IMPACTS OF OVERTURN ON OCEAN HEAT AND CARBON FLUXES, AND ECOSYSTEM PROCESSES

Alison Macdonald (WHOI)

With thanks to Susan Lozier, Mary Jane Perry, Galen McKinley and others

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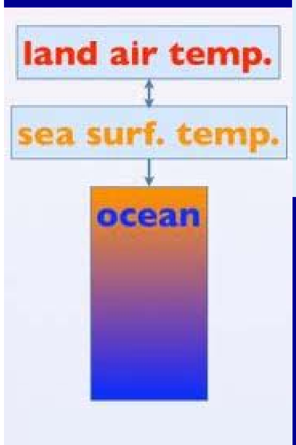
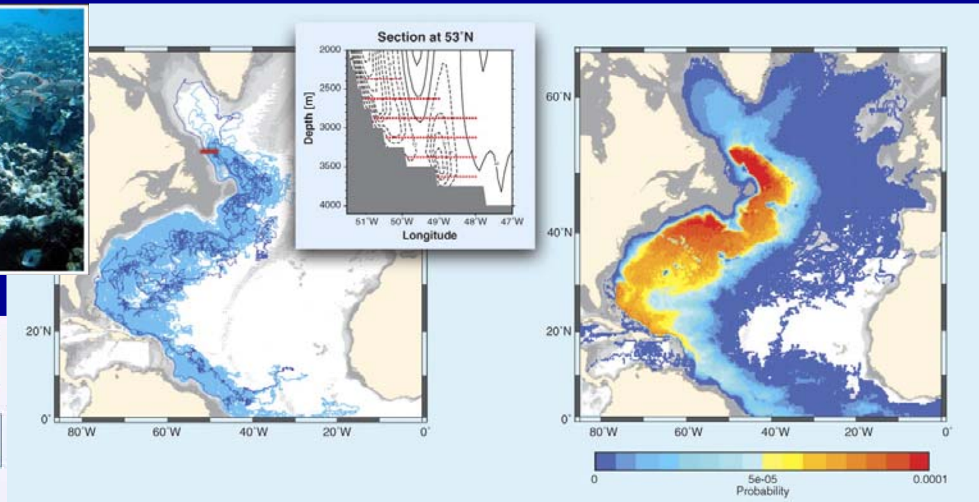
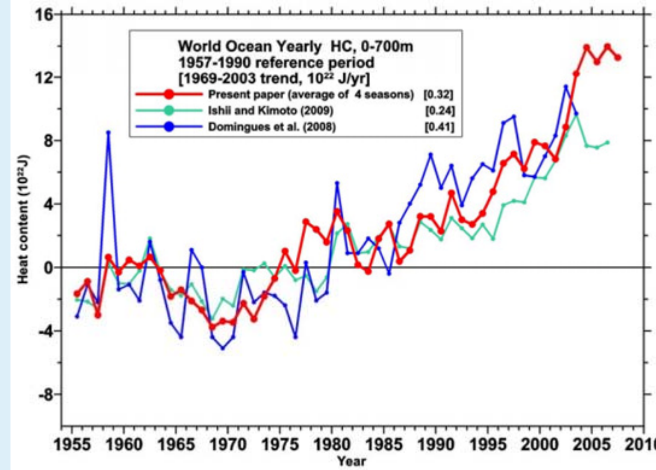
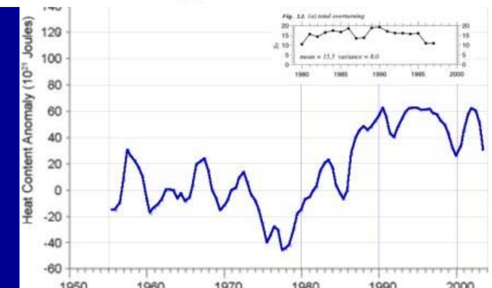
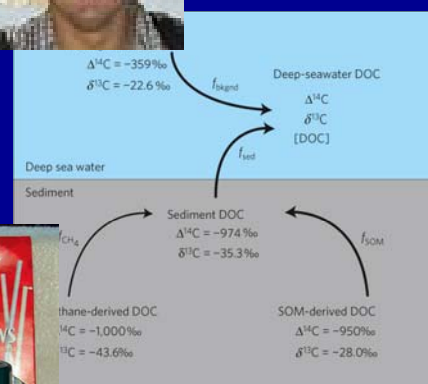
overturn ocean heat carbon ecosystems

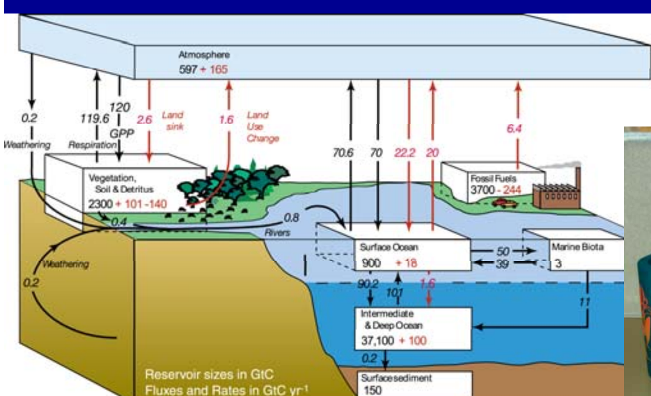


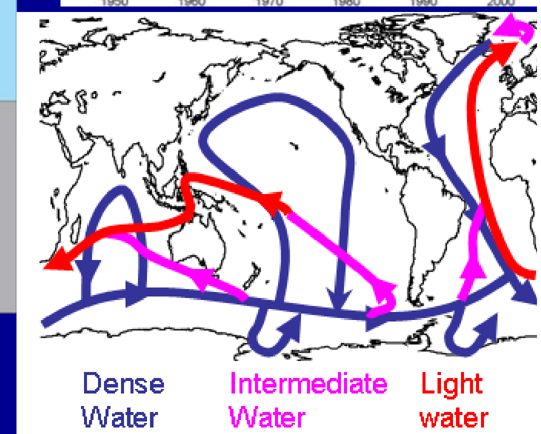










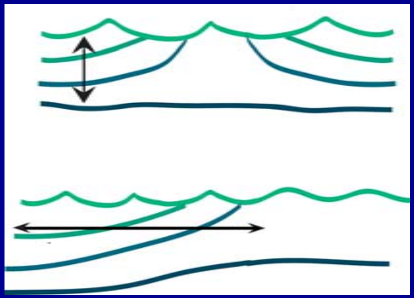


Outline

- Overturn – what is it?
- Overturn and heat transport
- Variability – what do we know?
- Overturn carbon transport
- The connection to ecosystem processes
- Dash toward: What are the questions?

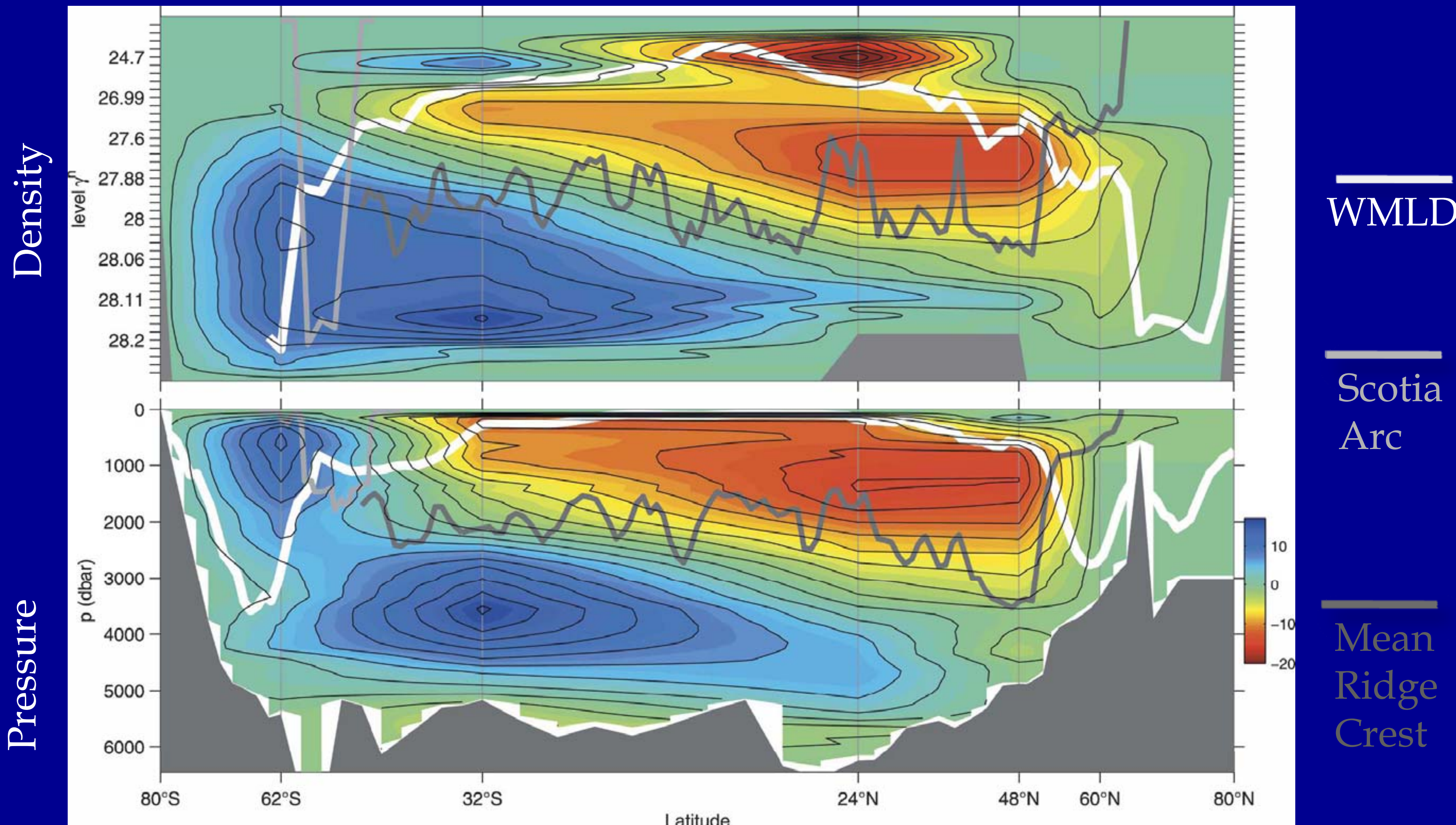
Overturn:
cross isopycnal flow

- Often associated with thermohaline circulation
- Can also be wind driven
- Vertical
- Horizontal



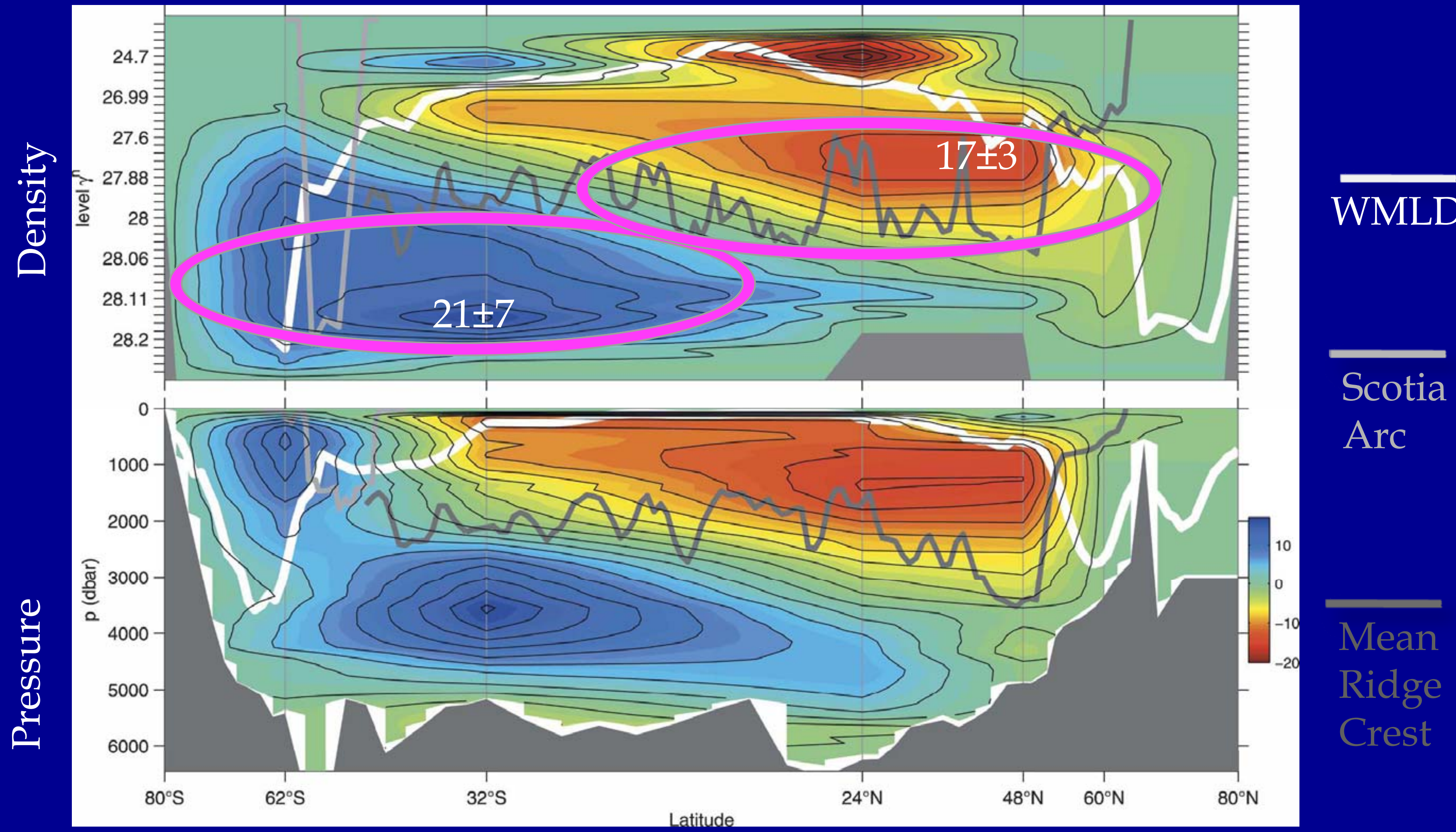
- Occurs on a variety of spatial and temporal scales
- Local processes with global connections & feedbacks
- A fundamental component of the climate system
- Where to begin?

Global, Zonally Integrated Estimate of Overturn



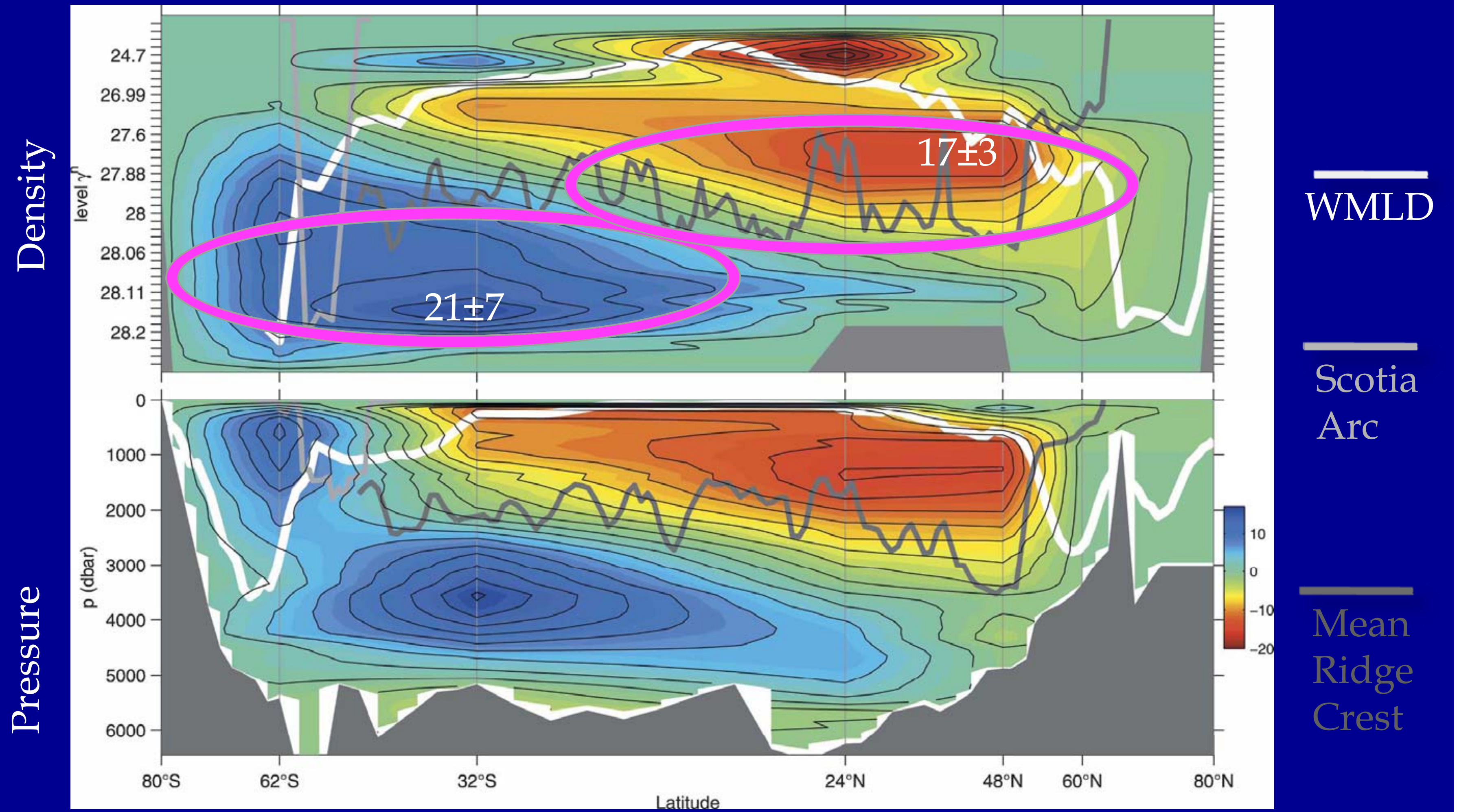
Lumpkin & Speer, 2007

Global, Zonally Integrated Estimate of Overturn



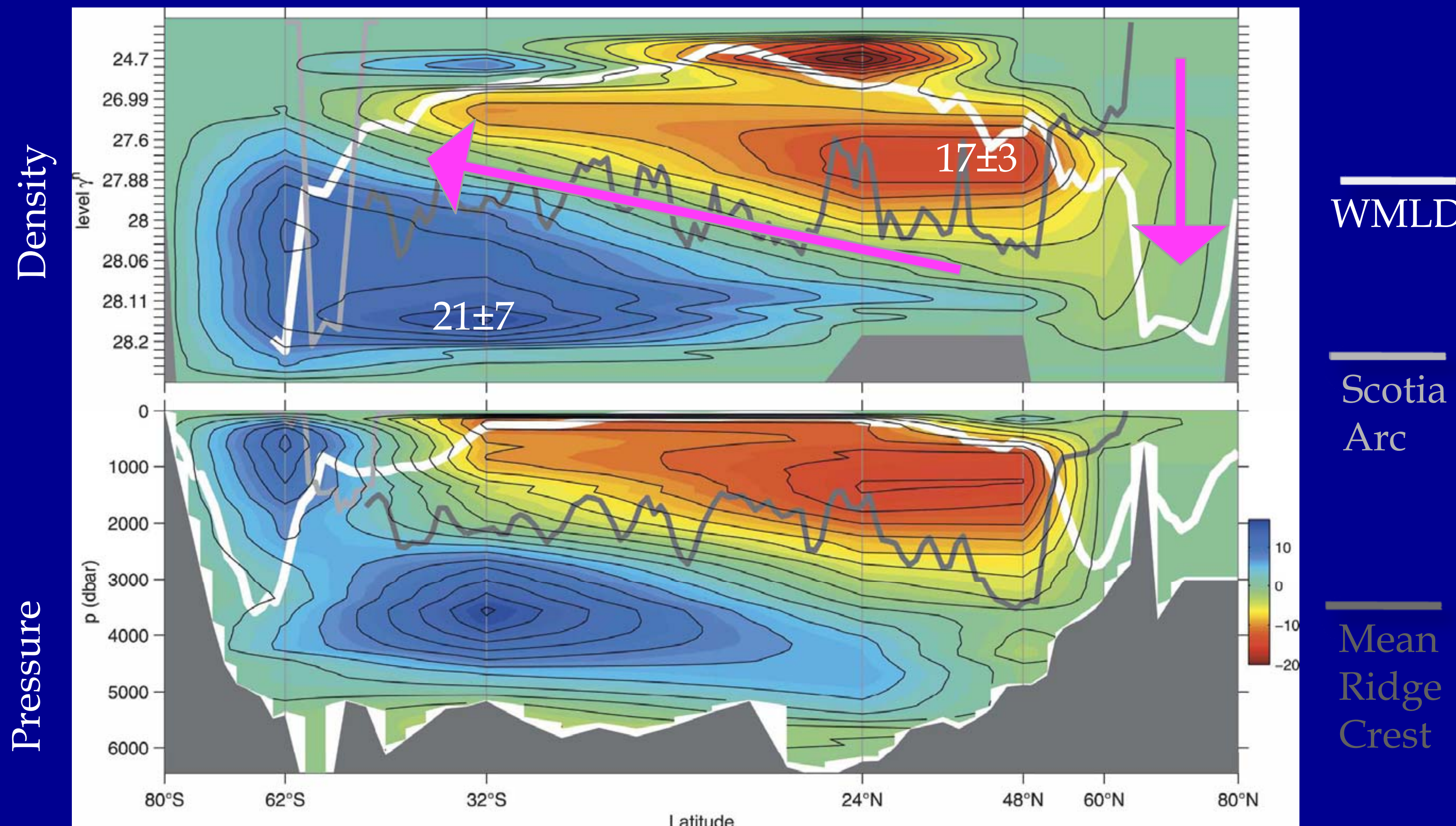
Lumpkin & Speer, 2007

Dense overflows and outflows account for most of the lower cell and ~1/2 of the upper cell.



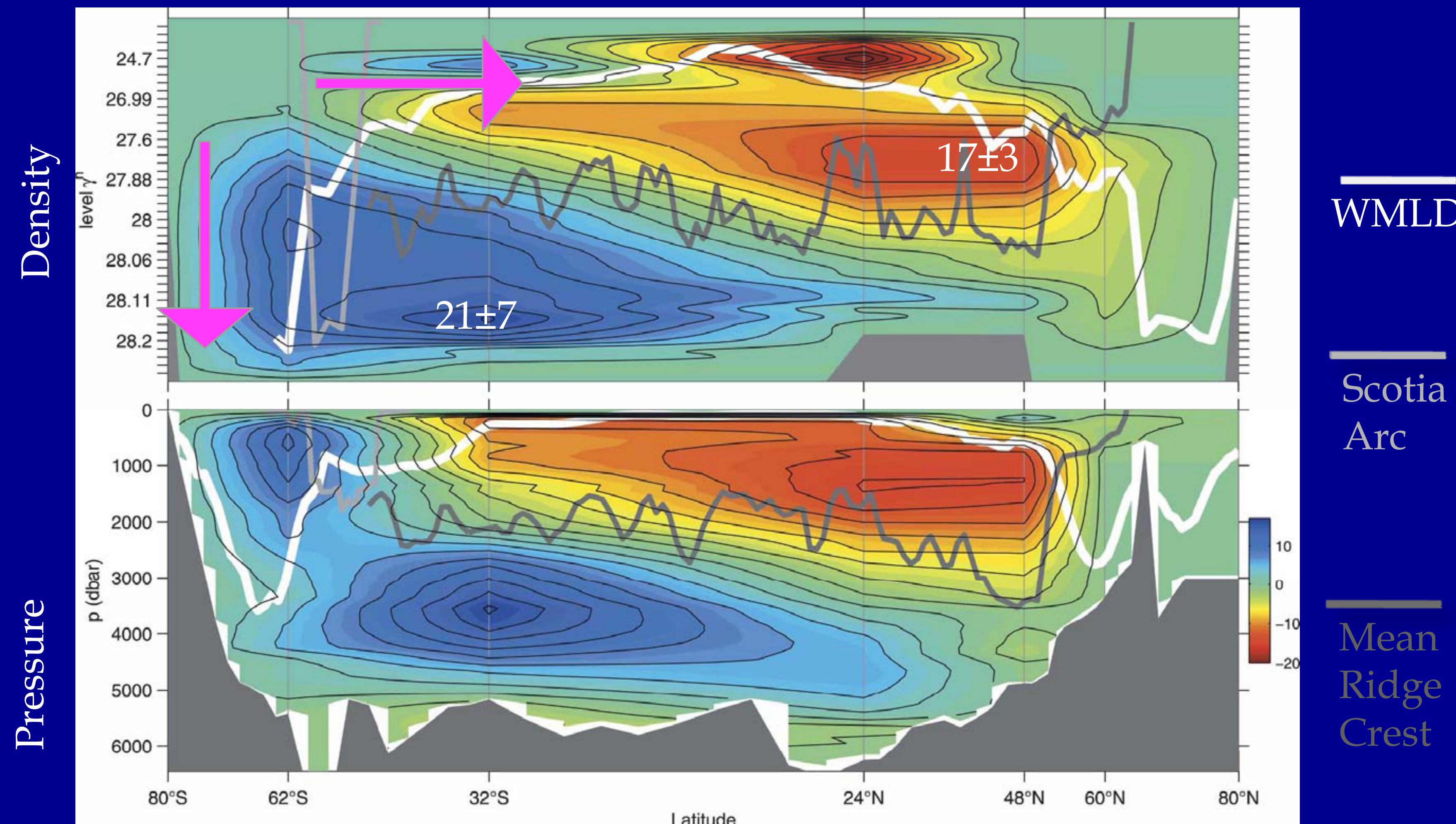
Lumpkin & Speer, 2007

In the north: surface and subsurface transformations



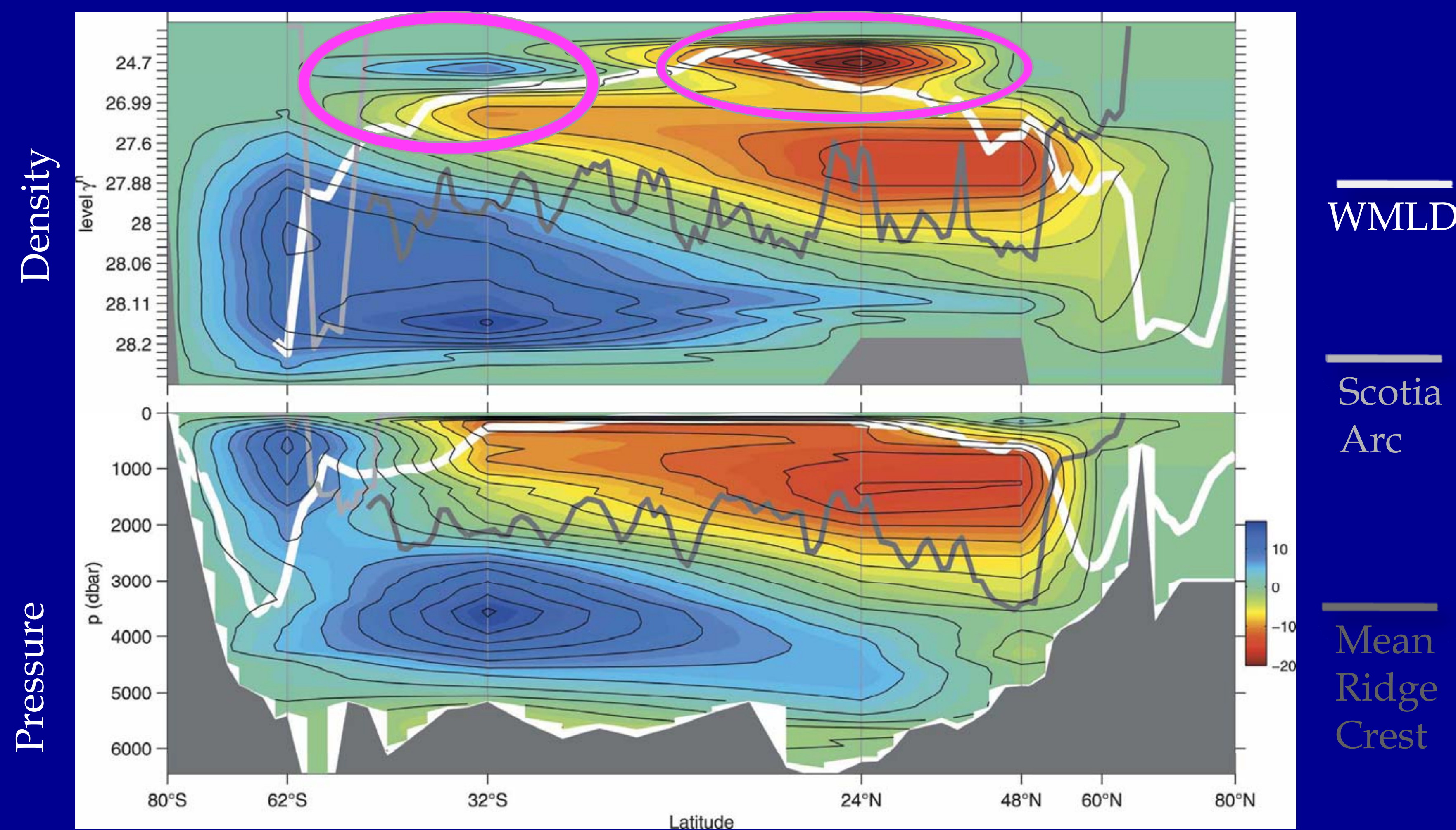
Lumpkin & Speer, 2007

In the south: flows split

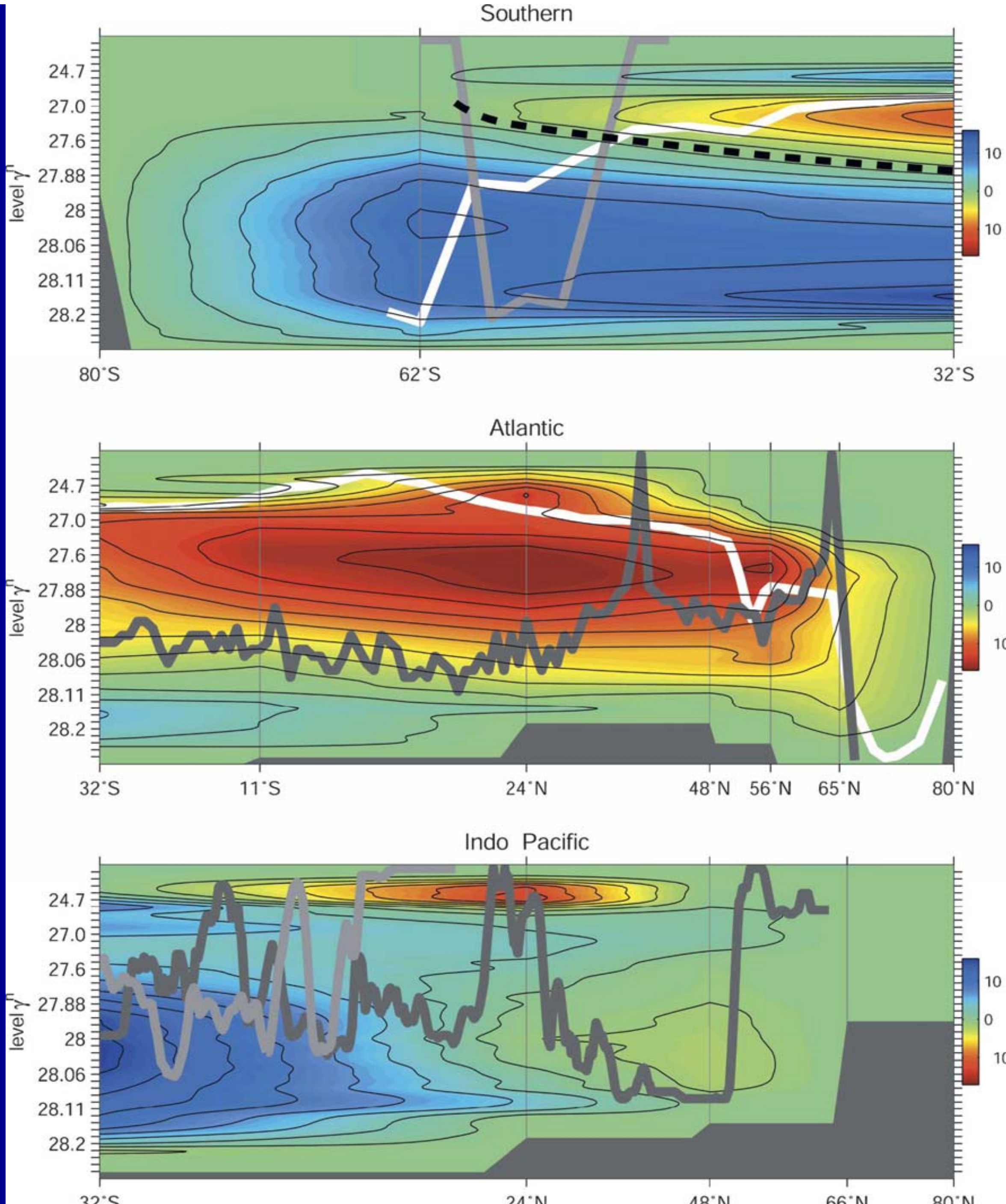


Lumpkin & Speer, 2007

Shallow Overturn

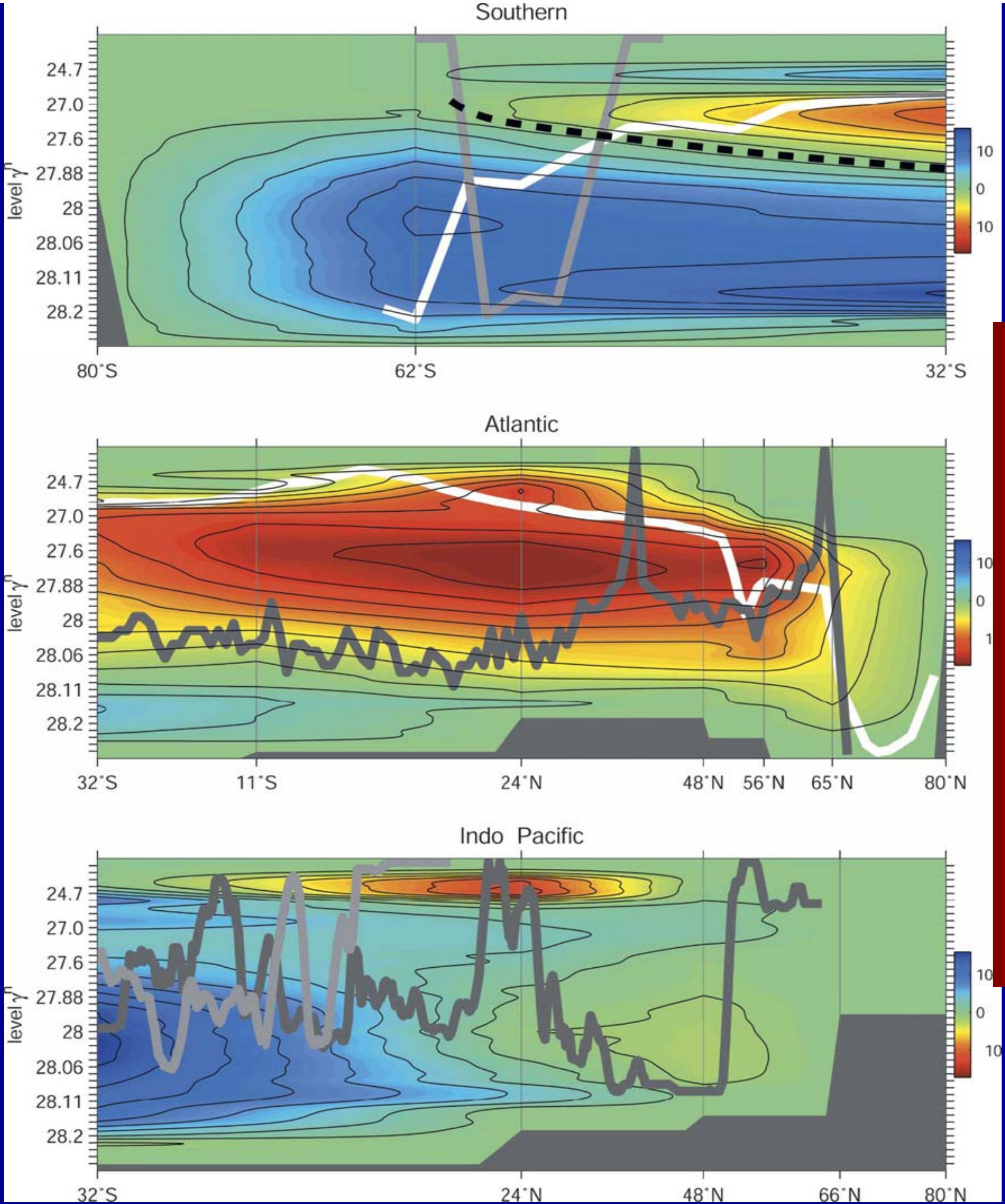


Lumpkin & Speer, 2007



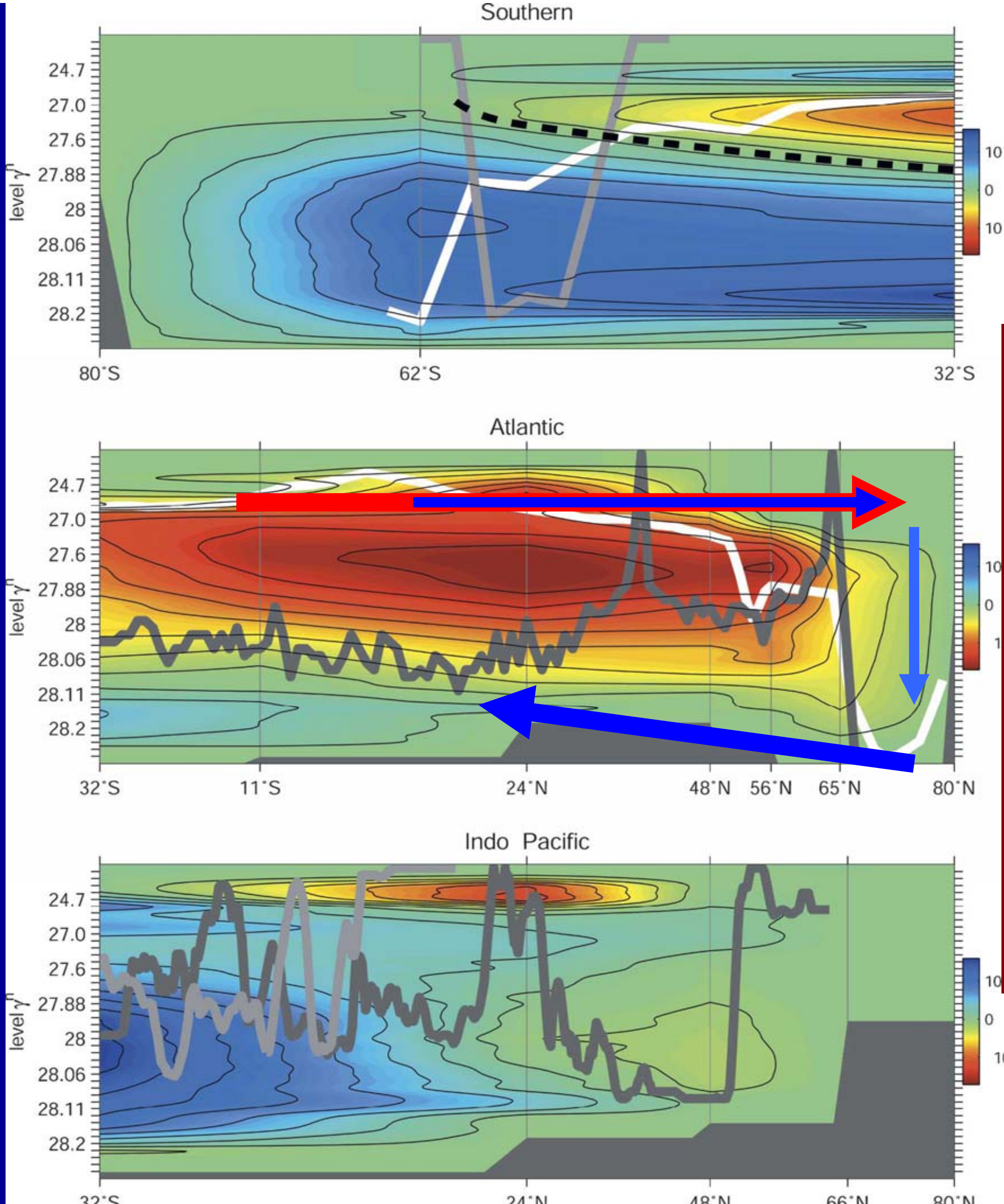
Basin Integrated Overturn

Lumpkin & Speer, 2007



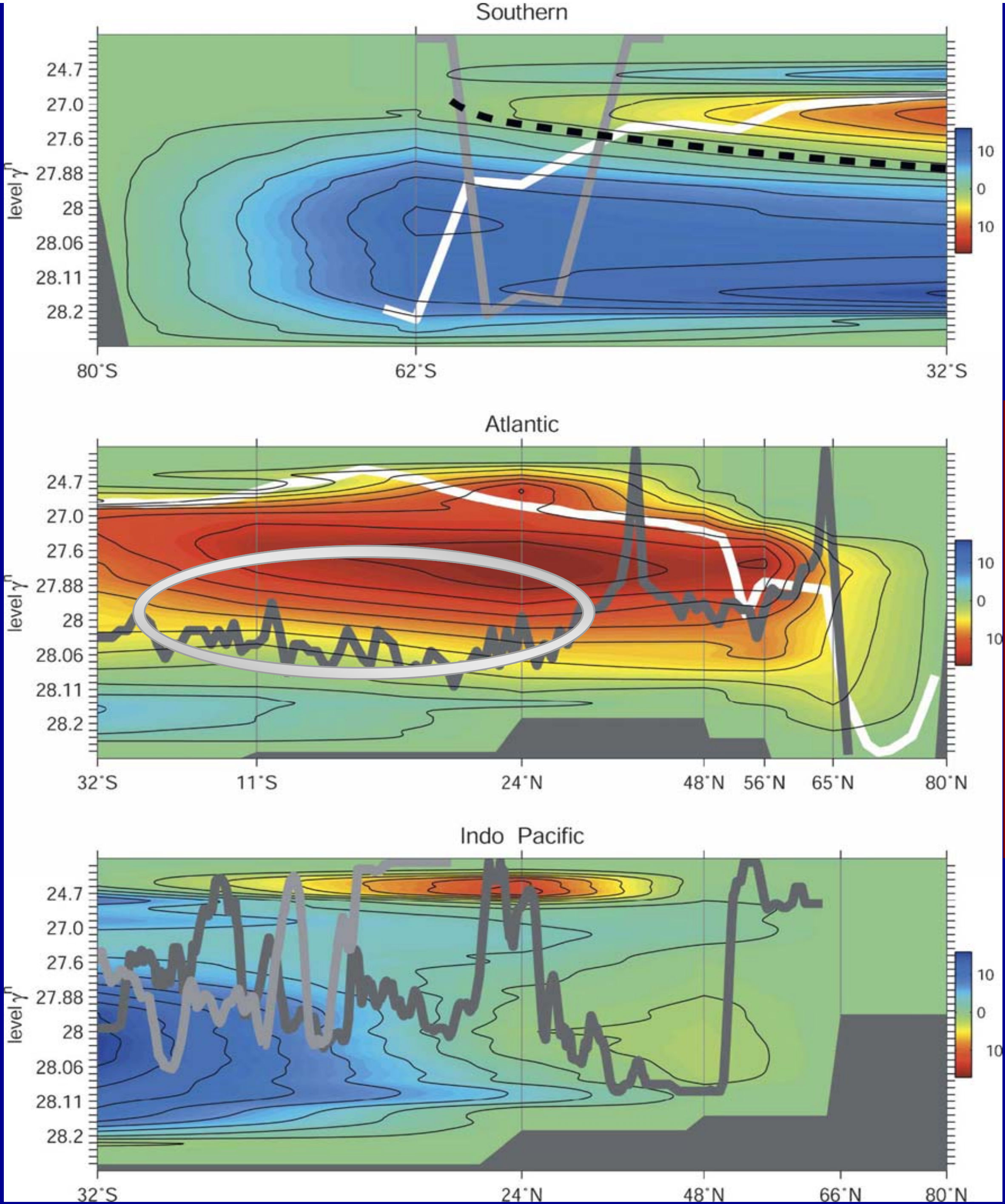
Atlantic Meridional Overturning Circulation (AMOC)

Lumpkin & Speer, 2007



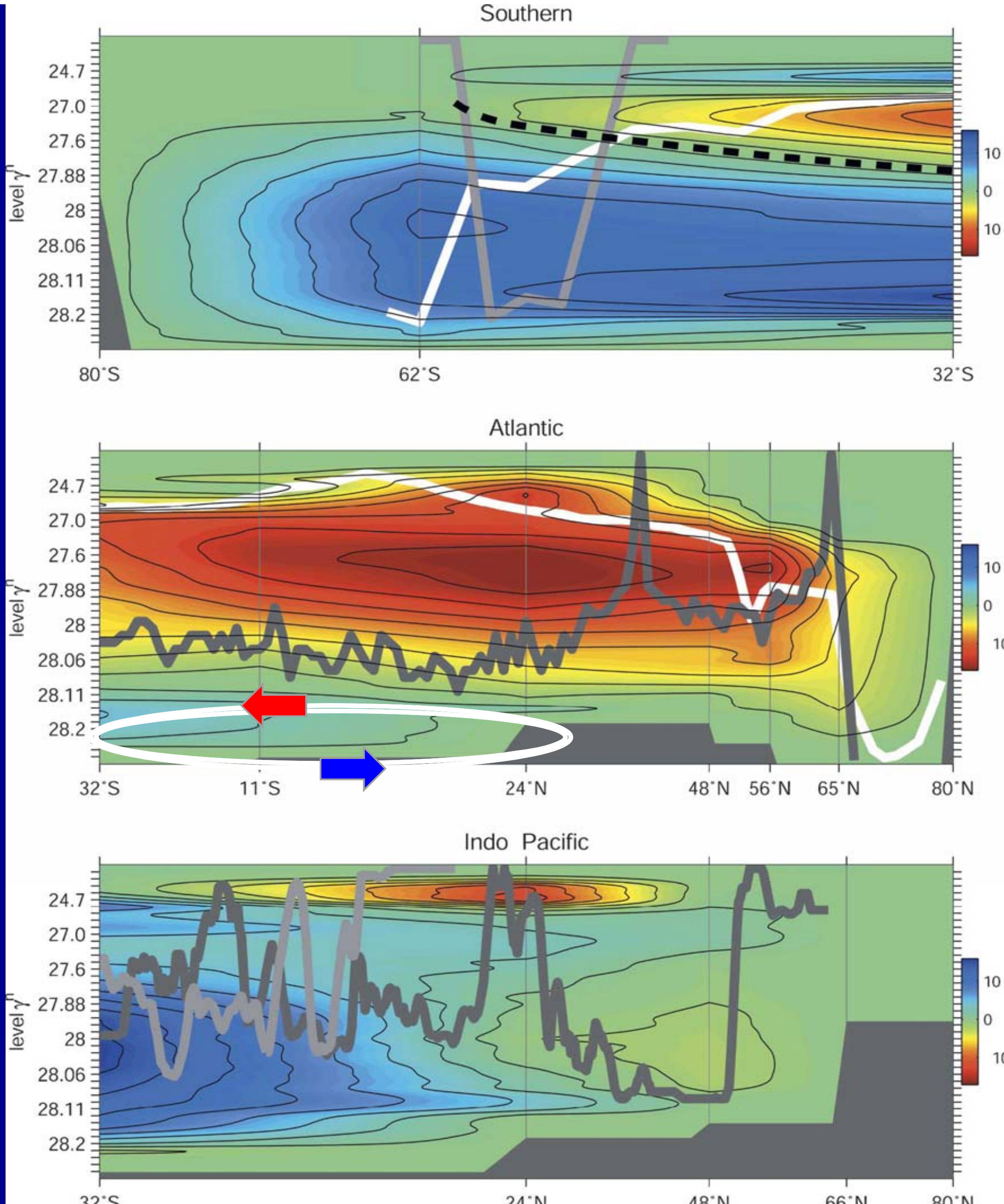
Upper Limb waters are transformed to NADW

Lumpkin & Speer, 2007



Above the MAR there is no significant diapycnal transformation

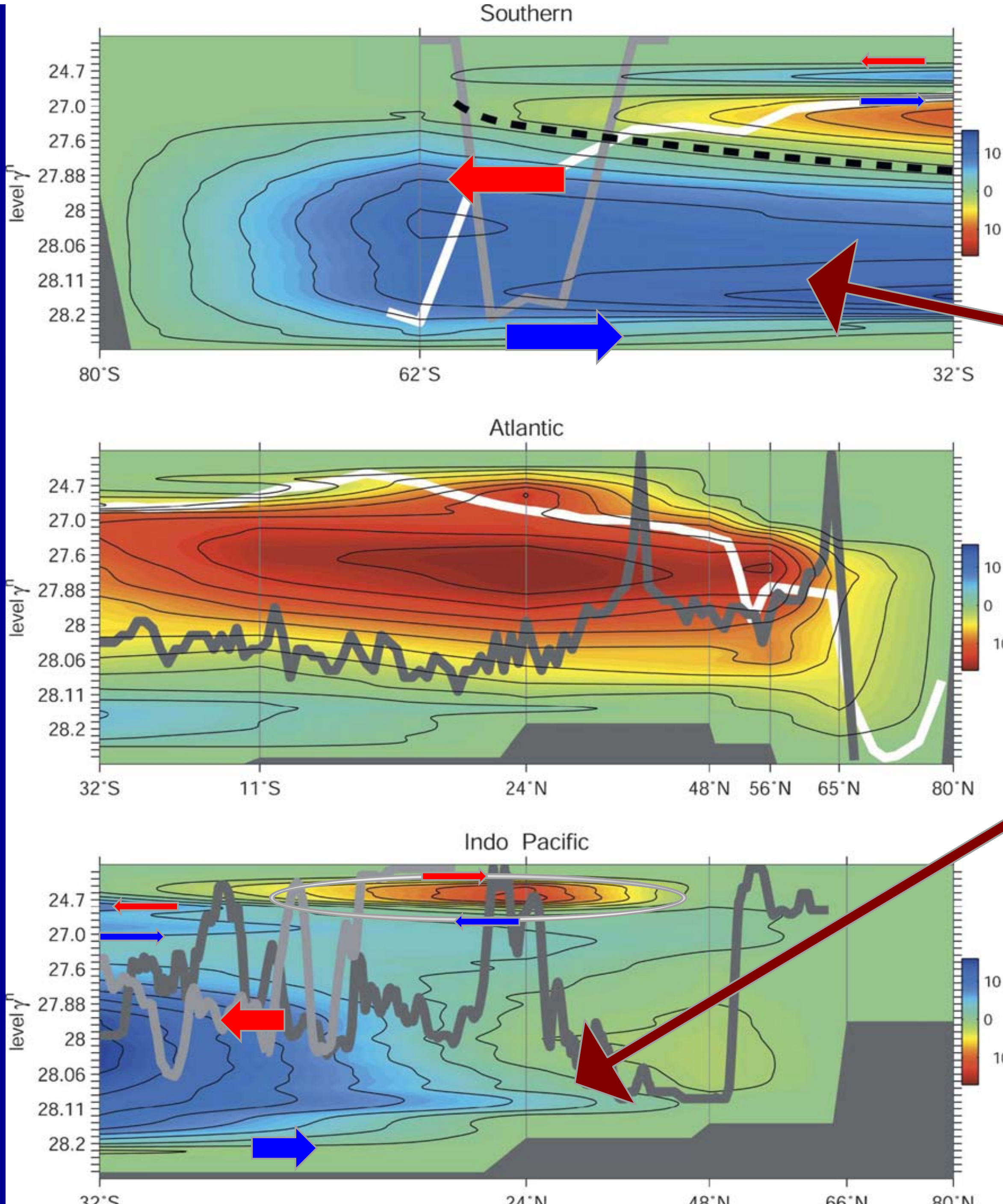
Lumpkin & Speer, 2007



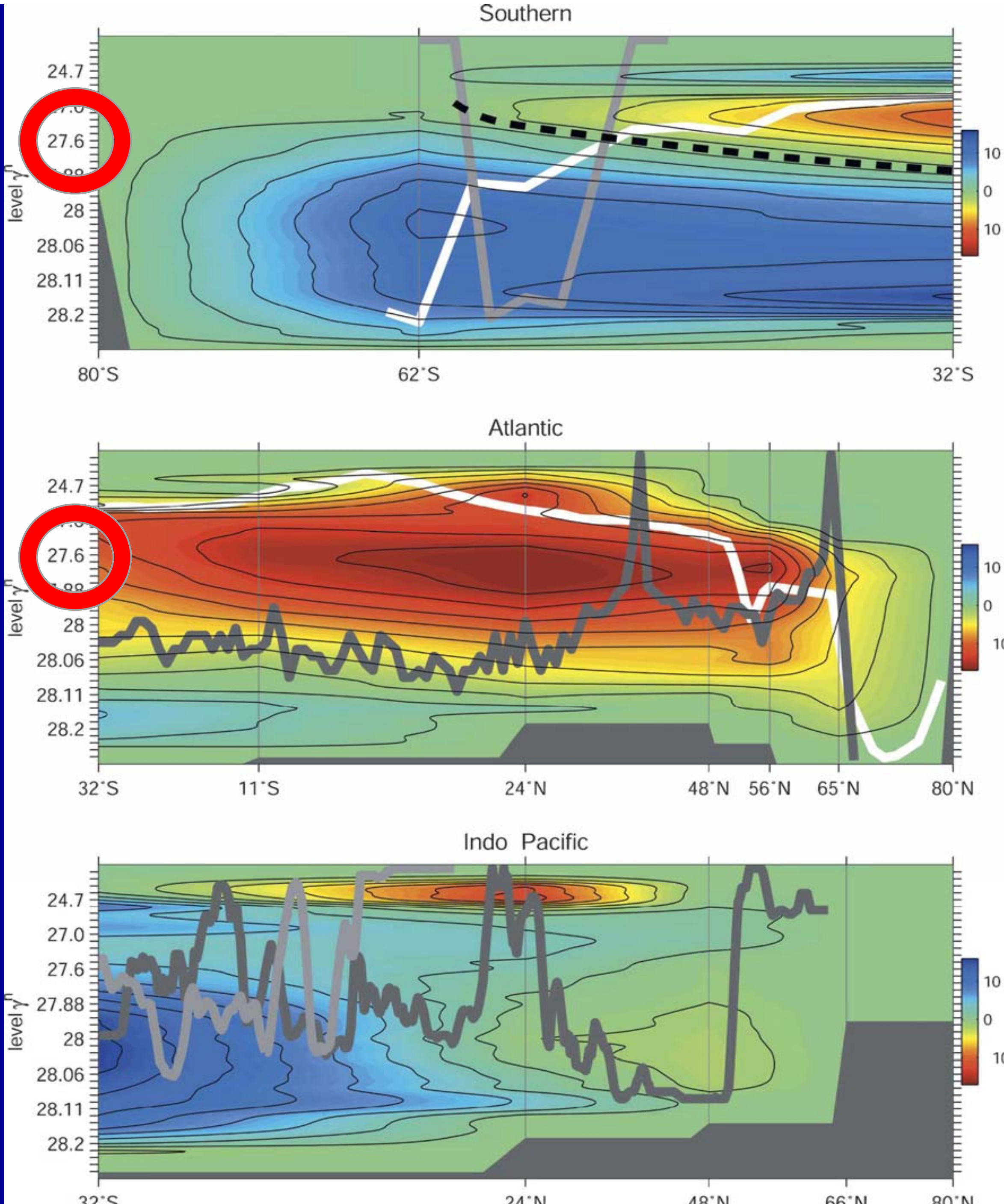
5.6+/-3 Sv AABW enters at 32S is transformed through tropical/subtropical diapycnal mixing

Lumpkin & Speer, 2007

The Other Meridional Overturning Circulation



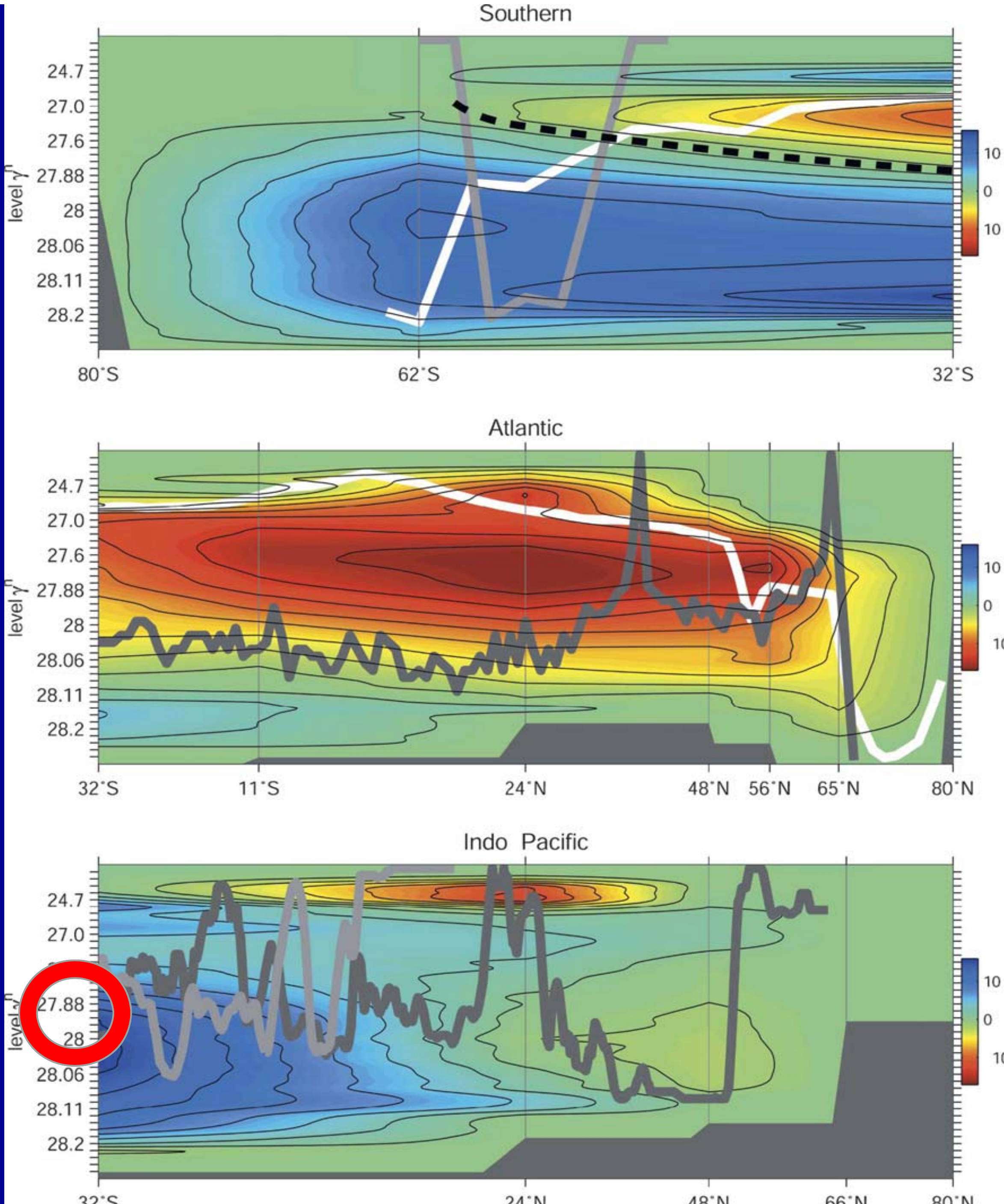
Lumpkin & Speer, 2007



¾ NADW denser that 27.6, ~division between upper and lower cells in S.O.

Implies most NADW does not return directly in the upper limb.

Lumpkin & Speer, 2007



¾ NADW becomes either AABW or CDW that enter the Indo-Pacific (12±3, 10±5) where transforms to waters lighter than 27.9 before returning to S.O

Lumpkin & Speer, 2007

Pacific Overturn

16 x 10^9 kg/s at 17°S

Core at ~120 m

Laterally: EAC with interior return

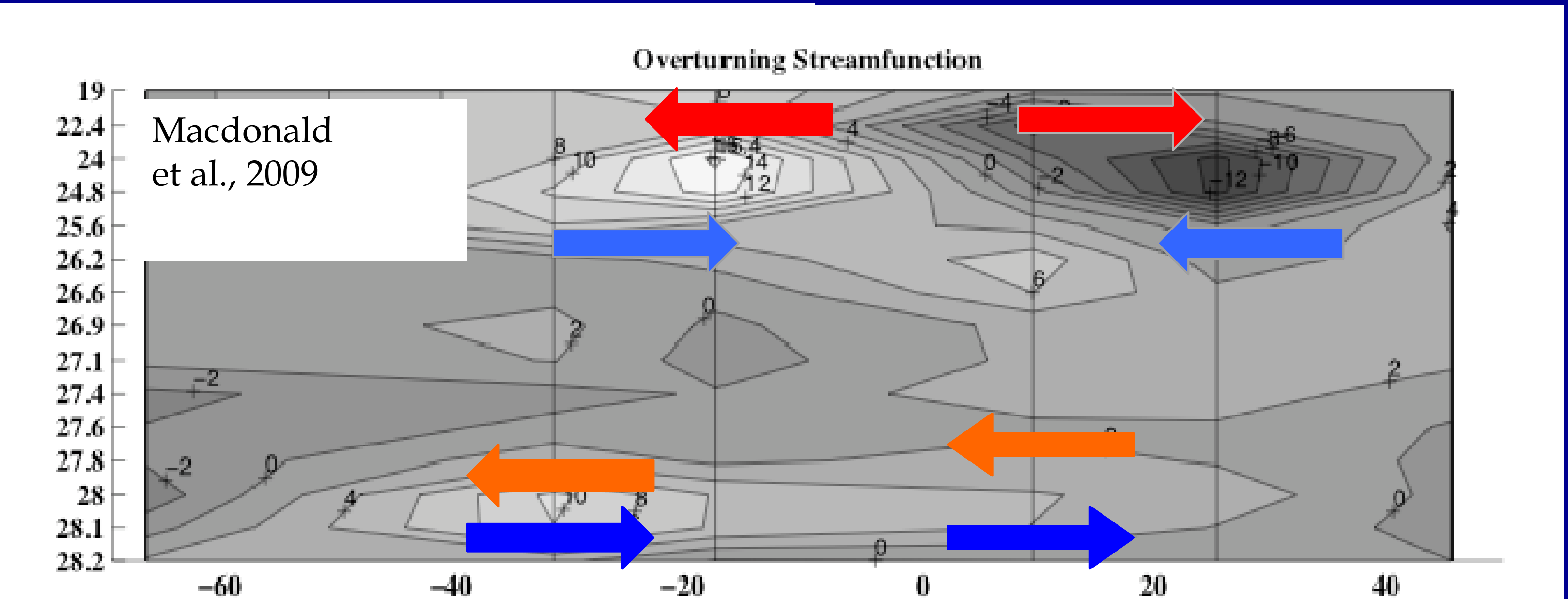
Extension across the equator

12 x 10^9 kg/s at 24°N

Core at ~90 m

Laterally: Kuroshio with interior return

Upwelling near equator



Calculating Meridional Overturning Heat Transport

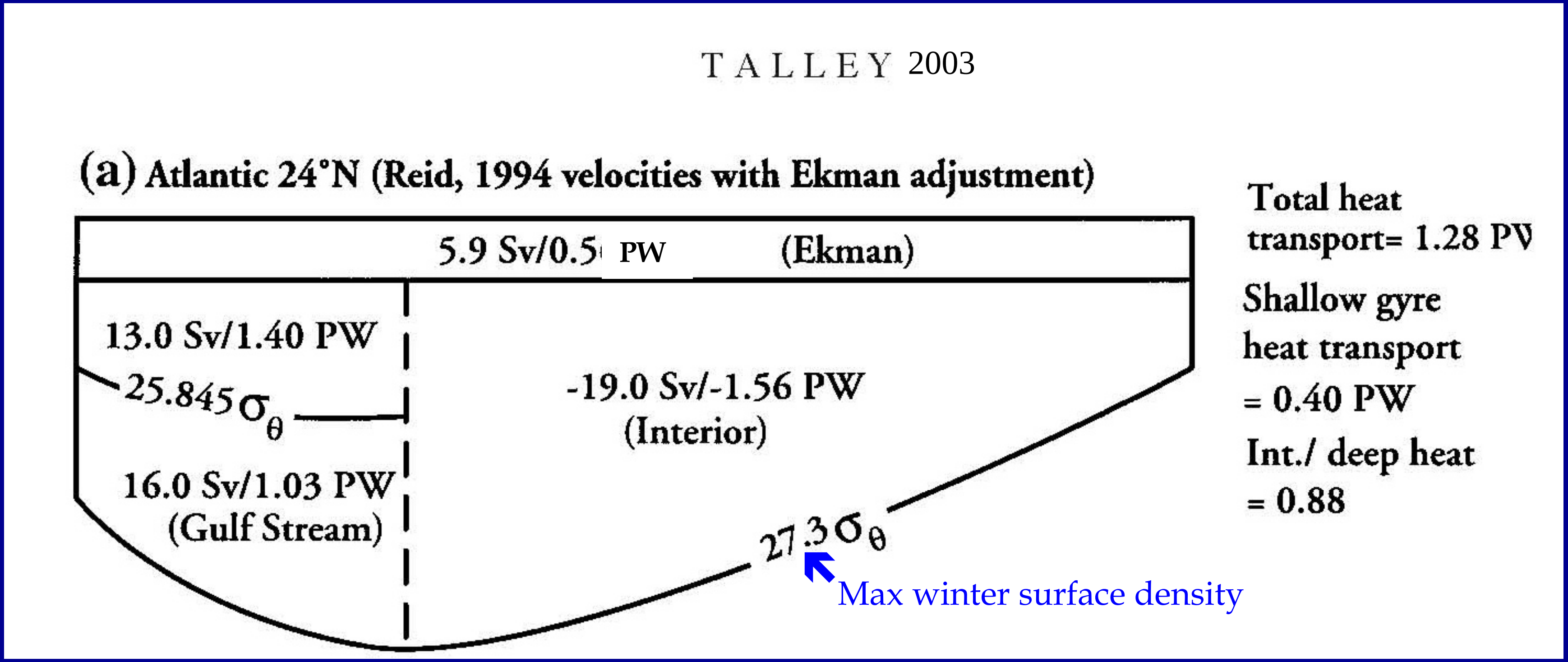
- Hall and Bryden, 1982
  - Depth averaged (barotropic), and vertically varying component (baroclinic, overturn)
- Rintoul and Wunsch, 1991
  - Along section average (overturn component) and a variation from the average (gyre or eddy component).
- Bryden and Imawaki, 2001
  - Net transport at a section average temperature
  - Zonally averaged vertical component: overturn
  - Horizontal heat transport (gyre/eddy component)
- Talley 2003
  - Shallow, Intermediate and Deep Overturn

3 Aspects of Overturn

- SHALLOW (to the base of the thermocline): within wind-driven subtropical gyres
- INTERMEDIATE (to 500-2000 m): within the North Atlantic and North Pacific
- DEEP (into depths below 2000 m): in the subpolar North Atlantic and around Antarctica

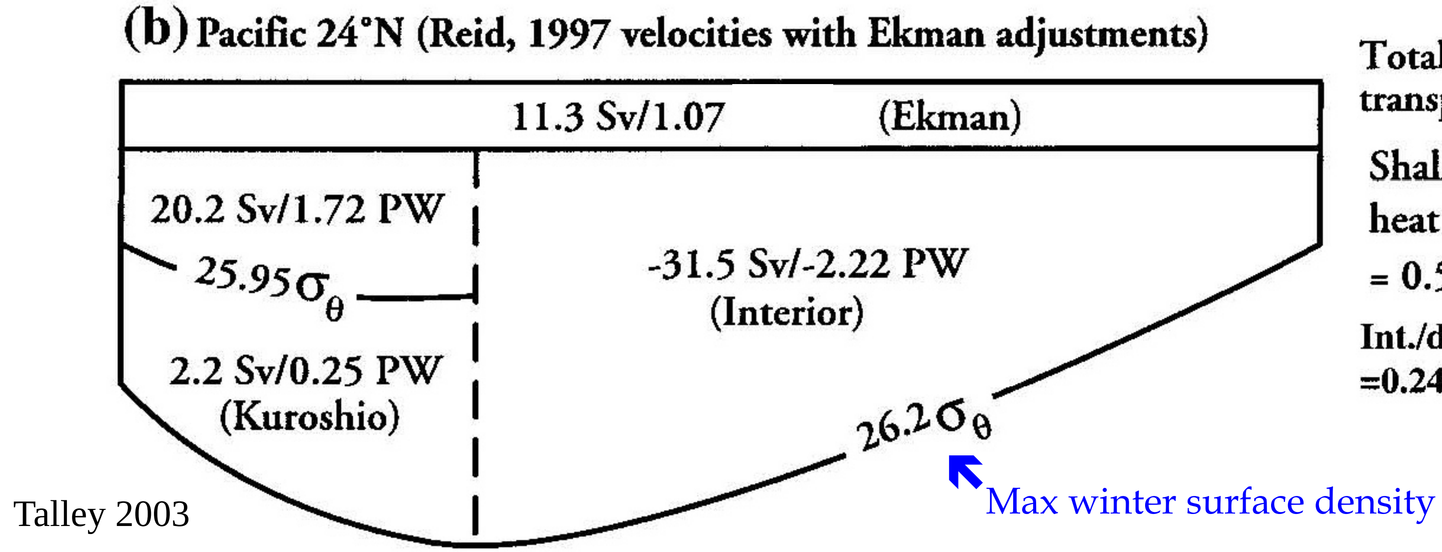
Talley, 2003

Example: Overturning Heat Transport at 24N Atlantic



Dependent upon both vertical and horizontal temperature differences

Example: Overturning Heat Transport at 24N Pacific

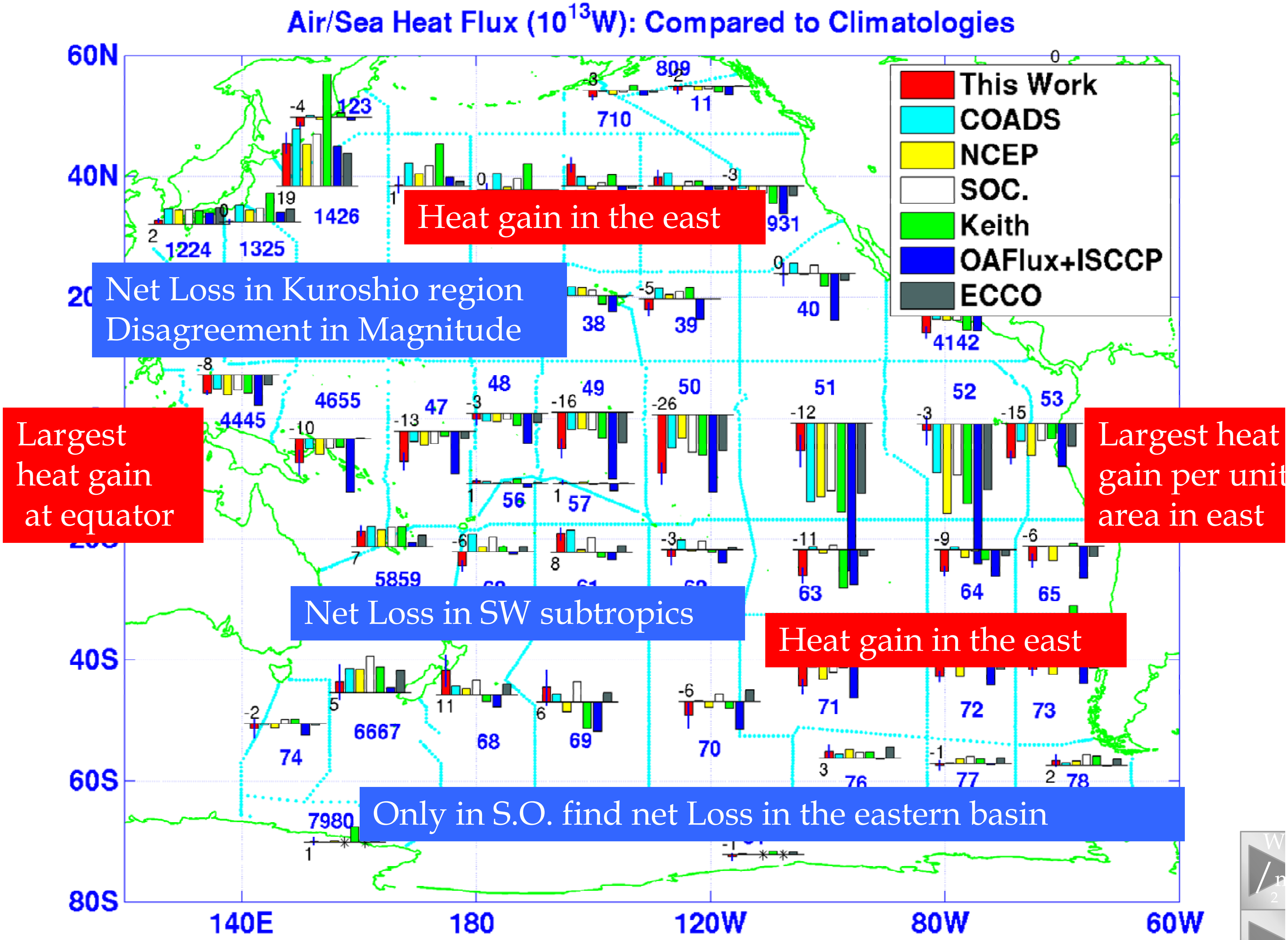


Total heat transport= 0.81 PW

Shallow gyre heat transport = 0.57 PW

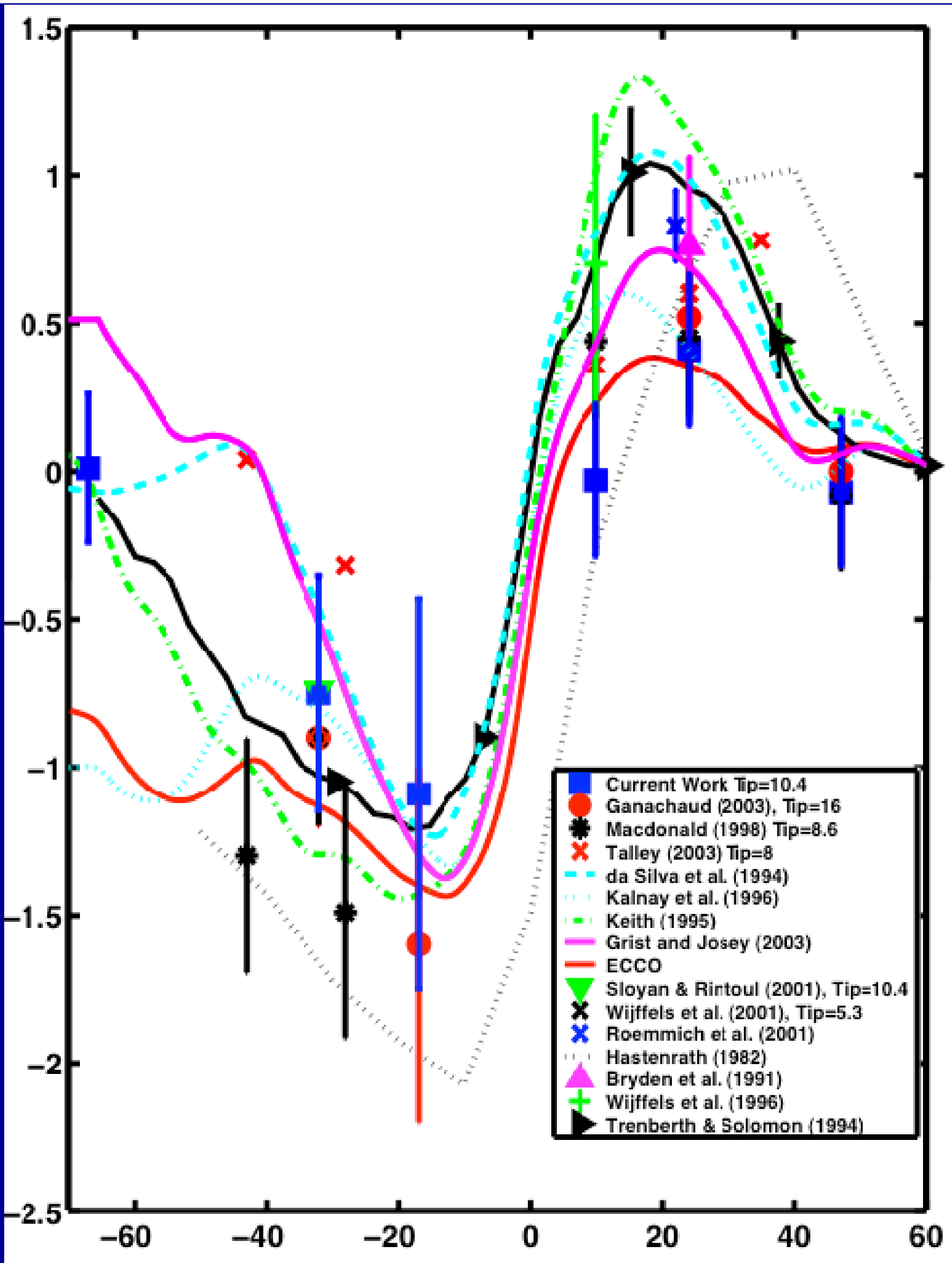
Int./deep heat =0.24 PW

Shallow gyre overturn dominates the heat transport



Air/Sea Heat Flux (10^{13}W): Compared to Climatologies
60N
40N
40S
60S
80S
140E
180
120W
80W
60W
This Work
COADS
NCEP
SOC.
Keith
OAFlux+ISCCP
ECCO
Heat gain in the east
Net Loss in Kuroshio region
Disagreement in Magnitude
Largest
heat gain
at equator
Largest heat
gain per unit
area in east
Net Loss in SW subtropics
Heat gain in the east
Only in S.O. find net Loss in the eastern basin

Indo-Pacific Meridonal Heat Transport



Overturning Heat Transport

(largely, but not exclusively, from Talley, 2003)

- Dependent upon vertical and horizontal differences
- All shallow overturns support poleward heat fluxes, larger in NH than SH
- Pacific heat transport dominated by shallow cells
- North Atlantic dominated by deep and intermediate cells
- Deep to upper upwelling in the north is important to Indian and S. Pacific heat budget
- Downwelling to the north is important in the Atlantic
- Downwelling in Antarctic transforms thermocline waters to SAMW/AAIW, and northern deep waters to bottom waters
- Deep cells carry significant heat transport

Overturn Variability

- There have been variability studies in all basins
- Not necessarily focused on overturn
- N. Atlantic is arguably the best observed and the best understood
- Does not mean that in terms of the impact of overturn on the physics, chemistry or biology, that it is the only place that is important in terms of either global or regional overturn processes.

Overturn Variability (AMOC)

- At 26°N (RAPID-MOC Array Johns et al., 2008)
- Over the course of 14 months (coast to 76.5°W)
  - Mean net southward transport of DWBC: -26.5 Sv
    - ½ UNADW and ½ LNADW
    - Similar to historical hydrography
  - Above 1000 m range: -15 to +25 Sv
  - Below 1000 m range: -60 to 3 Sv
  - Much of variability: short timescale barotropic fluctuations (Lee et al., 1996, Meinen et al., 2006)
  - Slower baroclinic variations also exist
    - 10 days Nov. 2004 DWBC shut off
    - Similar shut off in LNADW flow across full basin (Cunningham et a., 2007)

Impacts of AMOC Variability

- Linked variations SST ((Knight et al. 2005 ,Delworth et al. 2006) and inter-hemispheric SST gradient
- Northward advection of heat and heat loss to the atmosphere affect W. Europe & larger scale climate
- Weakening linked to cooling N. tropics, warming in S. tropics, southward shift of ITZ ➔ rainfall, storms (Knight et al 2006, Zhang and Delworth 2006, Sutton and Hodson 2005, Smith et al 2010)
- Linked to reduction in Arctic sea ice (Serreze et al., 2007) and the Greenland ice sheet (Rignot and Kangaratnam, 2006) ➔ freshwater feedback
- Steric and dynamic sea level changes (Vellinga and Wood, 2008)

List and references from O-SNAP introduction courtesy of S. Lozier

What we don't know about the physical aspects & impacts of overturn & overturn variability

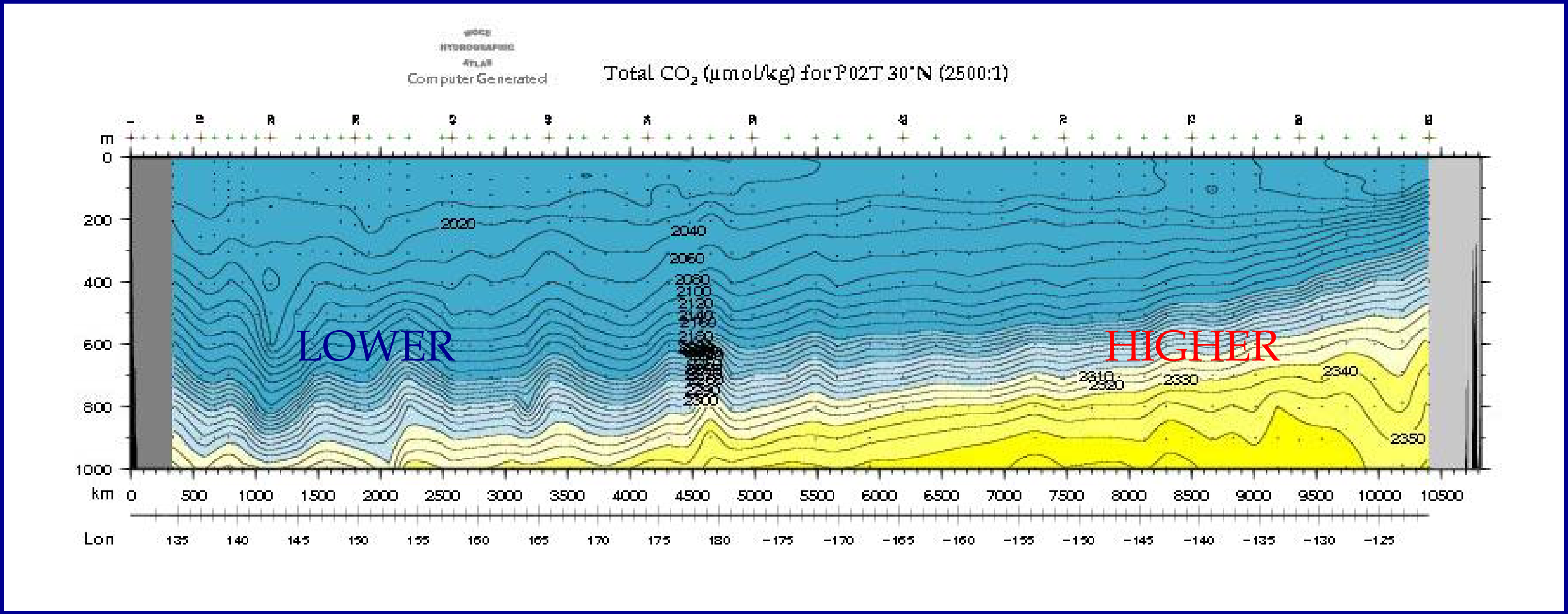
- What is the driving mechanism for change (buoyancy vs wind)
- If freshwater is carried in narrow boundary currents, then coarse resolution hosing experiments cannot tell the whole story (Condron and Winsor, 2011)
- What about the effects of bottom water warming?
- What are the mechanisms for feedbacks among physical processes producing & affected by overturn variability (T, S, ice-melt, rainfall, sea level rise etc.)?
- Still work to be done on the pathways, timescales of pathways, and variability in pathways of DWBC's that support overturn (Link between LSW formation & down stream transport)
- What are the interactions between different timescales of variability (seasonal, annual, decadal, longer)
- We know the North Atlantic best – but much needs to be learned about the other basins

Impact of Overturn on Carbon

Overturn suggested tranports of Contemporary Carbon

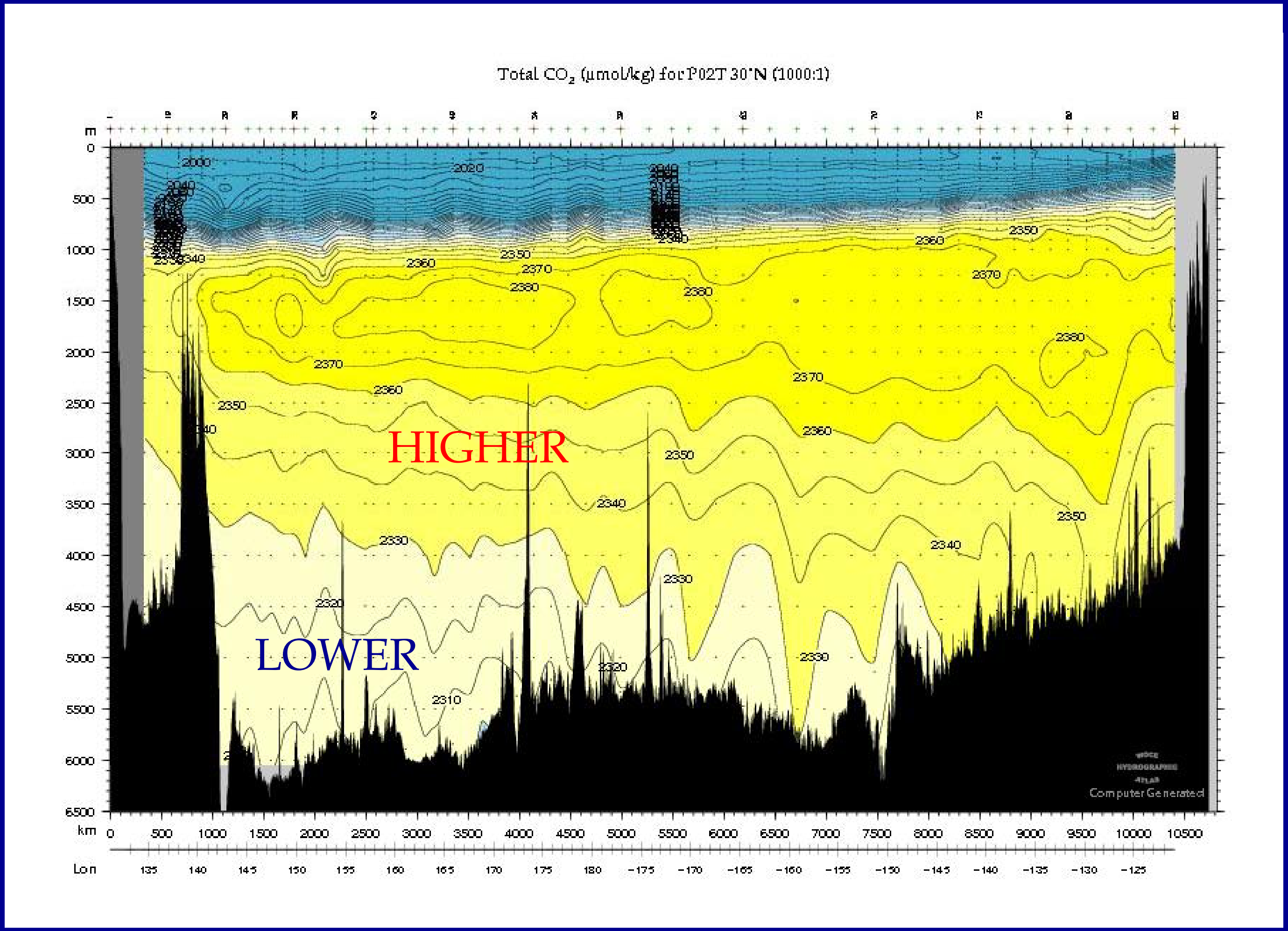
- North Atlantic: given increasing concentration with depth & dominance of surface to deep overturn
  - Suggests: Net southward transport
- North Pacific?

DIC 30N Pacific – upper 1000m



Shallow overturn → Southward DIC transport

DIC 30N Pacific

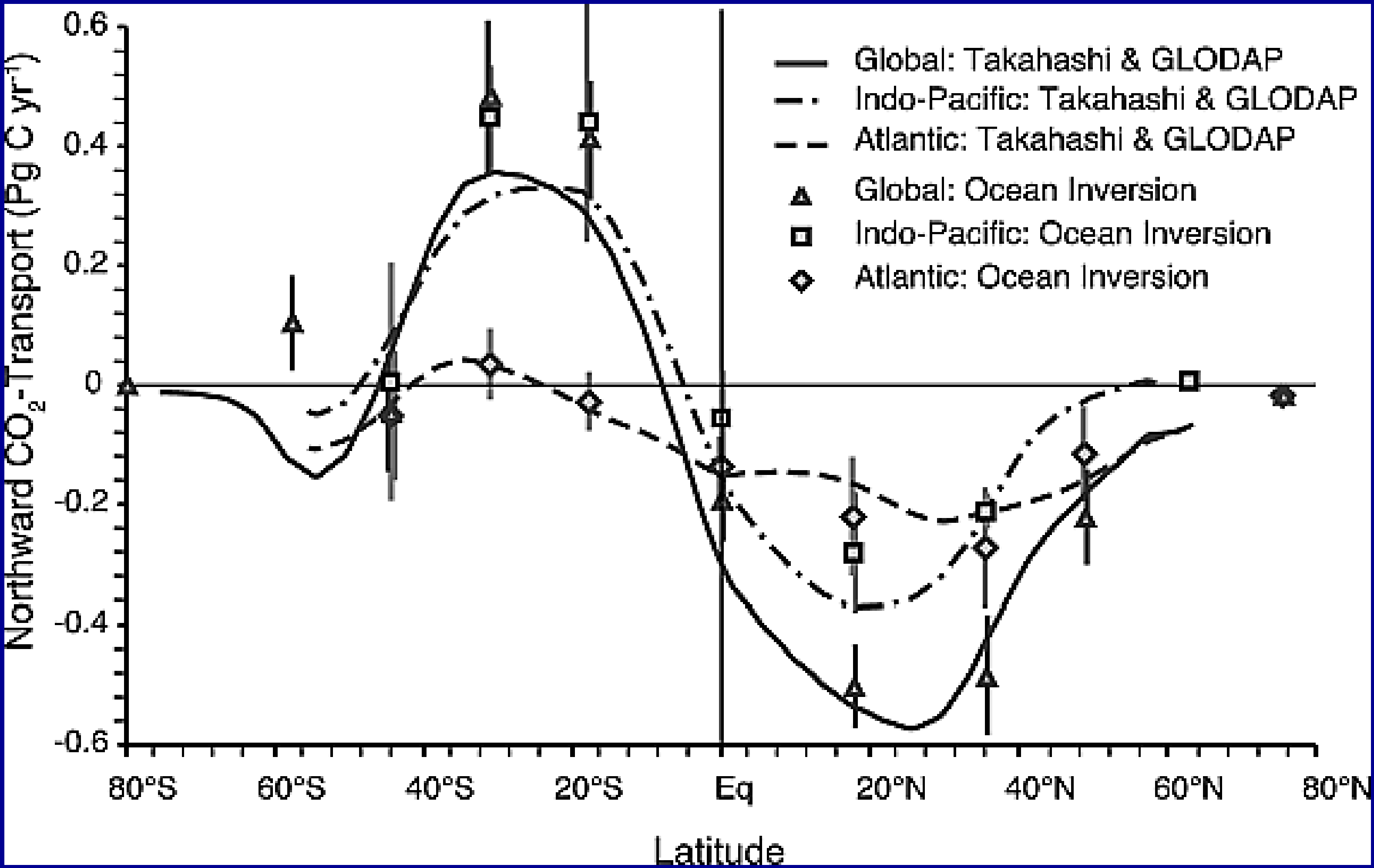


Bottom to deep overturn ➔ southward DIC transport

Overturn suggested tranports of Contemporary Carbon

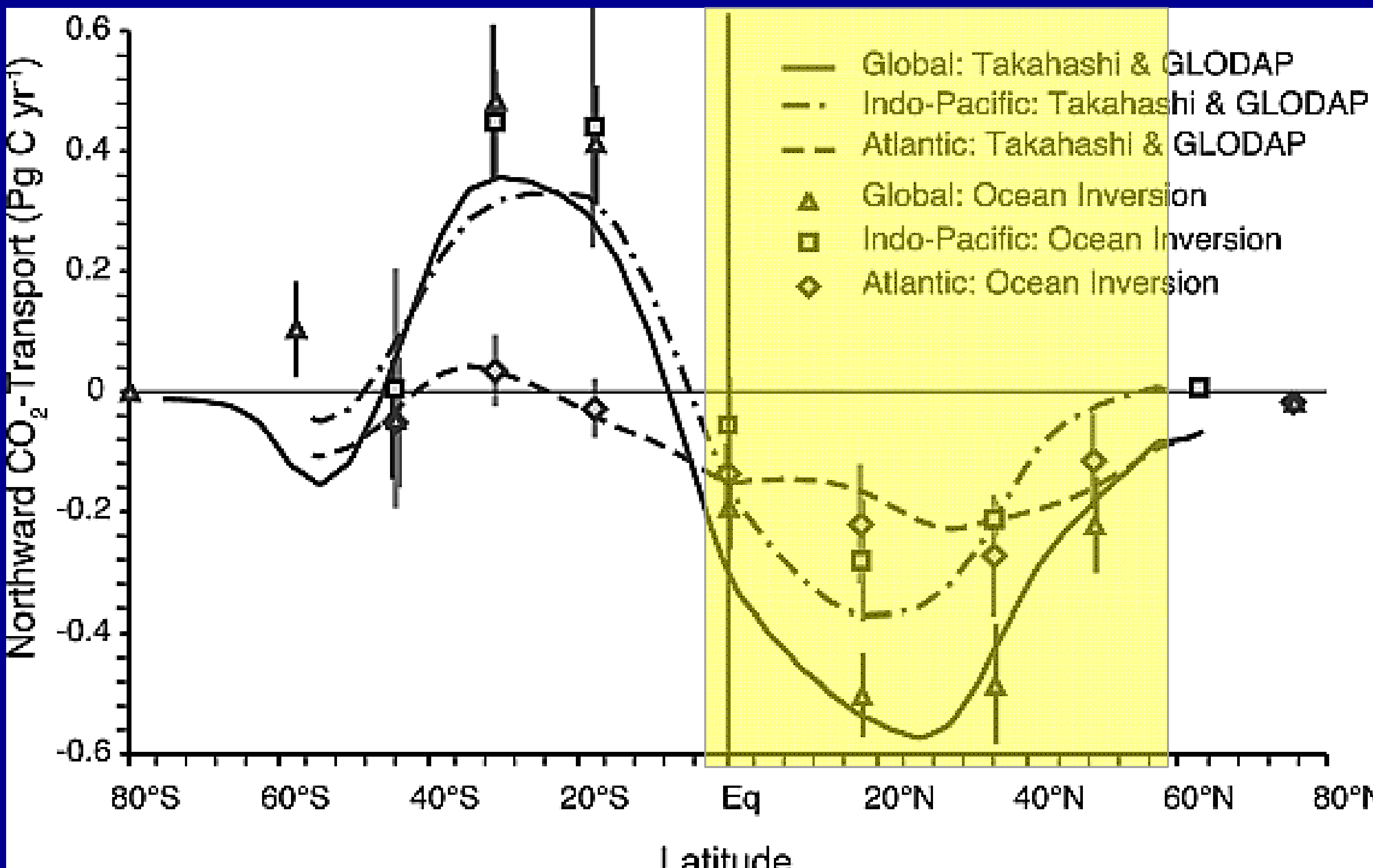
- North Atlantic: given increasing concentration with depth & dominance of surface to deep overturn suggests: net southward transport
- South Atlantic – greater influence of AAIW/AABW – not obvious
- North Pacific: shallow overturn (southward)
- North Pacific deep overturn (southward)
- South Indian/Pacific deep overturn (southward)
- Indo-Pacific shallow
    - Suggests: Pacific northward, Indian southward
    - Net not obvious

Contemporary Carbon Transport

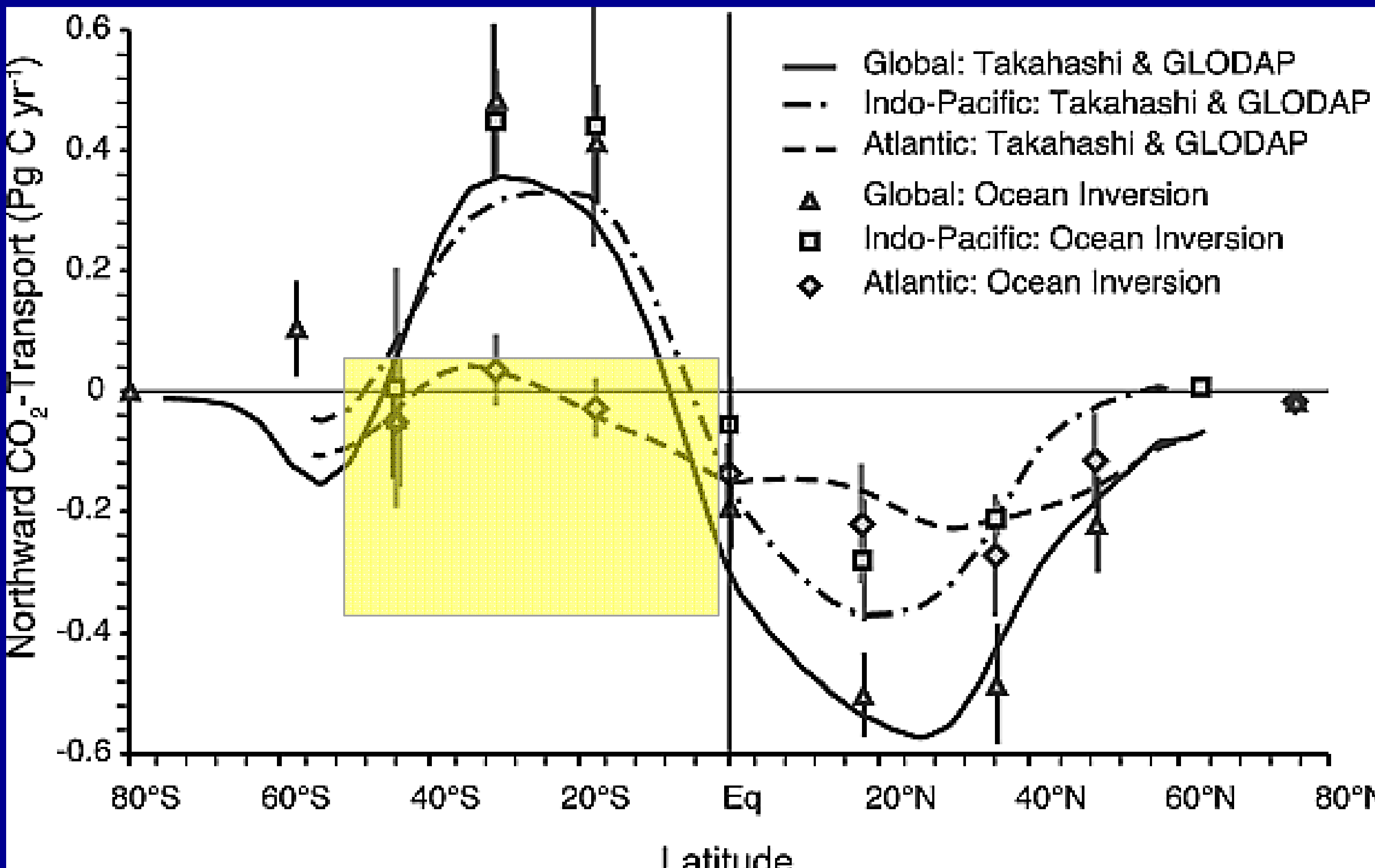


Gruber et al. 2009

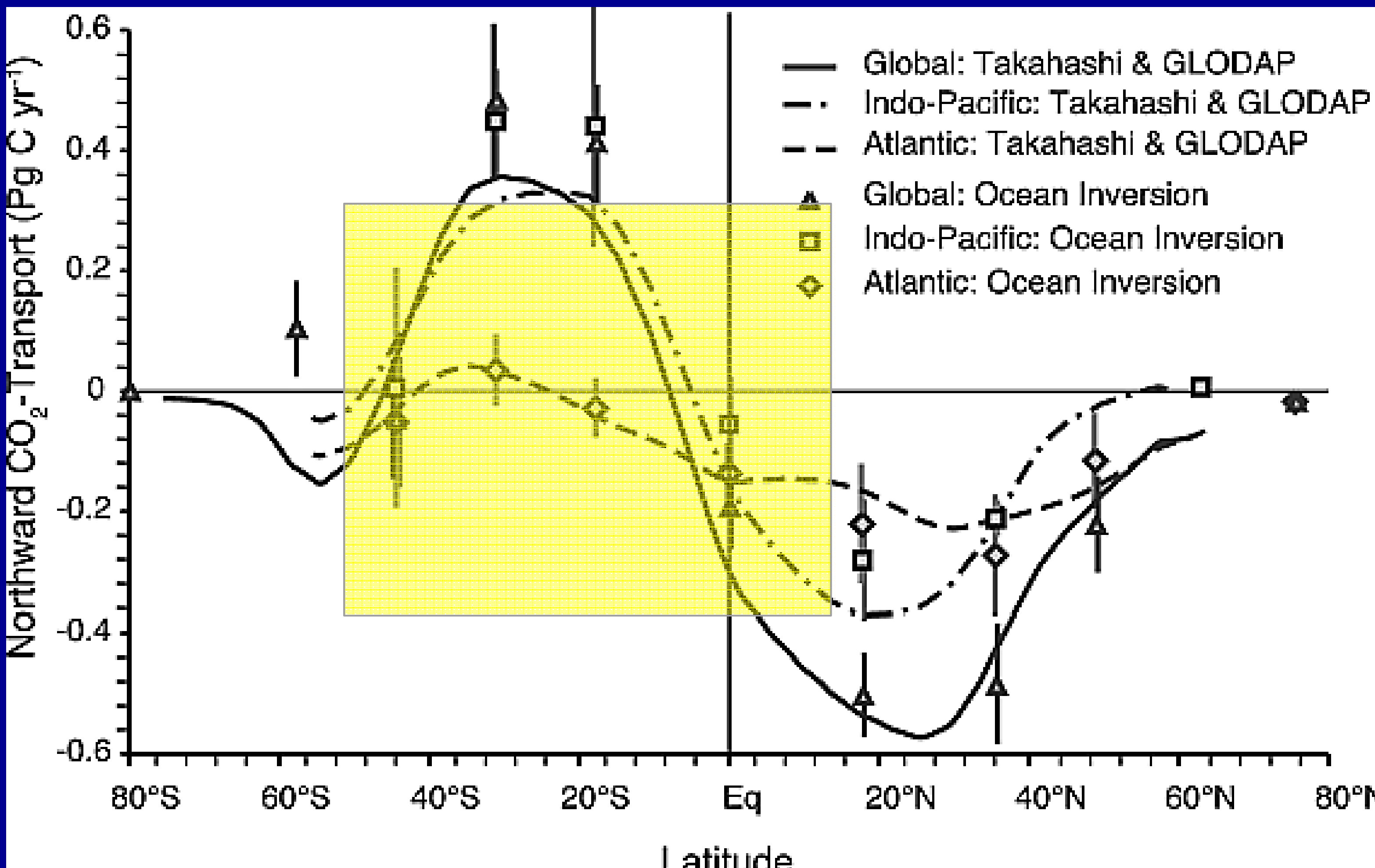
Contemporary Carbon Transport



Contemporary Carbon Transport

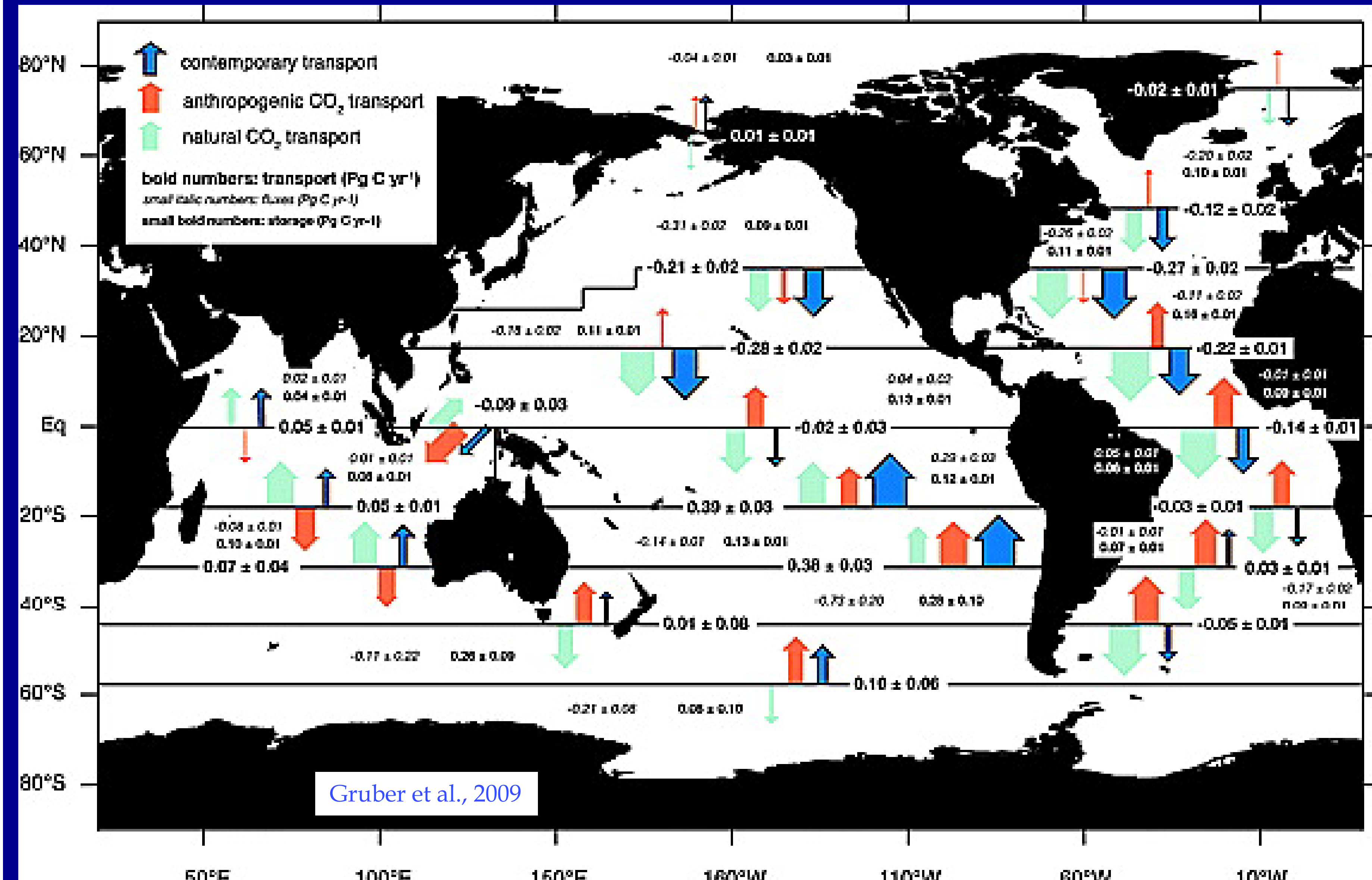


Contemporary Carbon Transport



Is there a dominance of the net northward transport in the Pacific?

Carbon Transport & Overturn



Decoupling of CFC and Cant transport
(Alvarez and Gourcuff, 2010)

- Across A25 (Spain to Greenland)
  - Cant transported northeastward
  - CFC's transported southwestward
- CFCs's and Cant have different
  - Atmospheric histories
  - Temperature dependencies
  - Air-sea gas exchange equilibrium rates
  - Leads to different regions of uptake, accumulation rates and so transport pathways
  - Further implies that overturn variability would affect them differently

What we don't know about the impacts of overturn & overturn variability on carbon transport

- Can the ocean continue to take up CO_2? At the same rate? At a different rate? Differently in different basins?
  - Does overturn or do changes in overturn affect the outcome?
  - How do overturn pathways affect uptake?
  - How do changing vertical and horizontal gradients affect uptake?
  - Affects of variable North Atlantic deep water formation
  - Affects of changing Mode, Intermediate and Bottom Water ventilation
  - Affects of overflow water changes (Arctic)
  - Coupling of Cant transport to that of other tracers (CFCs) globally?

- What are the mechanisms for feedbacks between increasing atmospheric carbon -> increasing ocean temperature and overturn?
- What are the interactions between different timescales of variability (seasonal, annual, decadal, longer) in the physics, and in the chemistry?
- We know the North Atlantic best – but much needs to be learned about the other basins

Ecosystems and Overturn

- Nutrients (upwelled in the tropics, possibly also S.O. source) are carried northward into the North Atlantic in the Gulf Stream (upper component of overturn).
- What are the effects to biology of changes to this source?
- Respiration, photosynthesis ➔
- Decrease O_2 ➔ increase CO_2 ➔ decrease pH
- Would slowing of circulation at depth increase oxygen minimum zones?

Palter and Lozier, 2008

Chemistry, Biology, Mixed Layer Depths and Overturn

- Remineralization leads to depletion of O_2 and production of CO_2
- When it occurs below the winter mixed layer then CO_2 is not ventilated
- Do subpolar MLD changes affect CO2 ventilation and on what spatial and temporal scales?

Phenology and Overturn

- Phenology: synchronization or dis-synchronization of timing of biological cycles
- Ocean example: shallow winter mixing – leads to shallow MLD – phytoplankton spend more time in the light – so bloom may occur earlier and more quickly – while grazers go into hibernation in the winter (diapause) having migrated to depth (800 m), what is the queue for coming up – is it related to the MLD, something else? Is it linked to the spring bloom?
- When does phytoplankton spring bloom start? Are the queues synchronized?
- What changes could overturn variability effect?

Size Structure and Overturn

- In subtropics (high stratification, shallower ML and low nutrients)
  - → smaller phytoplankton → smaller grazers
  - Smaller plankton have higher metabolic rates, so they are made and consumed more quickly
  - → less carbon export because little critters don't sink as readily.
- More effective in production of larger size population

- What is the potential for changes in overturn on various scales to effect changes in size structure and species composition?

Organismal Boundaries & Overturn

- Organismal boundaries: where organism are found, particularly in relation to each other.
- Changes in overturn are associated with changes in water mass characteristica (T, S, O_2 etc.)
- Fish, shrimp etc…sensitive to water temperature
  - Economic impacts
  - Are they only affected by temperature?
- What are the organismal boundaries?
- Why are they found here or there?
  - Does change in day length (say, with latitude where species end up) affect the species? Are there more subtle differences that can affect species?
  - Example: most higher order species don't make fatty acids, but rather rely on the consumption of smaller species that do. So do certain species rely on particular smaller species (i.e. another smaller species won't supply what is necessary to the survival of the larger species). Long term evolutionary dependence
- Could a rapid change have unforeseen consequences?
- What is 'rapid'?

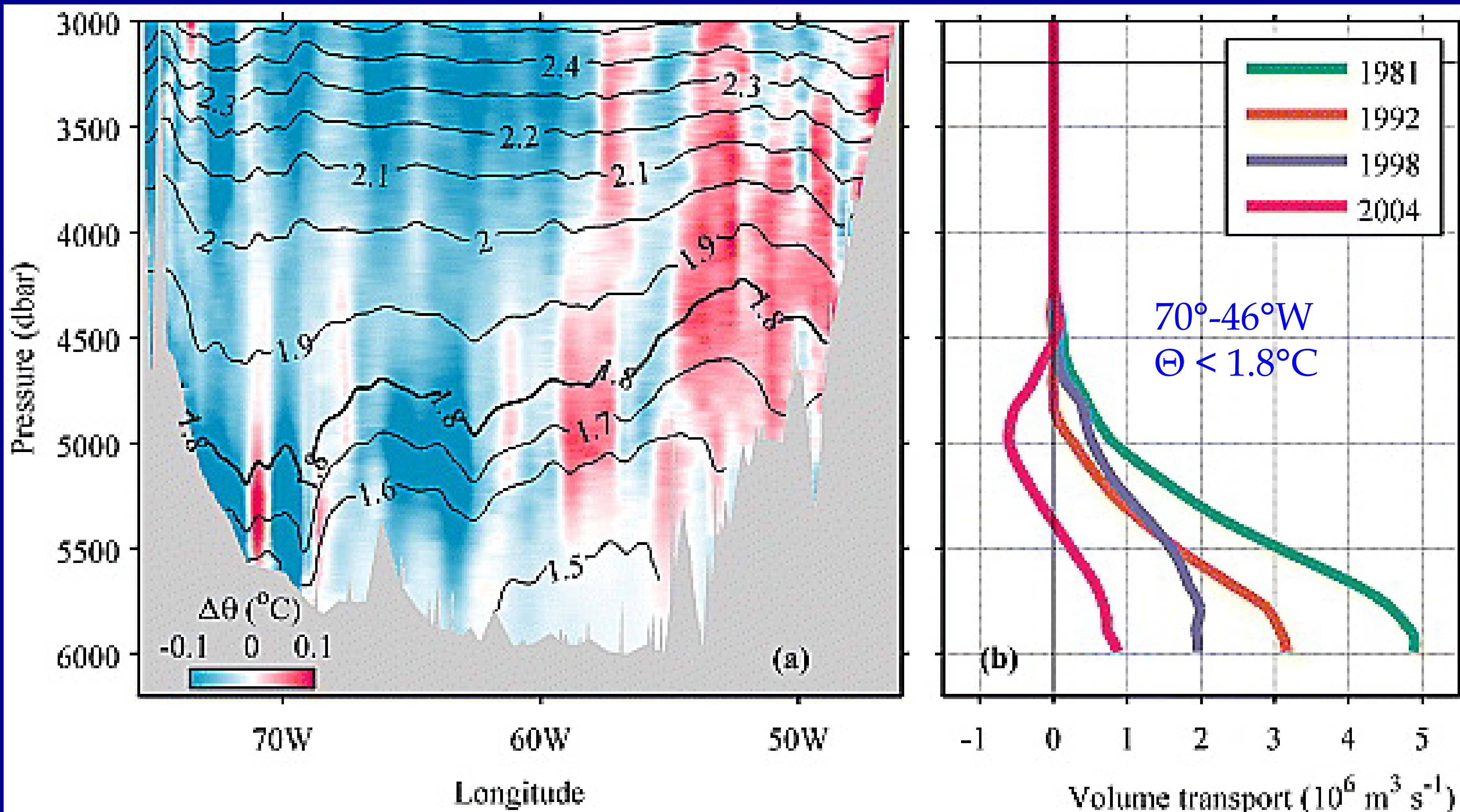
Ecosystems and Overturn

- What are the effects to biology of changes to overturn related nurient source?
- Do subpolar MLD changes affect CO_2 ventilation and on what spatial and temporal scales?
- Can changes in MLD affect the timing of spring bloom synchronization of queues?
- What is the potential for changes in overturn to effect changes in size structure, species composition and organismal boundaries?

Where does that leave us?

- What are the physical feedbacks (ocean, atmos.)?
- How are the chemistry and biology affected by changes in overturn (different scales)
- Feedbacks within the chemical cycles
- Feedbacks within the biological cycles
- Interaction and possible feedbacks amongst all three (four).
- Detection – how much data do we need?
- Observations, models (complex, simple). Combined.
- Interdisciplinary vocabulary and conversation

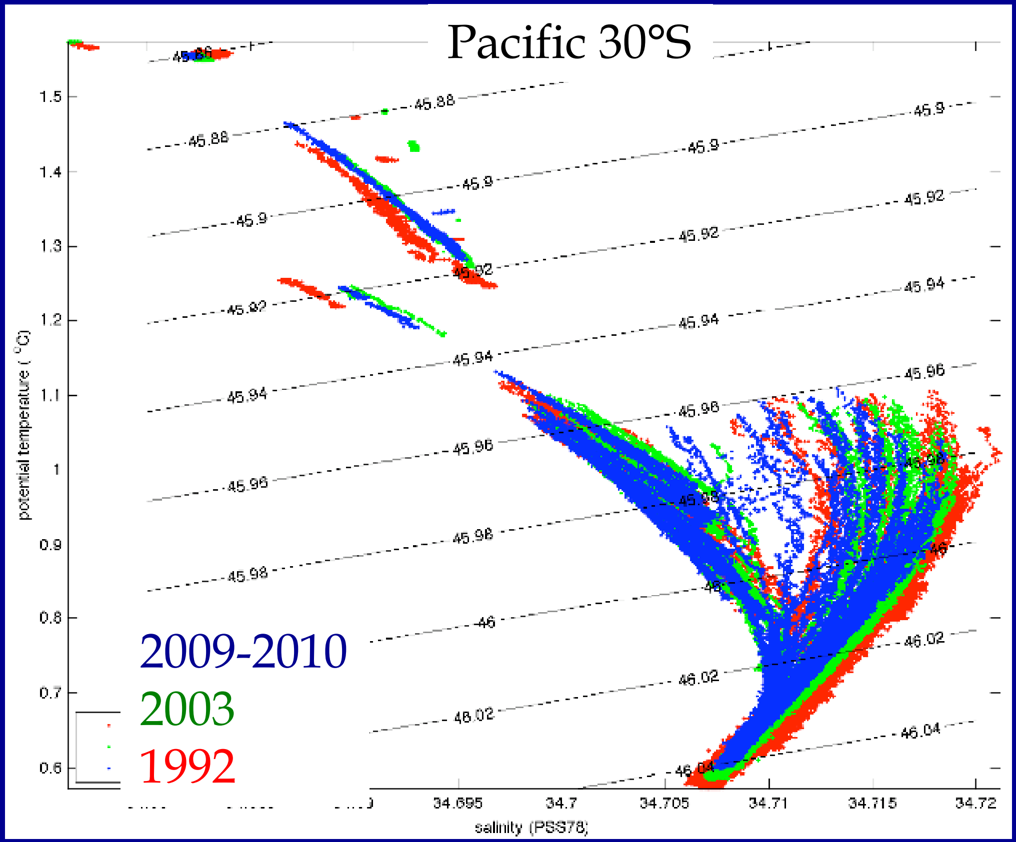

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930
Thank You
Photos by K. Kostel and J. Nishikawa

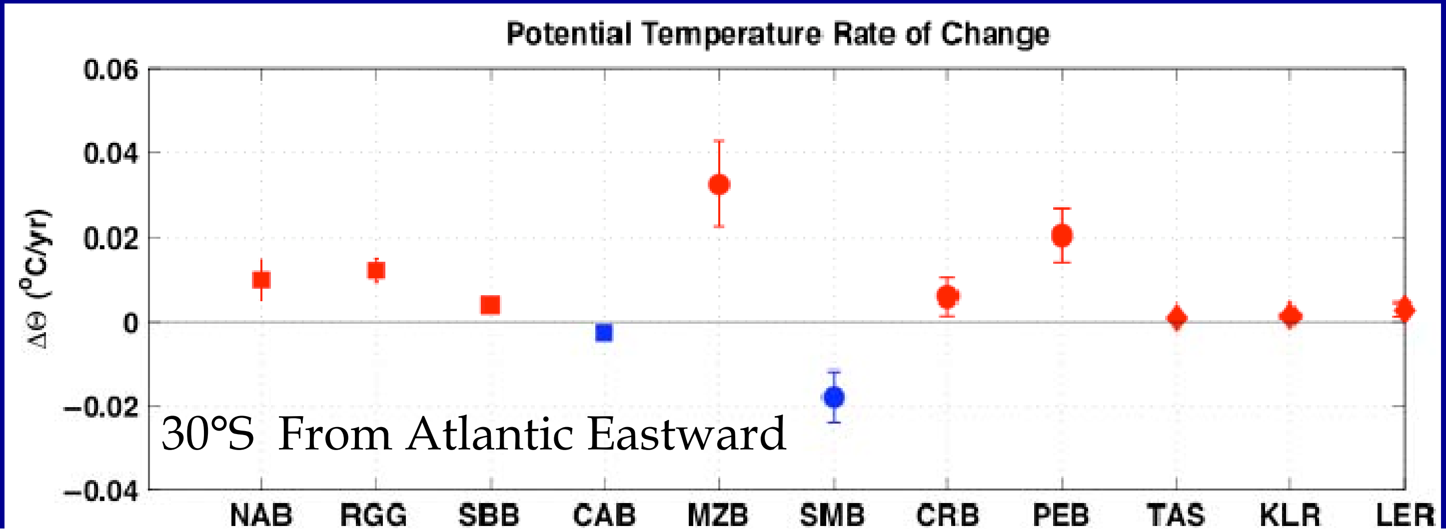


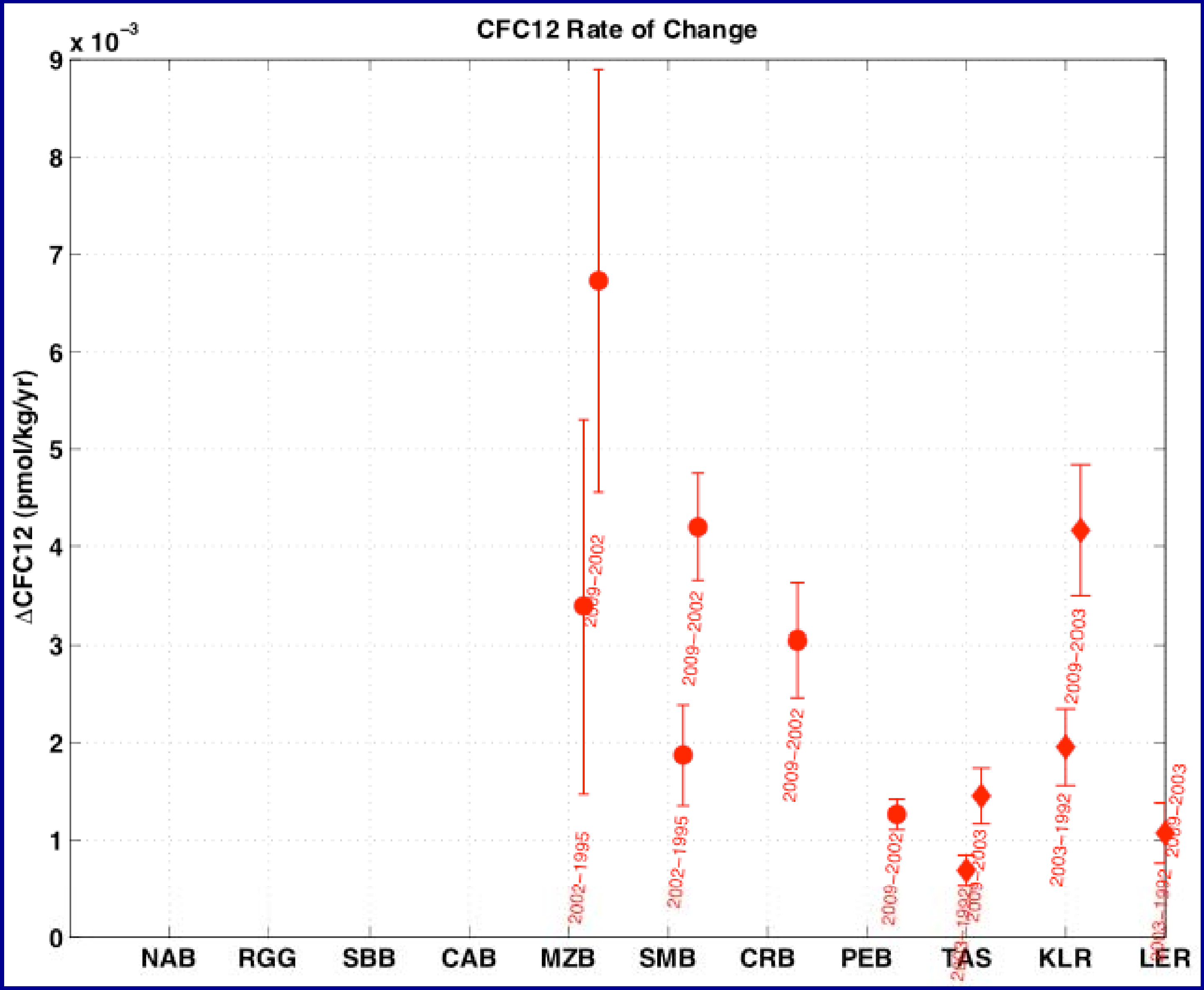
Warming of bottom waters away from the western boundary flow of NADW.
Consistent with a decreased northward volume transport of AABW.

Johnson et al., 2008

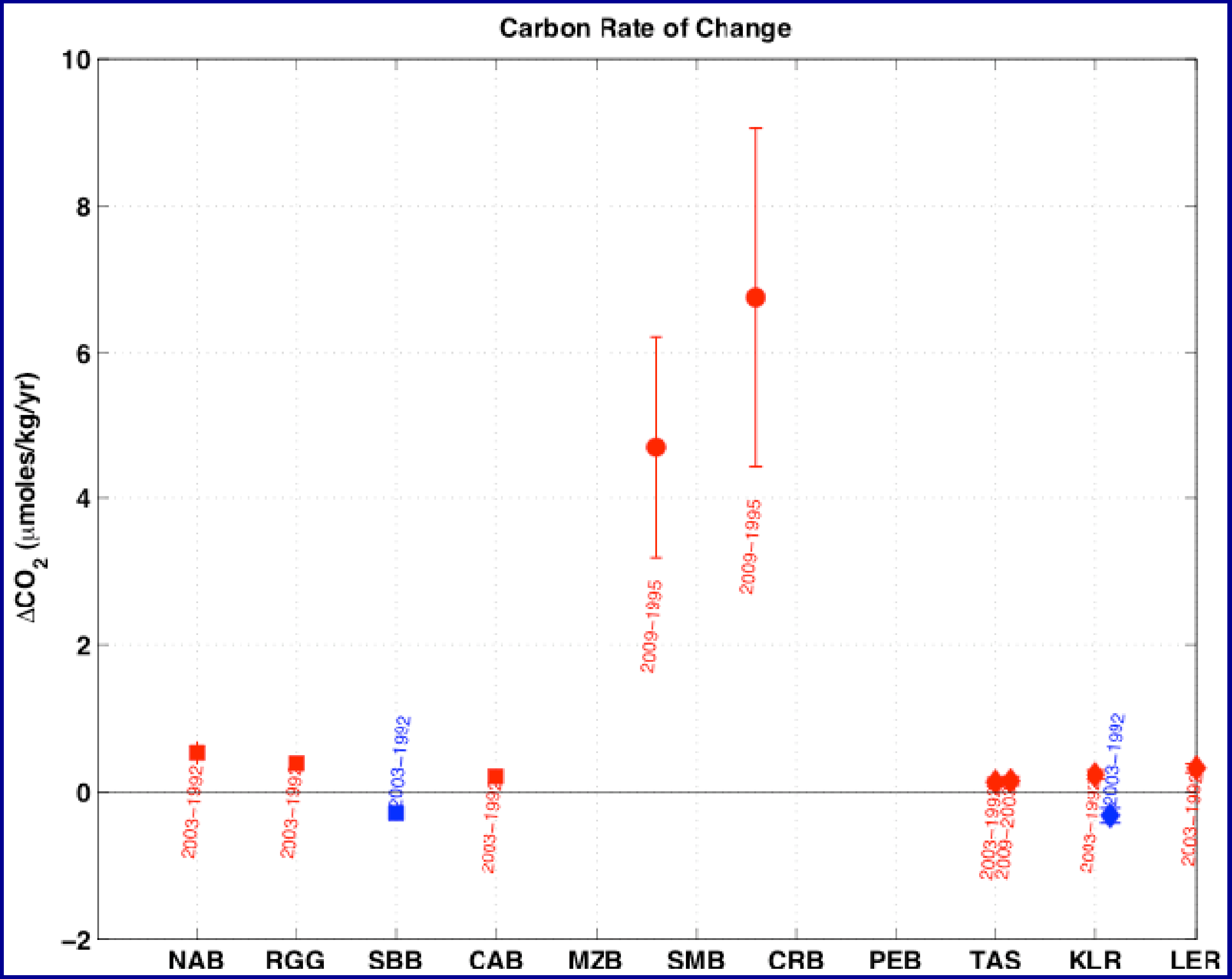
Below 4000 db, < 1.8°C







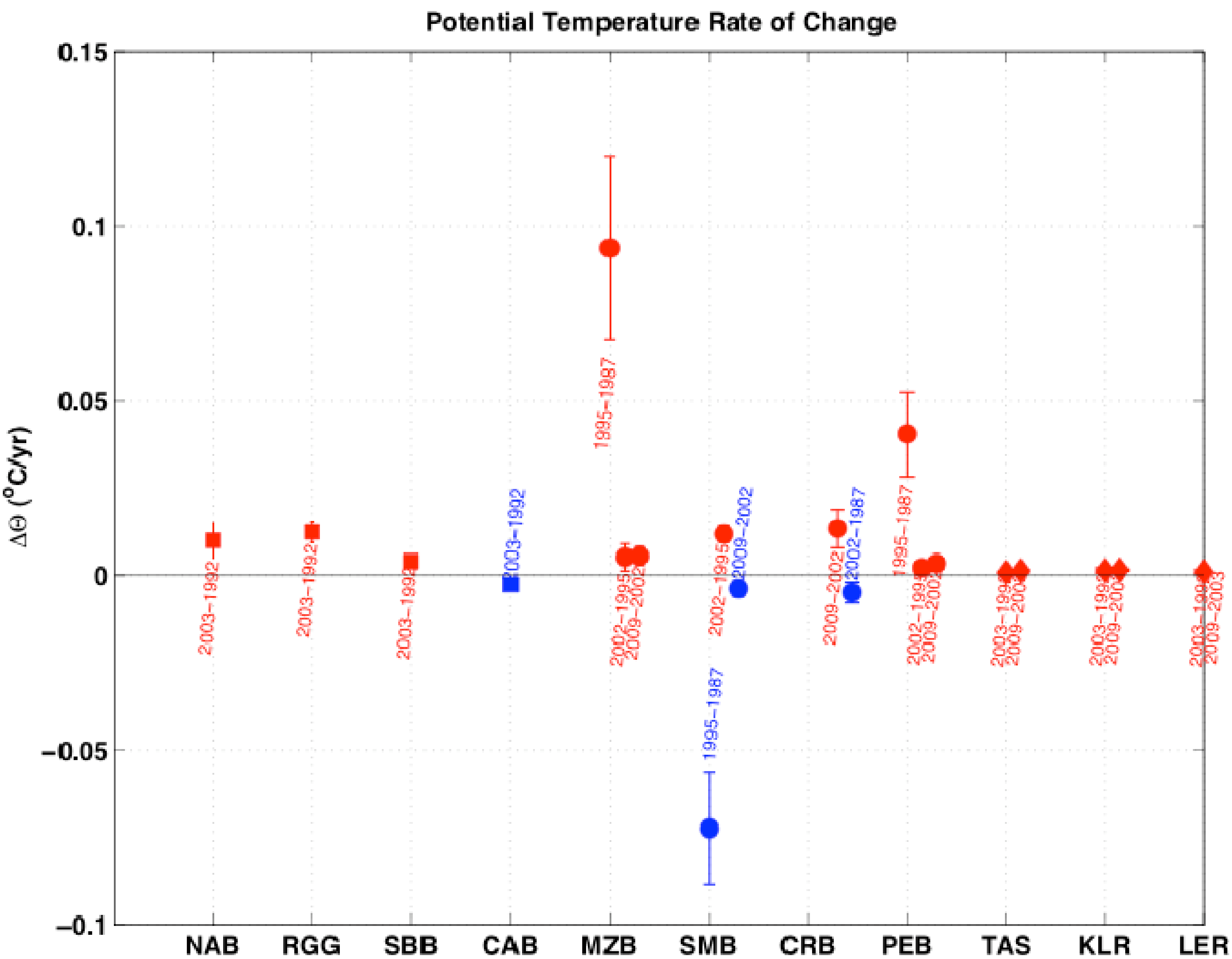
CFC12 Rate of Change
x 10^-3
ΔCFC12 (pmol/kg/yr)
0
1
2
3
4
5
6
7
8
9
NAB
RGG
SBB
CAB
MZB
SMB
CRB
PEB
TAS
KLR
LER
2002–1995
2009–2002
2002–1995
2009–2002
2009–2002
2009–2002
2009–2003
2003–1992
2009–2003



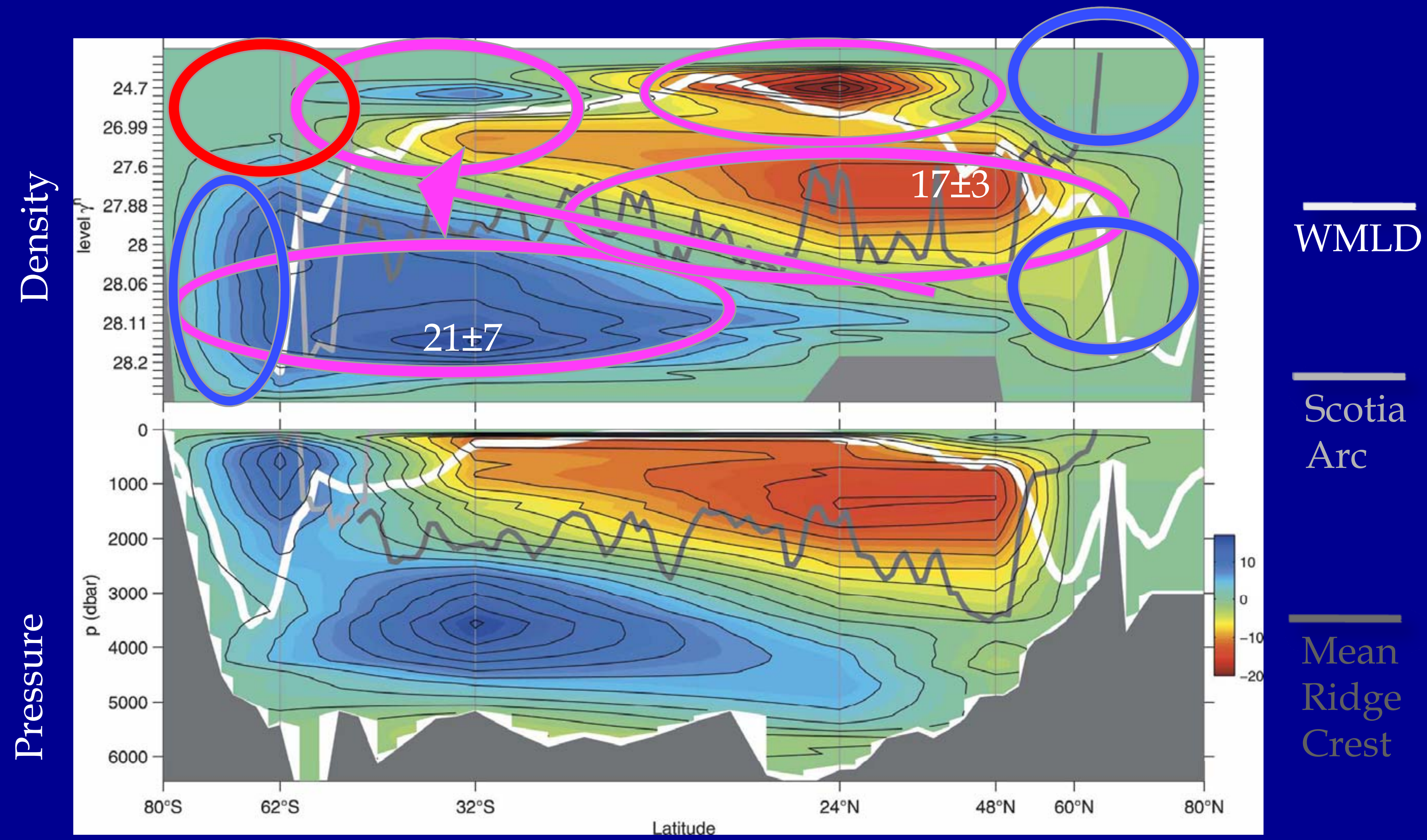
Carbon Rate of Change
ΔCO_2 (µmoles/kg/yr)
10
8
6
4
2
0
−2
NAB
RGG
SBB
CAB
MZB
SMB
CRB
PEB
TAS
KLR
LER
2003−1992
2009−1995
2009−2003

Below 4000 db, < 1.8°C

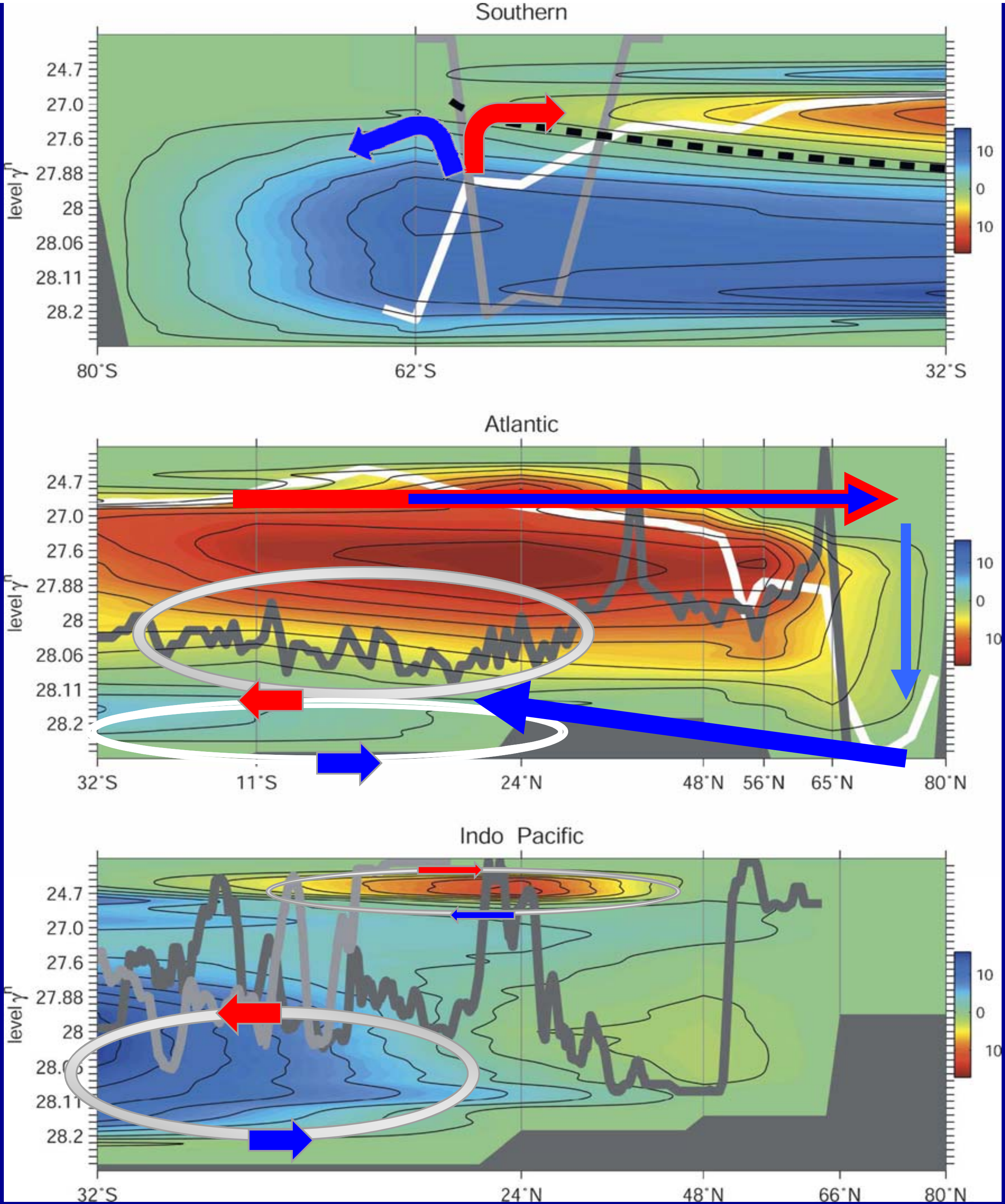
30°S From Atlantic Eastward



Global, Zonally Integrated Estimate of Overturn



Lumpkin & Speer, 2007



Basin Integrated Overturn

Lumpkin & Speer, 2007