How is abrupt (paleo) climate change transmitted to the mid latitude Southern Hemisphere?

-or - In defense of the “wind hypothesis”

Connecting the tropics to polar regions

LDEO, 2-3 June 2014

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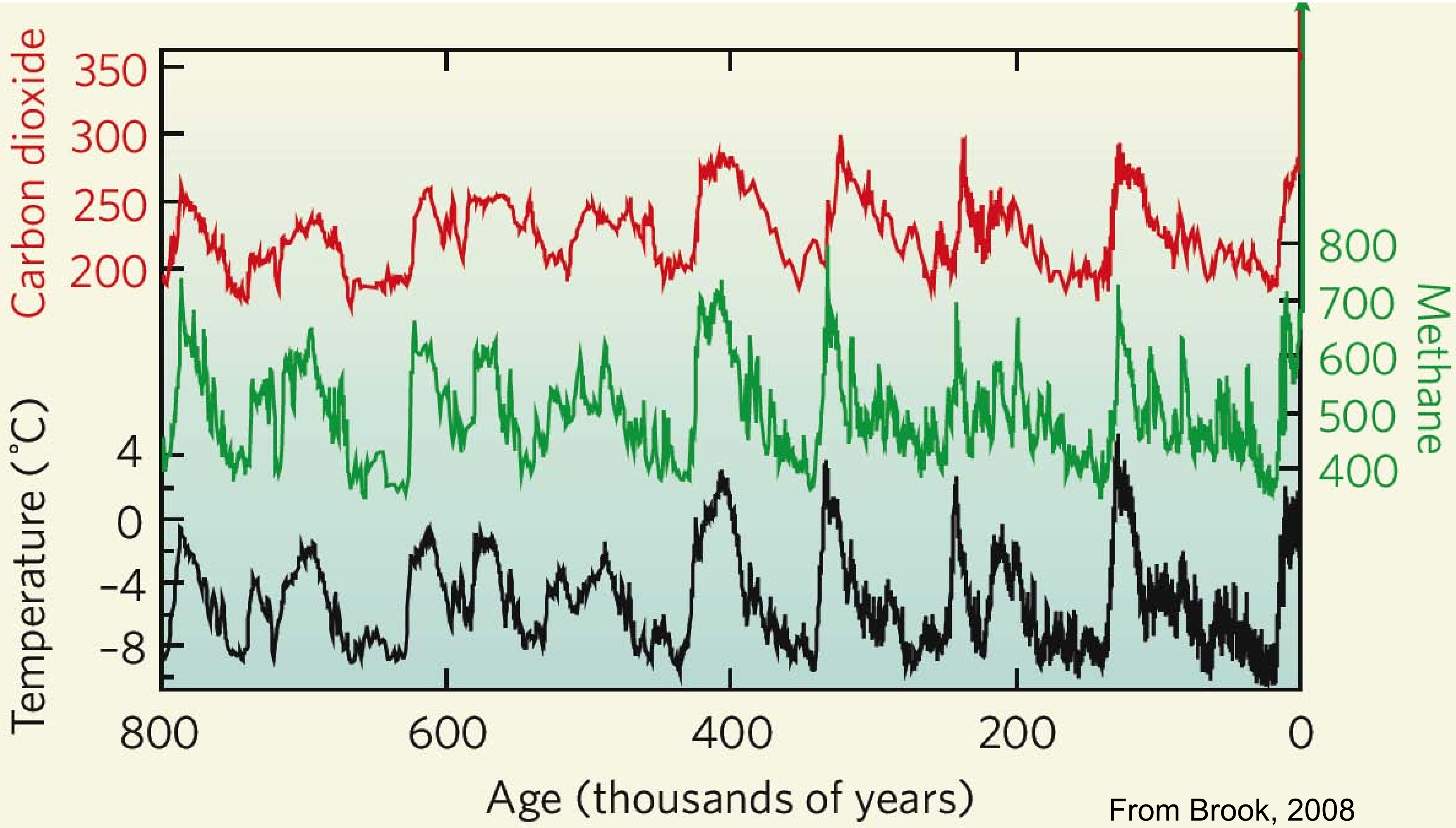
Premise and Outline

Abrupt (paleo) climate changes provide natural experiments to study carbon, climate and their interactions.

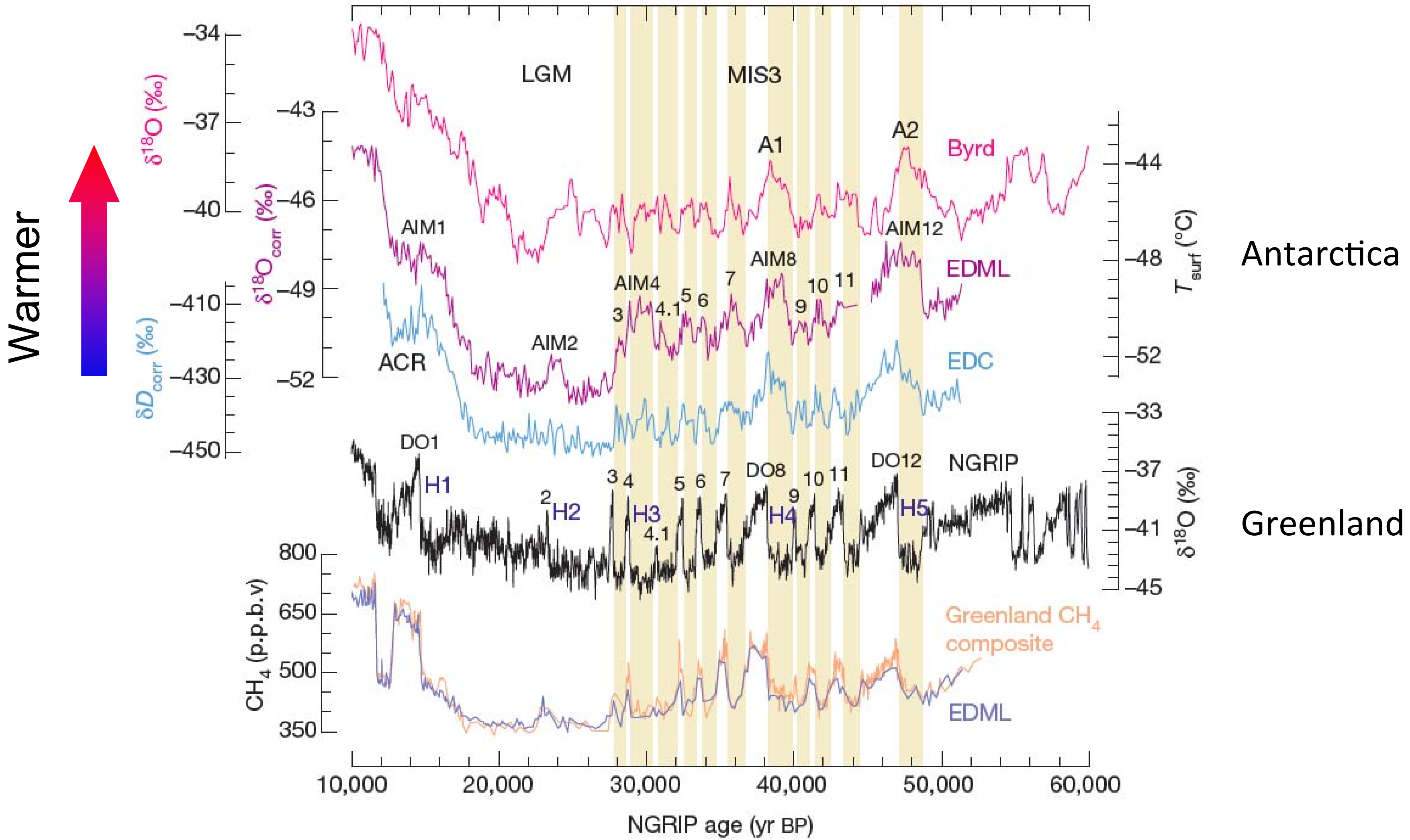
1) Introduction: Abrupt change, CO_2, winds & controversy
2) Where is there consensus - Tropics?
3) Last Glacial Maximum in the southern mid latitudes
4) Heinrich Stadial warming in the SH mid latitudes
5) Model-data comparison
6) Summary: Features consistent with wind hypothesis that must be explained by alternative conceptual models

Ice core records reveal tight coupling between CO_2 and climate



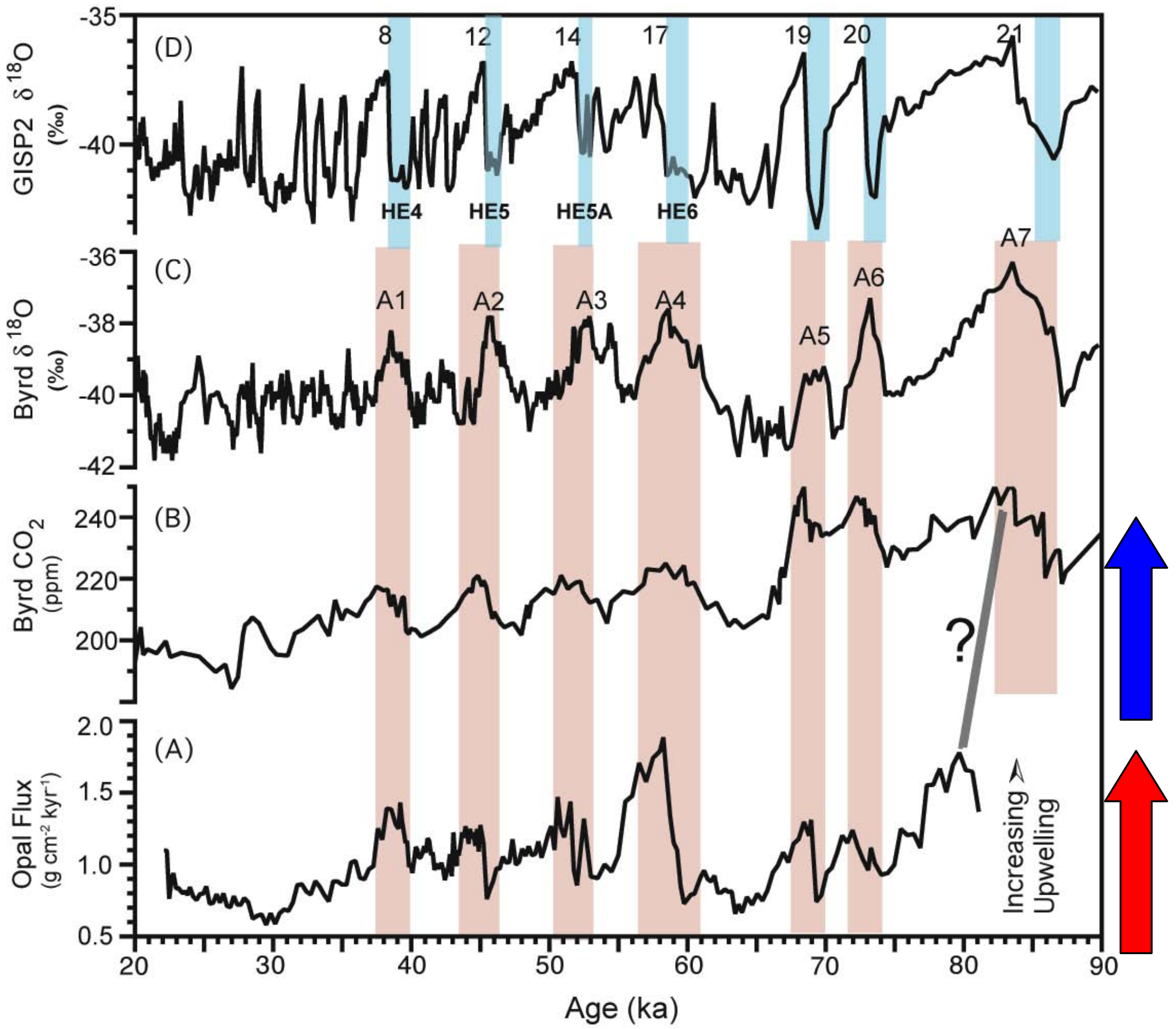
From Brook, 2008

Antiphase temperature changes of the last glacial period



EPICA community members 2006

Upwelling proxy correlates with pCO_2 throughout last glacial period



TN057-14: Increased upwelling (opal flux) coincided with:

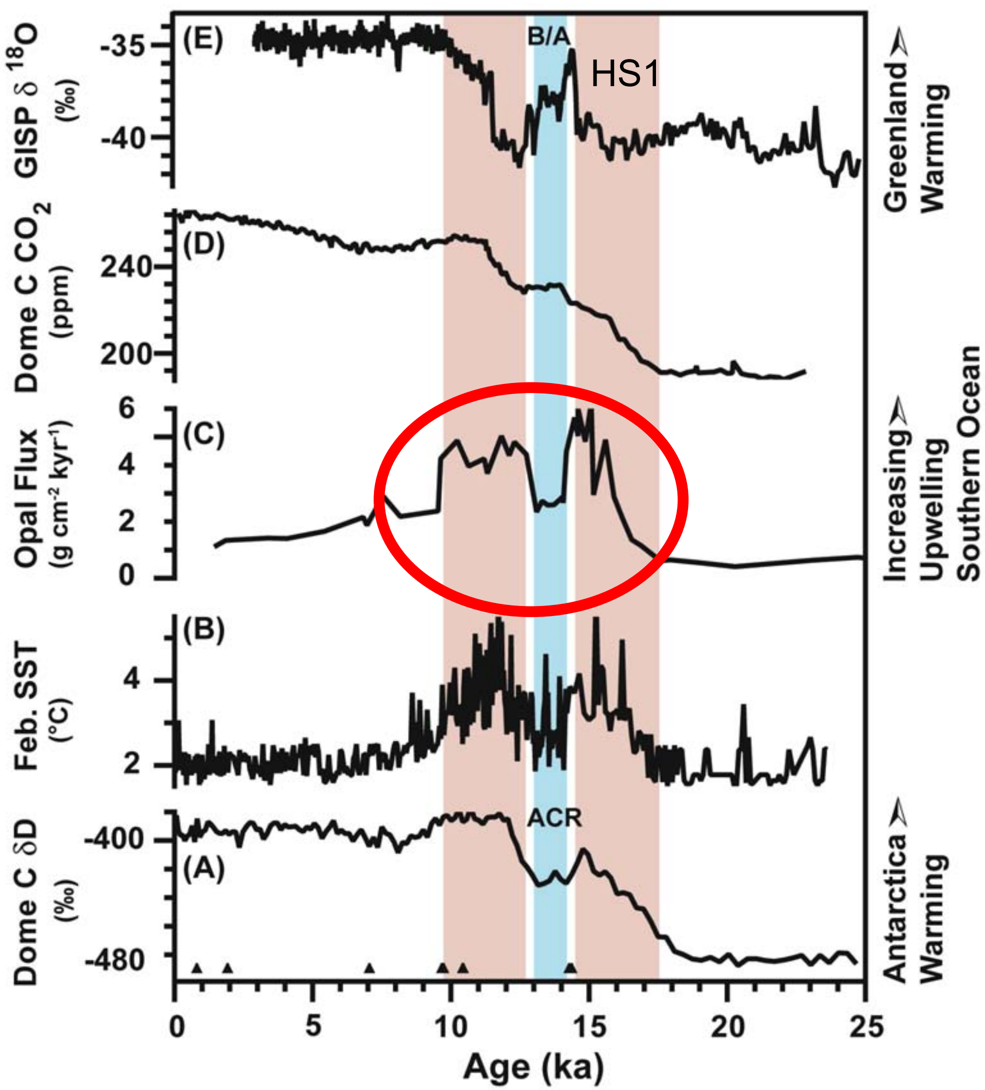
Cold in Greenland

Warmth in Antarctica

Rising CO_2

Anderson et al., 2009

Maximum So. Ocean upwelling coincided with deglacial rise in CO_2



<u>SUMMARY OF EVIDENCE</u>:

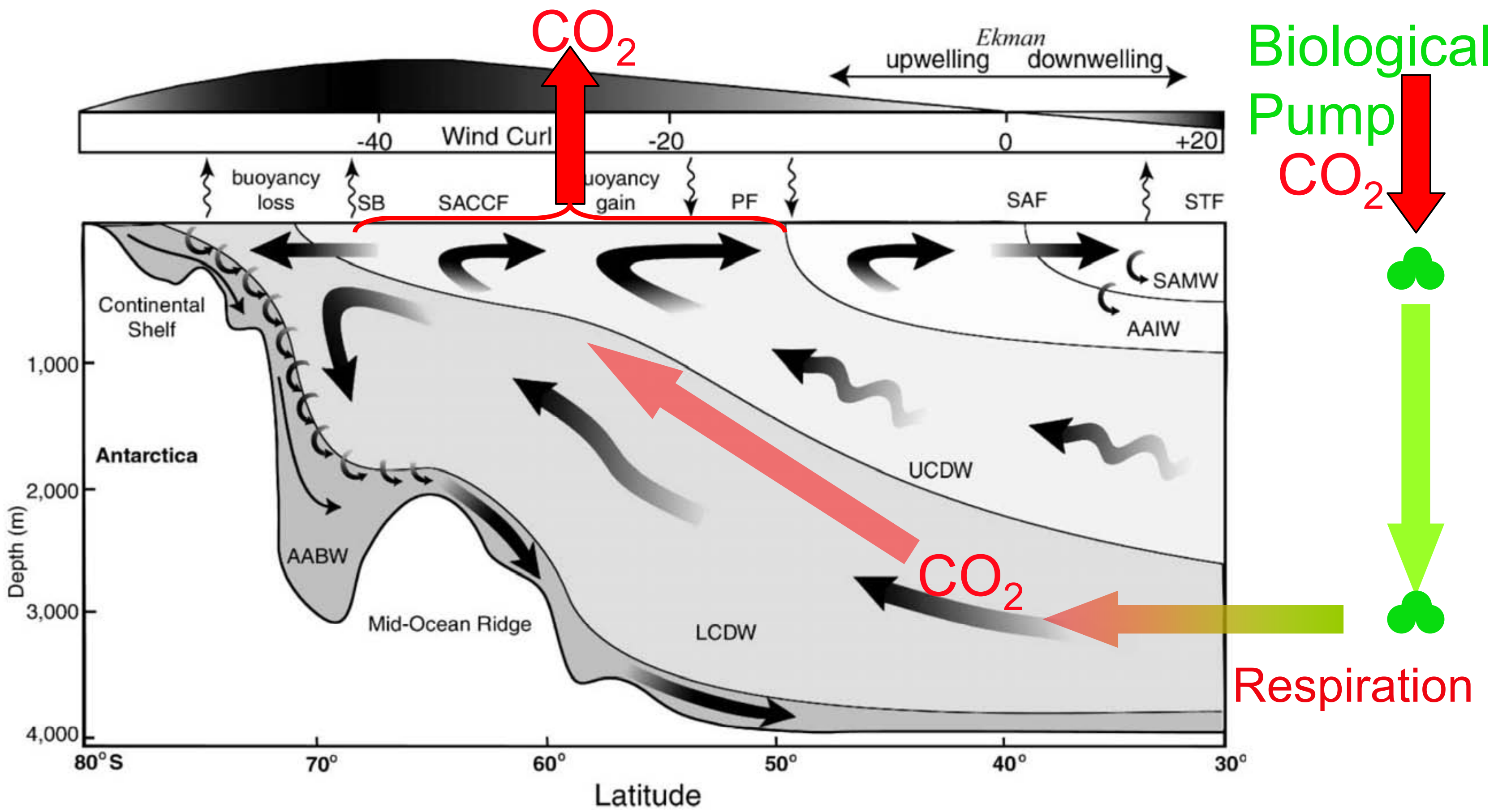
Peak upwelling (opal flux) coincided with:

- warming in Antarctica,
- deglacial rise in CO_2
- "cold" in Greenland

Including reversal during B/A-ACR

Modified from Anderson et al., 2009

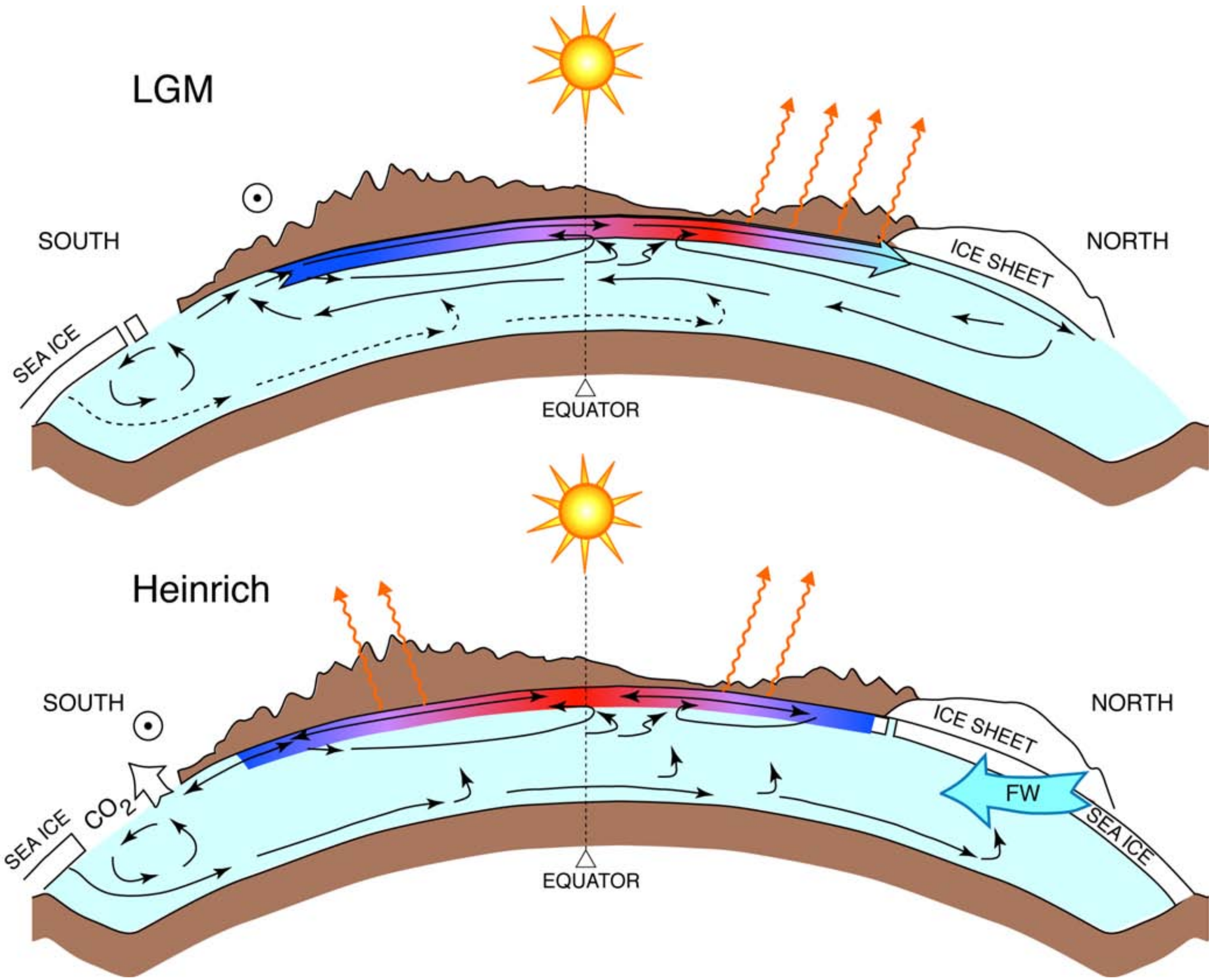
Wind-driven upwelling in the Southern Ocean "ventilates" deep waters



Atmospheric CO_2 reflects a global balance between biological drawdown and physical ventilation.

Figure of K Speer redrawn by T Trull

Can ocean processes account for changes? (Bipolar Seesaw)

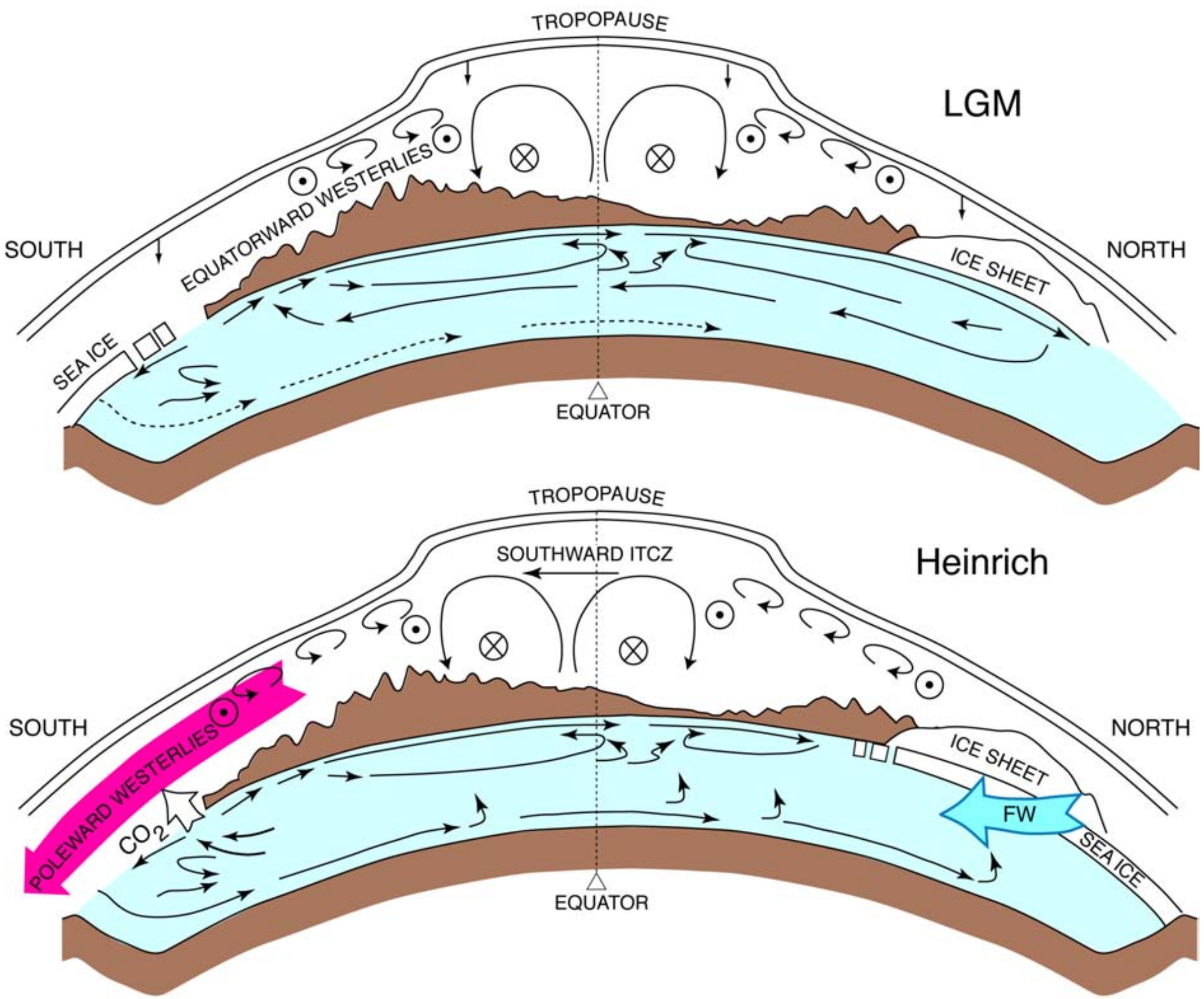


Glacial
AMOC "on"

Heinrich Stadial
AMOC "off"
Surface warming

1) Heats Antarctica
2) Melts sea ice
3) Releases CO_2

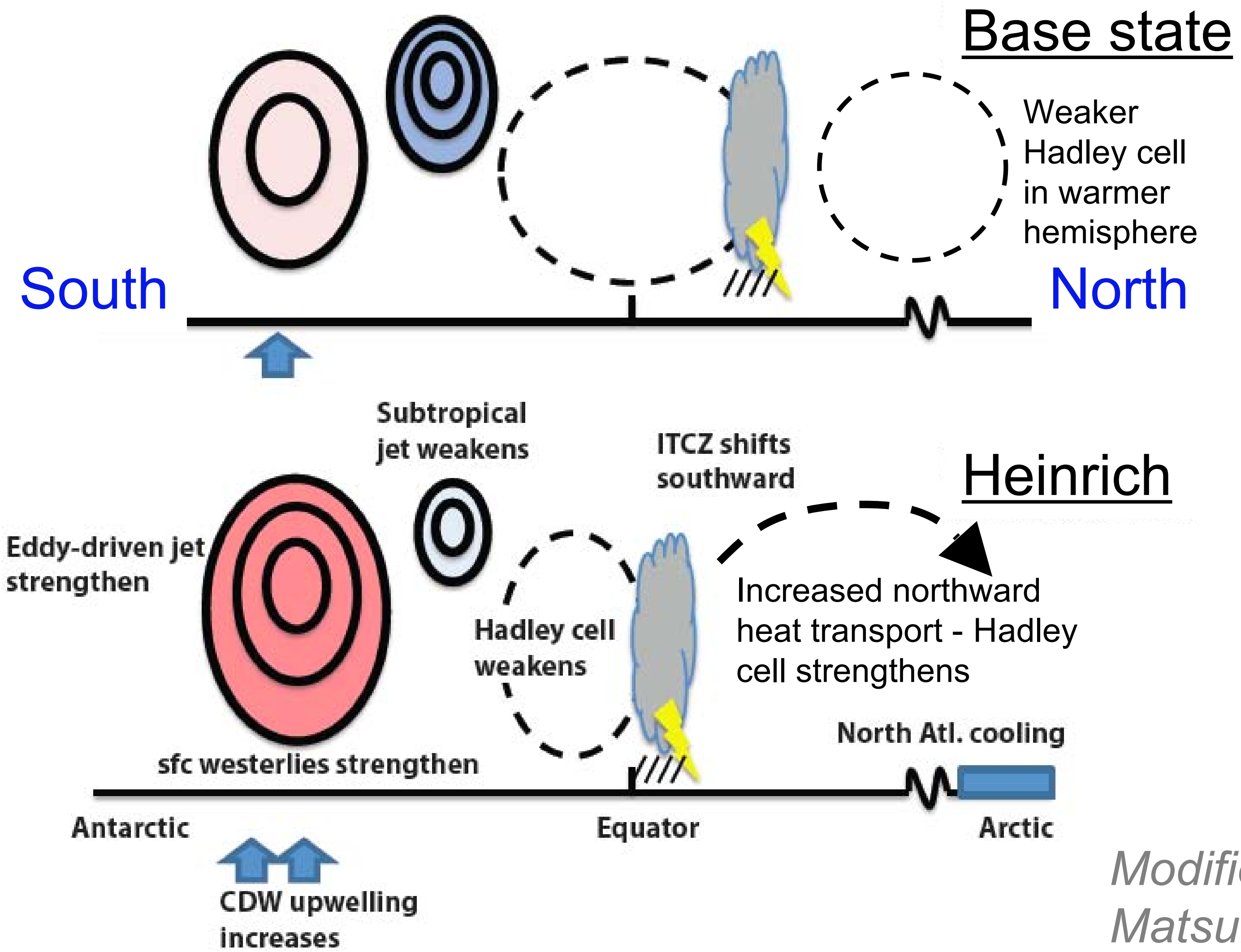
Atmospheric reorganization



Glacial
AMOC "on"
Equatorward
SH westerlies

Stadial: AMOC "off"
SH westerlies
1) Increase upwelling
2) Heat Antarctica
3) Melt sea ice
4) Release CO_2

SH westerly response to N Atlantic cooling: Based on established atmospheric principles



ITCZ southward

NH Hadley cell strengthens

SH Hadley cell weakens

Eddy momentum strengthens SPJ

Modified from Lee, Chiang, Matsumoto, Tokos, 2011.

But: Models show no consistent change in the position of the SWW during the LGM

Selected recent papers:

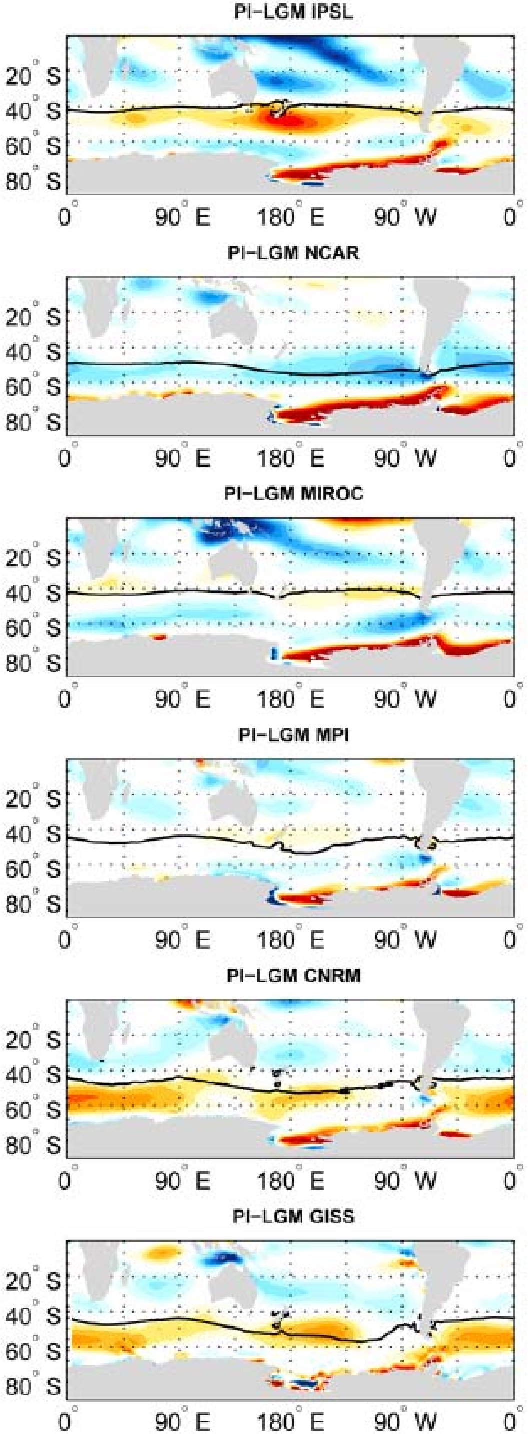
Chavaillaz, Y., F. Codron, and M. Kageyama. 2013. Southern westerlies in LGM and future (RCP4.5) climates. *Climate of the Past 9*(2): 517-524.

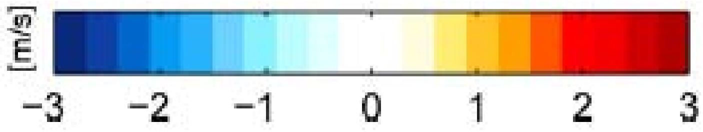
Rojas, M., P. Moreno, M. Kageyama, M. Crucifix, C. Hewitt, A. Abe-Ouchi, R. Ohgaito, E.C. Brady, and P. Hope. 2009. The Southern Westerlies during the last glacial maximum in PMIP2 simulations. *Climate Dynamics 32*(4): 525-548.

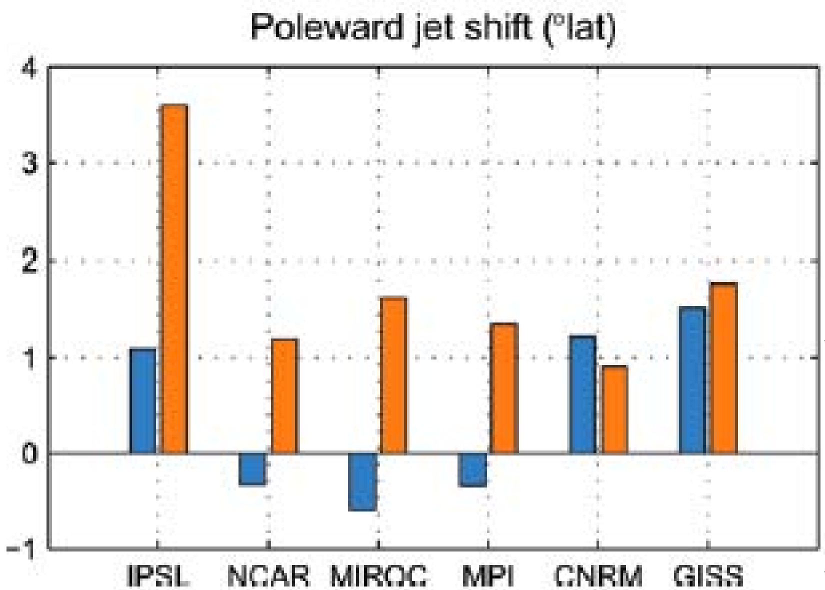
Rojas, M. 2013. Sensitivity of Southern Hemisphere circulation to LGM and 4 × CO2 climates. *Geophysical Research Letters*(40): 965–970 doi:910.1002/grl.50195.

Sime, L.C., K.E. Kohfeld, C. Le Quéré, E.W. Wolff, A.M. de Boer, R.M. Graham, and L. Bopp. 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: model-data comparison. *Quaternary Science Reviews 64*: 104-120.

PMIP3: No consistent change in strength or position of the SWW: Preindustrial minus LGM







Poleward in LGM

Equatorward
In LGM

Blue: PI - LGM

Orange: RCP4.5 - PI

Chavaillaz et al., Clim Past, 2013

And: Models show no consistent CO_2 response to imposed change in the position of the SWW

Selected recent papers:

Chikamoto, M. O., A. Abe-Ouchi, A. Oka, R. Ohgaito, and A. Timmermann (2012), Quantifying the ocean's role in glacial CO2 reductions, Clim. Past, 8(2), 545–563.

d'Orgeville, M., W. P. Sijp, M. H. England, and K. J. Meissner (2010), On the control of glacial-interglacial atmospheric CO2 variations by the Southern Hemisphere westerlies, *Geophys. Res. Lett.*, *37*(21), L21,703.

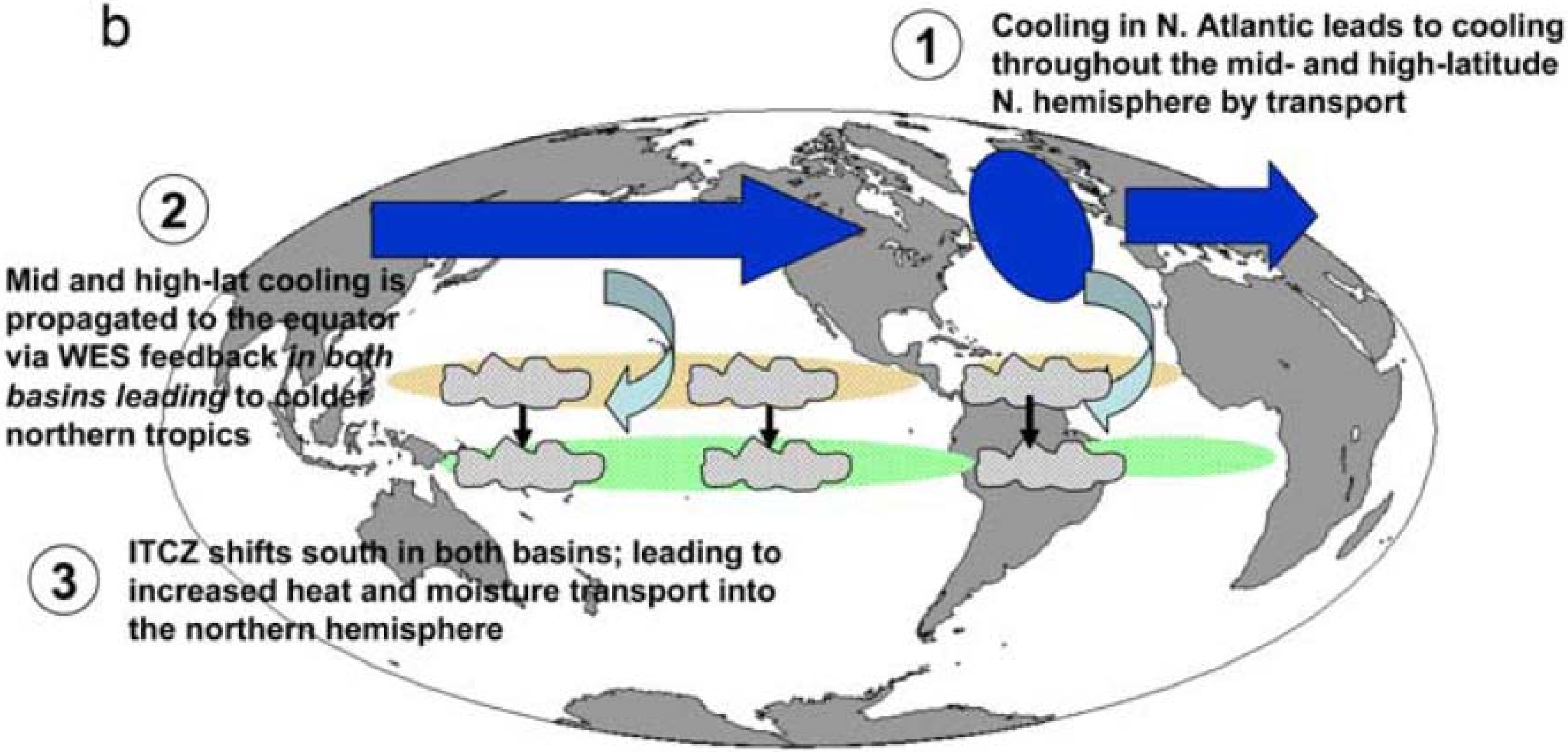
Lauderdale, J., A.N. Garabato, K.C. Oliver, M. Follows, and R. Williams. 2013. Wind-driven changes in Southern Ocean residual circulation, ocean carbon reservoirs and atmospheric CO2. *Climate Dynamics* *http://dx.doi.org/10.1007/s00382-012-1650-3:* 1-20.

Menviel, L., A. Timmermann, A. Mouchet, and O. Timm (2008), Climate and marine carbon cycle response to changes in the strength of the Southern Hemispheric westerlies, *Paleoceanography*, *23*(4), PA4201.

Tschumi, T., F. Joos, and P. Parekh (2008), How important are Southern Hemisphere wind changes for low glacial carbon dioxide? A model study, *Paleoceanography*, *23*, PA4208, doi:10.1029/2008PA001592.

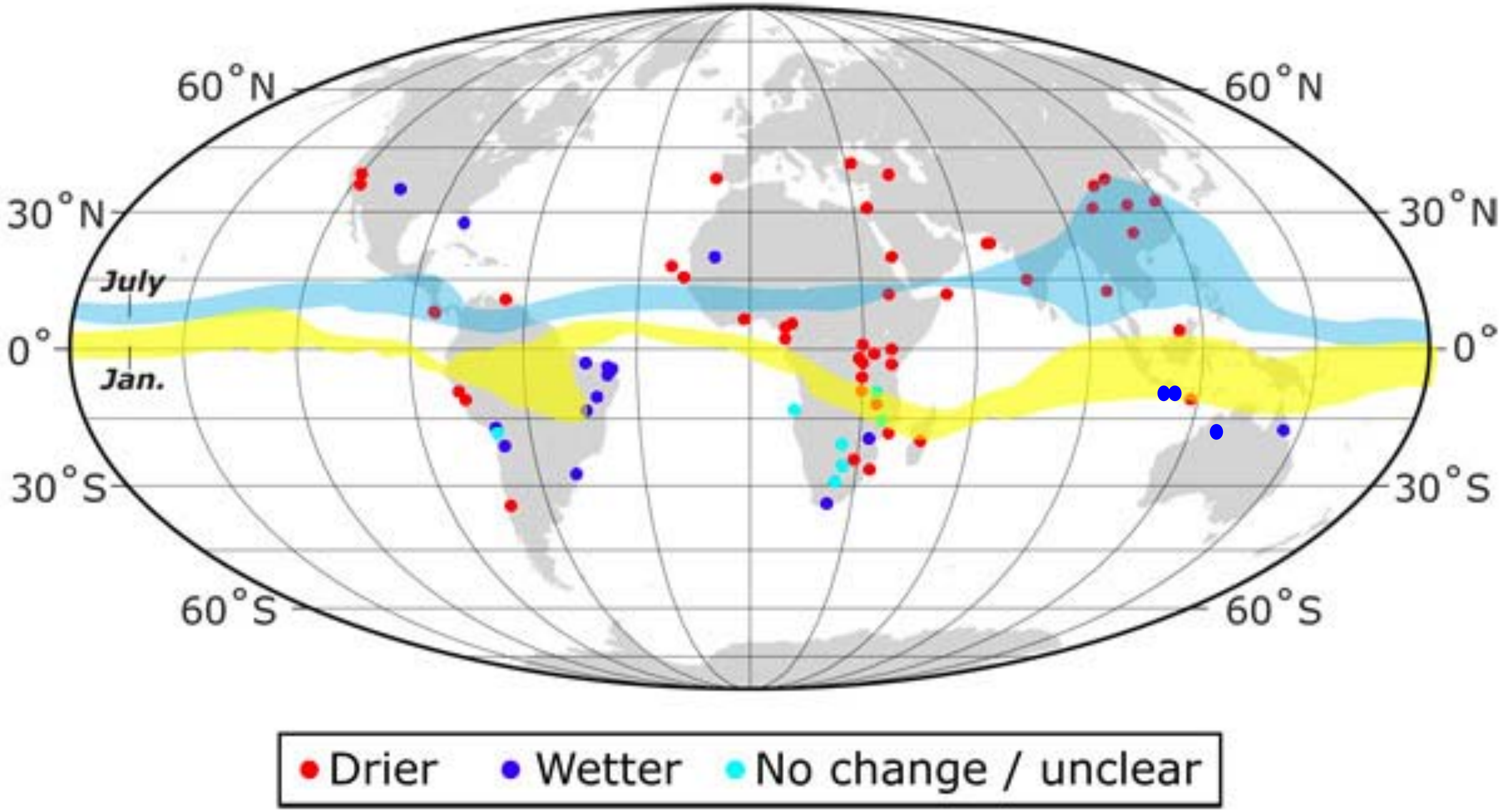
2. Is there consensus about the tropics?

NH Cooling: Strengthens NH Hadley cell & Shifts tropical convection (ITCZ) southward



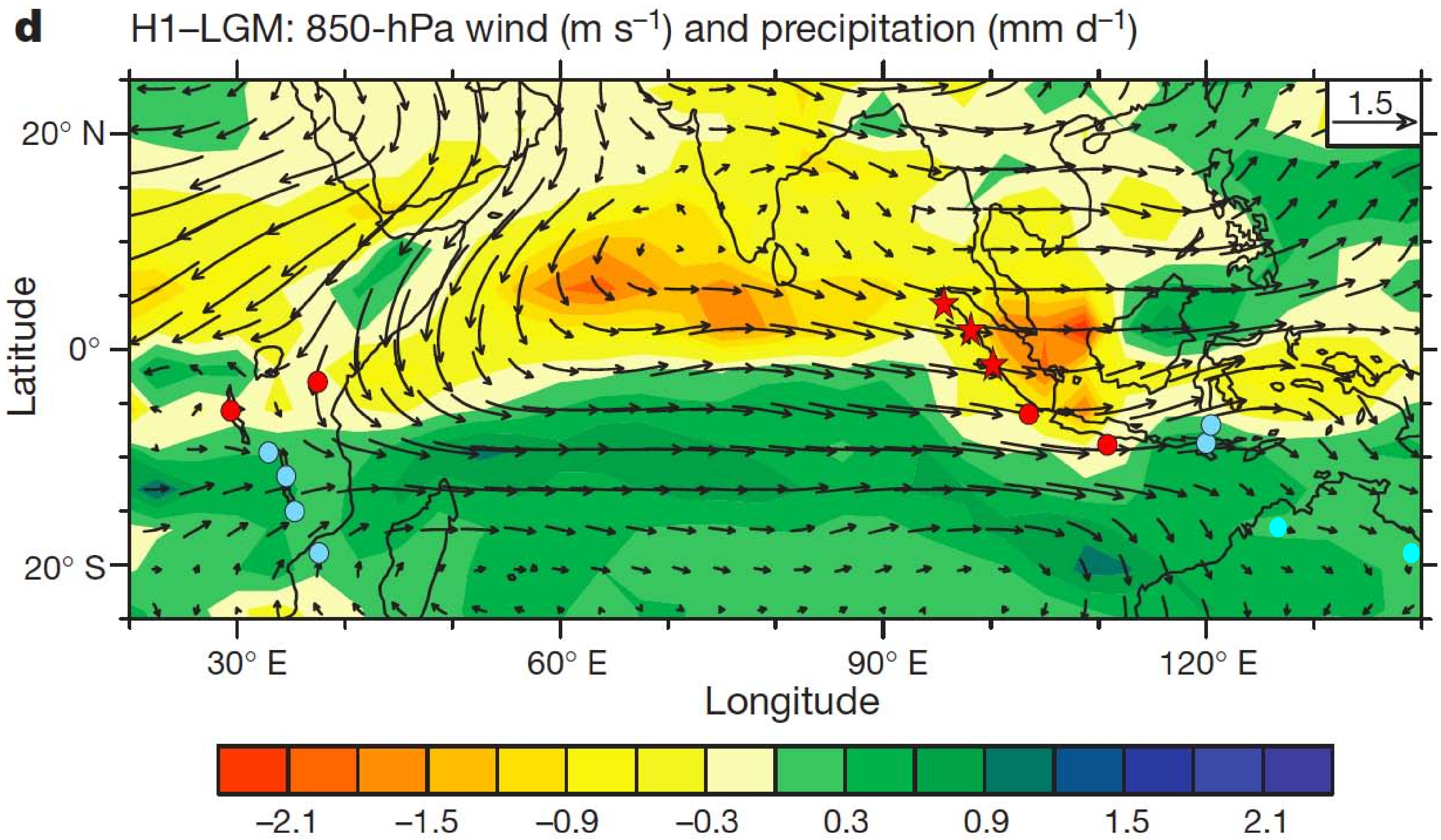
Clement & Peterson, 2008

Hydrological changes from LGM to HS1: Southward shift of tropical precipitation



Modified from Oppo and Curry 2012

Hydrological changes from LGM to HS1: Indian Sector model-data comparison



Proxy records: Red = drier; Blue = wetter

Modified from Mohtadi et al., Nature 1 May 2014

Hydrological changes from LGM to HS1: Consistency between models and proxy data

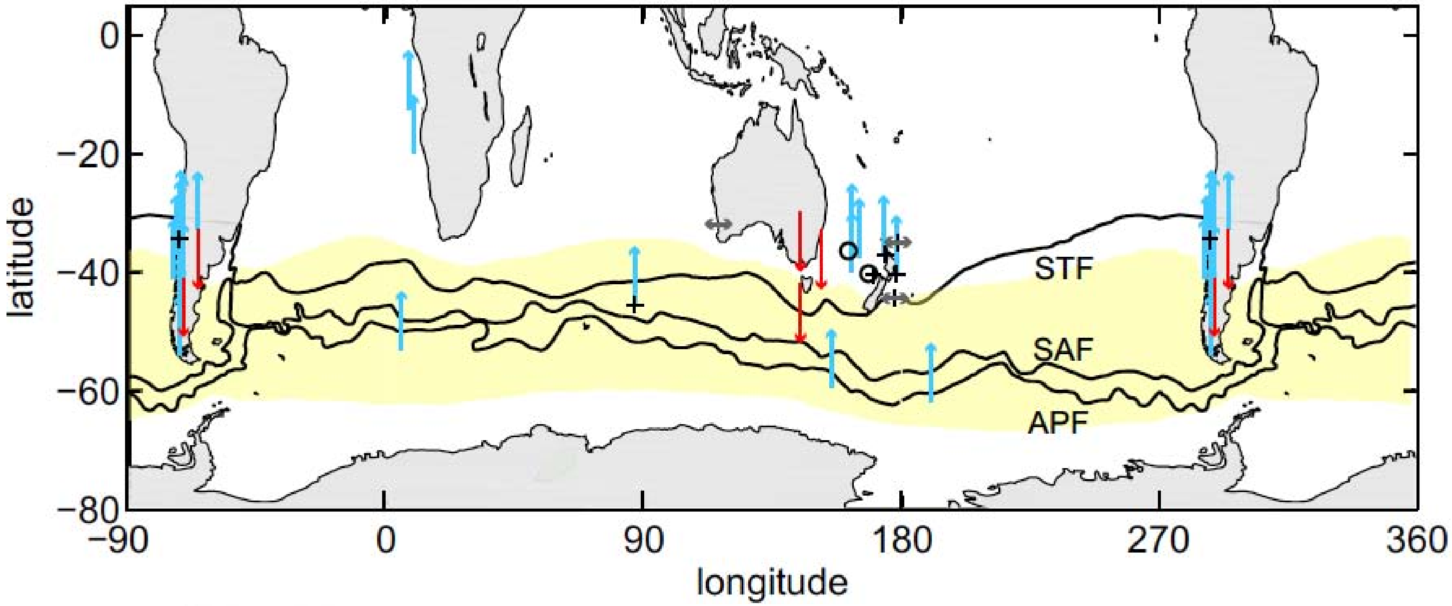
"…the entire Australasian monsoon system responded rapidly to climate events in the northern high latitudes."
Ayliff et al., Nature Communications, 2014

Cooling the North Atlantic region strengthens the NH Hadley Cell and shifts the ITCZ southward.

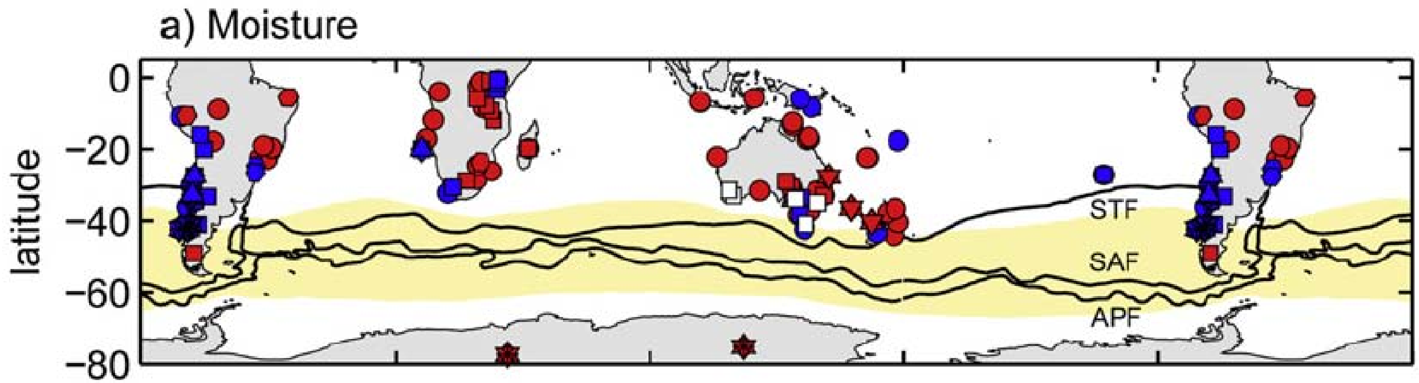
Do changes in atmospheric circulation extend to the mid latitudes of the Southern Hemisphere?

3. LGM changes in the SH mid latitudes

SWW displacement inferred from moisture: LGM - Preindustrial



Arrow indicates inferred SWW displacement from modern (yellow)

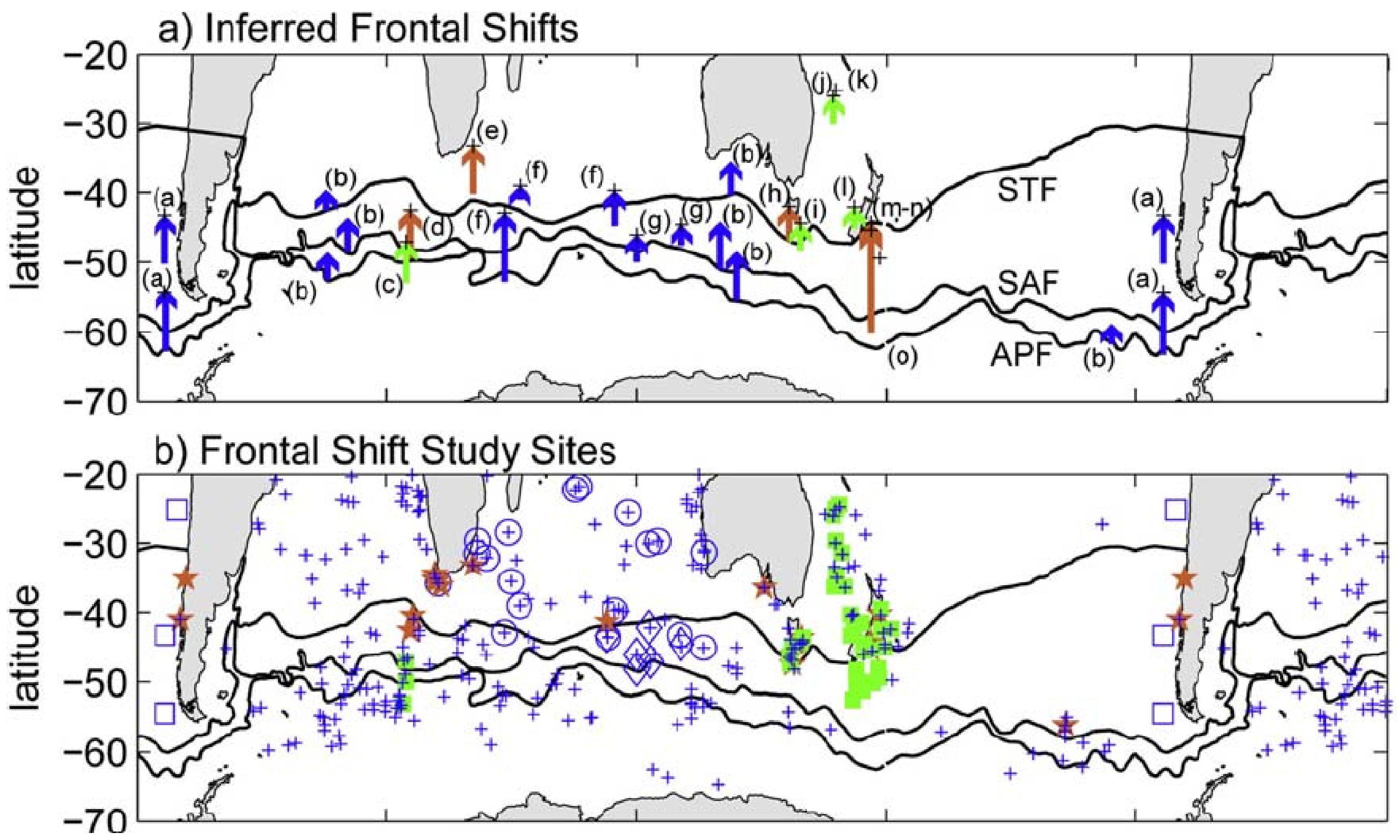


Red: LGM drier

Blue: LGM wetter

Synthesis by Kohfeld et al., 2013

Ocean front displacement inferred from various proxies: LGM - Preindustrial



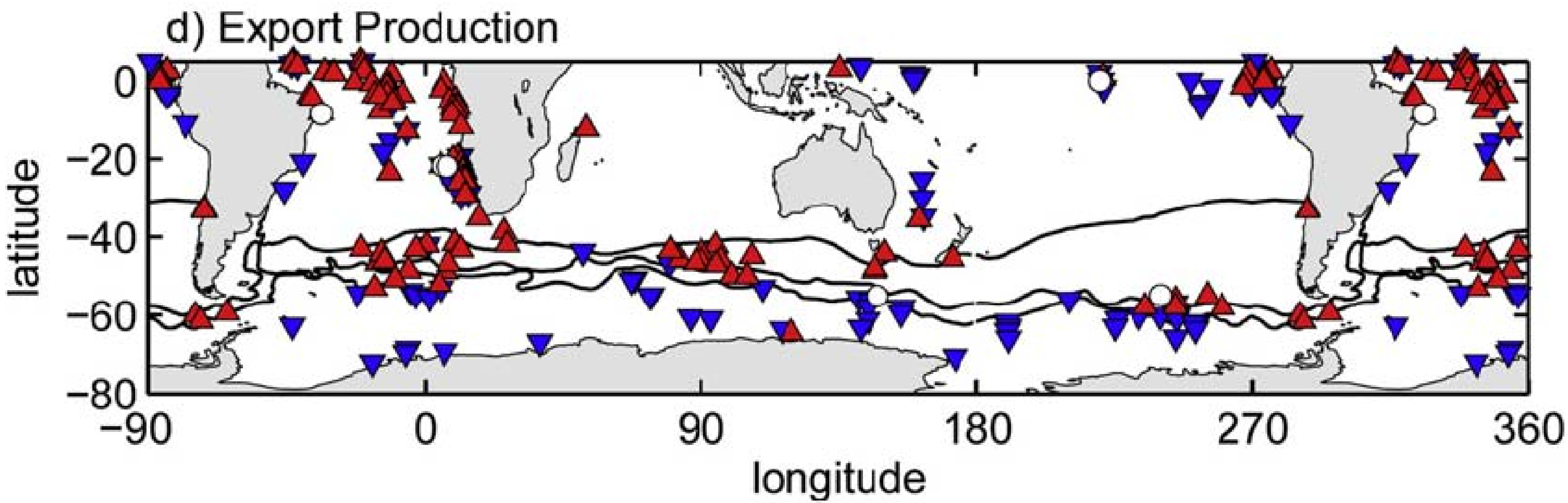
Arrow indicates inferred front displacement from modern location

Green: SST gradient

Blue: Single isotherm displacement

Synthesis by Kohfeld et al., 2013

Pattern of export production reflects northwward shift in deepwater (nutrient) supply



Red: Export production greater during LGM

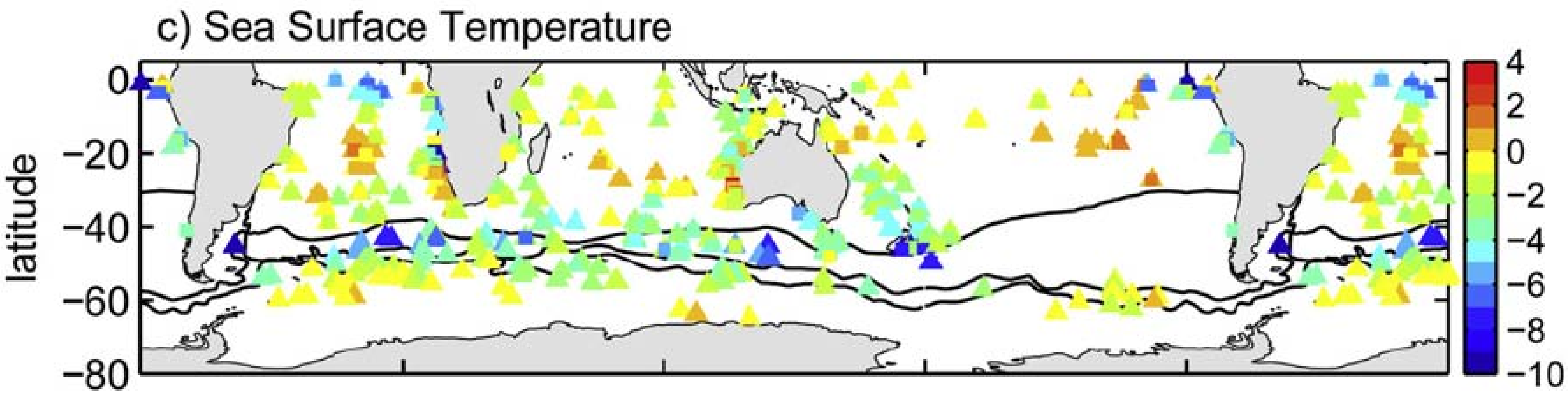
Blue: Export production greater during Holocene

Combining export production with proxies for nutrient utilization ($\delta^{30}Si$, $\delta^{15}N$) indicates that LGM upwelling was lower than today S of the APF and greater than today to the north.

Synthesis by Kohfeld et al., 2013

See also Anderson et al., Phil Trans RS London, in press

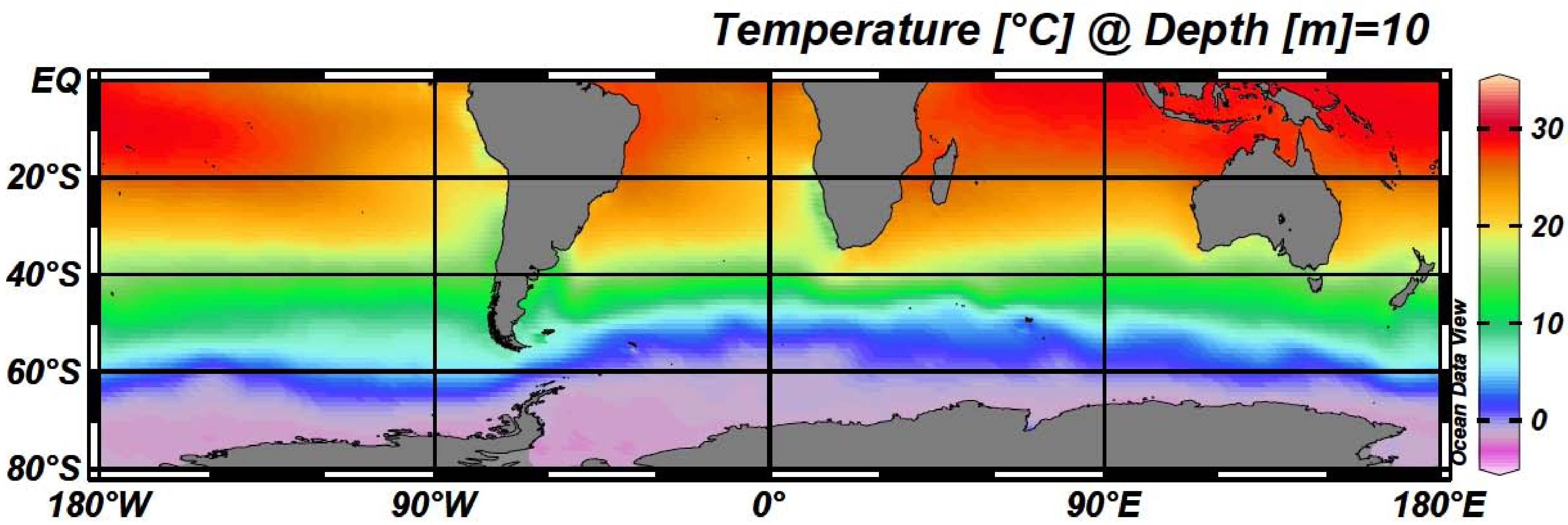
Largest deglacial SST warming at midle southern latitudes



Blue symbols indicate warming >4°C (light blue) to >6°C (dark blue -- concentrated in band 40 - 50°S

Synthesis by Kohfeld et al., 2013

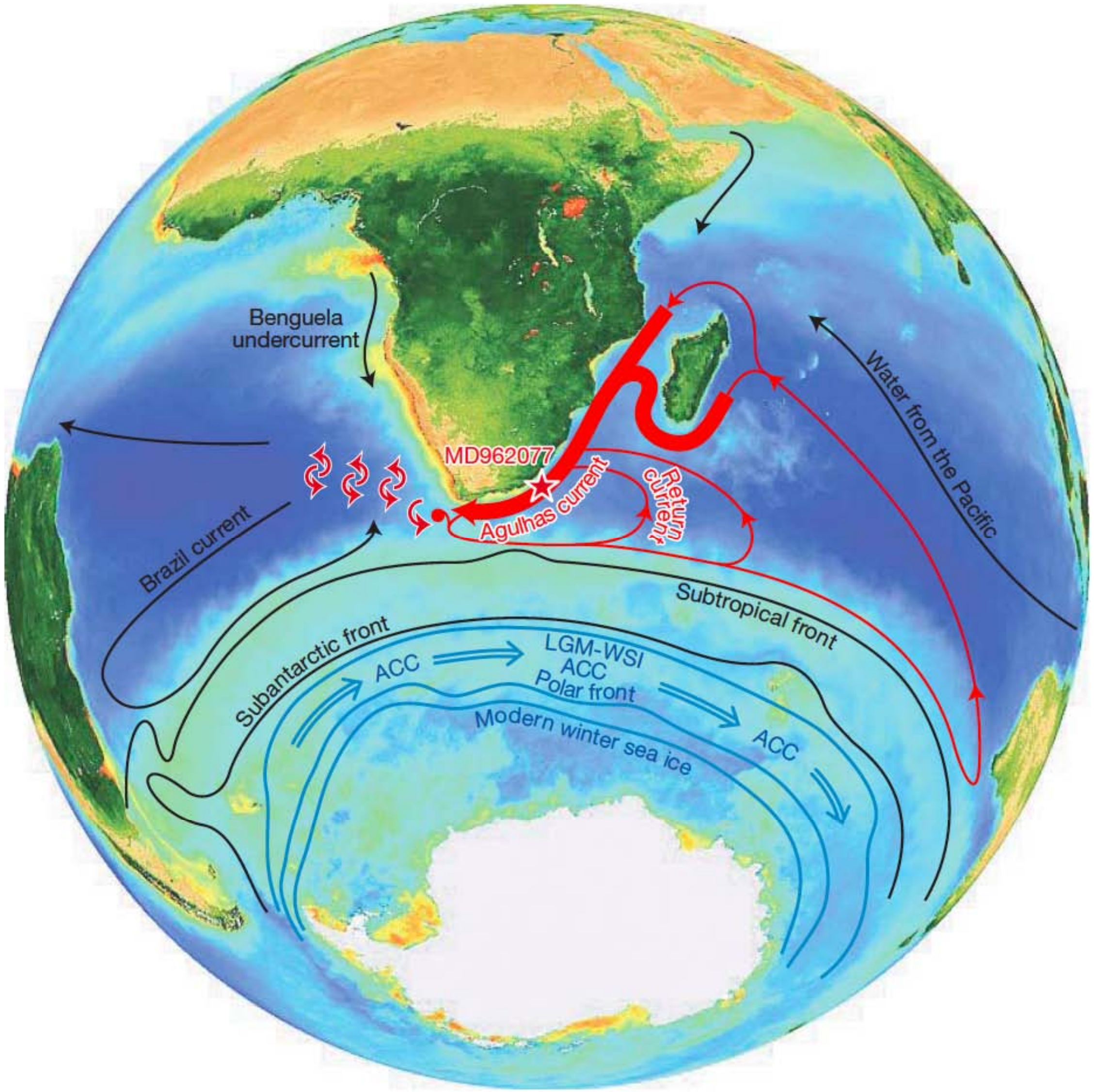
STF: Strong SST gradients at ~40°S - Deglacial migration northward enhanced regional warming



Wind-driven expansion of SH subtropical gyre:

- Shifted SST gradients (STF) southward
- Altered ocean circulation
- Created rapid warming at mid SH latitudes

Variable Agulhas leakage and shifts in the latitude of the STF support wind forcing



<u>Agulhas - Cape Basin</u>:
Bard & Rickaby, 2009
Peeters et al., 2004
Franzese et al., 2006
Barker et al., 2009

<u>Chile</u>:
Lamy et al., 2007
Ho et al., 2012

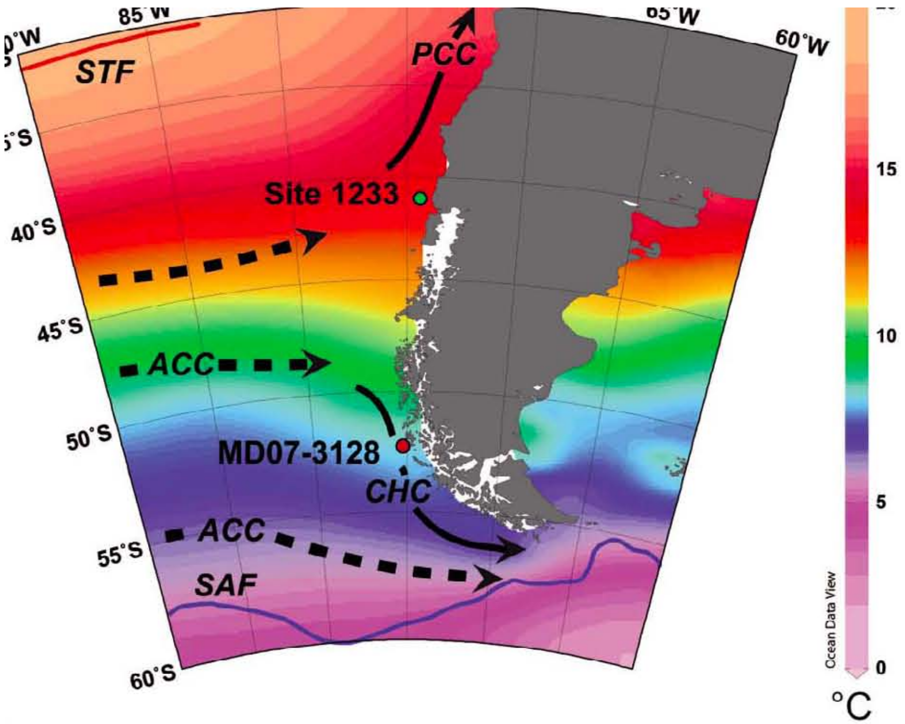
<u>Australia</u>:
STF South of Tasmania
Sikes et al., 2009

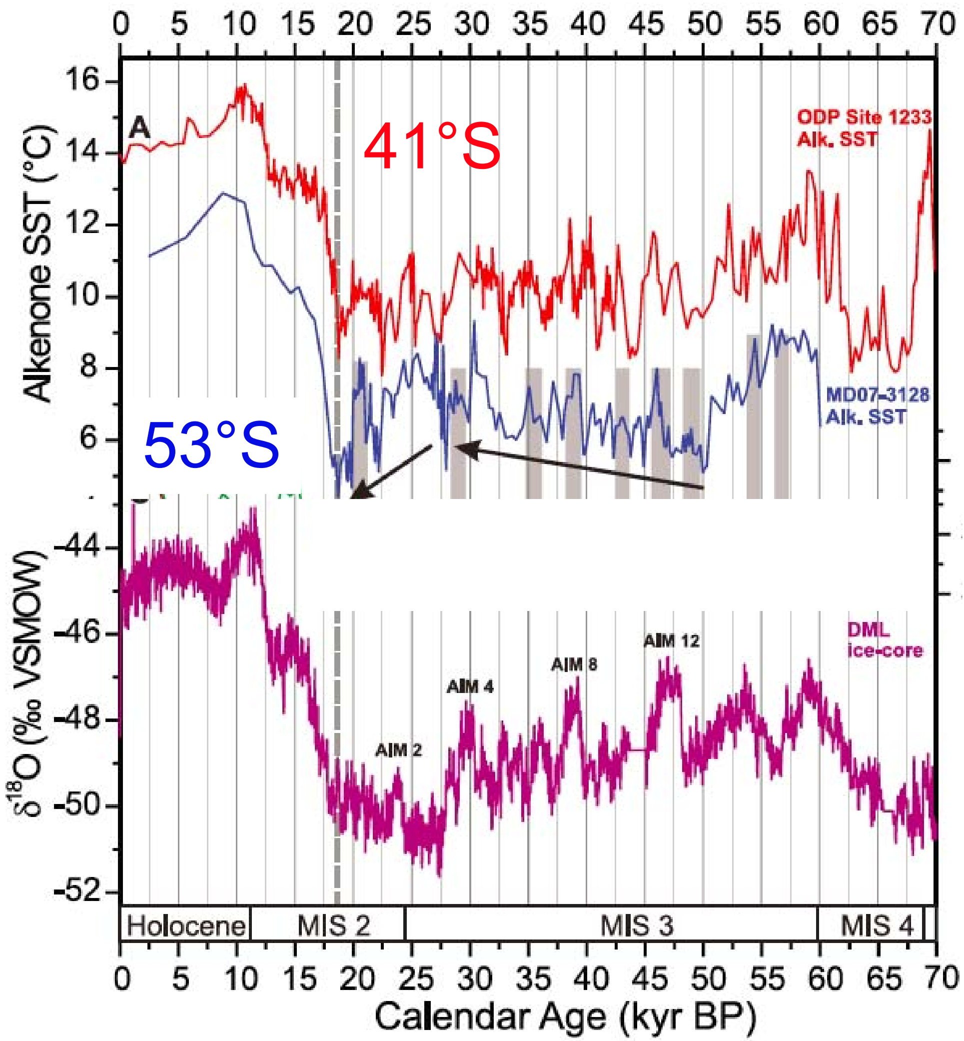
<u>Leeuwin Current</u>:
deDeckker et al., 2012

<u>New Zealand</u>:
Bostock et al., 2010

4. HS1 warming and ocean circulation

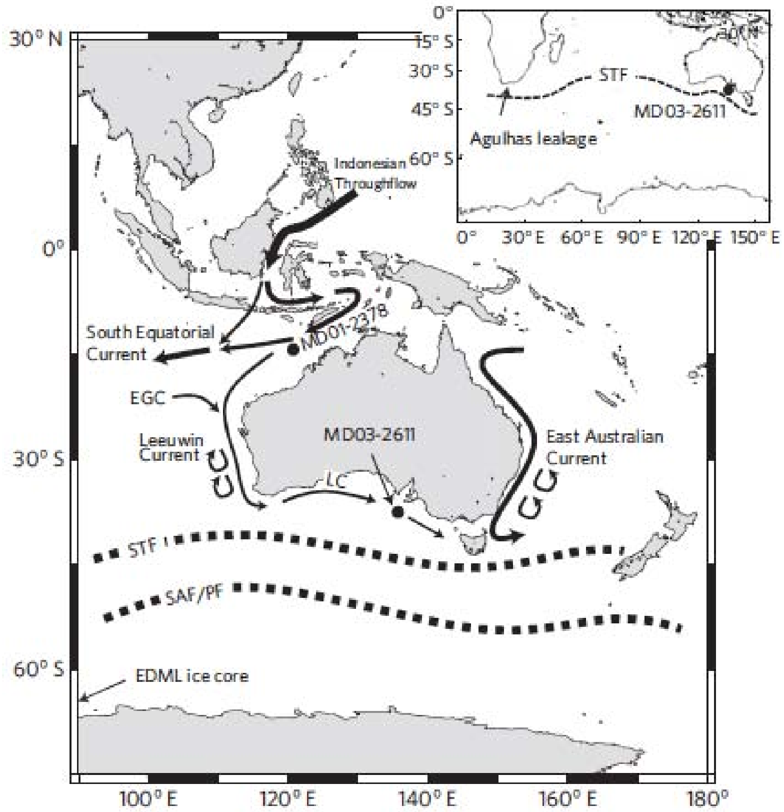
HS1: Rapid SST increase @41-53°S linked to southward displacement of STF (18 ka)

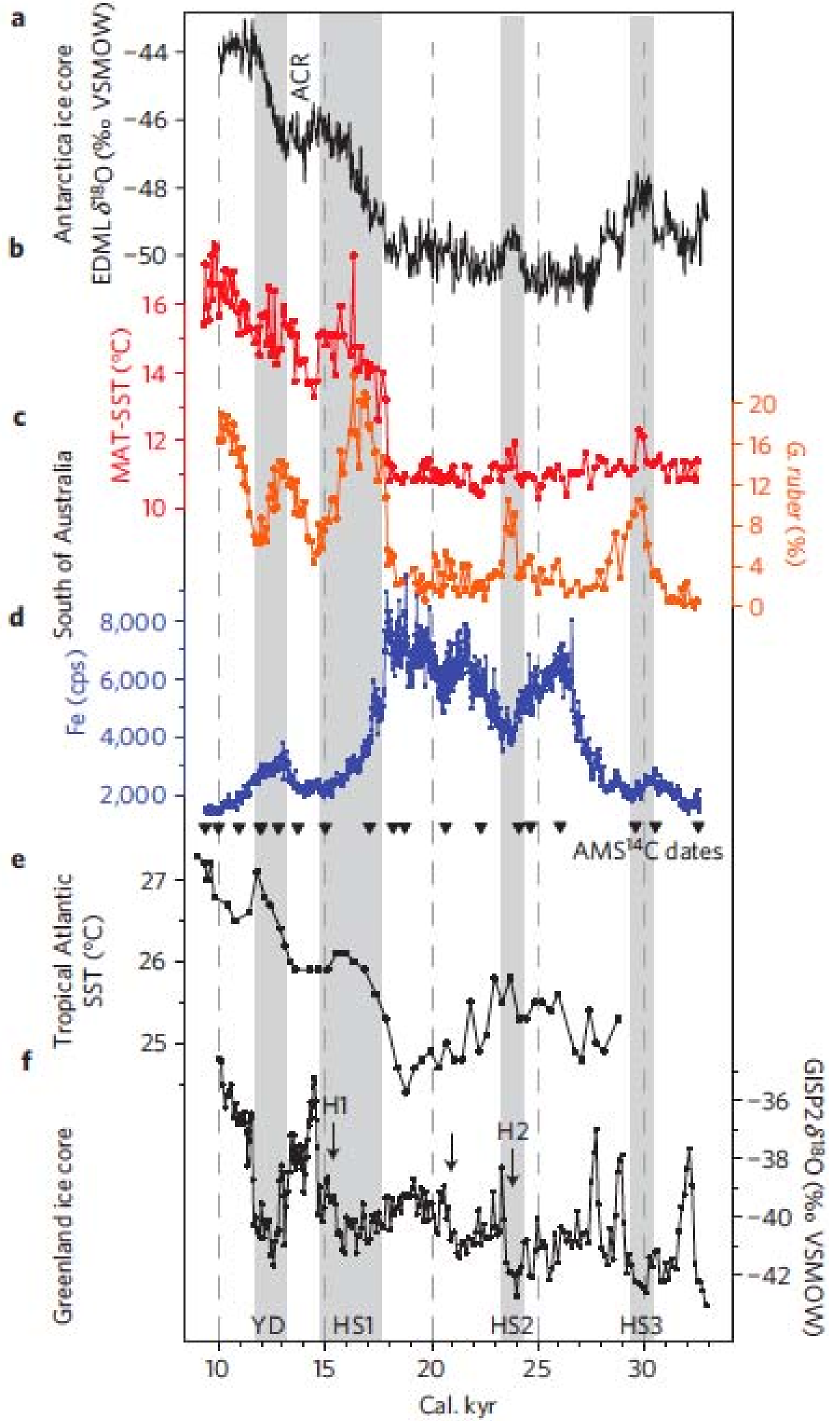




Caniupán et al., 2013

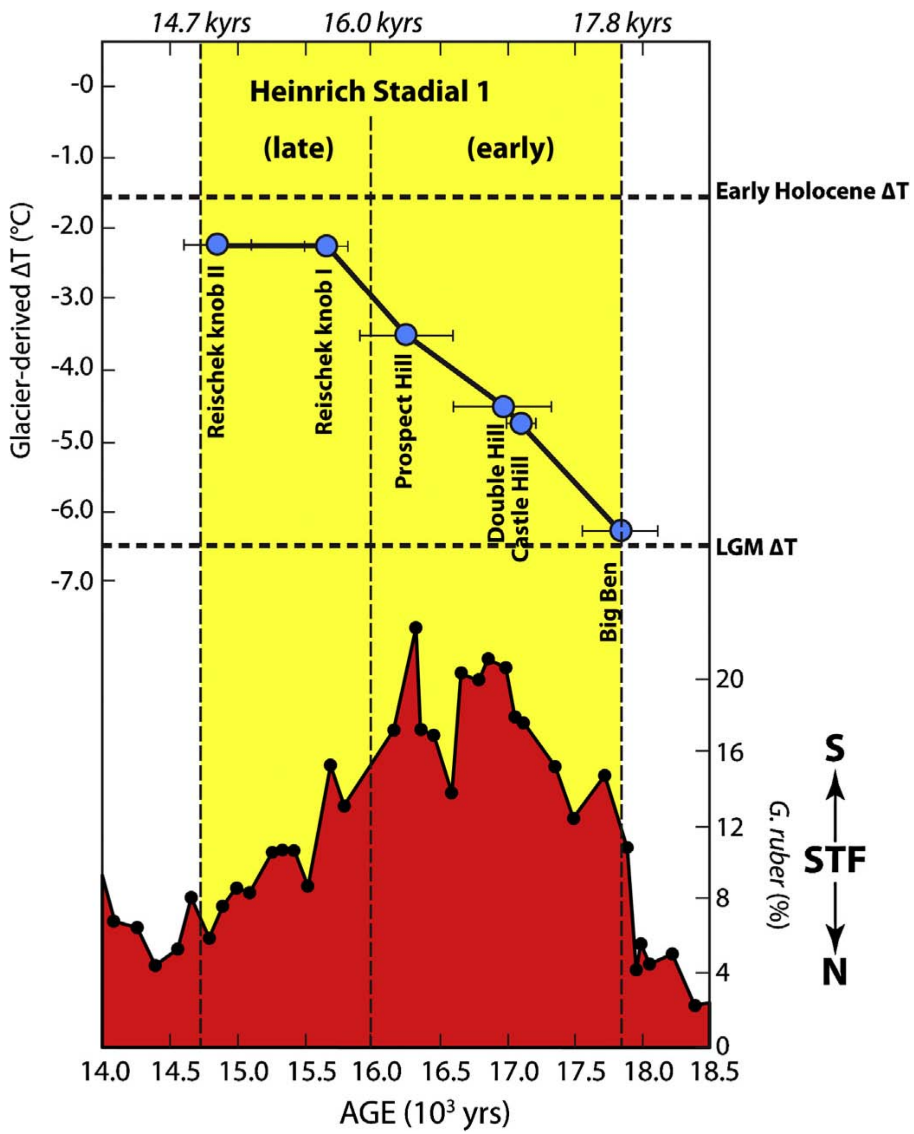
HS1: Rapid SST increase and extension of Leeuwin current south of Australia





De Deckker et al., 2012

New Zealand temperature rose 4°C during Heinrich Stadial 1 (18 - 16 ka)



Temperature from
mountain snow line depression

Requires regional amplification by southward shift of warm ocean waters:

- Southward displacement of STF
- Expansion of subtropical gyre

Putnam et al., EPSL 2013

Land and ocean records indicate rapid warming 40-50°S during Heinrich Stadial 1 (18 - 16 ka)

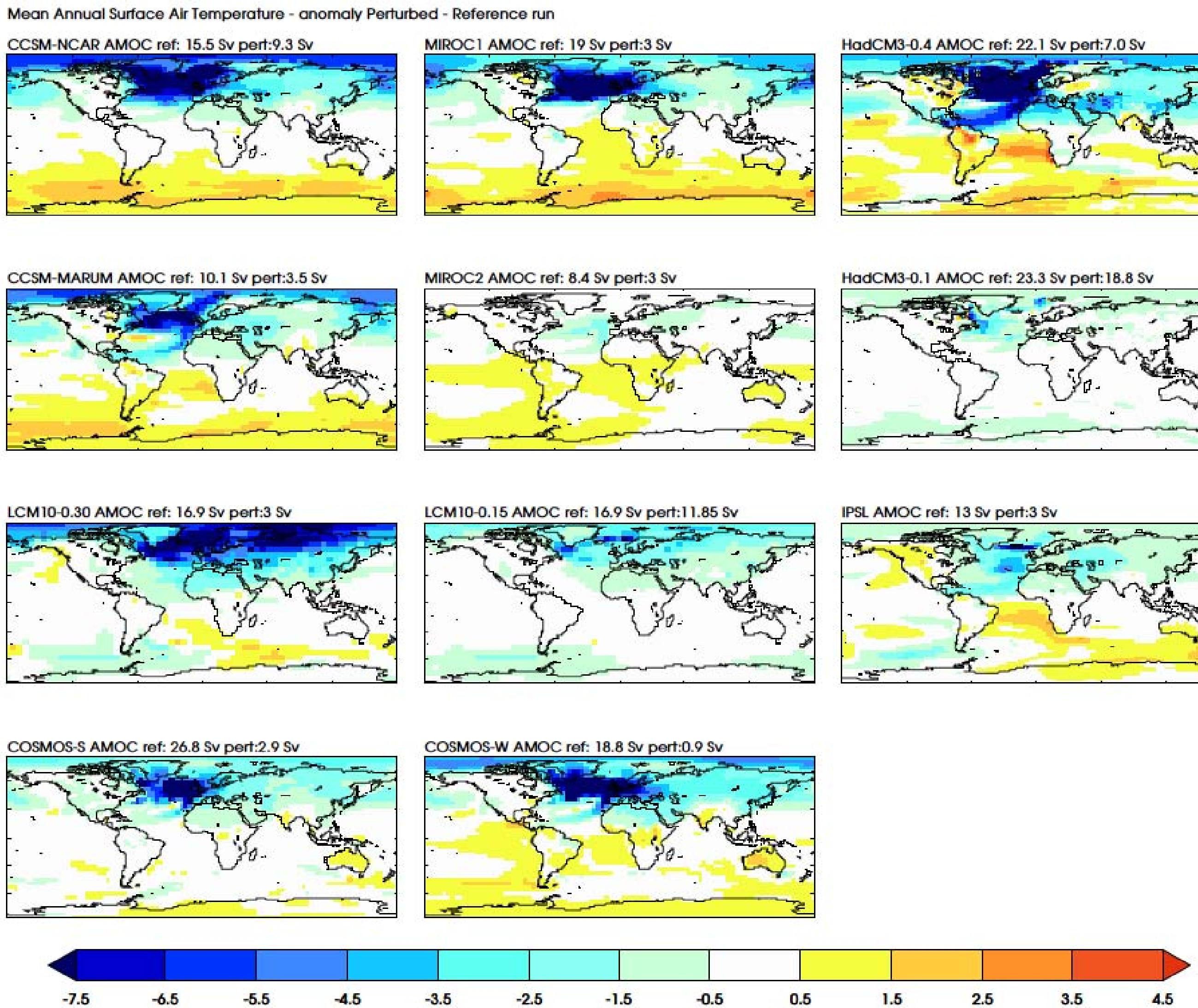
5. HS1: Models show little warming

Inconsistencies among 11 models in Glacial “water hosing” experiment

Note SE Pacific

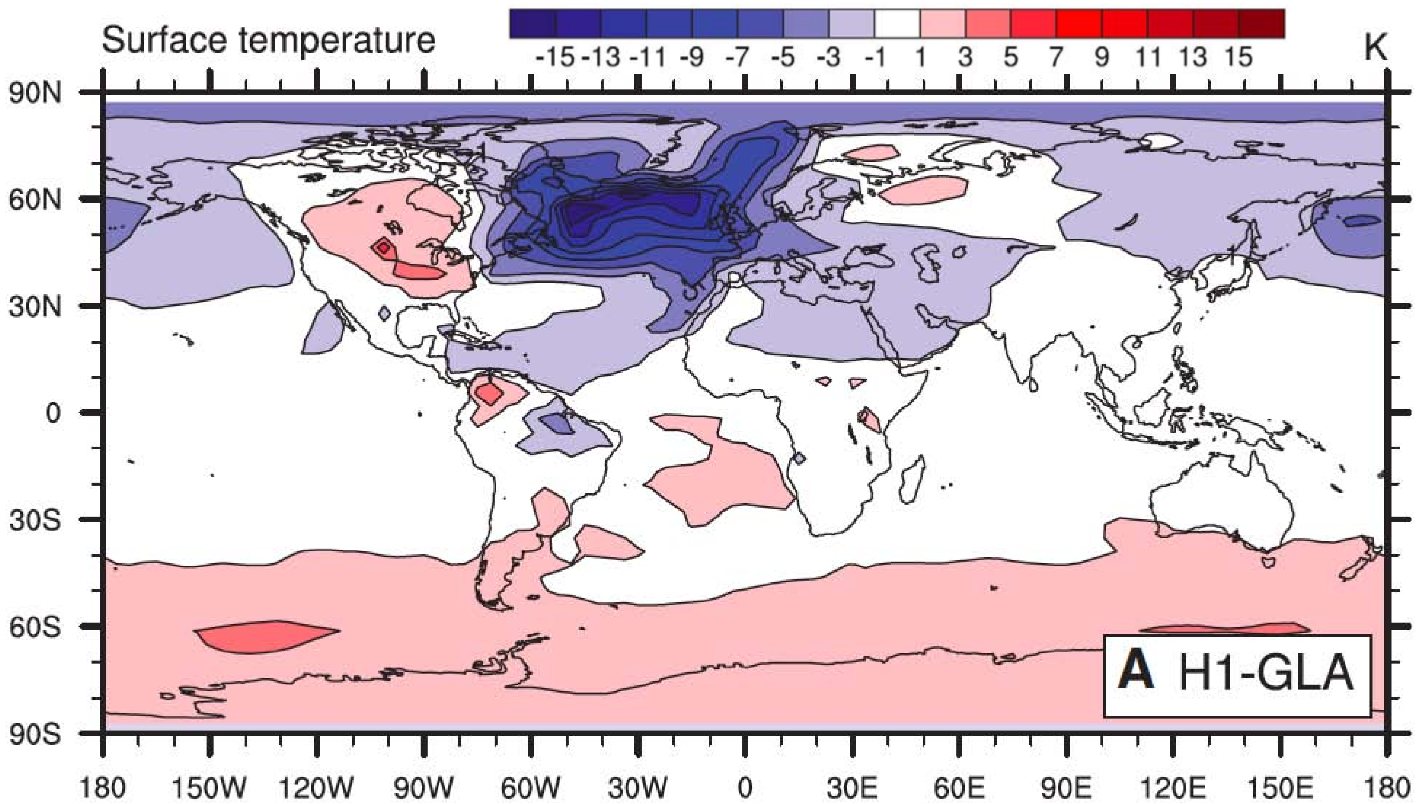
Warming=>

Cooling=>



Kageyama et al, 2013

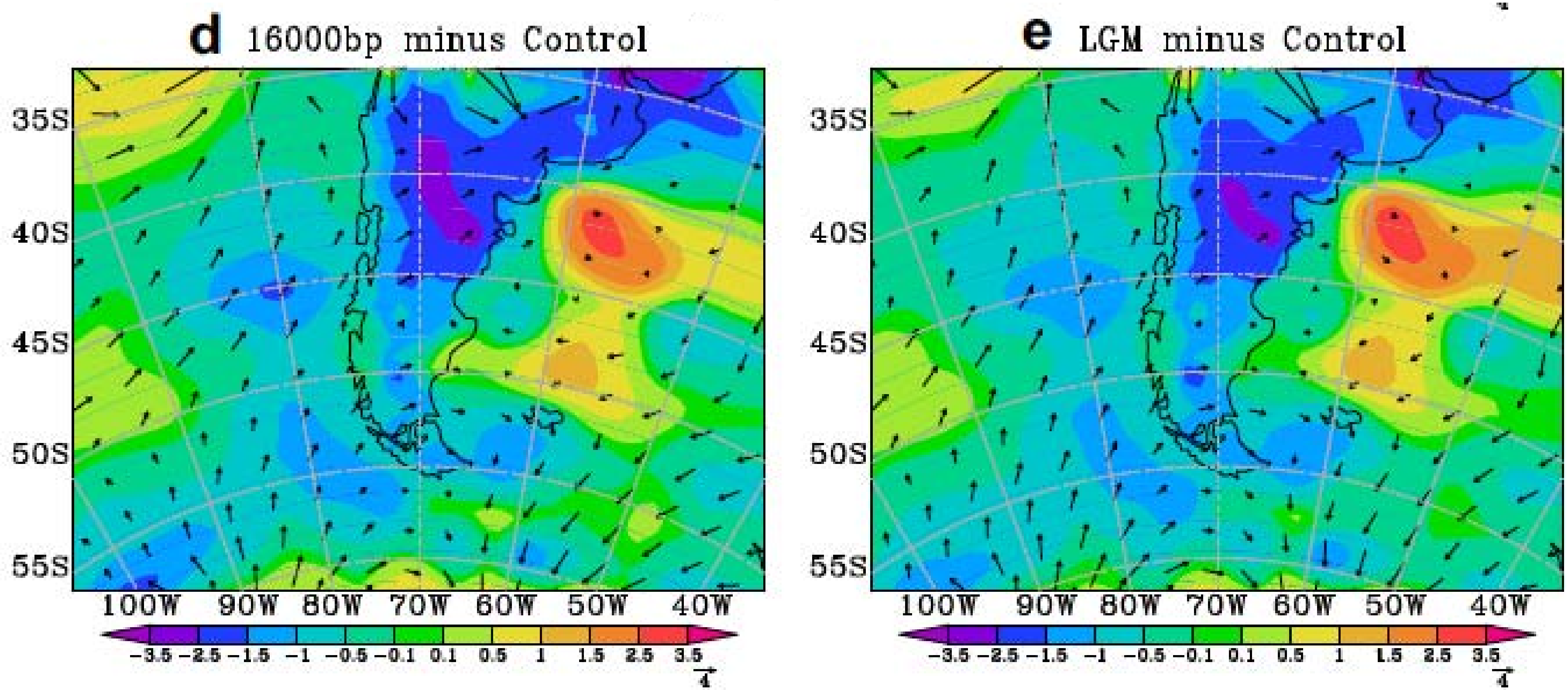
CCSM3: HS1 warming ~1°C @40°S
Proxy records indicate ~4°C



Bipolar seesaw in NCAR CCSM3 run from 22 - 14 ka
Surface temperature difference: HS1 - LGM
(Liu et al., 2009)

PSU/NCAR MM5 mesoscale model forced by Princeton GFDL global atmosphere-ocean model

Temperature

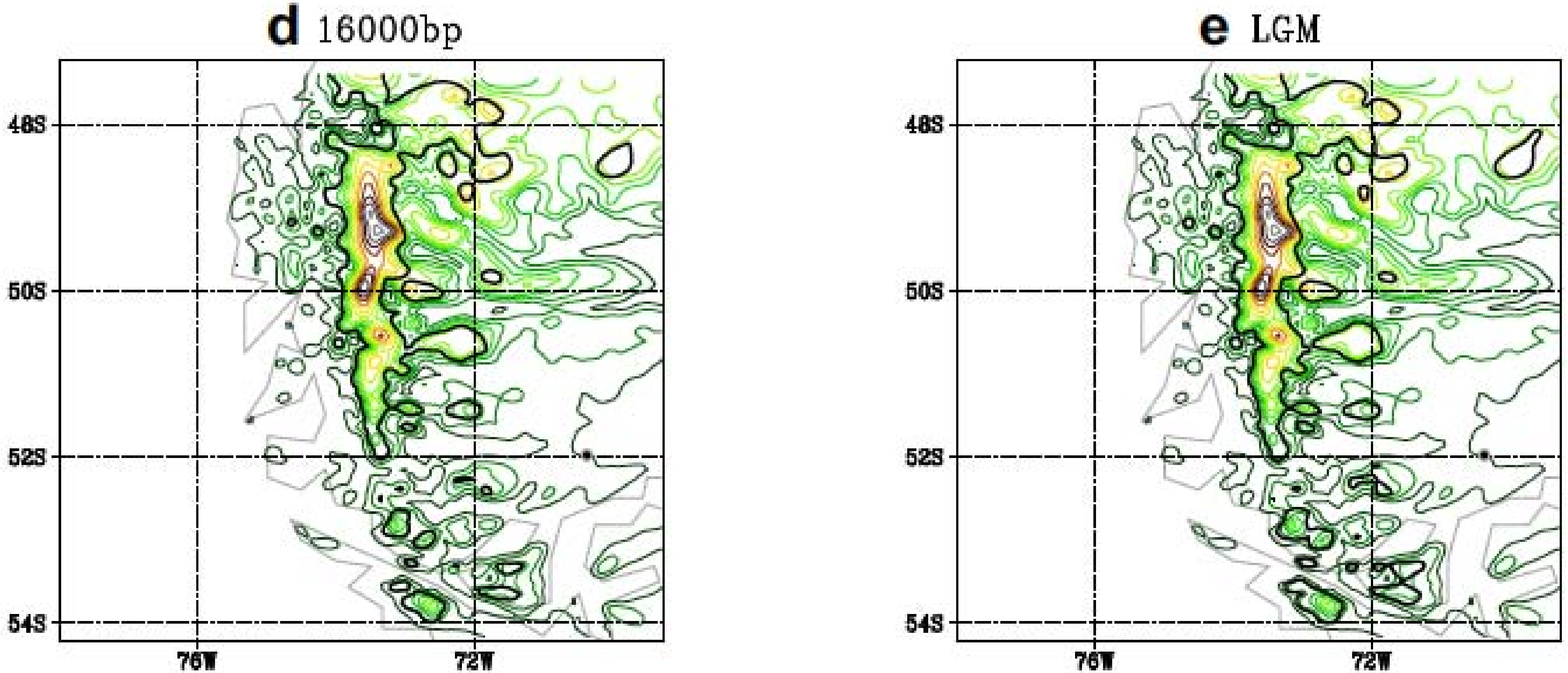


No warming between LGM and 16 ka

-- contrasts proxy data showing ≥4°C warming.

(Pollock and Bush, 2013)

PSU/NCAR MM5 mesoscale model forced by Princeton GFDL global atmosphere-ocean model



No ice retreat between LGM and 16 ka

-- contrasts proxy data showing rapid retreat.

(Pollock and Bush, 2013)

6. Summary: Features that must be accounted for in (conceptual) models

LGM (relative to preindustrial)

- Lower deep water exposure (nutrient supply) S of APF
- Greater deep water exposure in Subantarctic Zone
- Subantarctic cooling > regions to north or south
- Reduced flow of subtropical water S of Africa & S of Australia
- Increased moisture on west side of continents
- Shoaling of AAIW/UCDW interface

HS1/Deglacial

- Greatly increased deep water exposure (nutrient supply) S of APF
- Reduced deep water exposure in Subantarctic Zone
- Rapid Subantarctic warming & warming > regions to north or south
- Rapid retreat of mountain glaciers (18 to 16 ka)
- Increased flow of subtropical water S of Africa & S of Australia
- Southward displacement of STF
- Deepening of AAIW/UCDW interface

Each of these features is consistent with meridional displacement of the Southern Westerly Winds.
Alternative models must be consistent with all of these observations.