Reviewing the Proxy-Data Evidence for the Ocean Circulation during the LGM

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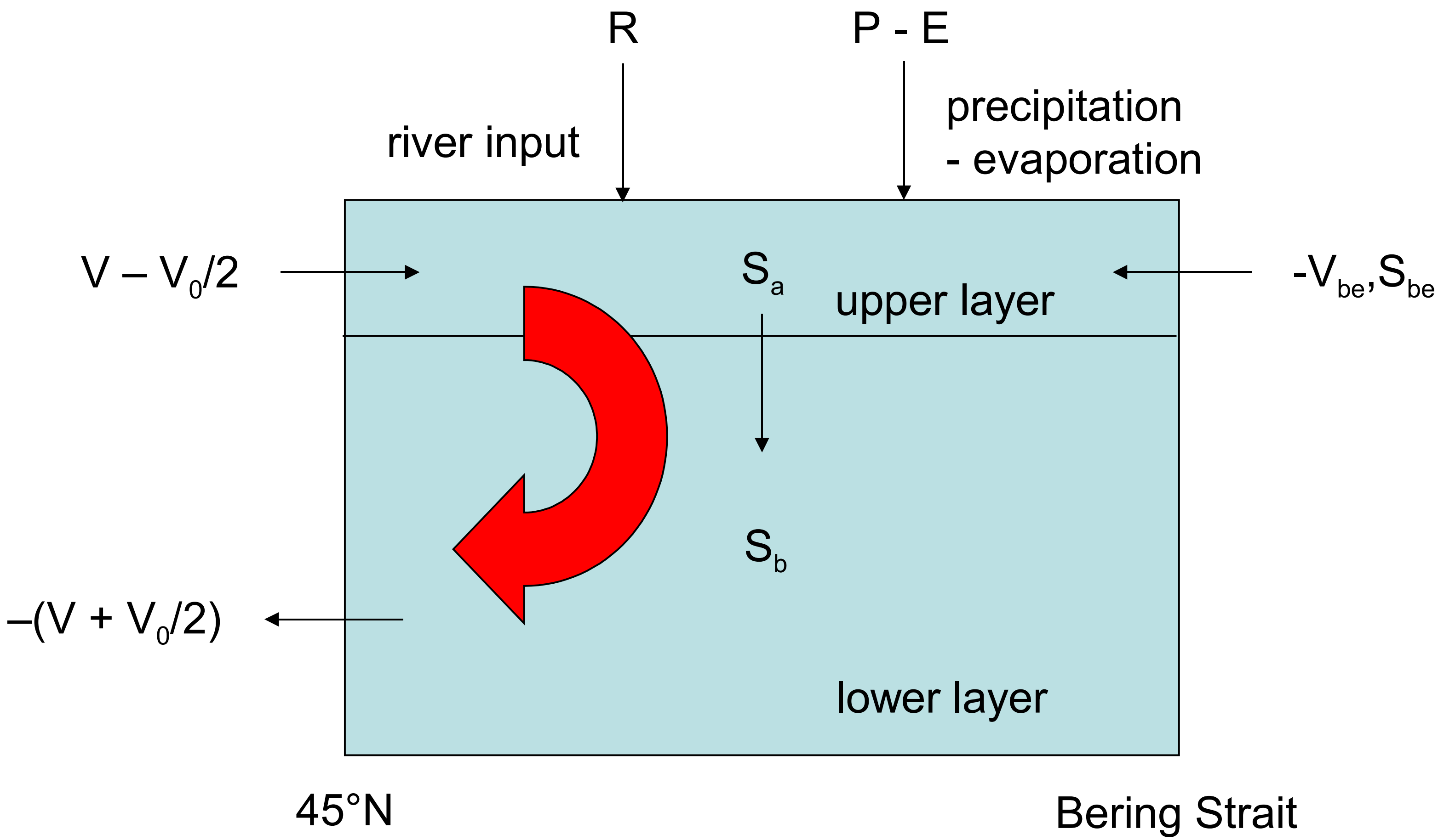
Focus on: Atlantic meridional overturning circulation (AMOC)

Associated heat and freshwater transports

- allow for Europe‘s maritime climate
- provide return circuit for atmospheric vapor transport

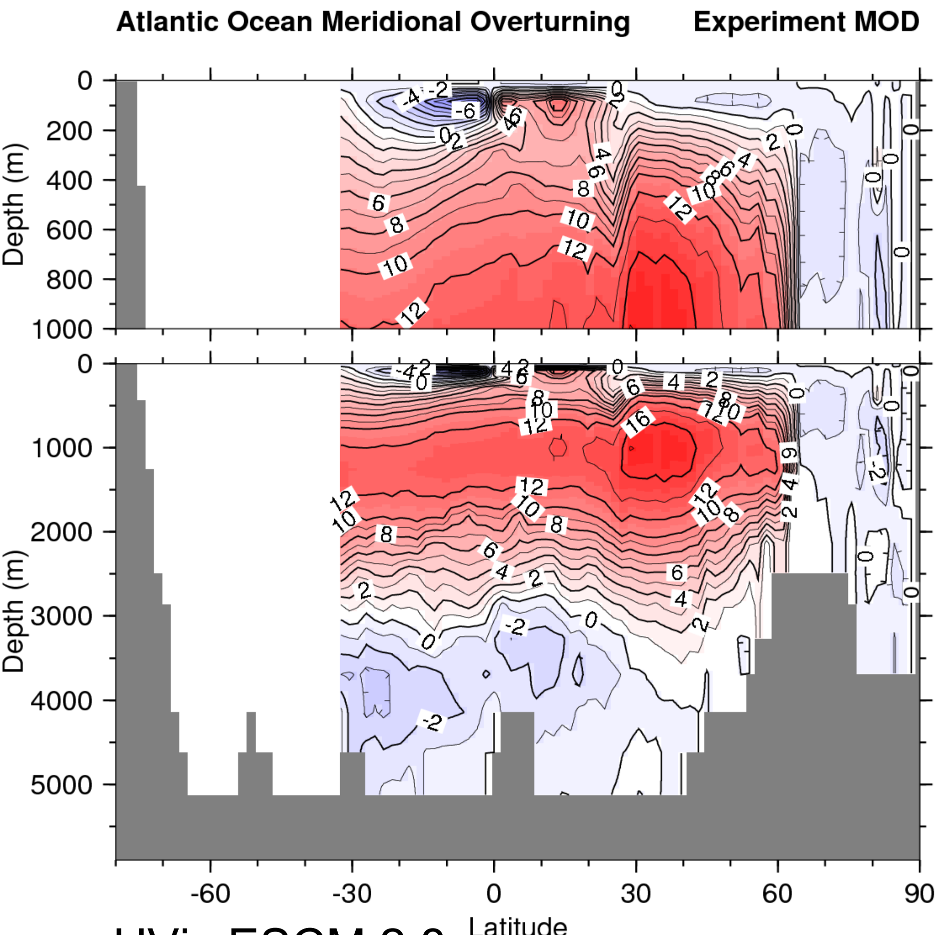
Two-layer box model for modern AMOC



Overturning V~30 Sv, heat transport ~0.9 PW diagnosed from modern hydrographic data (Rhines and Häkkinen, *ASOF Newsletter,* 2003)

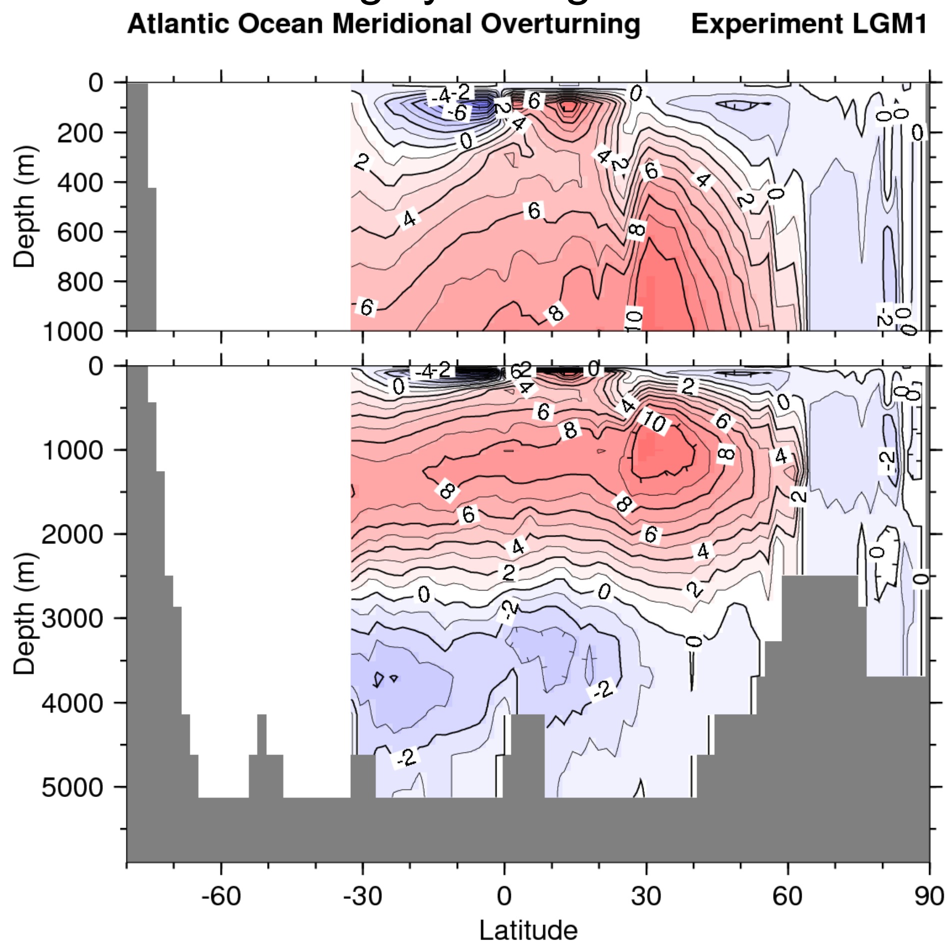
Earth-system model of intermediate complexity for change in AMOC

Modern



UVic ESCM 2.8
(3.6°x1.8°, prescribed wind and wind-stress fields)

LGM:
- NADW cell weaker and shallower
- AABW slighly stronger



- Take at face value?
- Chance result?

Large spread of model results

Model	Type	Maximum of overturning (Sv) Modern	LGM	Modern-to-LGM change	Reference(s)	In Weber et al. (2006)
CCSM1.4	AOGCM	21.6	13.1	-40%	Peltier and Solheim (2003)	X
CCSM3.0	AOGCM	20.8	17.3	-17%	Shin et al. (2003), Otto-Bliesner et al. (2006)	X
CCC (?)	AOGCM	10	4	-60%	Kim et al. (2002, 2003)	
CLIMBER-2	EMIC	23.0	18.4	-20%	Ganopolski et al. (1998)	X
ECBilt/CLIO	EMIC	13.8	18.4	+25%		X
HadCM3	AOGCM	18.3	21.7	+19%	Hewitt et al. (2001, 2003)	X
HadCM3M2	AOGCM	17.4	16.9	-3%	Hewitt et al. (2006)	X
LOVECLIM	EMIC	25	30	+20%	Roche et al. (2007)	
MIROC3.2	AOGCM	18.8	26.1	+39%	Kageyama et al. (2006)	X
MRI-CGCM1	AOGCM	27.1	29.5	+9%	Kitoh et al. (2001), Kitoh and Murakami (2002)	X
NASA/GISS Model E	AOGCM	15	27	+80%	Thresher (2004)	
MOM2	OGCM	10	9	-10%	Paul and Schäfer-Neth (2003, 2004), experiments G3/GC	
UVic ESCM 1.?	EMIC	16	8	-50%	Weaver et al. (1998)	
UVic ESCM 2.?	EMIC	20.4	14.2	-30%	Schmittner et al. (2002)	X
UVic ESCM 2.8	EMIC	17	11	-35%	This study (experiment LGM1 with present-day wind-stress field)	

For some more results, see poster XY0167

For recent review, see Weber et al. (*CP,* 2007).

Need proxies to constrain models

Proxy class →	Target	Examples
Surface proxies	Surface temperature	Microfossil assemblages, magnesium/calcium (Mg/Ca) ratios, Uk'37 index based on alkenones
Paleo-nutrient proxies	Water mass distribution (“geometry”)	$\delta^{13}C$, cadmimum/calcium (Cd/Ca) ratios
Kinematic proxies	Deep-water circulation rates	Grain sizes, radiogenic proxies: $\delta^{14}C$, $^{231}Pa/^{230}Th$, neodymium isotope composition ε_{Nd}
Dynamic proxies	Sea-water density	$\delta^{18}O$

For recent review, see Lynch-Stieglitz et al. (*Science,* 2007).

- Proxies support
  - Sharp water mass boundary at mid depth (~2 km)
  - Sustained deep water formation in Nordic Seas
  - Slowdown of Atlantic meridional overturning circulation
  - Cold and salty Antarctic Bottom Water
- Proxies do not support
  - Collapse or strong enhancement of Atlantic meridional overturning circulation

Sharp property gradient between shallower and deeper water masses

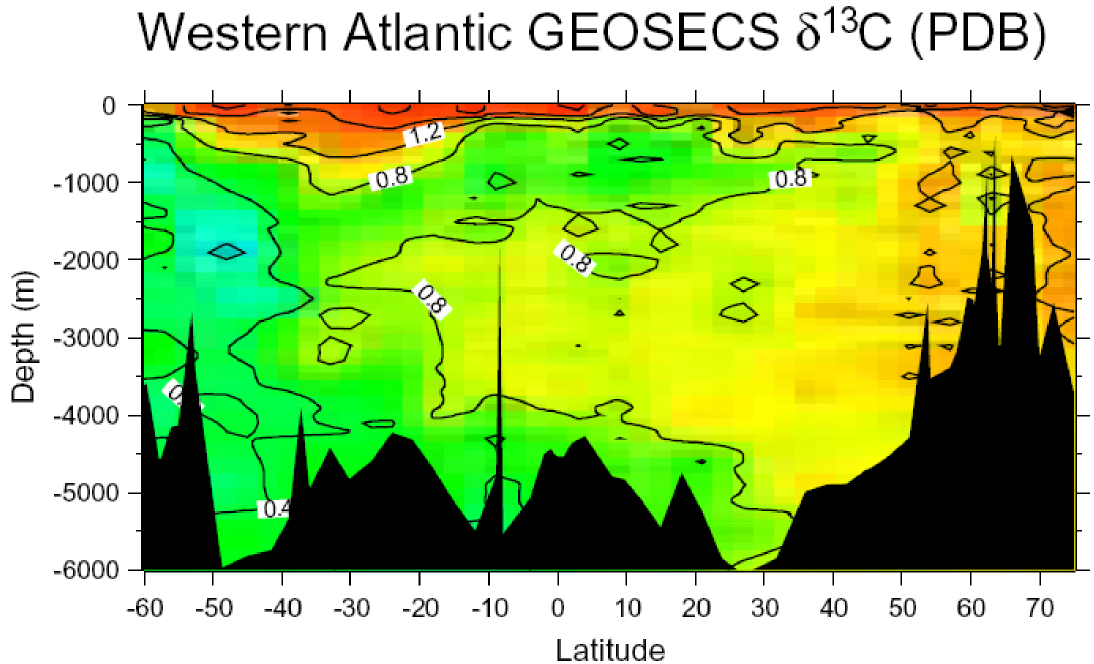
- Supported by
  - $\delta^{13}C$, Cd/Ca from North Atlantic: agree on division between low-nutrient water mass above 2 km depth and high-nutrient water mass below
  - ^{14}C: radiocarbon-rich (recently ventilated) waters above 2 km depth and radiocarbon-poor ("old") waters below
- Not supported by
  - $\delta^{13}C$ from South Atlantic

Curry and Oppo (*Paleoceanography,* 2005)

Marchitto and Broecker (*G^3,* 2007),

Bickert and Mackensen (Springer, 2004)

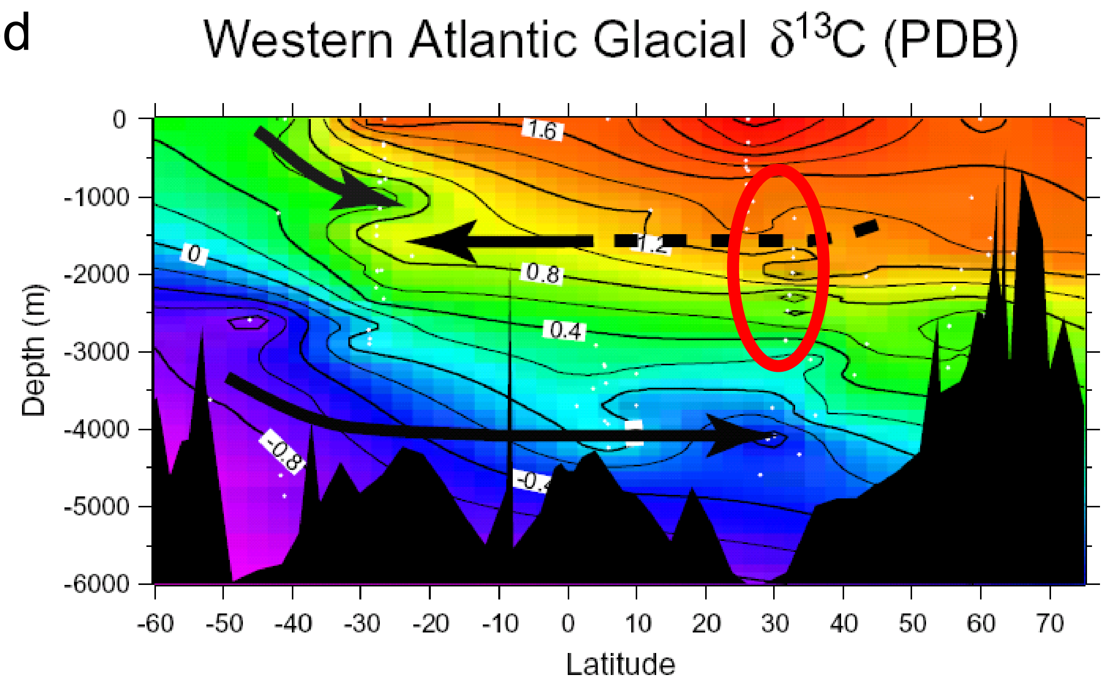
NADW: high $\delta^{13}C$/ low nutrient concentrations



Distribution of $\delta^{13}C$ of ΣCO_2 in the modern western Atlantic (Kroopnick 1985)

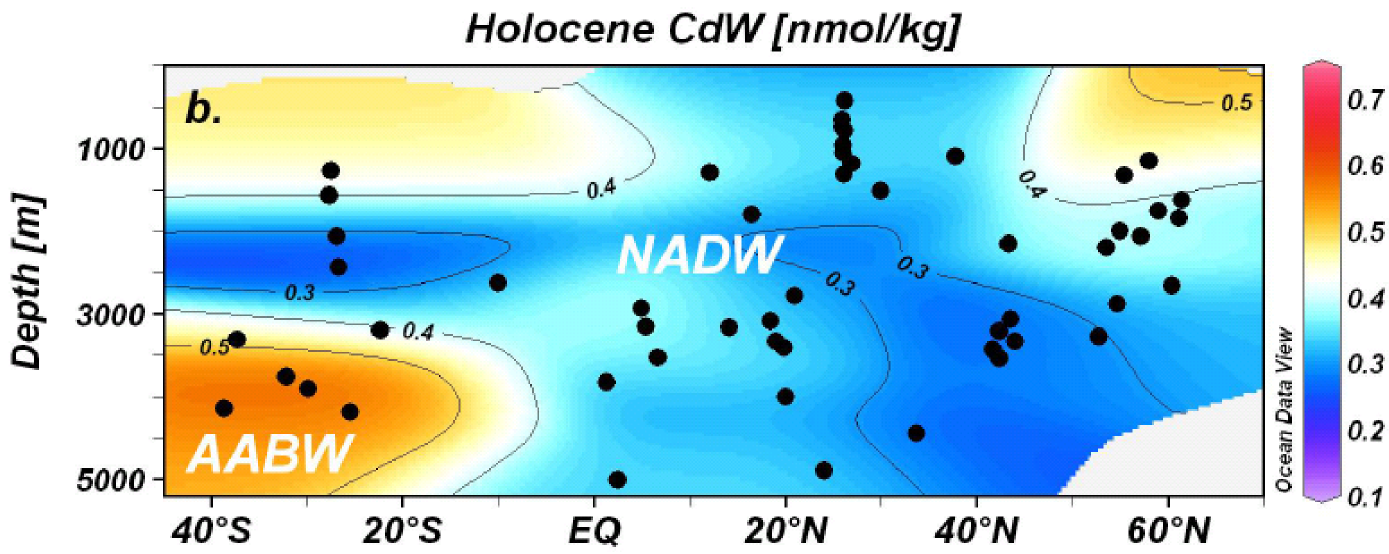
Three-component model proposed by Curry and Oppo (2005)

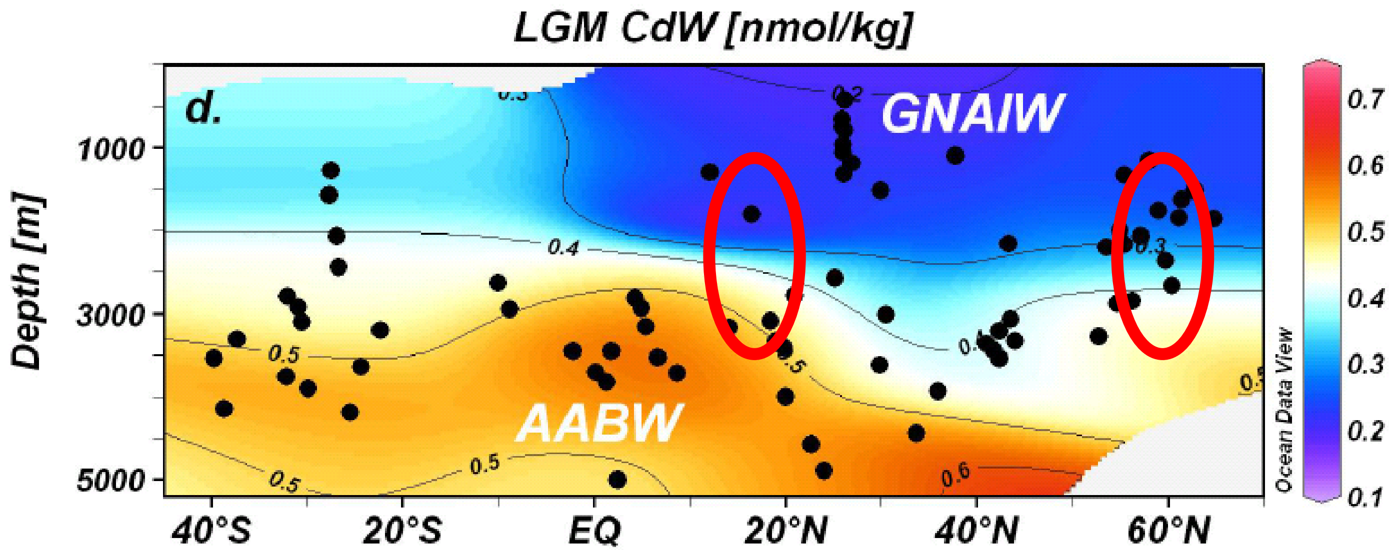
GNAIW: dominates and creates sharp vertical property gradient



Glacial transect of $\delta^{13}C$ of ΣCO_2 for the western Atlantic Ocean basins

Curry and Oppo (2005)





Meridional sections of inferred seawater dissolved Cd for the Holocene and LGM Atlantic Ocean

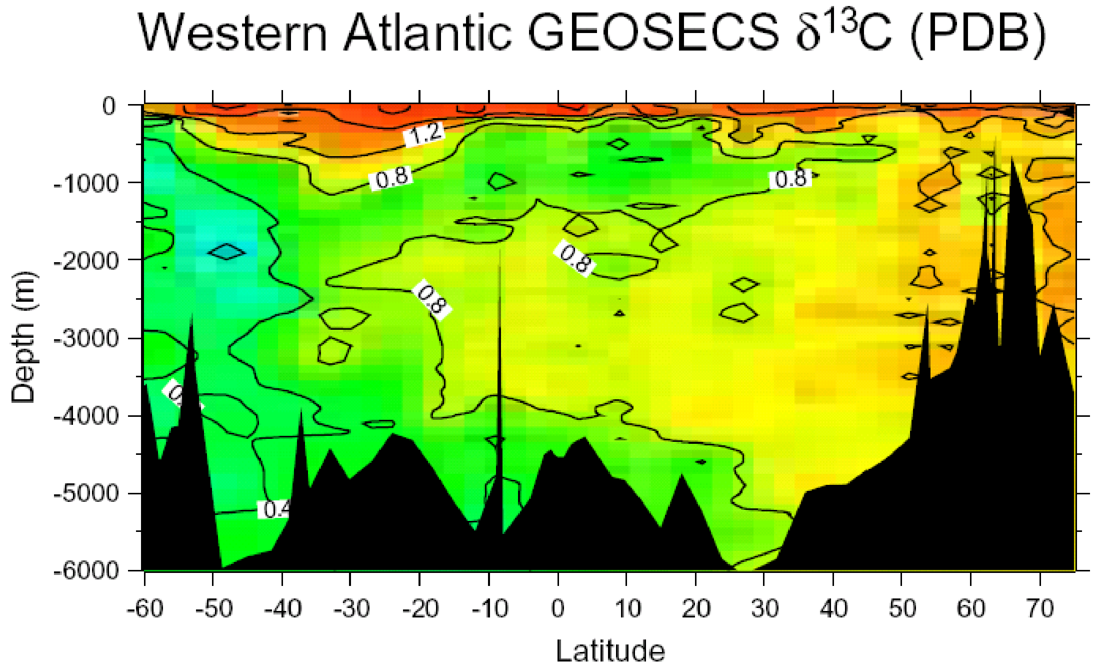
Marchitto and Broecker (*G*[3], 2006)

Sustained deep water formation in Nordic Seas

- Supported by
  - Higher $\delta^{13}C$/lower Cd values in deep (> 2 km) North Atlantic than South Atlantic
  - Epibenthic $\delta^{18}O$ and $\delta^{13}C$ data for Denmark Strait Overflow

Lynch-Stieglitz et al. (*Science,* 2007)

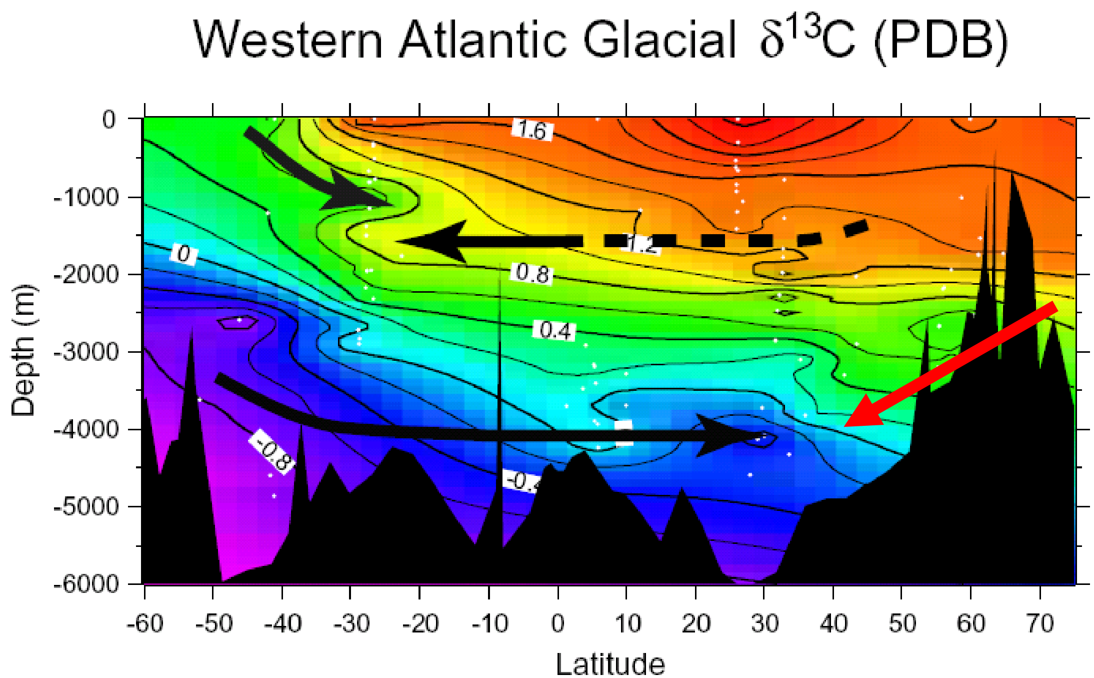
Millo et el. (*Boreas,* 2006)



Distribution of $\delta^{13}C$ of ΣCO_2 in the modern western Atlantic (Kroopnick 1985)

Four-component model

Still active deep-water formation in Nordic Seas (cf. Millo et al. 2006, Lynch-Stieglitz et al. 2007)



Glacial transect of $\delta^{13}C$ of ΣCO_2 for the western Atlantic Ocean basins

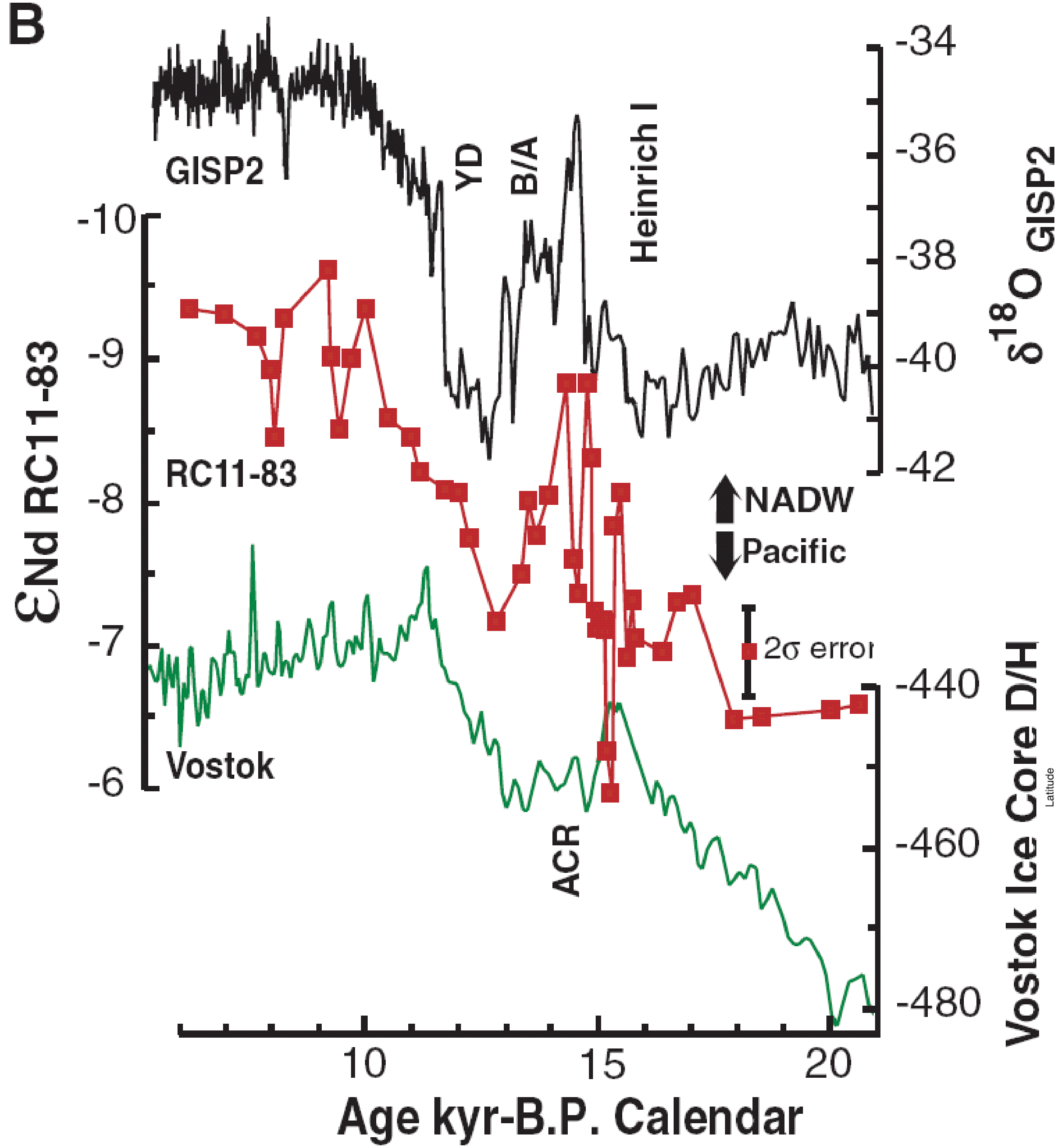
Curry and Oppo (2005)

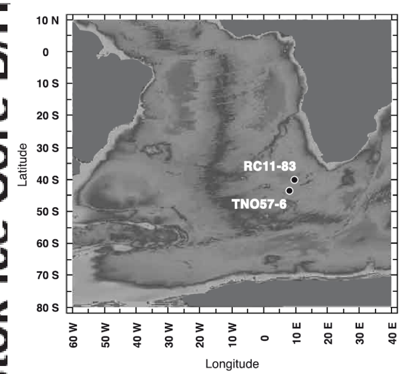
Slowdown of Atlantic meridional overturning circulation

- Supported by
  - $^{231}Pa/^{230}Th$ ratios higher than during Holocene: suggest reduction by up 30-40%
  - ε_{Nd}: at LGM, strength of NADW export only ~30%-50% of Holocene value

Rutberg et al. (*Nature,* 2000)
McManus et al. (*Nature,* 2004)
Piotrowski et al. (*Science,* 2005)
Foster et al. (*Geology,* 2007)

More negative values of ε_{ND} indicate more NADW





Piotrowski et al. (*Science*, 2005)

Slowdown of Atlantic meridional overturning circulation

- Questioned by
  - $\delta^{13}C$, Cd/Ca from North Atlantic: sharp vertical property gradient requires strong horizontal advection relative to vertical mixing
  - But gradient in end-member values (surface boundary condition) could produce similar result

Curry and Oppo (*Paleoceanography*, 2005)

Marchitto and Broecker (*G³*, 2006)

Rutberg and Peacock (*Paleoceanography*, 2006)

Cold and salty AABW

- Pore-water $\delta^{18}O$, combined with benthic foraminferal $\delta^{18}O$: bottom water homogenously cold, close to freezing point
- Pore-water chlorinity: AABW also much saltier

Adkins et al. (*Science*, 2002)
Schrag et al. (*QSR*, 2002)

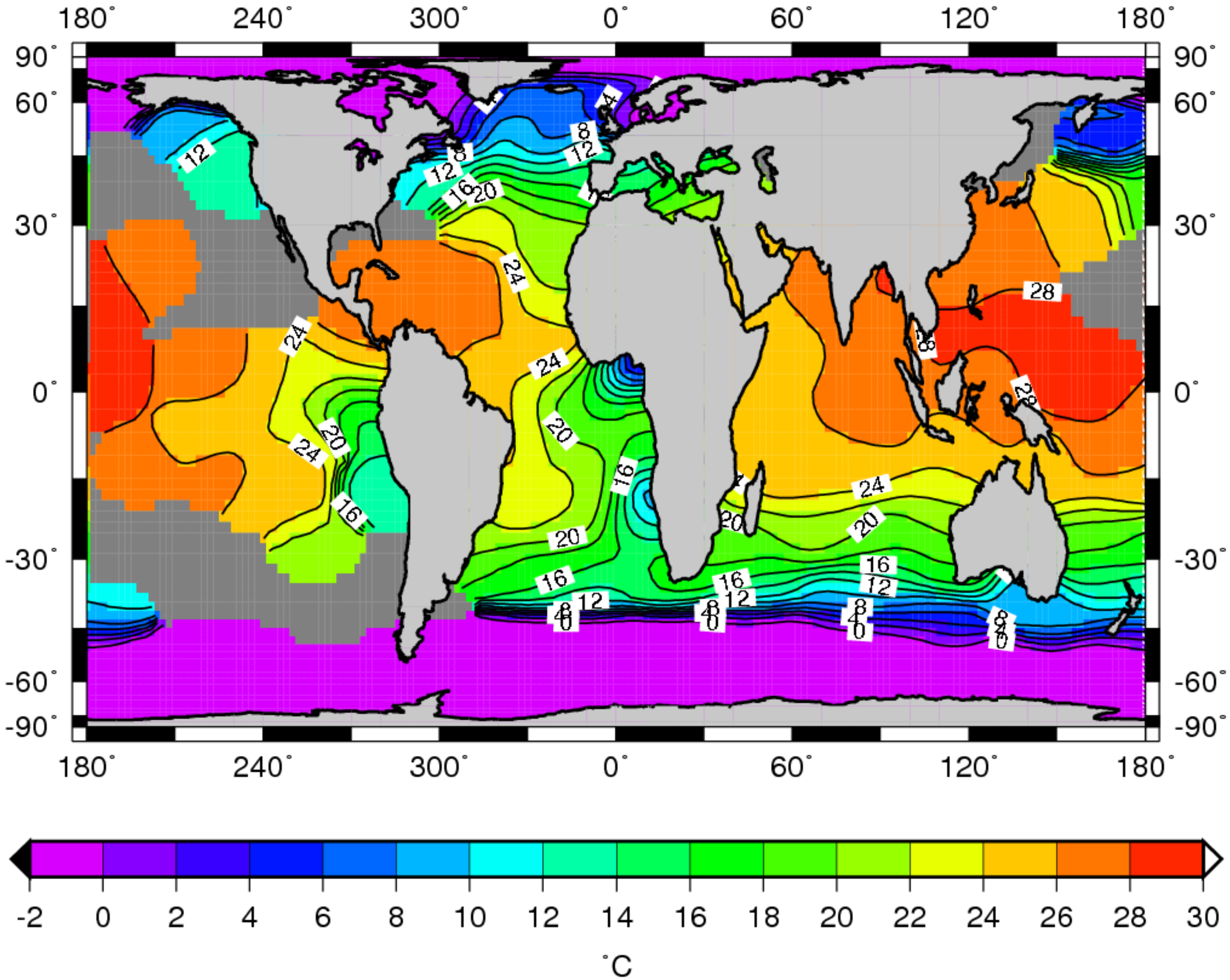
Collapse (or strong enhancement) of Atlantic meridional overturning circulation

- Not supported by
  - Surface proxies (MARGO SST/GLAMAP sea-ice boundaries): imprint of continued inflow of warm Atlantic waters
  - $\delta^{13}C$, Cd/Ca, $\Delta^{14}C$: require two end members, one nutrient poor/radiocarbon rich, the other nutrient rich/radiocarbon poor
  - $^{231}Pa/^{230}Th$ ratios: suggest active flushing of Atlantic deep waters and slightly slower circulation of deep and bottom waters

Sea-surface temperature

(MARGO reconstruction, July-August-September - JAS)

All MARGO proxies
- block-averaged on 5°x5° grid
-weigthed by reliability index, assigned by individual researcher
-sea-ice boundaries still from GLAMAP

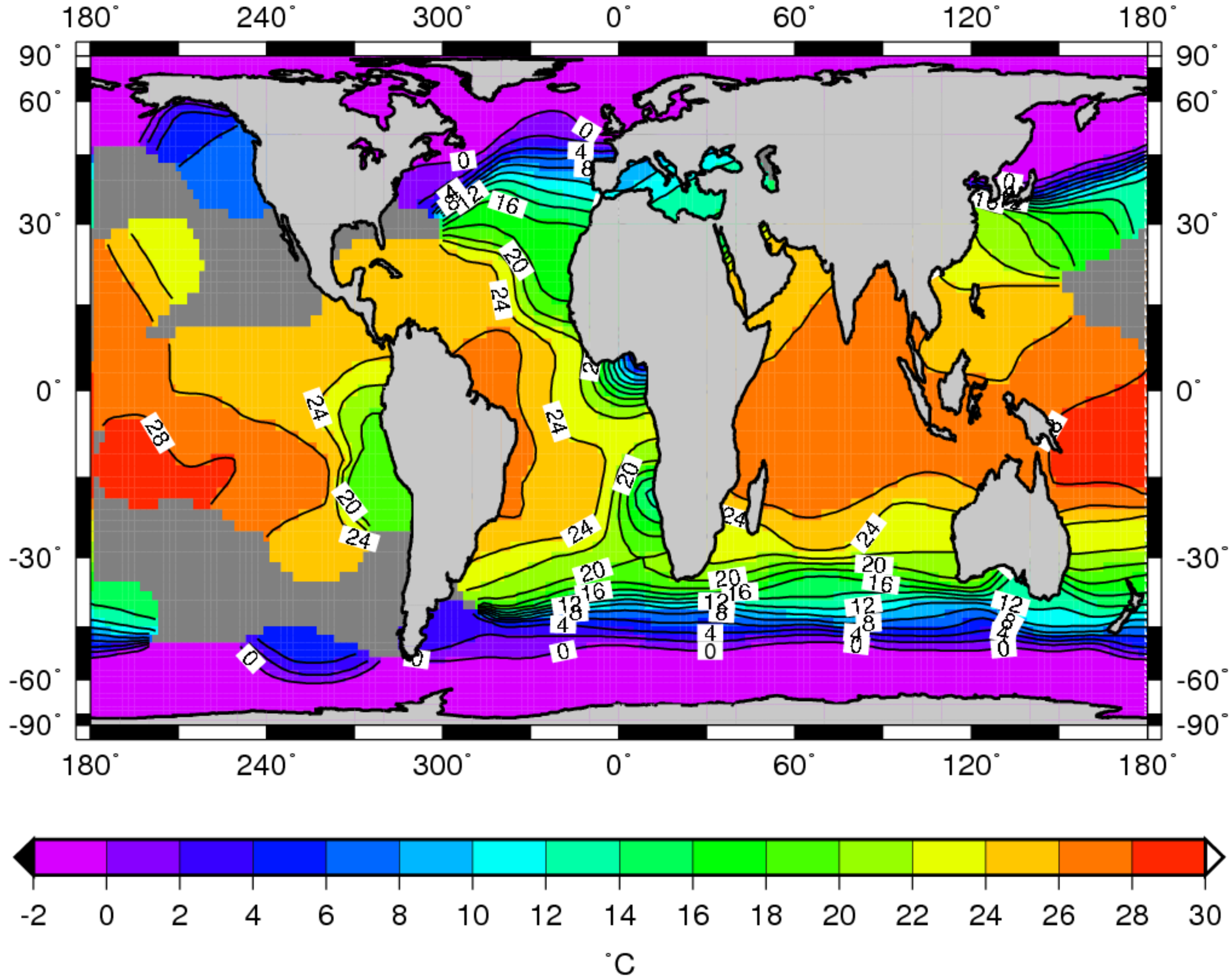


Note erroneous value in Gulf of Guinea

Data from Kucera et al. (2005) and PANGAEA

Sea-surface temperature

(MARGO reconstruction, January-February-March - JFM)



Note erroneous value in Gulf of Guinea

Data from Kucera et al. (2005) and PANGAEA

Comments on $\delta^{18}O$ as dynamic proxies

- Florida Straits estimate of reduced vertical shear
  - Would be consistent with weaker surface branch of overturning circulation (Lynch-Stieglitz et al., Paleoceanography 1999; Lynch-Stieglitz et al., *G*³ 2006)
  - But may have coincided with stronger barotropic (mean) flow (Hirschi and Lynch-Stieglitz, *G*³ 2006) – need more than section

- South Atlantic estimate of collapsed or reversed cross-basin density gradient
  - For current accuracy of reconstructions of paleodensities, 30°S may be too close to the equator and subject to noise because of „thermal wind relation“ (Hirschi and Lynch-Stieglitz, *G³* 2006)
  - Thus shallow overtuning of GNAIW not yet disproved

Conclusions

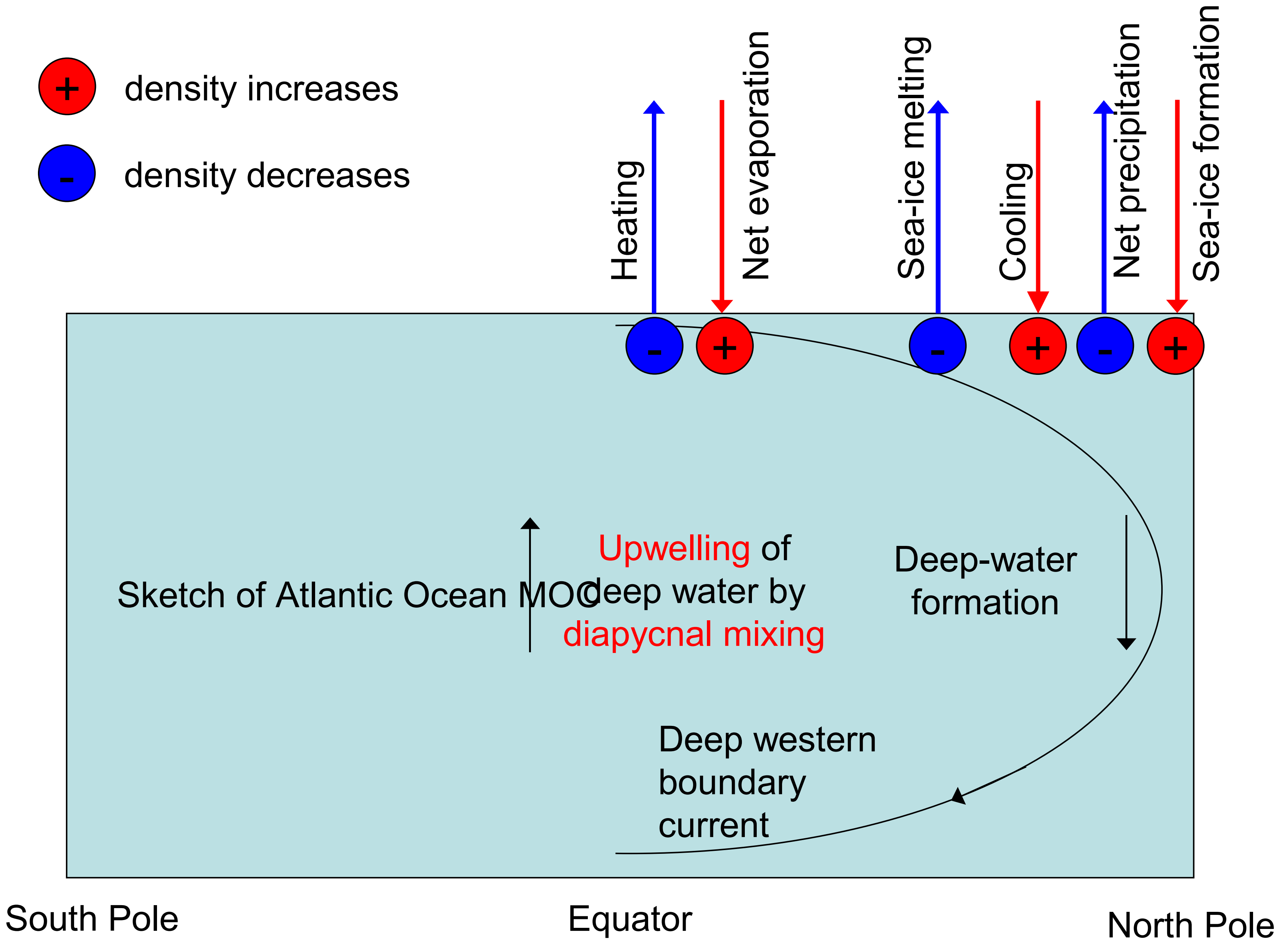
- Distribution ("geometry") of water masses at LGM rather well known
  - in the Atlantic Ocean, low nutrient concentrations down to about 2 km depth, higher than today below 2 km depth, sharp property gradient between shallower and deeper water masses
- But rate of deep overturning circulation still poorly constrained
  - with possibly a bias towards an Atlantic Ocean circulation (slightly) slower than at present

Supplementary material (not presented)

Why could the models fail?

- Sensitive balance of conflicting density fluxes
- Availability of energy for diapycnal mixing not yet considered
  - Ocean models possibly produce too much upwelling in low latitudes
- Formation of AABW not well represented
  - On shelf (today) vs. open ocean (at LGM?)

Conflicting density fluxes



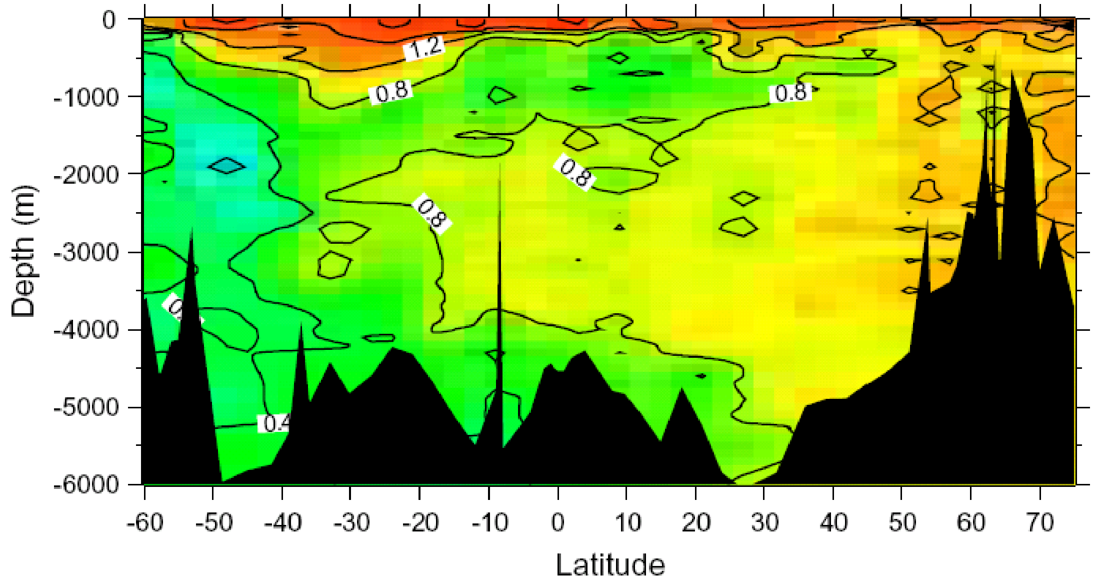
Why could the data fail?

- Better understanding of ancillary effects on proxies itself needed
  - e.g. for Cd: combination of benthic foraminiferal taxa, carbonate ion effect, within-sampled heterogenity, cleaning protocols (Marchitto and Broecker, *G*^{3}, 2006)
- Sparse coverage of mainly
  - South Atlantic and Southern Oceans
  - intermediate depths
  - how well are vertical gradients constrained?

Antarctic Intermediate Water denser than GNAIW

- Hypothesized by Keeling and Stephens (2001)
- Could be consistent with reconstructed reversal in cross-basin density gradient (Lynch-Stieglitz et al. 2006), which however is subject to noise

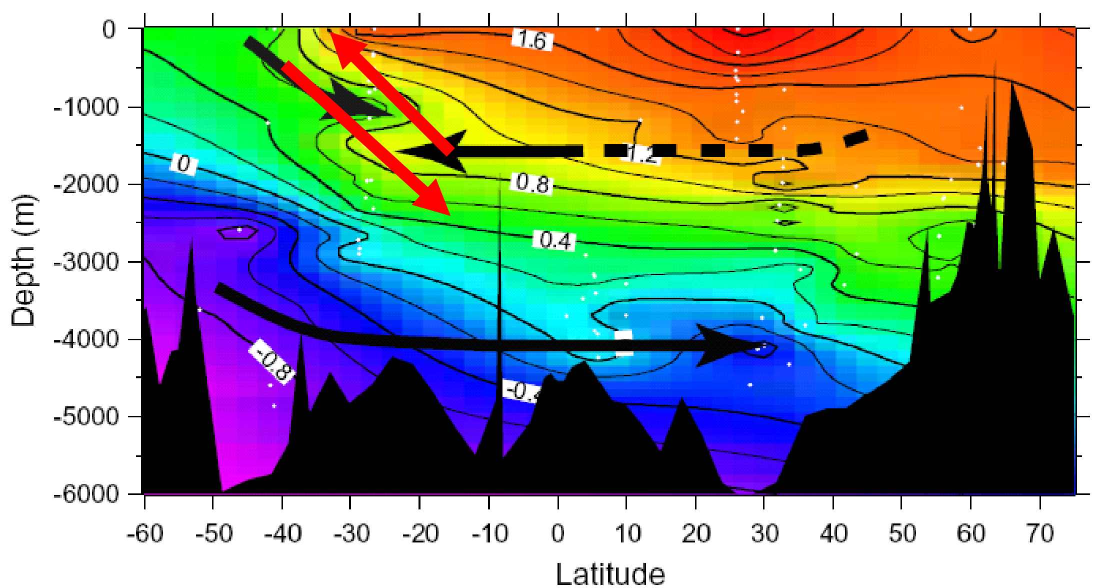
Western Atlantic GEOSECS $\delta^{13}C$ (PDB)



Distribution of $\delta^{13}C$ of ΣCO_2 in the modern western Atlantic (Kroopnick 1985)

Upwelling of GNAIW in Southern Ocean

Western Atlantic Glacial $\delta^{13}C$ (PDB)



Glacial transect of $\delta^{13}C$ of ΣCO_2 for the western Atlantic Ocean basins

Curry and Oppo (2005)

GNAIW cell closed in Atlantic Ocean

- Deepening of subtropical gyre could contribute to enhanced ventilation of North Atlantic Ocean - GNAIW cell could be partly closed in the horizontal

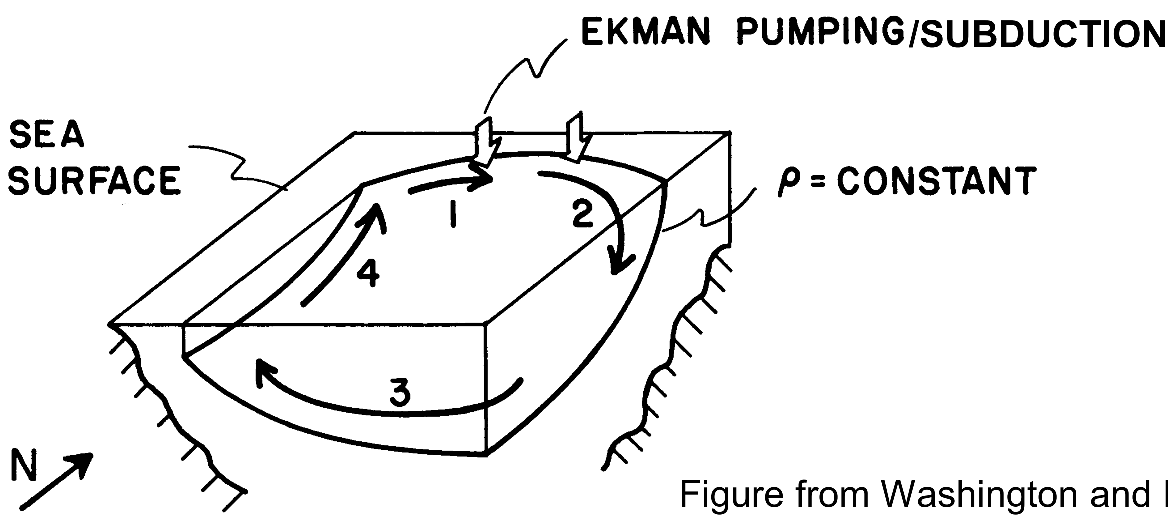


Figure from Washington and Parkinson (1986)