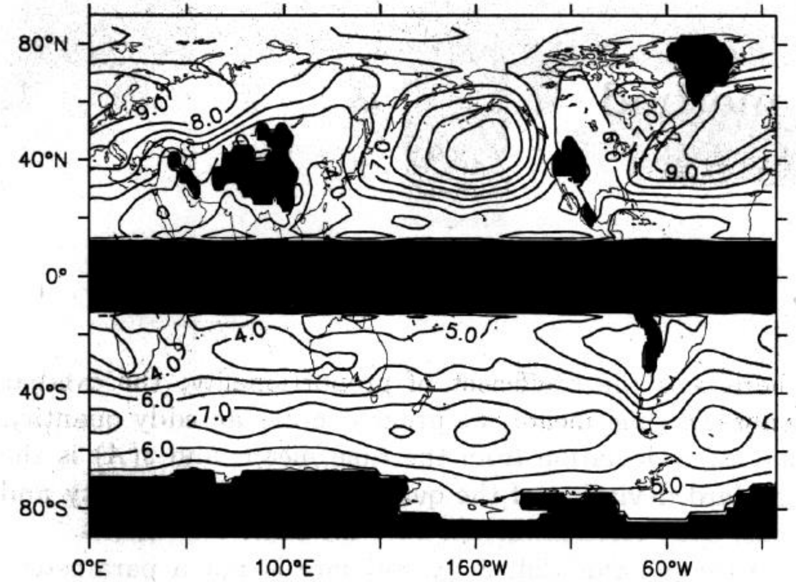


Da (2002-2008) minus Da(1989-2001) & JJA SST 2002-2008

Dependence of Da on SST

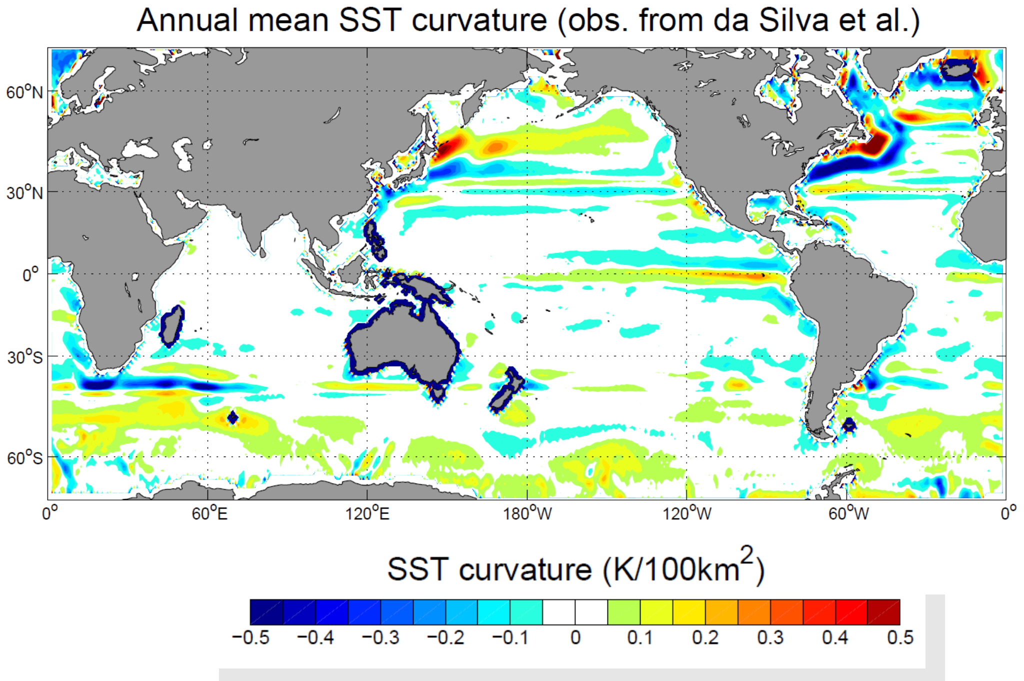
$$D_a = \nabla.\int vh\,dP/g = -\nabla.\int(\kappa\nabla h)dP/g = -[\overset{0}{\cancel{(\nabla\kappa)}}(\nabla h) + \kappa\nabla^2 h]\Delta P/g$$

$$\approx -\kappa(\nabla^2 h)\Delta P/g, \quad with\ h \equiv c_p T + l_v q + \Phi \propto SST$$



Kushner and Held (1999)

- Atmospheric diffusivities peak along the regions of interest so SST gradients are a small player
- Little curvature of the SST field over the Southern Ocean but larger values over the narrow North Atlantic → larger coupling Da/SST expected there



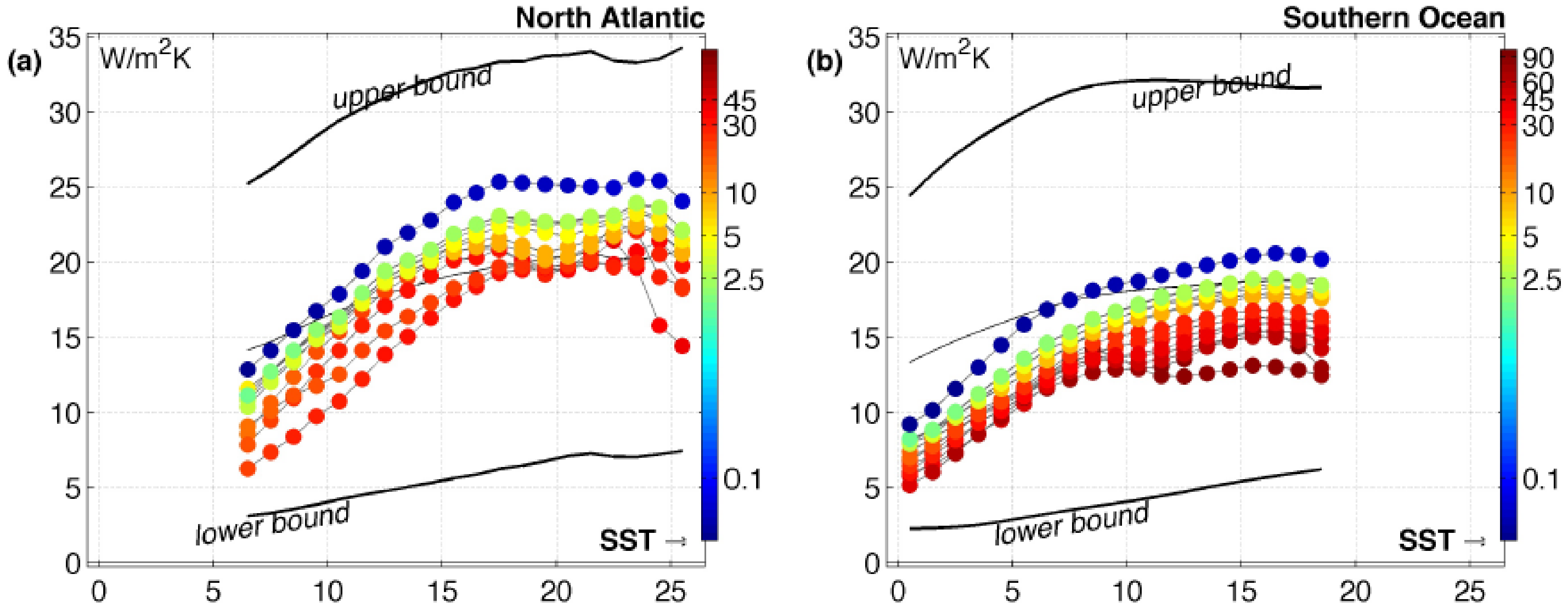
Observational estimate of γcoup

- In steady state, anomalies in TOA & surface fluxes and Da must satisfy:

$$D_A' = (ASR - OLR)' - Q_{net}' = (\gamma_{rad}^{surf} - \gamma_{rad}^{TOA} + \gamma_{turb})SST' \therefore \gamma_{coup} \approx \gamma_{turb}$$

Observational estimate of the turbulent heat flux feedback

γturb from ERAint



Hausmann et al. (2016)

Summary and implications for perturbed CO2 climate state

- All feedback terms are weak and comparable in magnitude in the Southern Ocean

$$\gamma_{adv} \approx \gamma_{rad} \approx \gamma_{coup} \approx 2Wm^{-2}K^{-1}$$

- This contrasts sharply with the North Atlantic:

$$\gamma_{adv} \approx 20 > \gamma_{coup} \approx 10 > \gamma_{rad} \approx 2Wm^{-2}K^{-1}$$

- By this metric, the coupling of atmospheric heat transport with the upper ocean plays a larger role in the Southern Ocean than in the North Atlantic

Summary and implications for perturbed CO2 climate state

- All feedback terms are weak and comparable in mag the Southern Ocean

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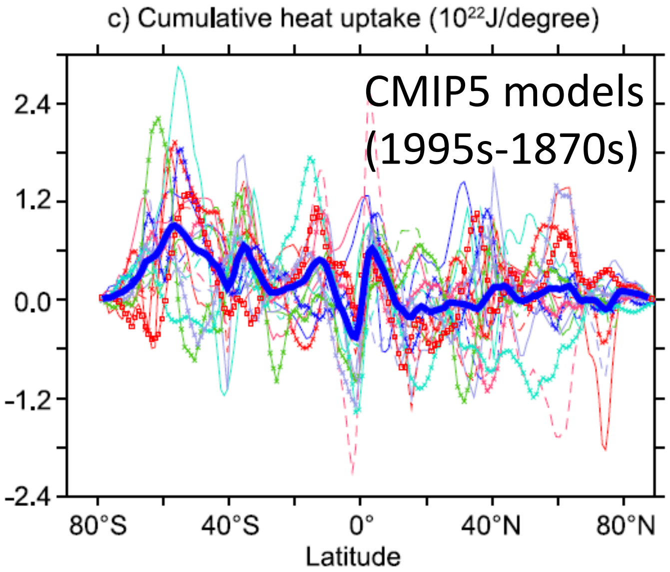


Frölicher et al. (2015)

- Heat uptake anomaly in response to a reduction in OLR =F' scales as:

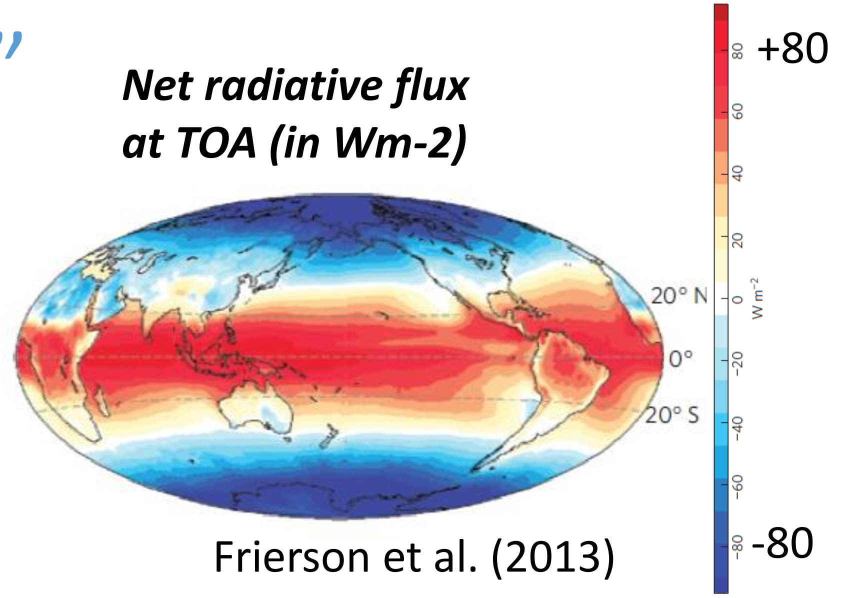
$$Q'_{net} = F'\gamma_{adv} / (\gamma_{adv} + \gamma_{coup} + \gamma_{rad}) \approx F'/3$$

Extras

Comparison with “observations”

- CERES-EBAF data: SW and LW radiative flux at the TOA (monthly, 2001-2010) from CERES and SORCE missions (Loeb et al., 2011)

Net radiative flux at TOA (in Wm-2)

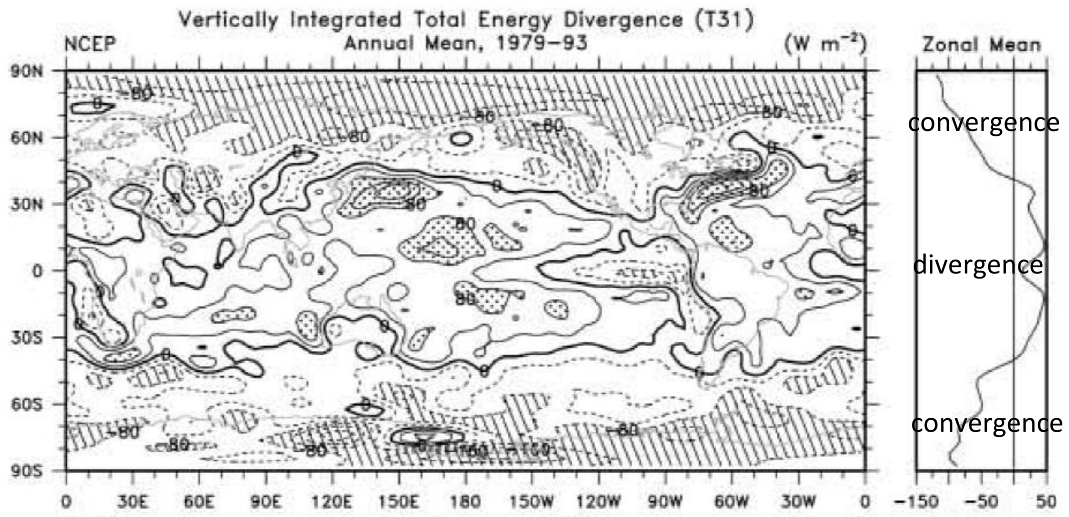


Frierson et al. (2013)

- Heat transport divergence (monthly, 1989-2008) from ERA-interim

$$D_A = \nabla . \int_0^{p_s} \vec{u}(c_p T + l_v q + gz + \frac{1}{2}\vec{u}^2)dp / g$$

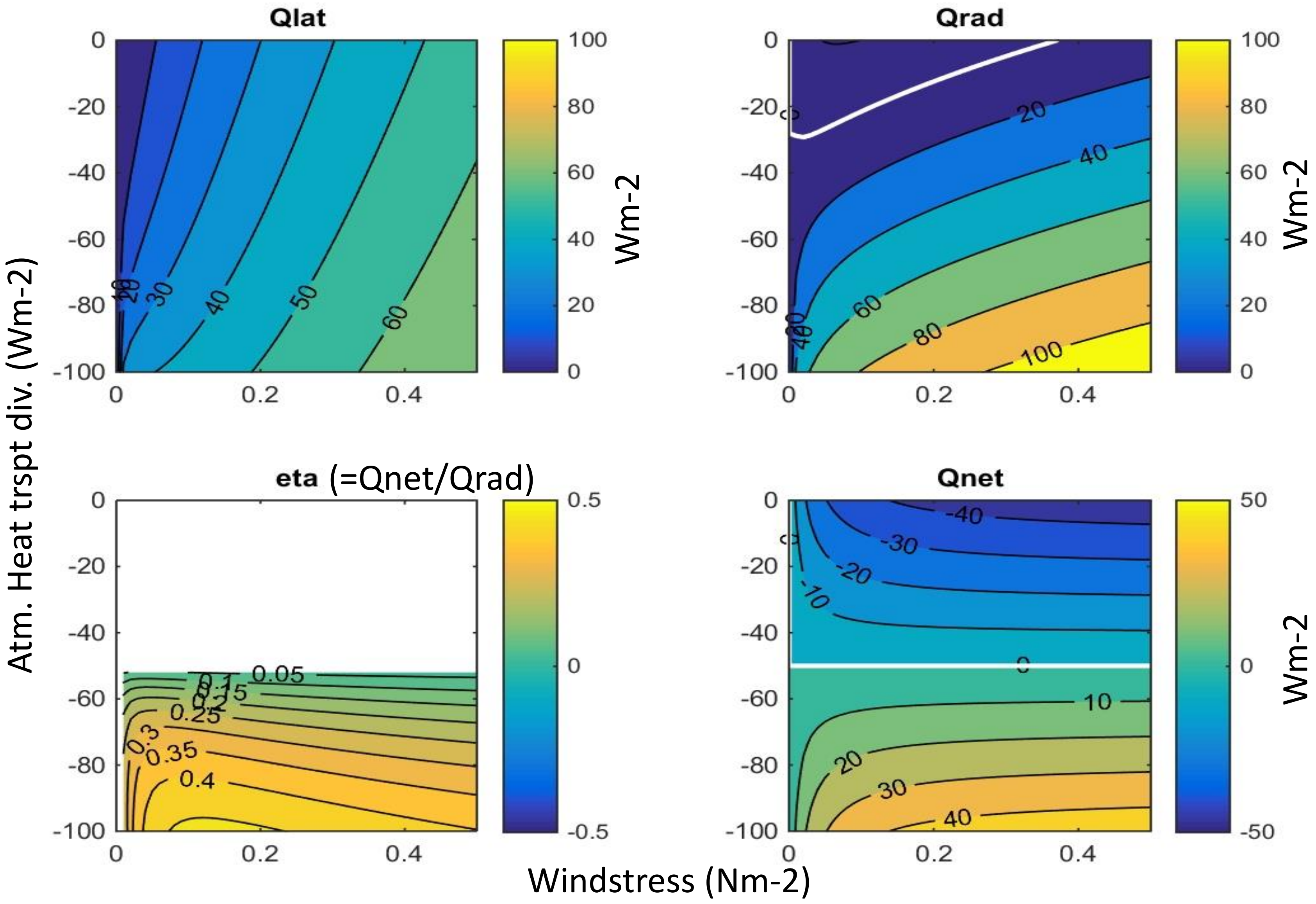
(in Wm-2)



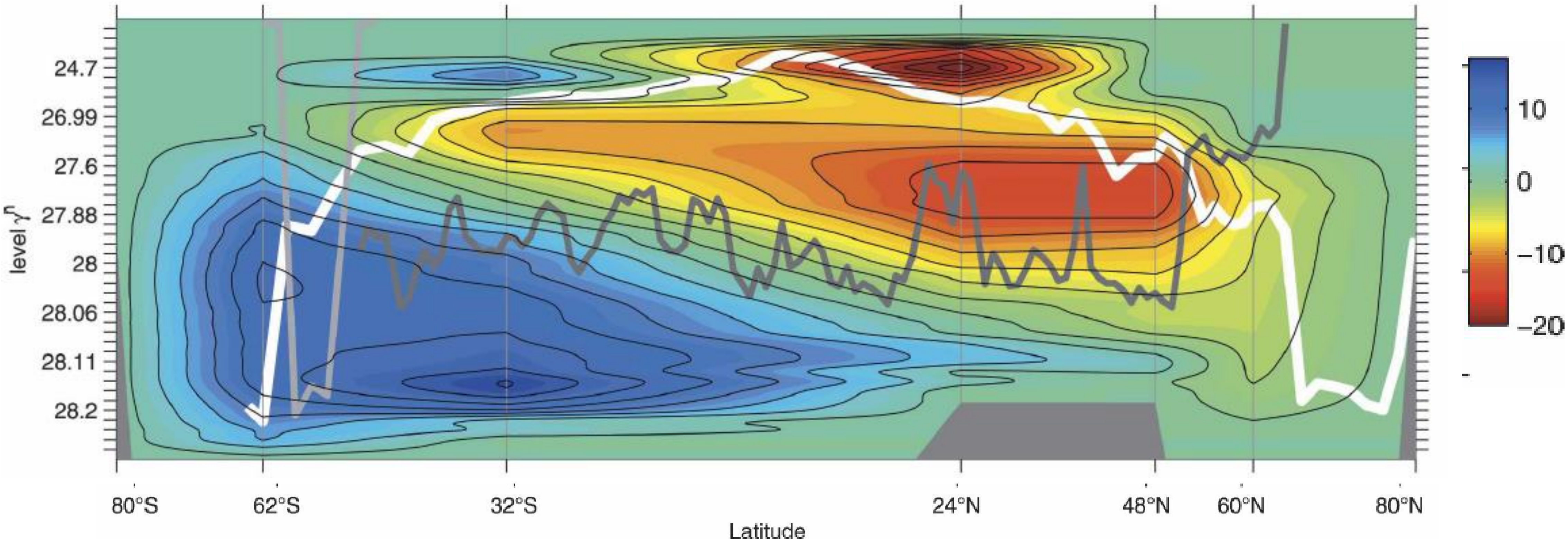
Trenberth et al. (2001)

Model prediction for air-sea interactions

- Good agreement with reanalysis data for TAUX~0.2 Nm-2 and DA=-67Wm-2
- Heating efficiency eta = Qnet/Qrad has a maximum
- Not clear how the increase in Qrad with TAUx physically occurs

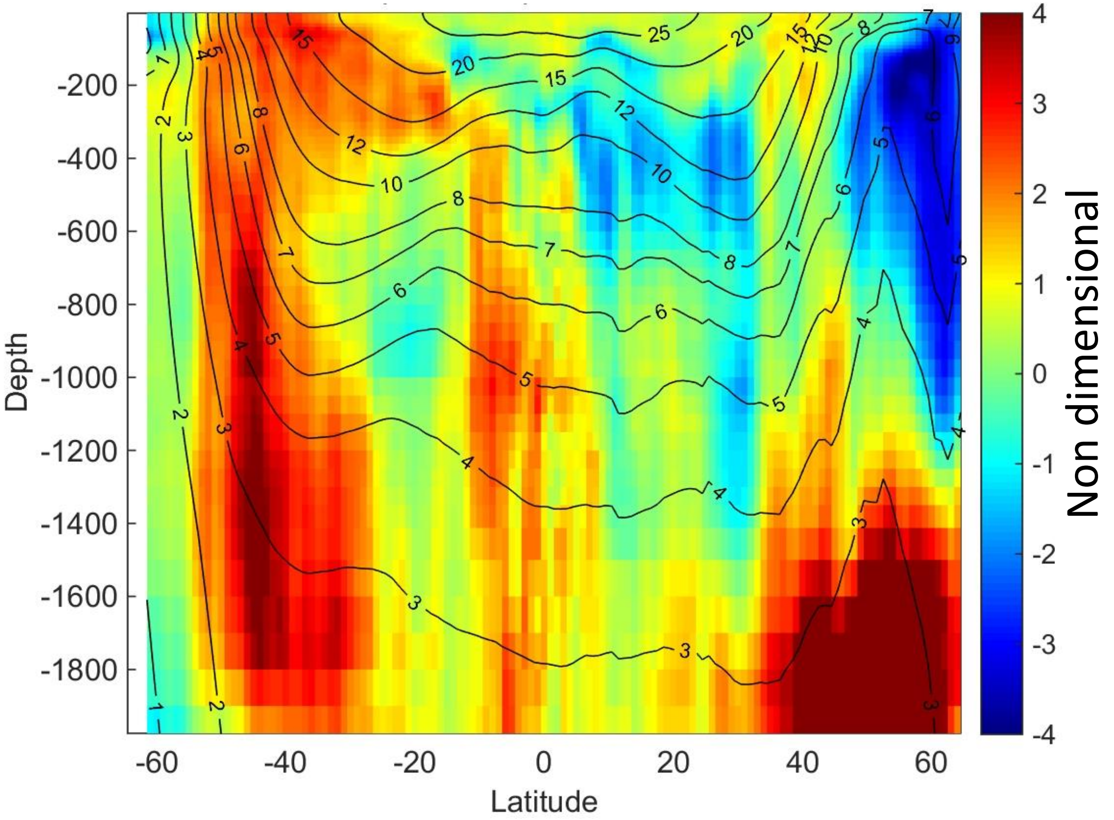


Global overturning in density coordinates
(Speer and Lumpkin, 2007)

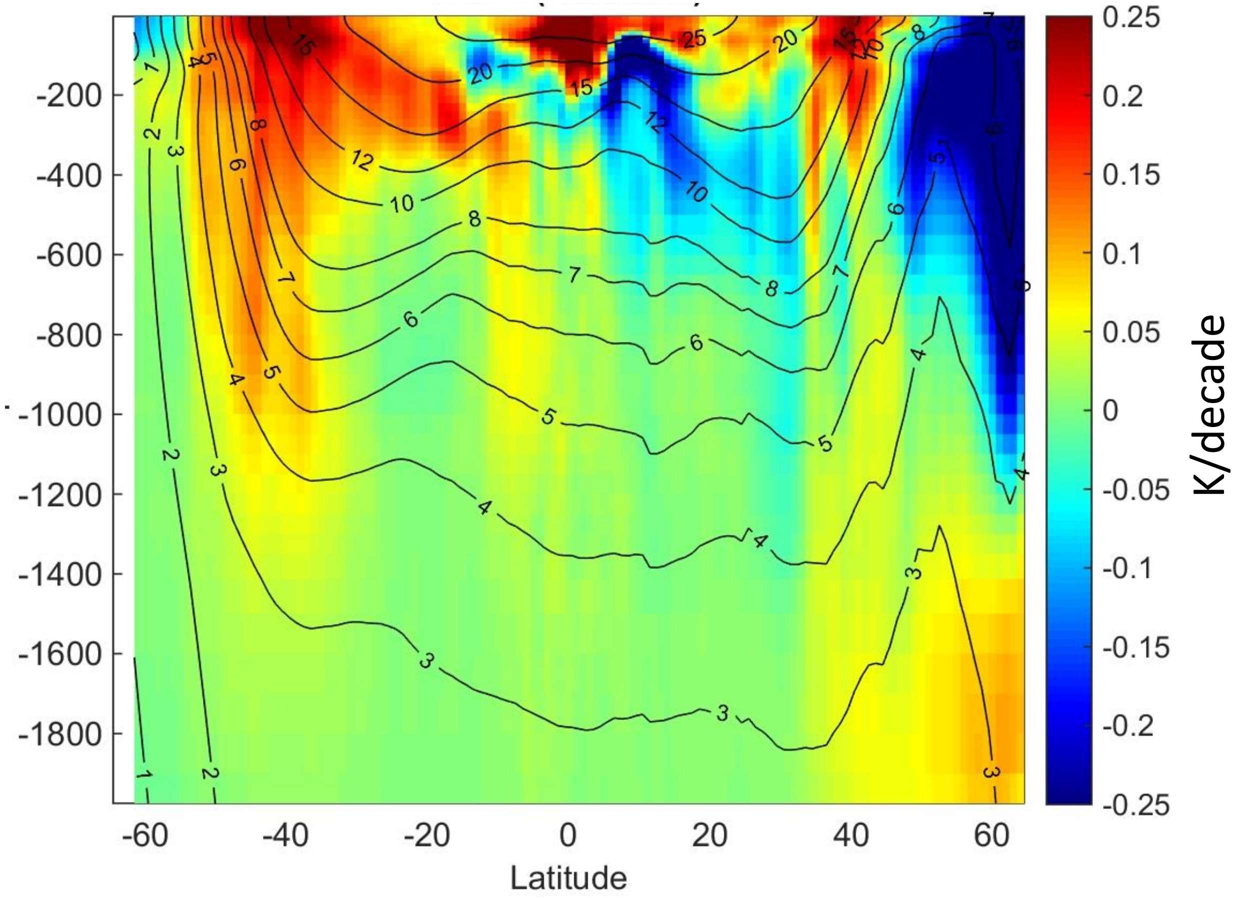


Observed changes in ocean heat content from Argo floats (2004-2015)

Norm. zonal mean heat content trend



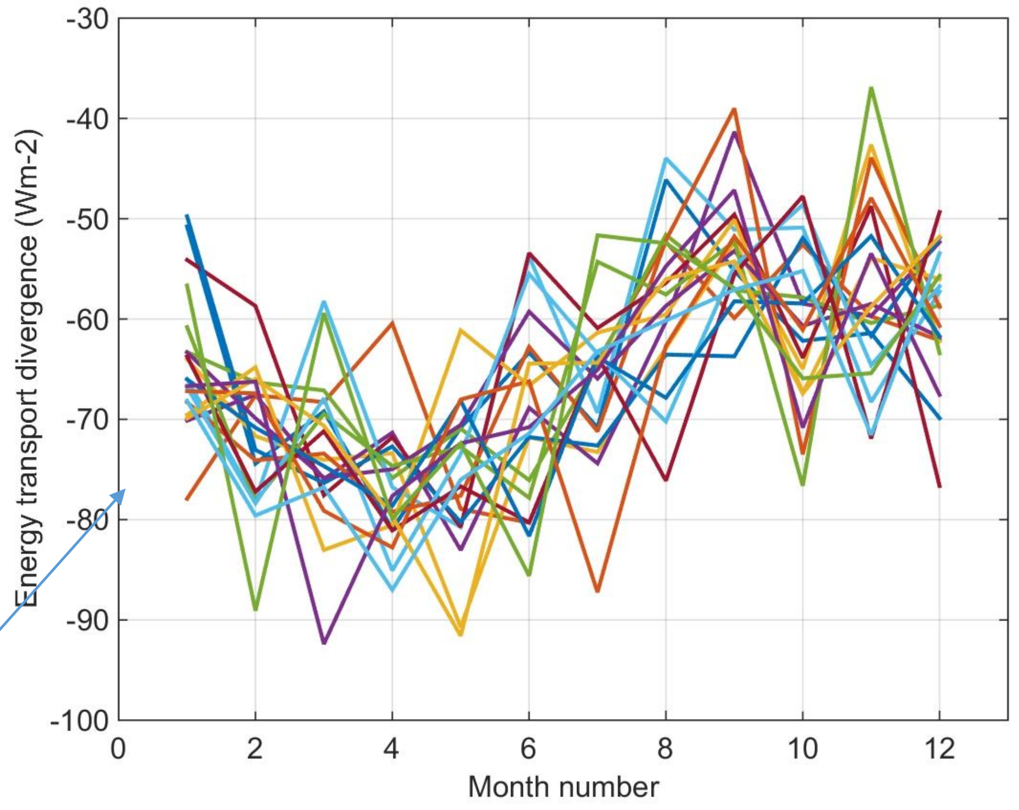
Zonal mean heat content trend

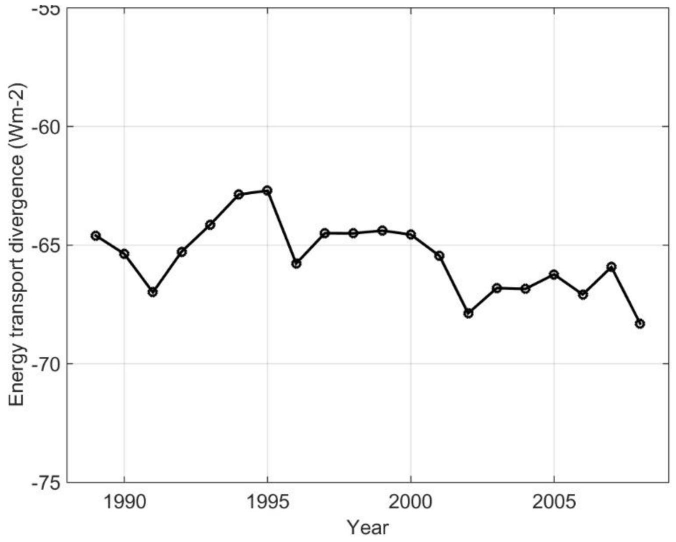


Global average ~0.5 W/m², dominated by the Southern Ocean (>2/3 comes from lat<20S, as estimated by Roemmich et al., 2015)

Observed variability of Da integrated over the ACC

- Seasonal cycle amplitude is 12Wm-2, yr-to-yr variability of each month is σ~7.4 Wm-2.
- Annual mean varies by only σ=1.4Wm-2, less than expected from random averaging (7.4/√12=2.1Wm-2)

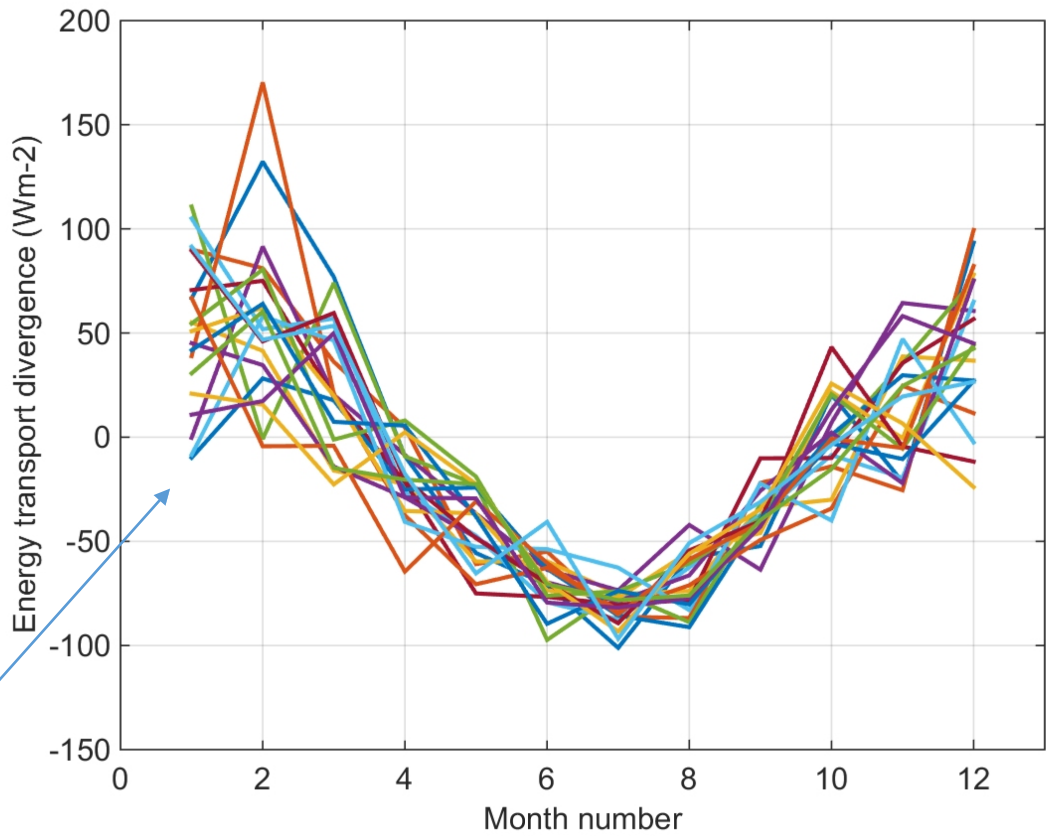


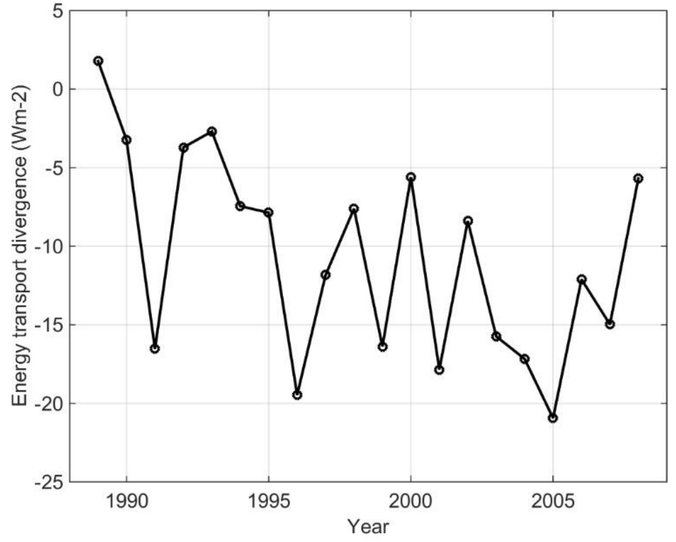


Average Da over ACC for monthly and annual mean data (ERAint, 1989-2008)

Observed variability of Da integrated over the NAC

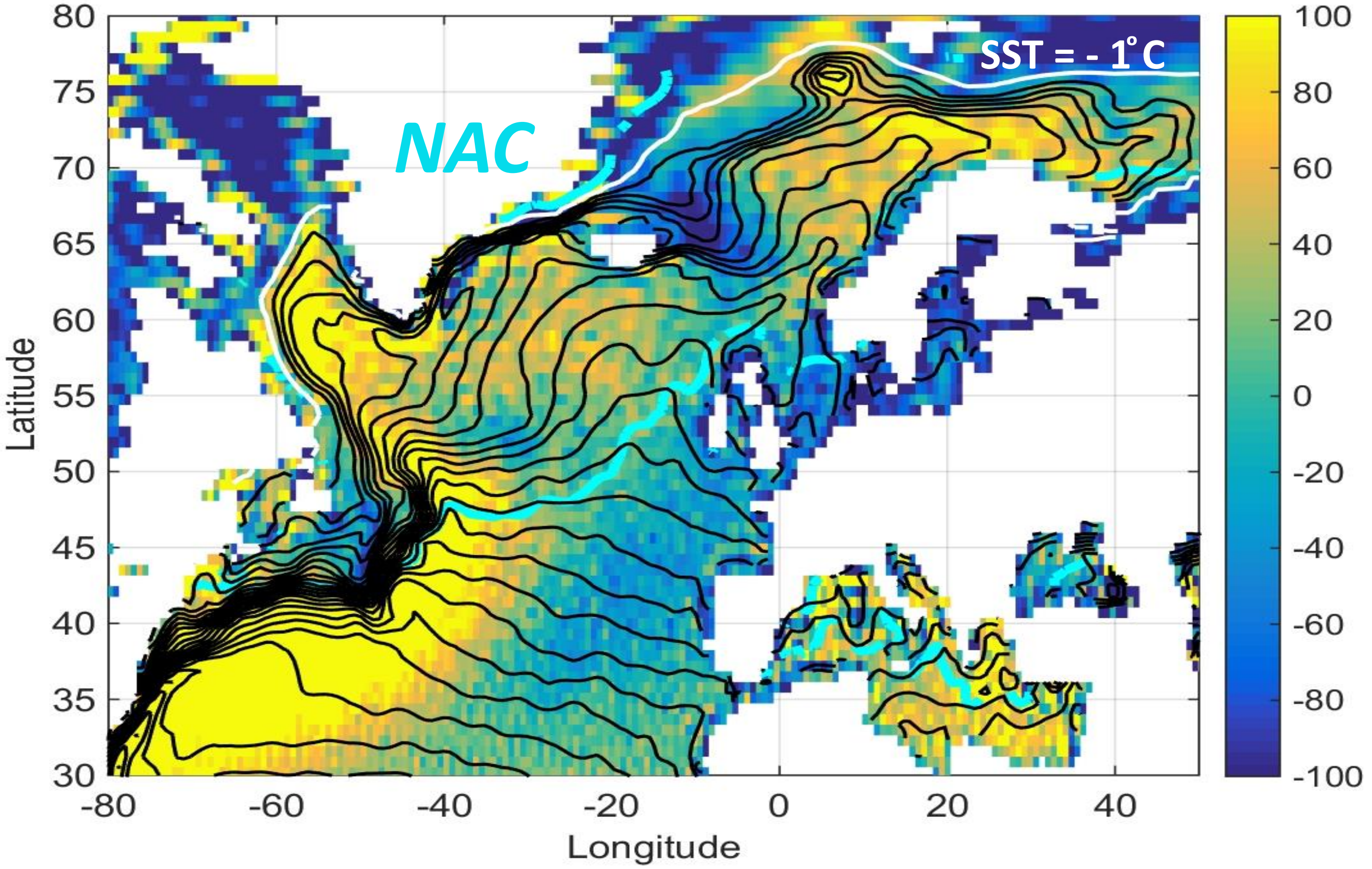
- Seasonal cycle amplitude is 40Wm-2, yr-to-yr variability of each month is σ~24.7 Wm-2.
- Annual mean varies by σ=6.5Wm-2, slightly less than expected from random averaging (24.7/√12=7.1Wm-2)



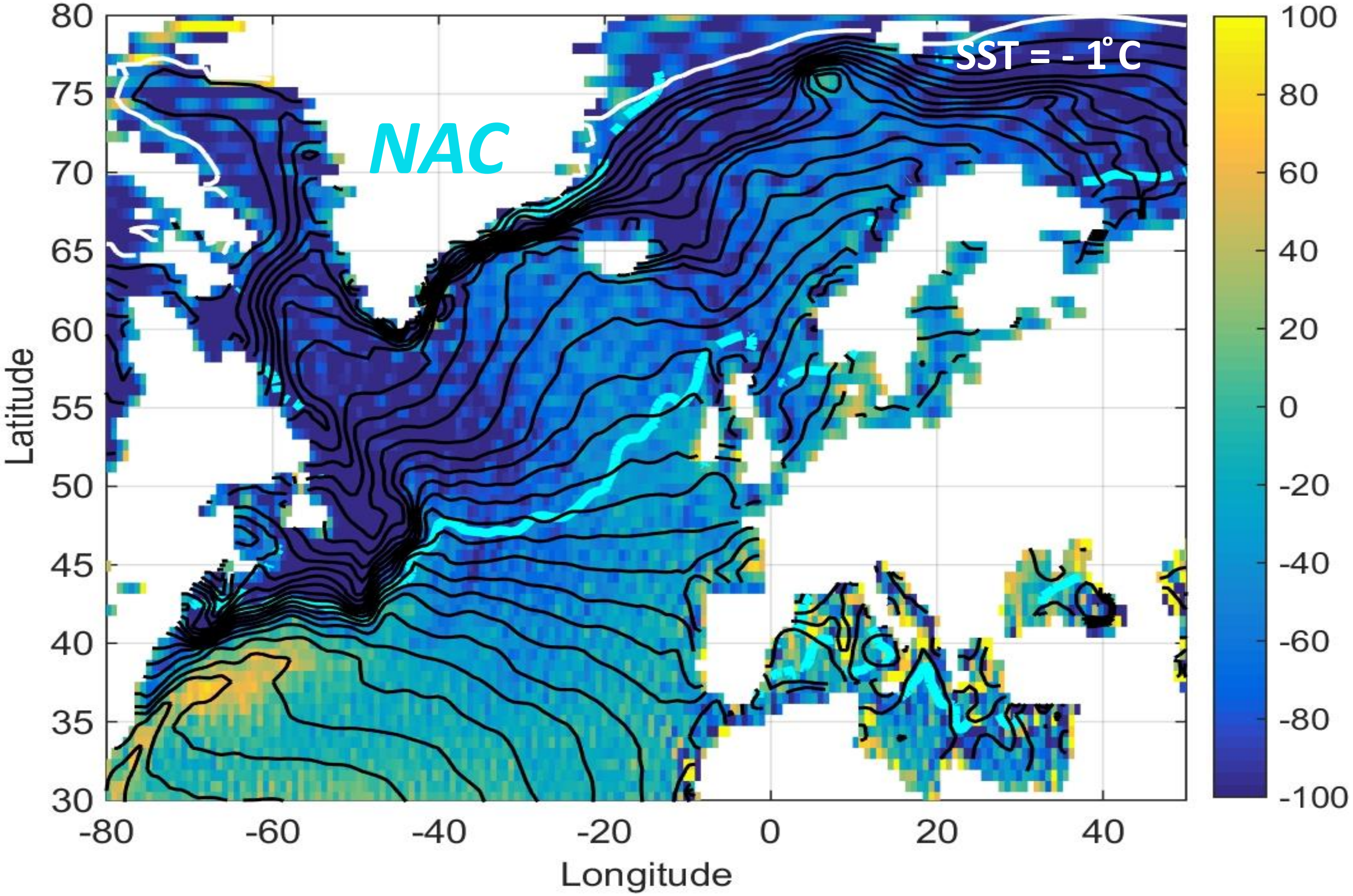


Average Da over NAC for monthly and annual mean data (ERAint, 1989-2008)

Atm. heat trspt. div. Da (colour) and SST (CI = 1K) –ERAinterim (DJF, 2002-2008)

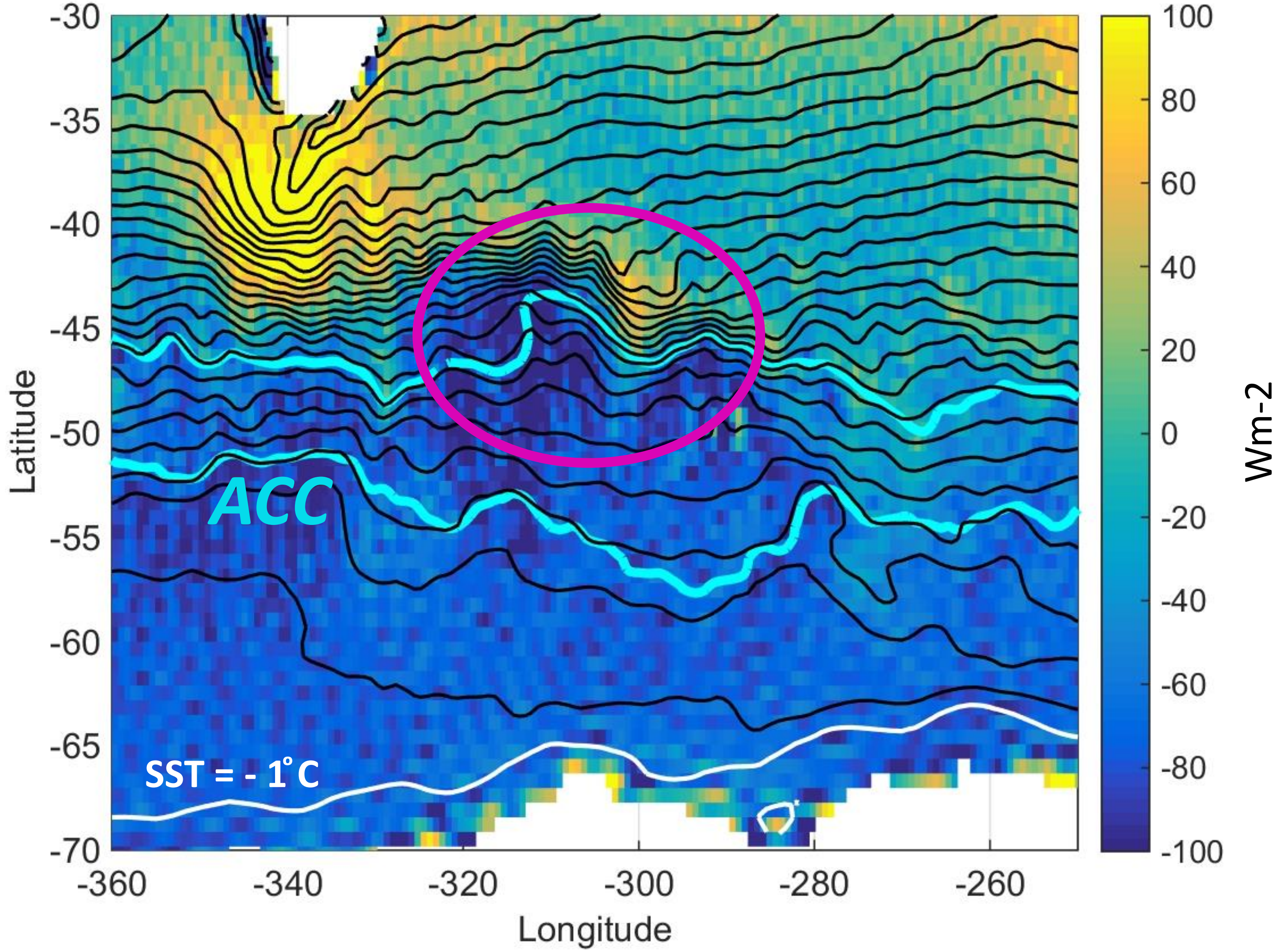


Atm. heat trspt. div. Da (colour) and SST (CI = 1K) –ERAinterim (JJA, 2002-2008)



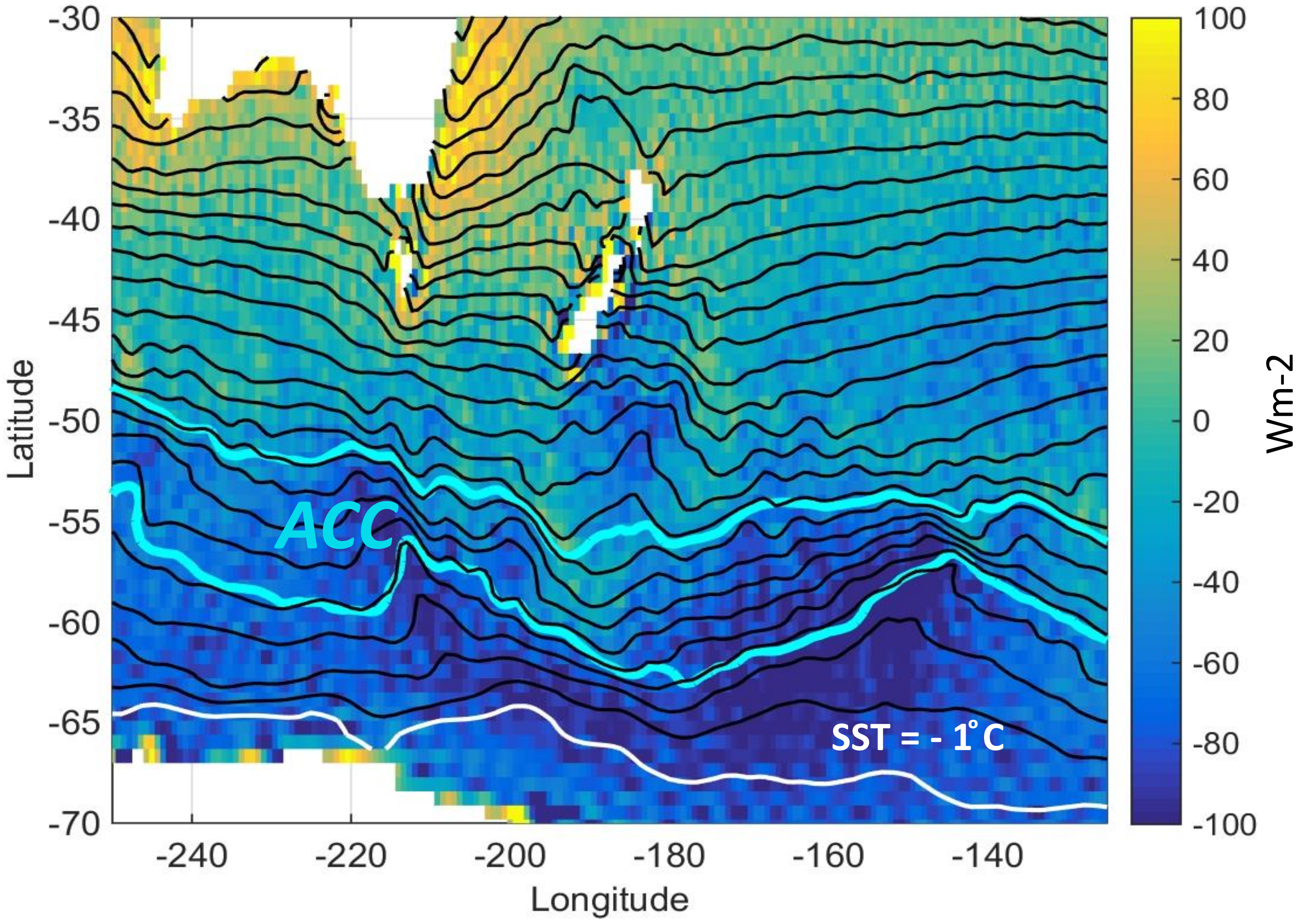
SST (CI = 1K) vs Da (colour): ERAinterim (DJF 2002-2008)

- *<u>Aguhlas portion</u>*:
- Da has a slanted dipolar structure across the strong SST front
- The ACC captures a bit of this dipole but mostly feels the larger scale convergence of the atmospheric heat transport



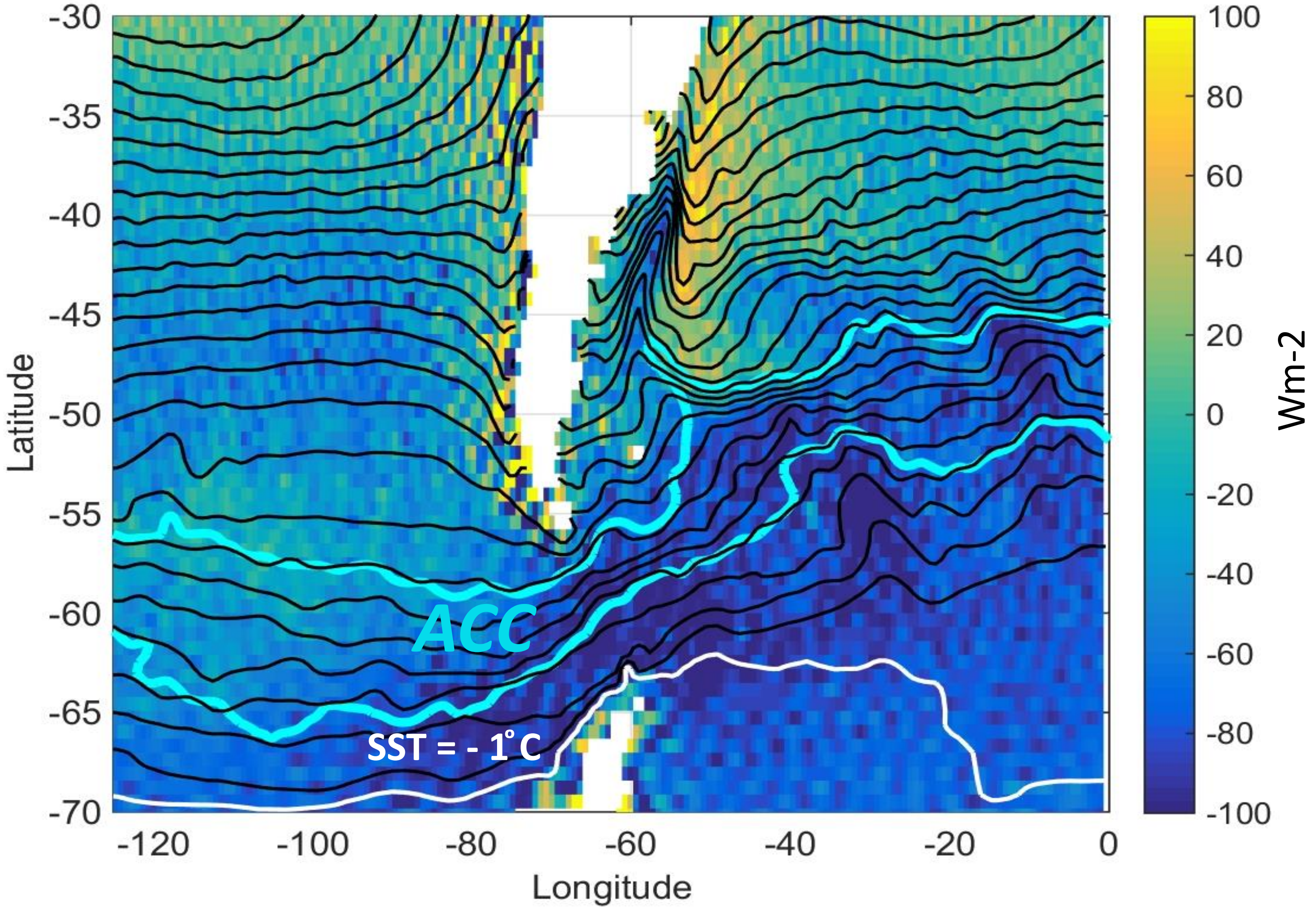
SST (CI = 1K) vs Da (colour): ERAinterim (DJF 2002-2008)

- *New Zealand portion*:
- Strong convergence (Da<0) towards Antarctica following the curving of the ACC south of the Campbell plateau
- The ACC only captures a bit of this feature on its southernmost portion and mostly feels the large scale convergence of the atmospheric heat transport



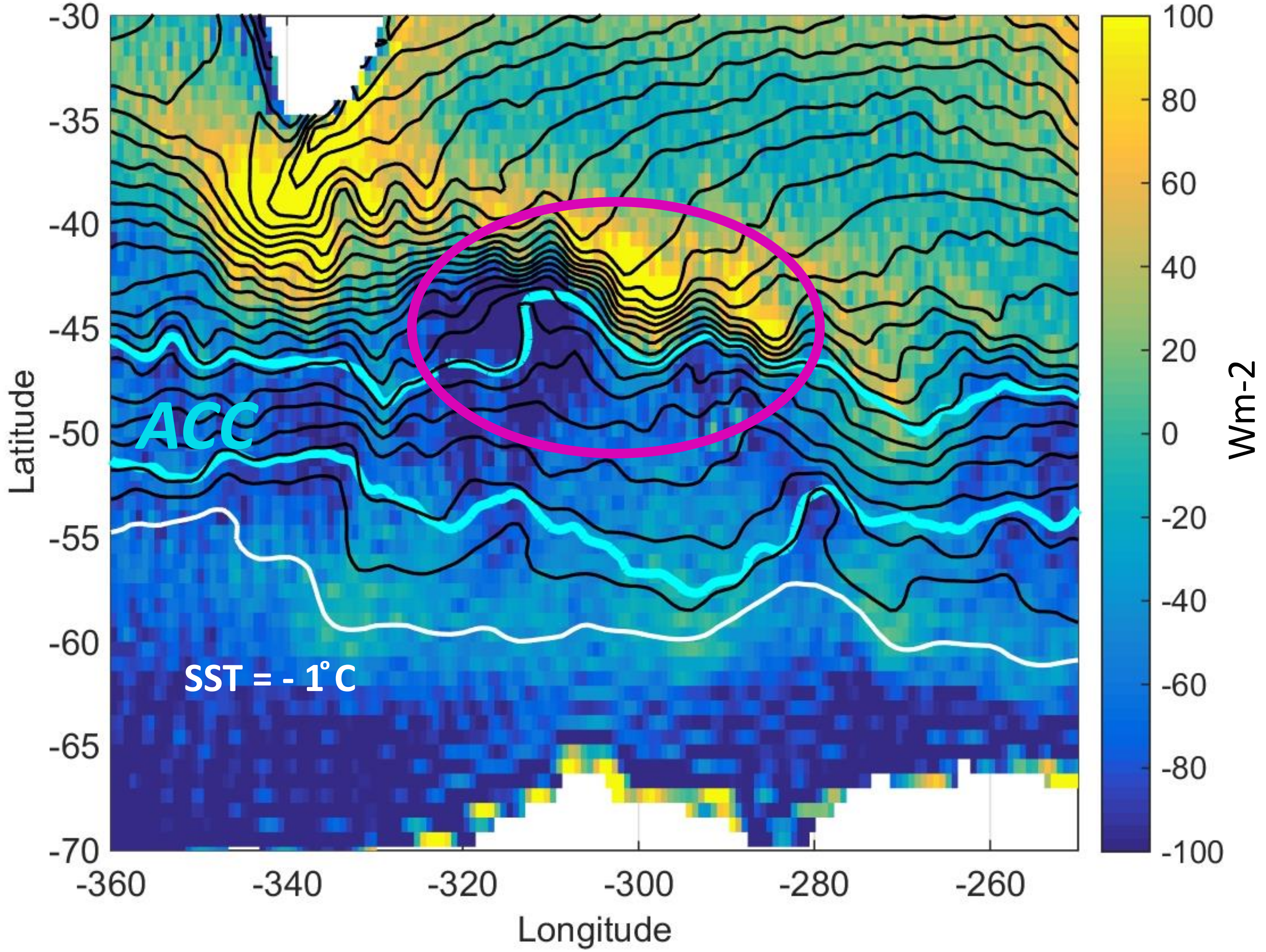
SST (CI = 1K) vs Da (colour): ERAinterim (DJF 2002-2008)

- *__Drake passage portion__*:
- Strong convergence (Da<0) towards Antarctica and dipolar structure in the Malvinas confluence region
- The intensified convergence broadly follows the northeastward tilt of the ACC but is mostly found south of the ACC.



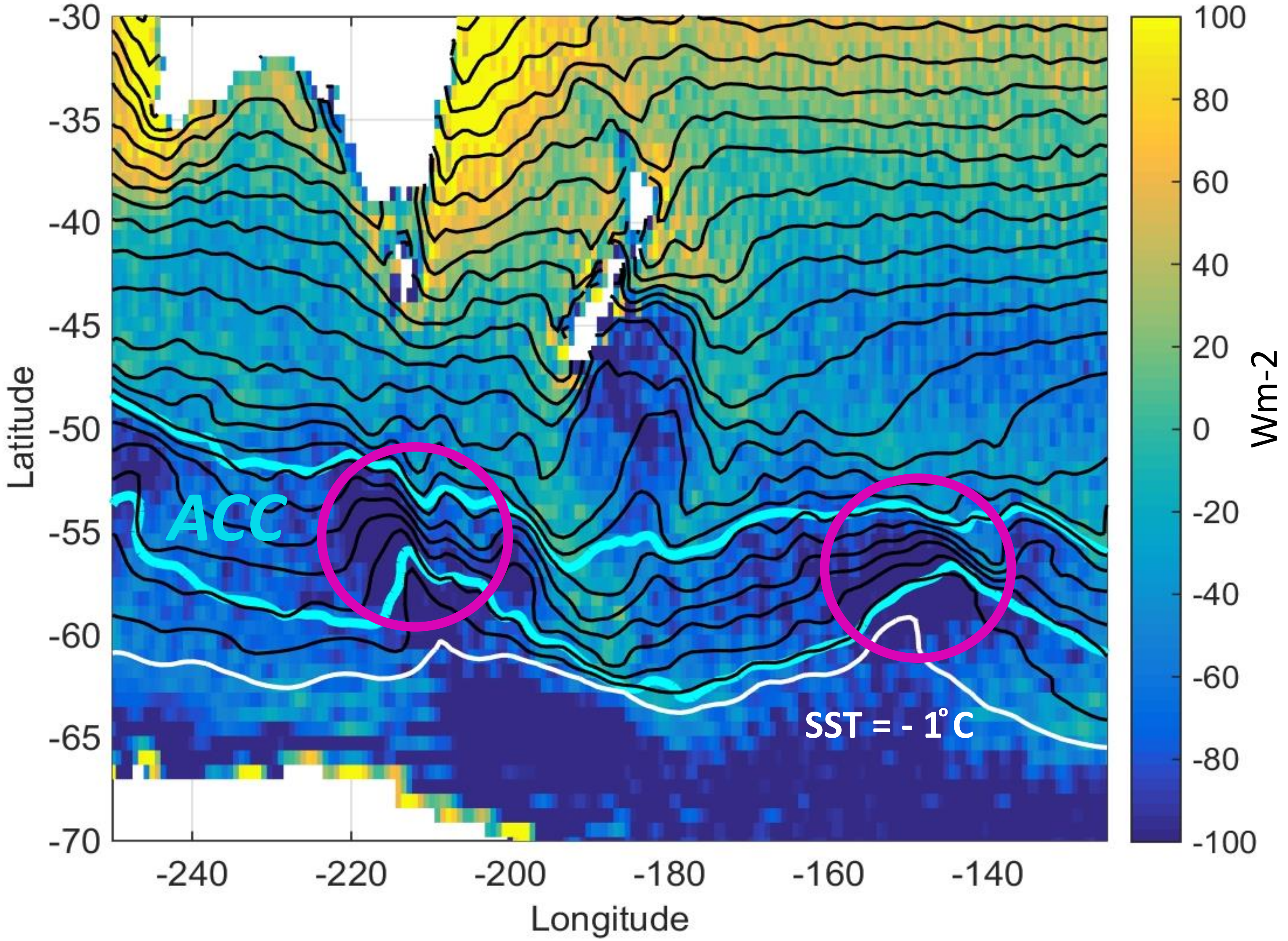
SST (CI = 1K) vs Da (colour): ERAinterim (JJA 2002-2008)

- *<u>Aguhlas portion</u>*:
- Da has a slanted dipolar structure across the strong SST front+convergence over sea-ice
- The ACC captures a bit of this dipole but mostly feels the larger scale convergence of the atmospheric heat transport



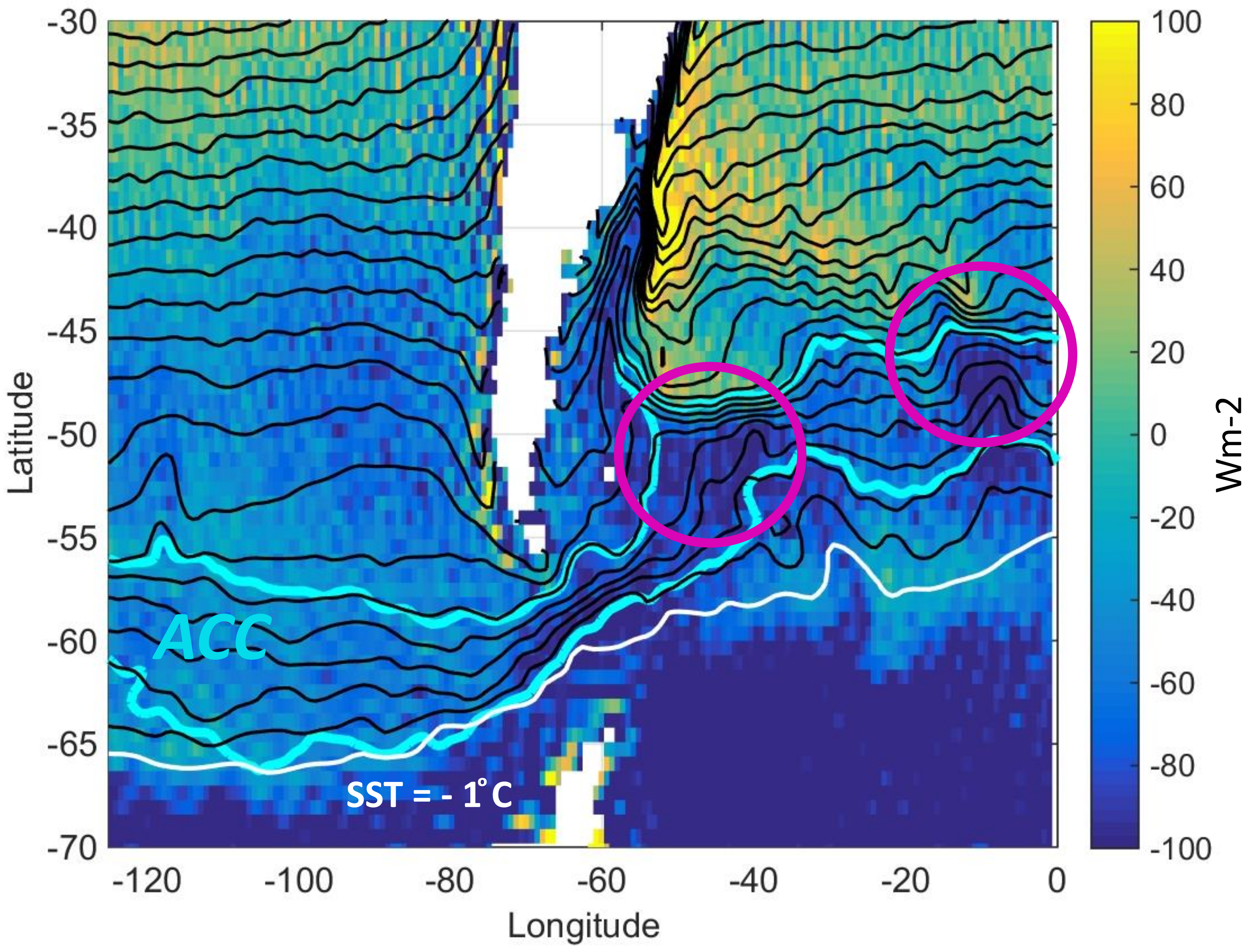
SST (CI = 1K) vs Da (colour): ERAinterim (JJA 2002-2008)

- *New Zealand portion*:
- Strong convergence (Da<0) just south of New Zealand, over the sea-ice and following the curving of the ACC towards Antarctica
- Two features can be related to SST fronts within the ACC. The rest is convergence on large scale

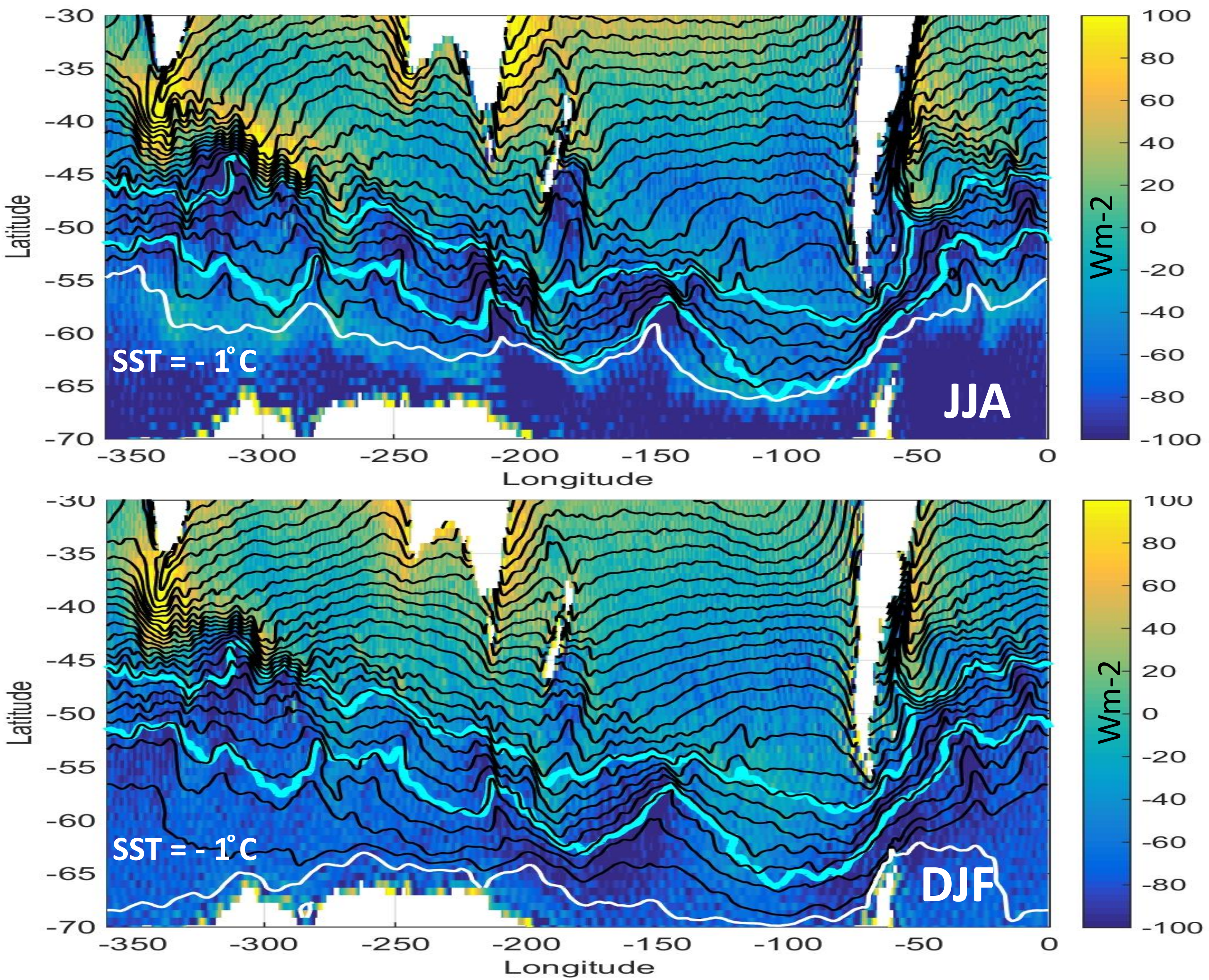


SST (CI = 1K) vs Da (colour): ERAinterim (JJA 2002-2008)

- *<u>Drake passage portion</u>*:
- Strong convergence (Da<0) towards Antarctica and along the ACC at Drake passage, dipolar structure in the Malvinas confluence region
- Two features can clearly be associated with the poleward flank of an SST front



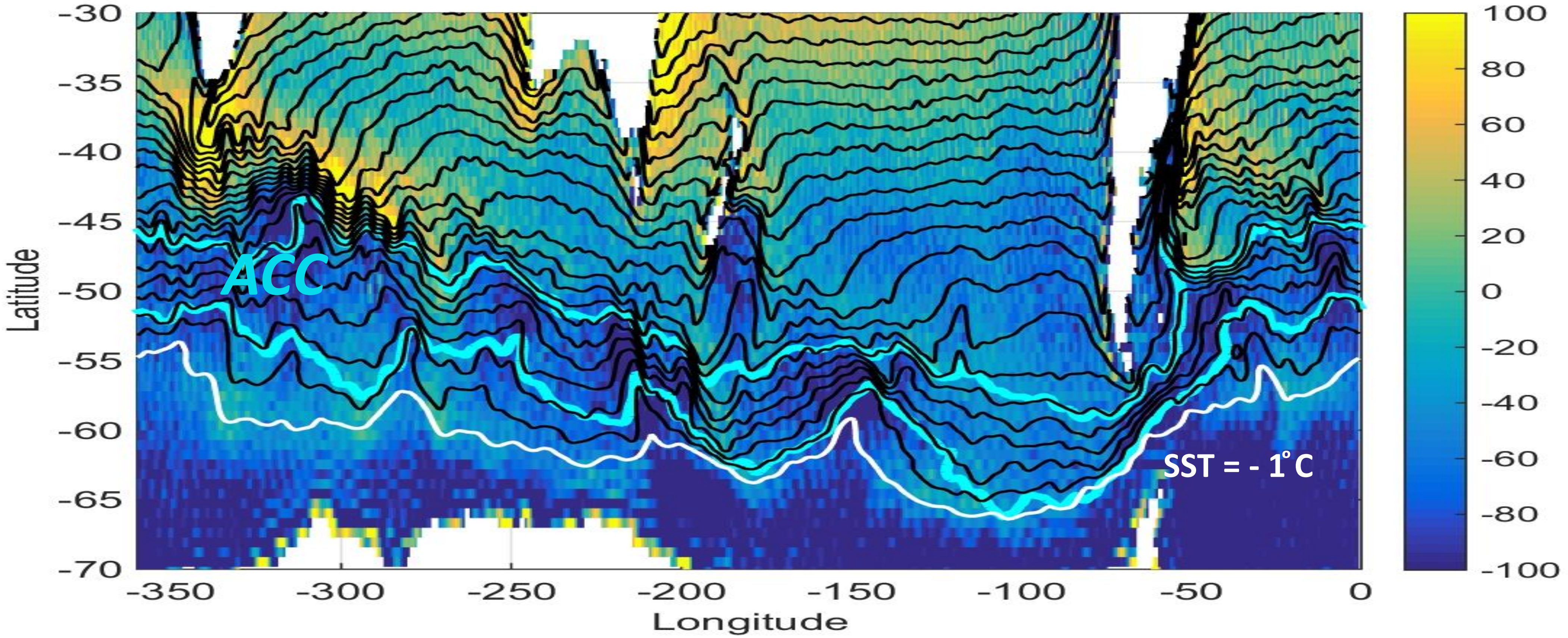
SST (CI=1K) & Da (colour): ERAinterim data (2002-2008)



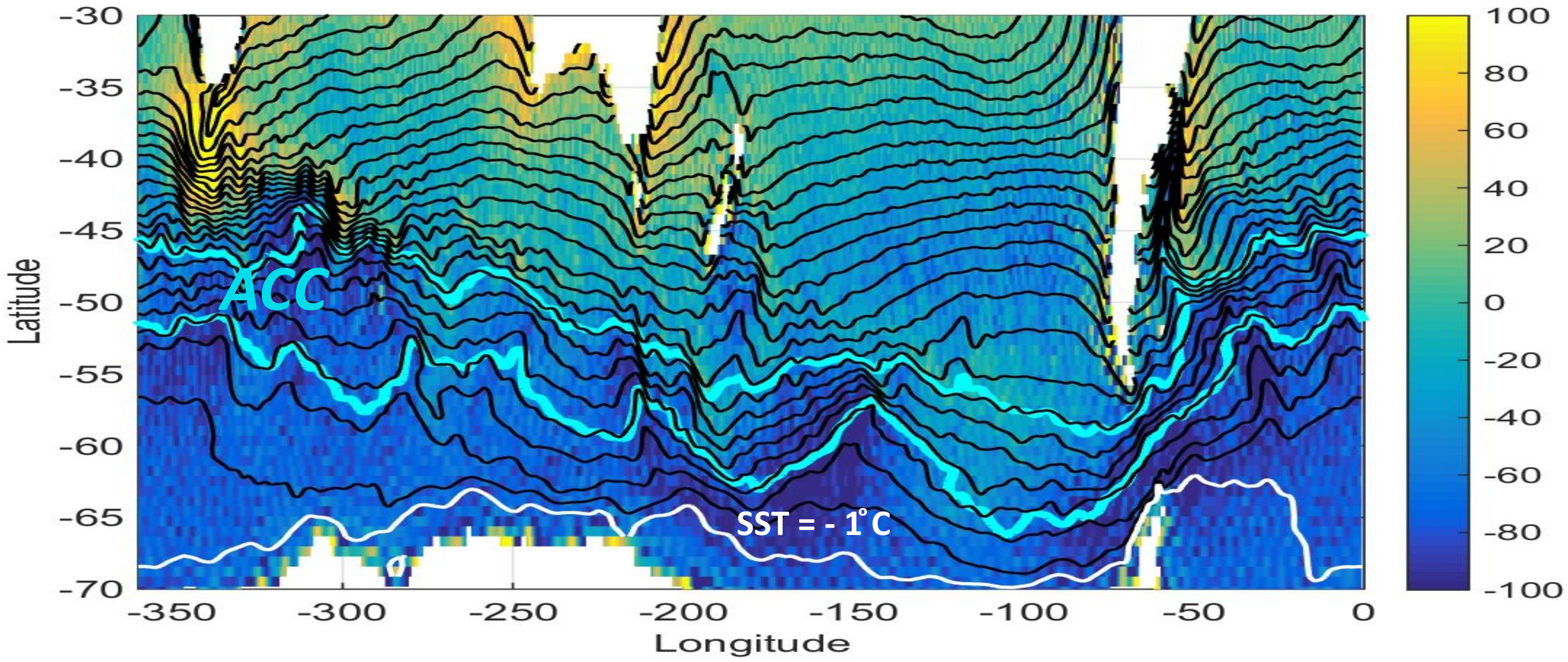
- Some oceanic frontal features are reflected in Da but most of the convergence over the ACC is large scale

ACC streamlines from Maximenko et al. (2009)

Atm. heat trspt. div. Da (colour) and SST (CI = 1K) –ERAinterim (JJA, 2002-2008)



Atm. heat trspt. div. Da (colour) and SST (CI = 1K) –ERAinterim (DJF, 2002-2008)



Estimating the diffusive feedback

- "From 1st principles"

$$D_a \approx -\kappa(\nabla^2 h)\Delta P / g = -\kappa(\nabla^2 c_{eff} SST)\Delta P / g$$

$$with\ c_{eff} = c_p + l_v dq / dSST$$

$$For \quad \kappa = 2.10^6 m^2 s^{-1}, c_{eff} = 5000 Jkg^{-1}K^{-1},$$

$$L = 1000km, \Delta P = 500hPa \rightarrow \gamma_{diff} = 10Wm^{-2}K^{-1}$$

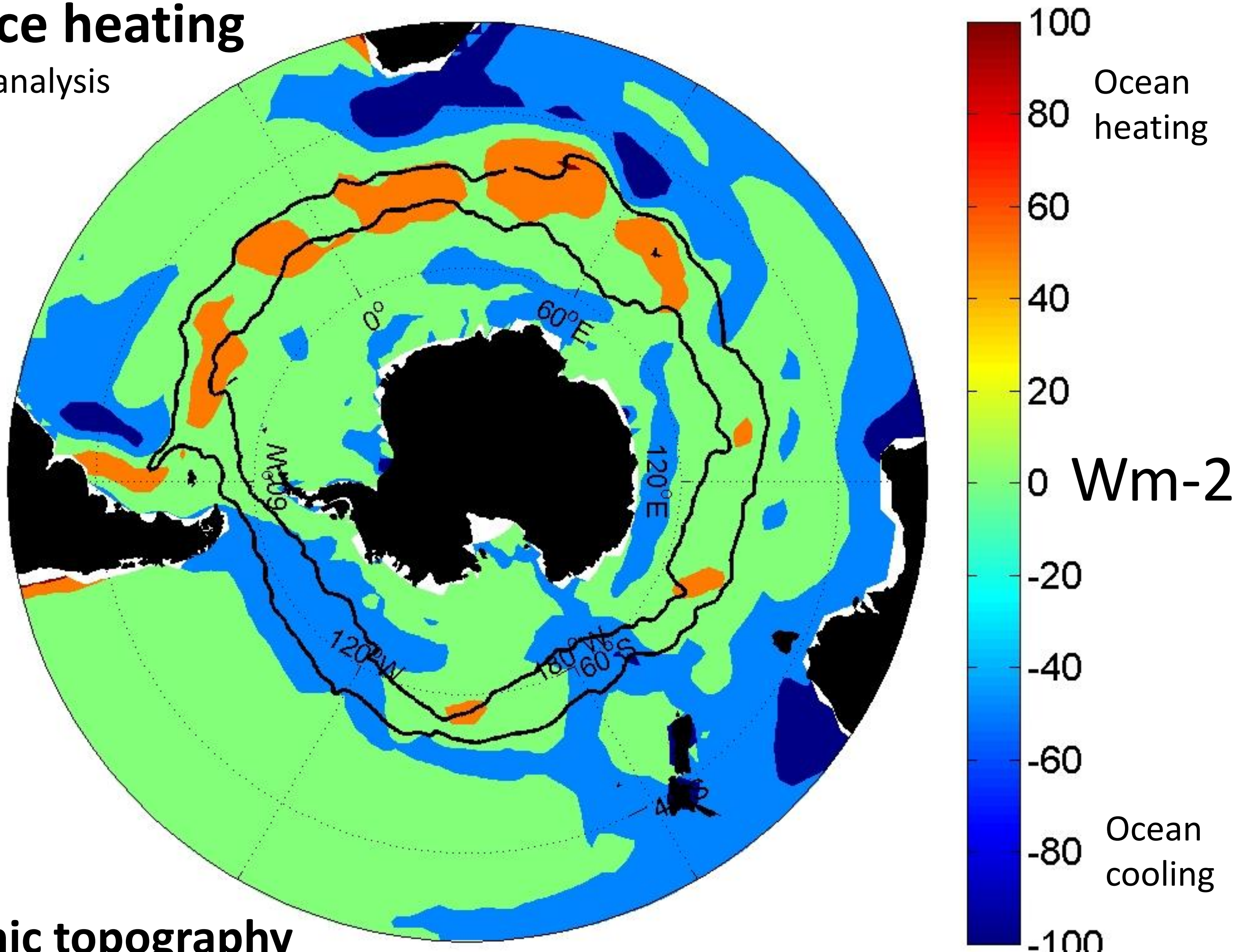
- From observations

$$D_a(SO) \approx D_{a,LS} \ \& \ D_a(NA) = \gamma_{diff} SST_o + D_{a,LS}$$

$$\therefore \gamma_{diff} \approx [D_a(NA) - D_a(SO)] / SST_o \approx [-10 + 70] / 6 \deg C = 10Wm^{-2}K^{-1}$$

Net surface heating

NCEP-NCAR reanalysis
(1980-2012)



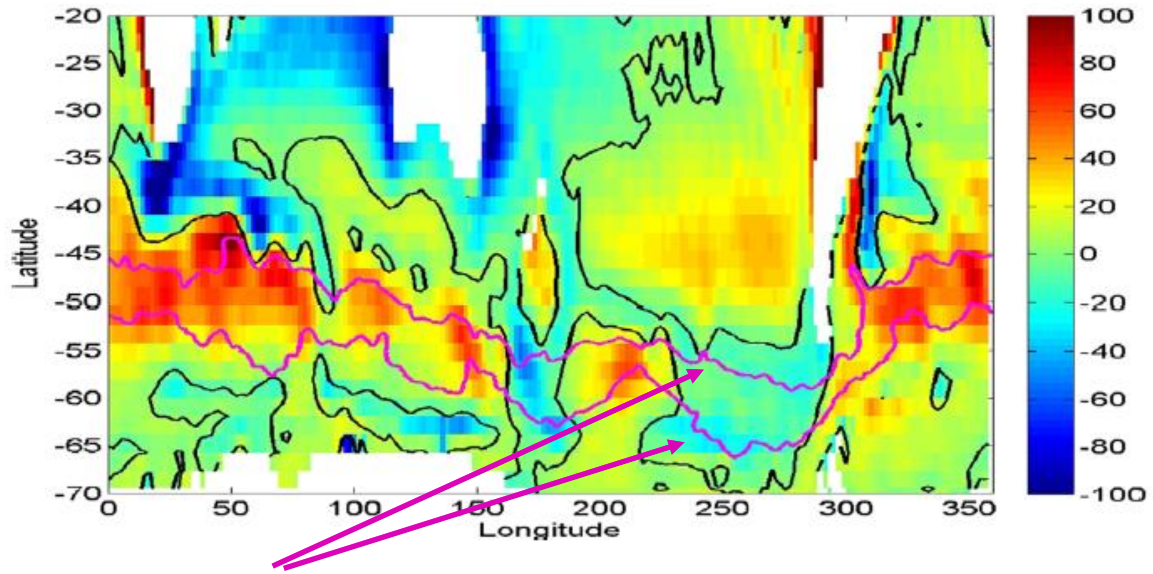
ACC dynamic topography

(-130 and -60 cm contoured)
Mean over 1992-2002 from Maximenko et al. (2009)

Surface heating in reanalyses data (NCEP 1980-2012)

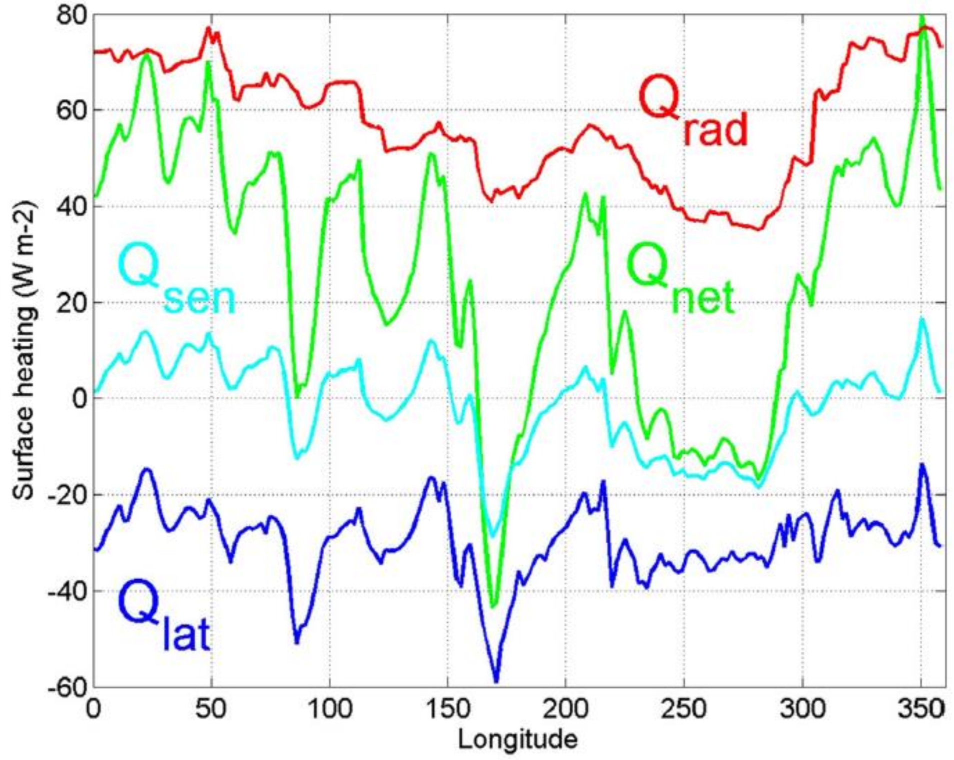
- Net heating (~+30Wm-2) is a residual between net radiative gain (~+60Wm-2) and surface latent heat loss (~-30Wm-2)

Net air-sea heat flux, annual mean



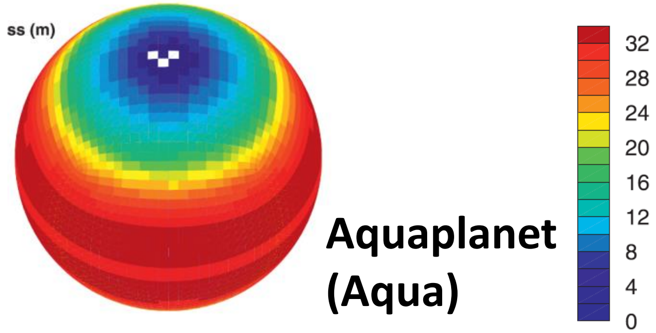
ACC streamline using Maximenko et al. (2009) mean dynamic ocean topography

ACC streamline-averaging of the various annual mean heat flux components

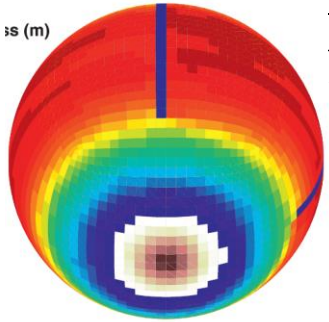


Surface heating in coupled MITgcm
(Ferreira et al., 2010,2011)

- Two set-ups: Aquaplanet and Double-Drake
- "ACC" within the 40S-60S band
- Warm aquaplanet, no heating on the poleward flank of the ACC and cooling on its equatorward flank
- Double Drake has weak surface heating of the ACC
- Main difference between the two is enhanced latent heat loss in the aquaplanet expt.

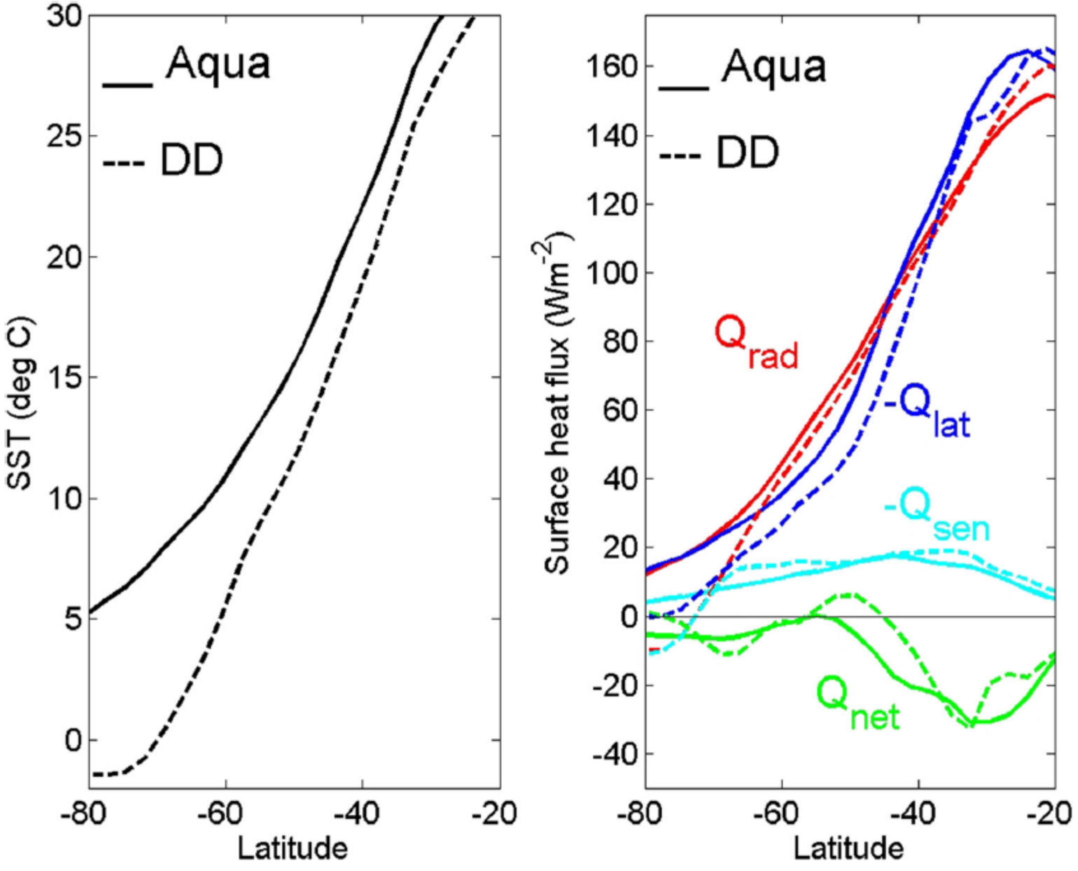


Aquaplanet (Aqua)



Two land barriers from 35S to 90N, 90 degrees apart

Double Drake (DD)



Summary of air-sea interactions over ACC

Averaging	ACC streamline	45° S–60° S	45° S–55° S	45° S–55° S
Data source	NCEP-NCAR reanalysis	NCEP-NCAR reanalysis	MITgcm "Aquaplanet"	MITgcm "Double Drake"
Q_{net}	+28	+20	−4	+4
Q_{sen}	−1	−4	−14.8	−15.9
Q_{lat}	−30	−35	−60.9	−47.6
Q_{rad}	+59	+59	+71.6	+67.5
SST	3.9	4.6	15.3	11.4

NB: Fluxes in Wm-2, SST in degree Celcius

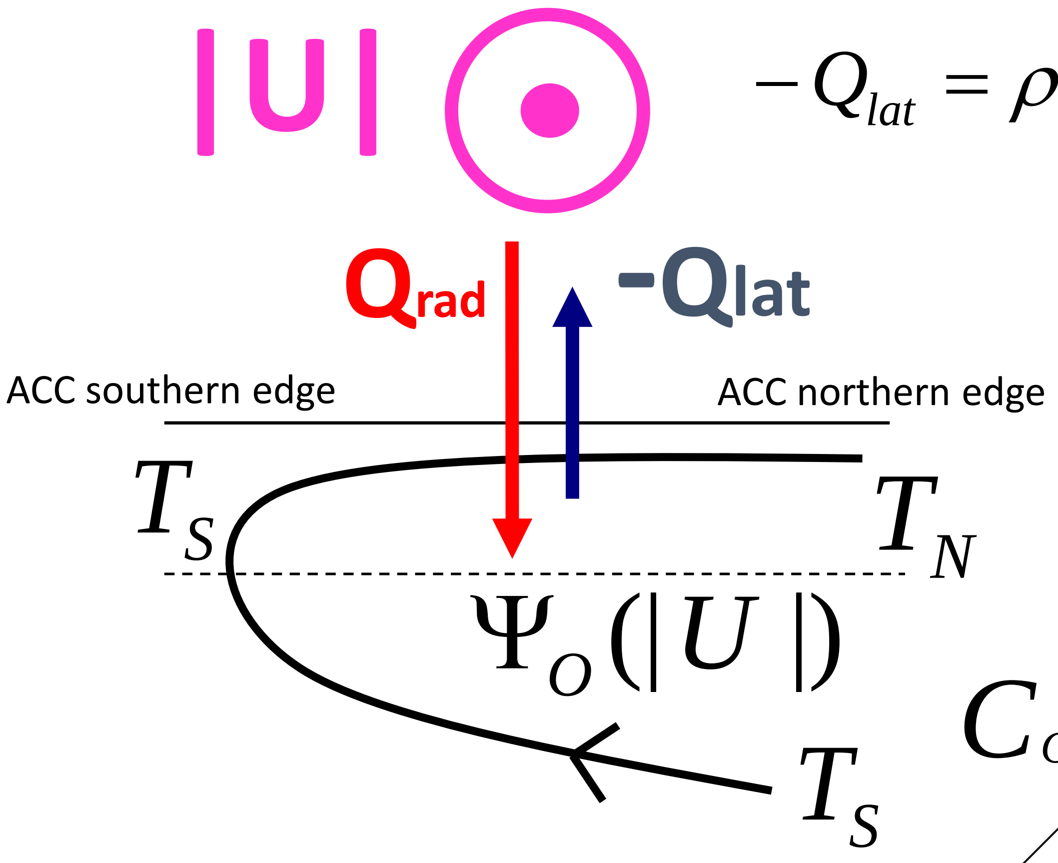
Mechanisms

- What fraction of a given surface radiative heating can be converted into ACC surface heating?

- What controls whether there is heating at all? The atmospheric view of the problem.

Air-sea interaction model for ACC surface heating

(Czaja and Marshall, 2015)



$$-Q_{lat} = \rho_a C_D |U| l_v (1-RH) q_{sat}\left(\frac{T_N + T_S}{2}\right)$$

windspeed

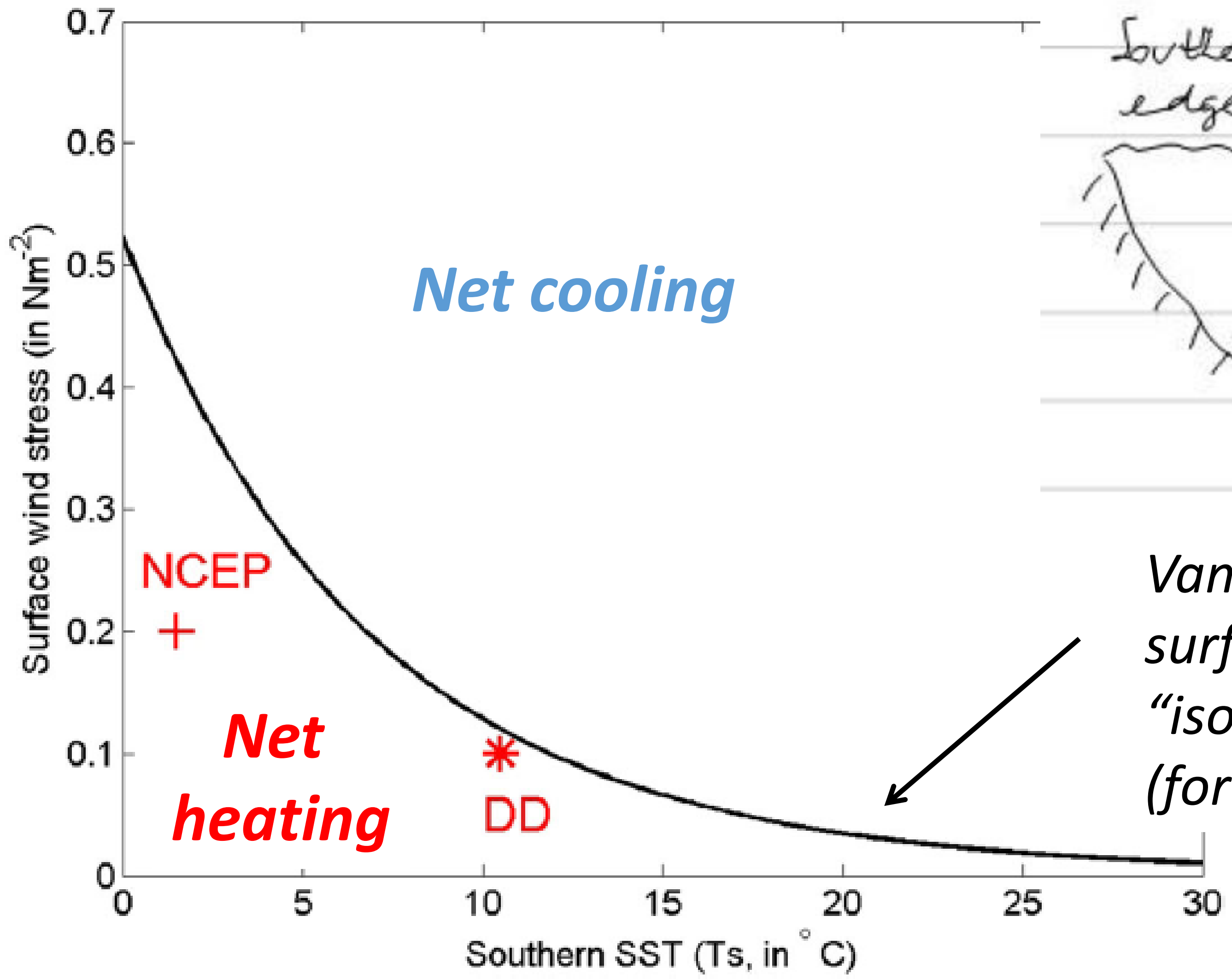
Set to 0.8

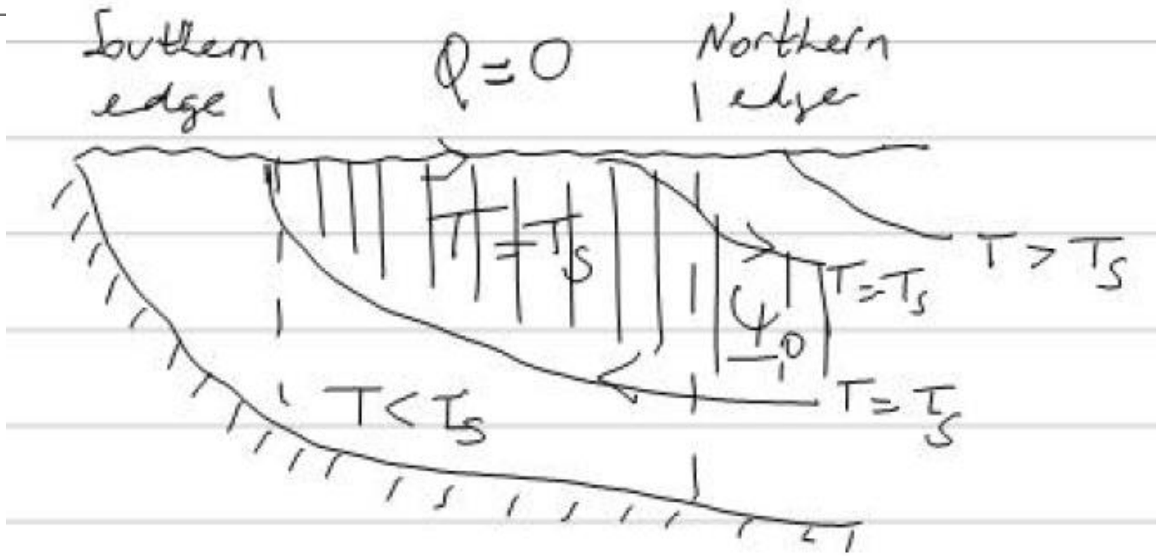
$$C_O \Psi_O (T_N - T_S) = A_{ACC}(Q_{rad} + Q_{lat})$$

Strength of residual Circulation (assumed to be a linear function of windstress from Abernathey et al., 2012)

Temperature at southern edge of ACC = T of upwelled water

Model prediction: heating and cooling regimes





Vanishing of the net surface heat flux: the "isothermal ACC" limit (for Qrad = 60Wm-2)

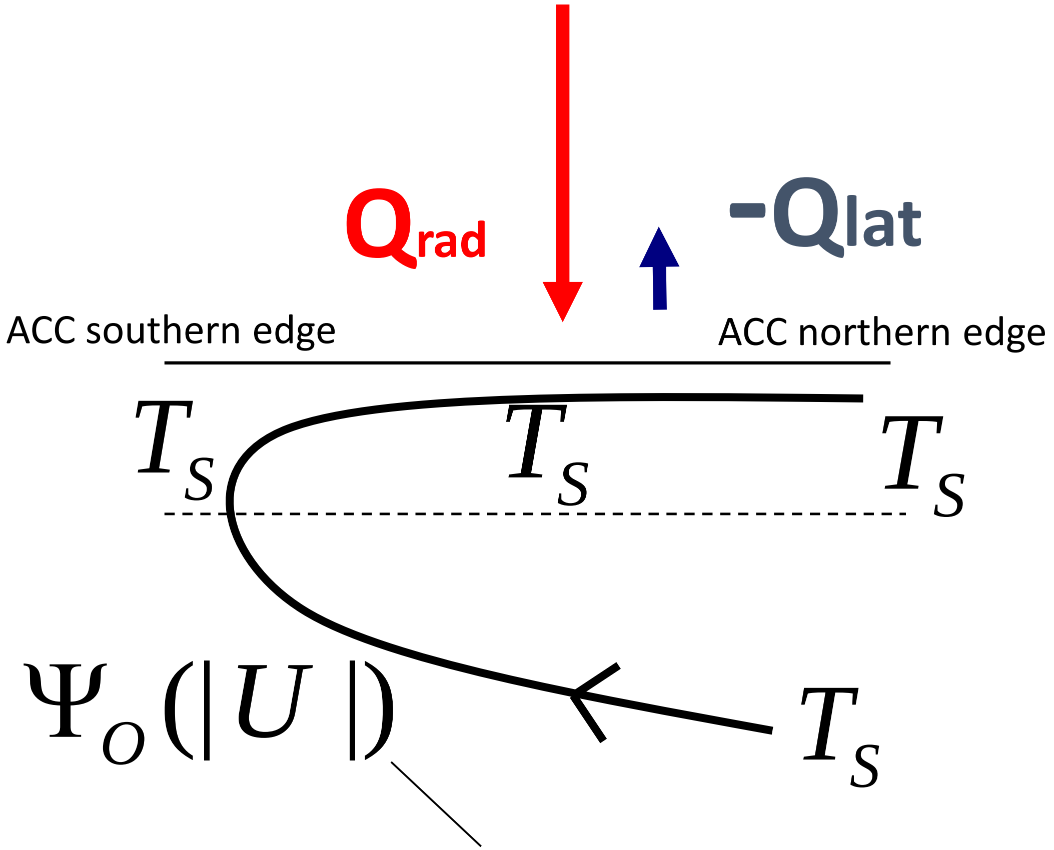
Model prediction: “heating efficiency”

- Prescribe a given amount of net radiative heat gain Qrad
- Work out the fraction ŋ going into net heating of the ocean

$$\eta \approx 1 - \frac{|Q_{lat}|}{Q_{rad}}$$

“heating efficiency”

Thought experiment: start with isothermal ACC with very large mixed layer heat capacity



Strength of residual Circulation (assumed to be a linear function of windstress from Abernathey et al., 2012)

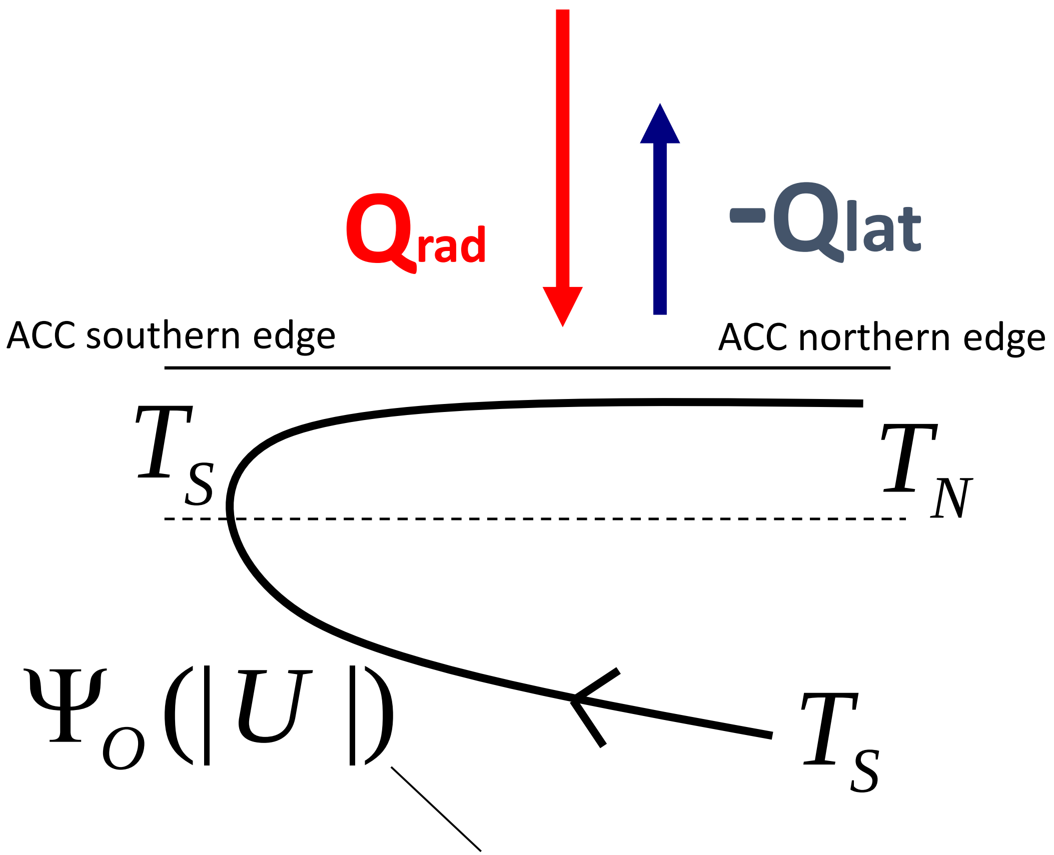
→Temperature remains unchanged

→Qlat is fixed by Ts and surface winds

→Heating efficiency $\eta = \eta_s$ with:

$$\eta_S = 1 - \rho_a C_E U l_v (1 - RH) q^{\star}(T_S)/Q_{rad}$$

…then suddenly allow for finite mixed layer heat capacity



Strength of residual Circulation (assumed to be a linear function of windstress from Abernathey et al., 2012)

→Surf. temperature now changes

→Cooling must oppose Qrad to reach a steady state

→Whether it is through advection or Qlat depends on the relative magnitude of air-sea heat flux ($\gamma_{air\text{-}sea}$) and advective (γ_{adv}) feedbacks

→Heating efficiency η now given by:

$$\eta = \eta(\eta_S, \gamma_{air-sea}, \gamma_{adv})$$

Model prediction at fixed radiative heat gain: ŋ=heating efficiency= (Qnet/Qrad)

- Application to NCEP suggests current ACC is ¾ of ŋs (cold Ts, strong surface winds, γ_{adv}=6 Wm-2K-1, $\gamma_{air\text{-}sea}$ = 2 Wm-2 K-1)
- Application to Double-Drake: weak efficiency explained by warm Ts
- Not applicable to Aquaplanet (neglect of "residual eddy heat fluxes" in the mixed layer)

Analytic solution for linear Clausius-Clapeyron equ.

$$\eta = \eta_S/(1+\gamma_{air-sea}/\gamma_{adv})$$

in which

$$\eta_S = 1 - \rho_a C_E U l_v (1-RH) q^\star(T_S)/Q_{rad}$$

$$\gamma_{air-sea} = \rho_a C_E U l_v (1-RH)\left(\frac{\partial q^\star}{\partial T}\right)_{T=T_S}$$

$$\gamma_{adv} = \frac{2 c_o \psi_b}{A_{ACC}}$$