RECONSTRUCTING ATLANTIC TEMPERATURE AND OVERTURNING OVER THE LAST MILLENNIUM

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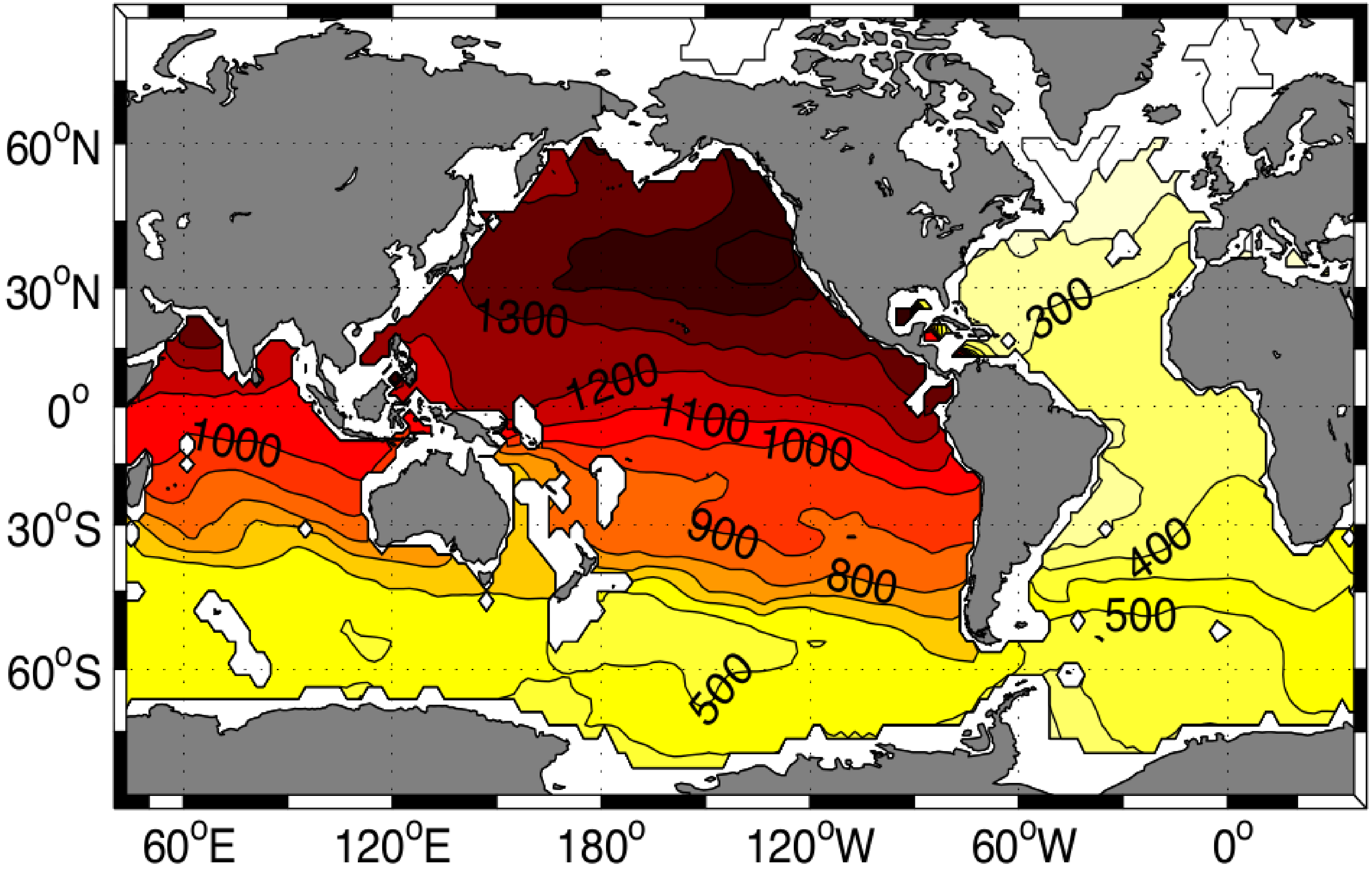
With credit to: Peter Huybers, Carl Wunsch, Harvard

Age of deep ocean water [years]: 2500 m



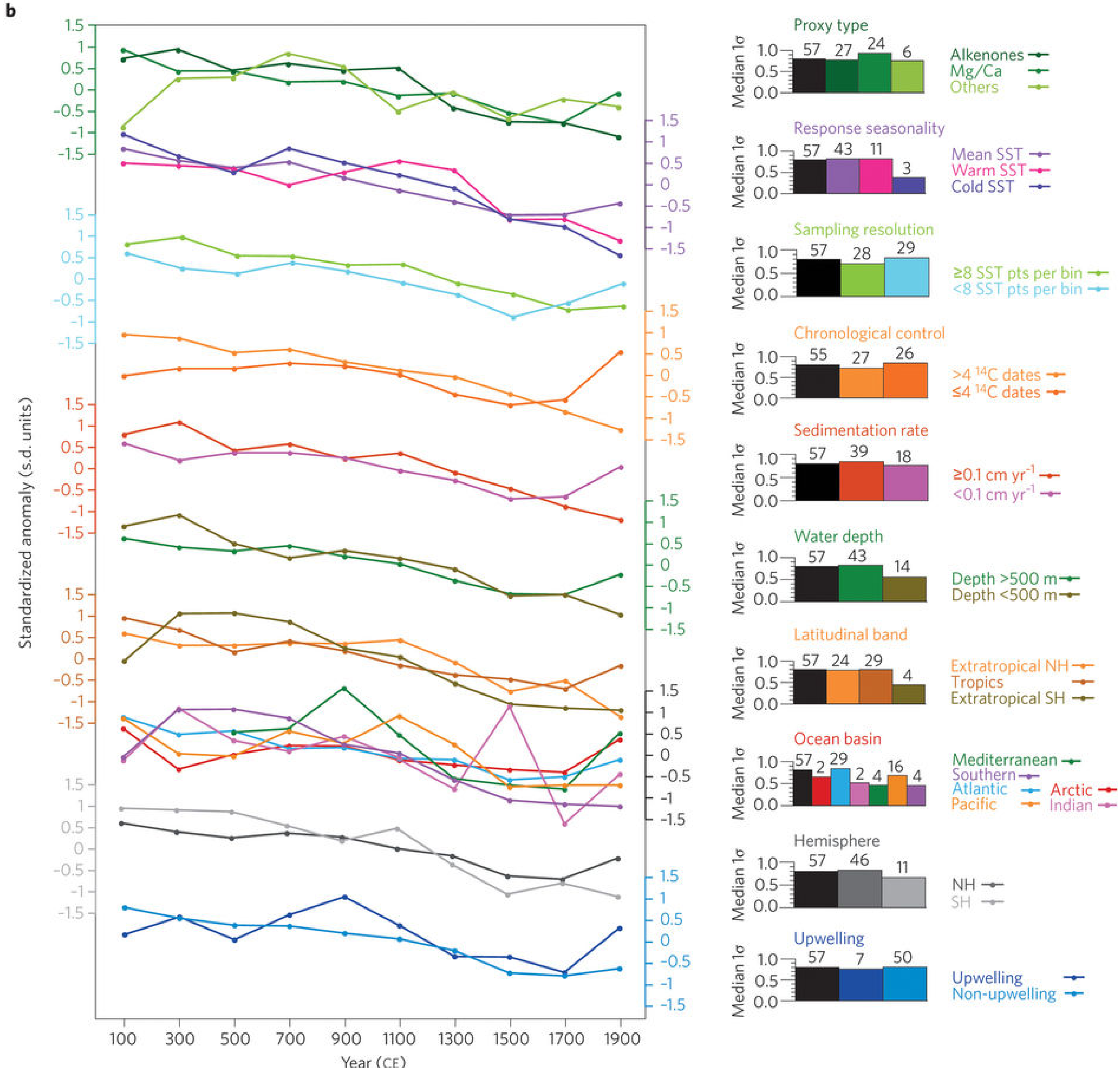
Does a signature of the Little Ice Age exist in today's ocean?

Primeau 2007; Gebbie & Huybers 2012

Outline

- Is a remnant effect of the Little Ice Age detectable in today's ocean?
- What is the expected interior ocean temperature response to the surface climate history of the last 2,000 years?
  - Simulation forced by paleoceanographic surface temperature records ("EQ-0015")
- Are the HMS *Challenger* (1872-1876) observations consistent with the model?
  - Model constrained by subsurface hydrographic data ("OPT-0015")
- Are the findings sensitive to changes in AMOC strength?

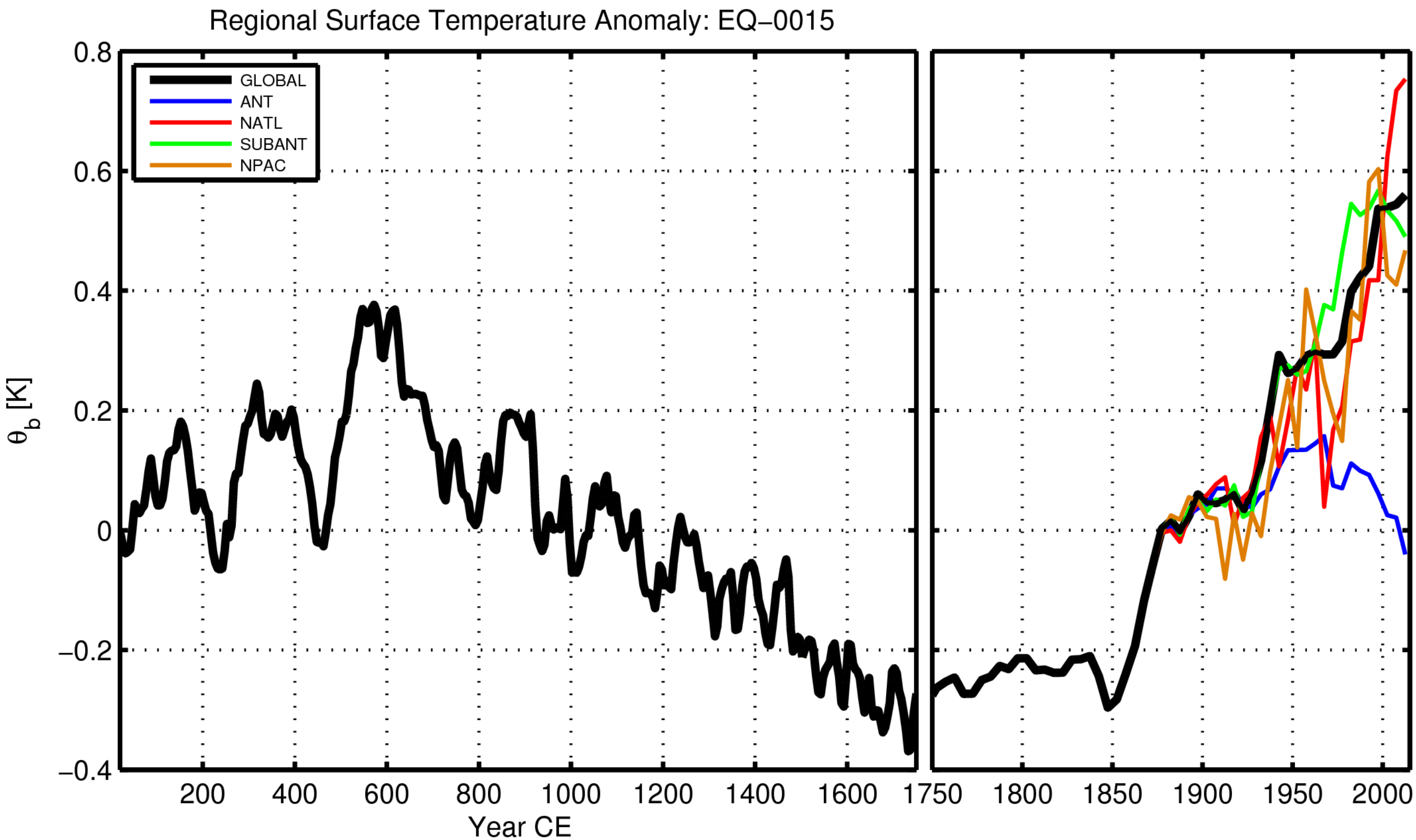
Common Era marine proxy records show cooling from 1000-1800 CE irrespective of data type or location.



Oceans2k project: 57 marine proxy records

McGregor et al. 2015

Forcing a Common Era Simulation: 15-2015 C.E.

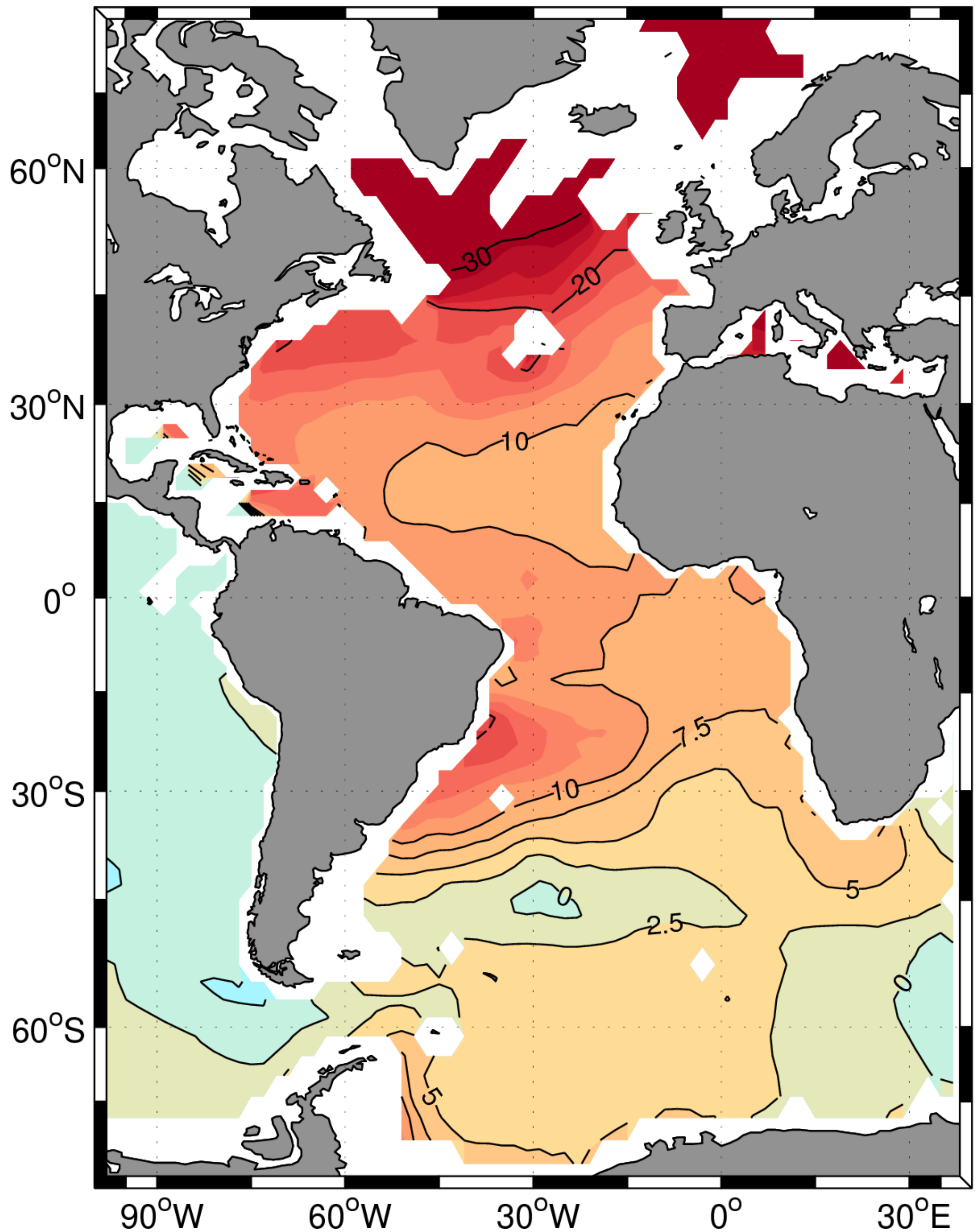


Blend of: HadISST 1.1 (1870-2017 C.E.) and 57 Ocean2k marine proxy records (15-1950 C.E.)

Rayner et al. 2003; McGregor et al. 2015

An inverse-derived model simulates a deep ocean response along deep western boundary currents.

T(1995)–T(1875): 2500 m [cK]



- Empirical model trained with WOCE/GLODAP T, S, PO_4, NO_3, O_2, $\delta^{18}O$, $\Delta^{14}C$
- Global with 2° x 2° horizontal resolution and 33 vertical levels
- 291,156 grid cells
- ~1.4 million seawater flux values

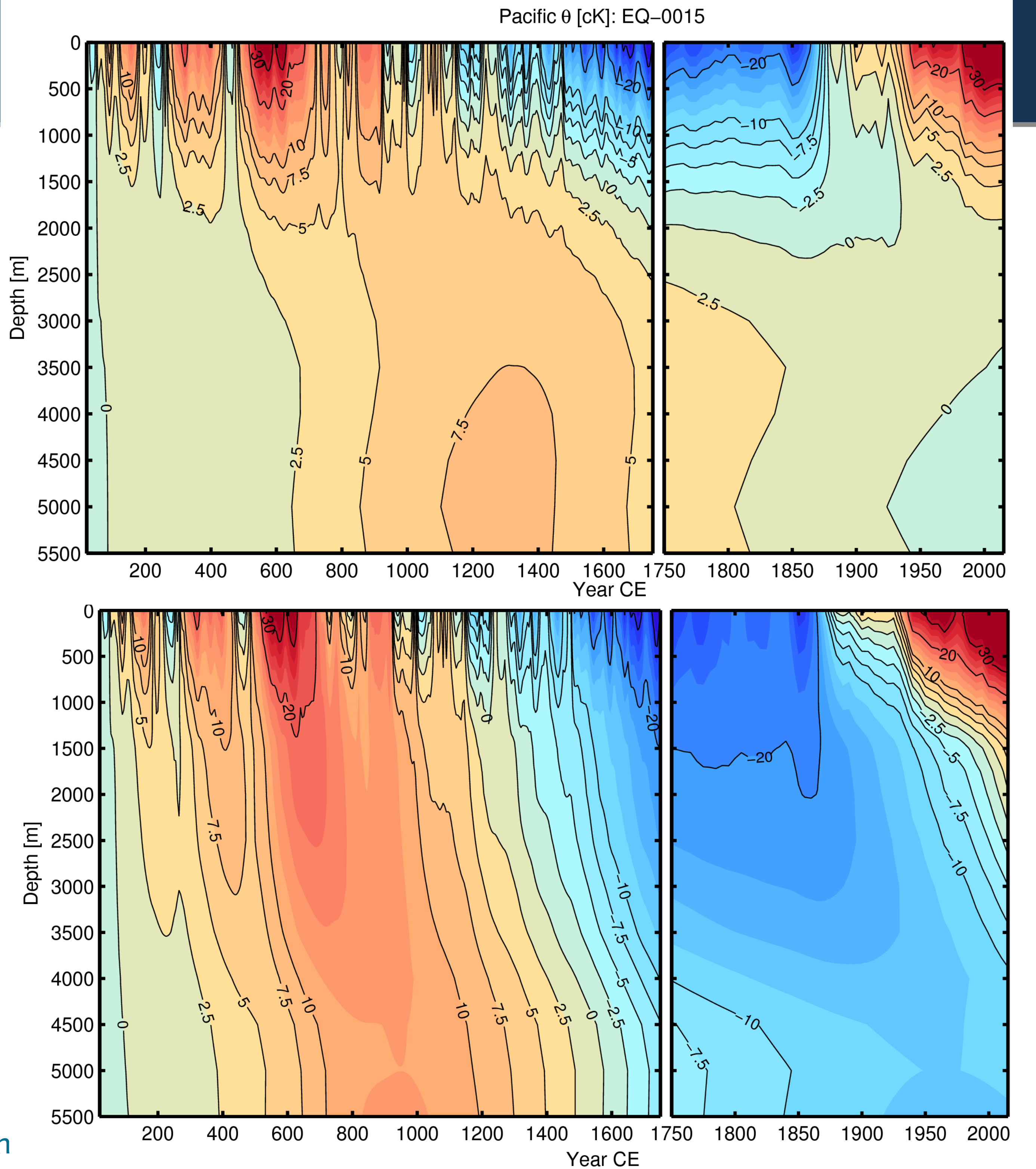
Following Gebbie, *Paleoceanography,* 2012

Also see,
Marshall, Scott, et al., 2015

Evolution of basinwide -average temperature profiles

PACIFIC AVERAGE [cK]

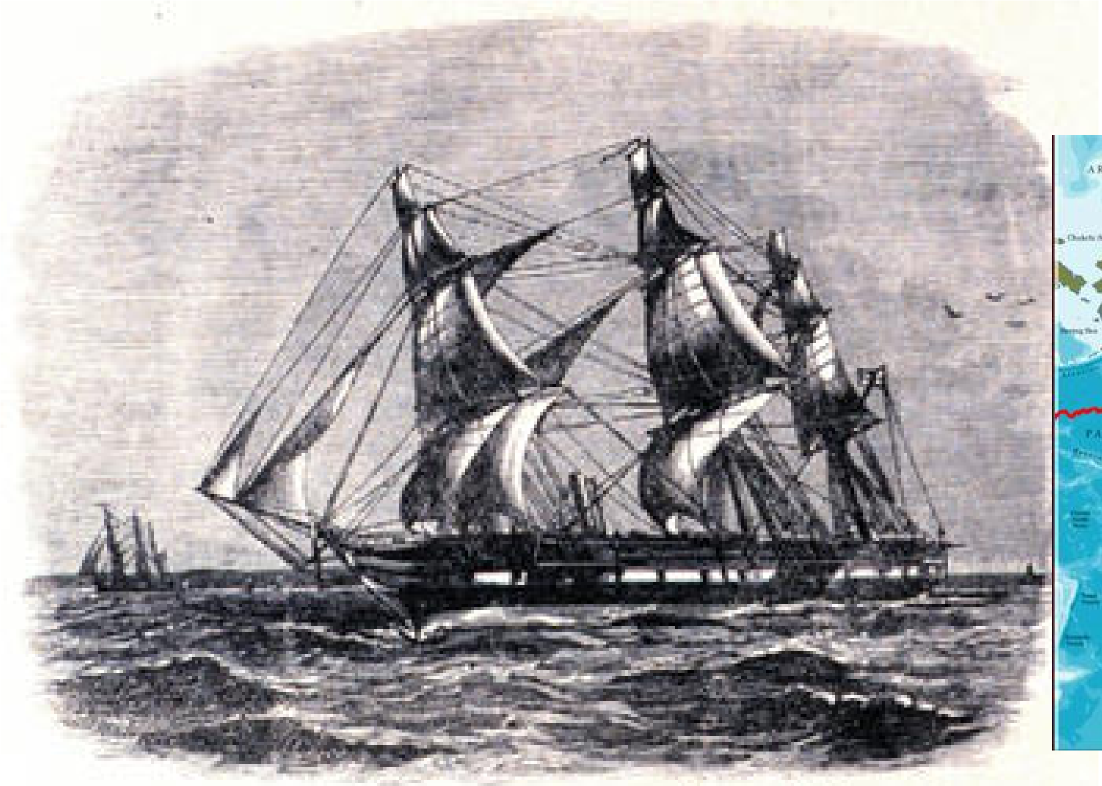
ATLANTIC AVERAGE [cK]



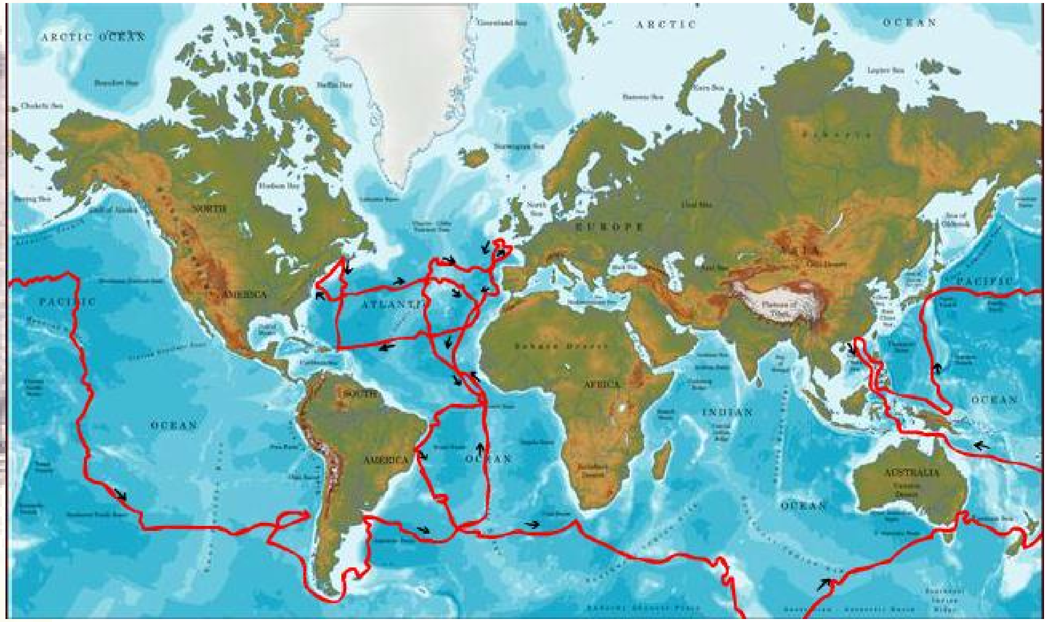
-Initialized from equilibrium at 15 C.E. ("EQ-0015")

Woods Hole Oceanographic Institution

HMS *Challenger* expedition (1872-1876)

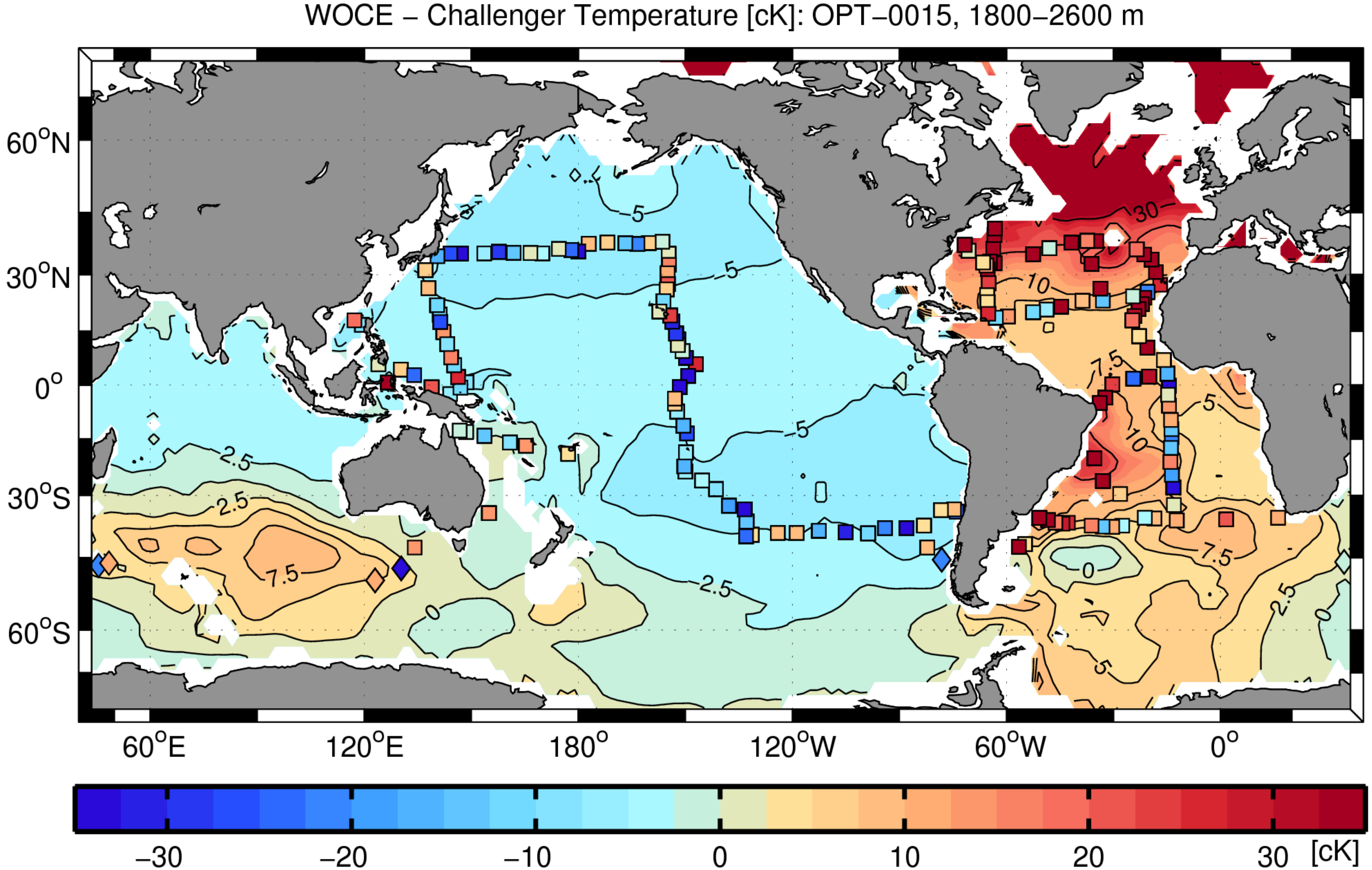


H.M.S. CHALLENGER UNDER SAIL, 1874.



Temperature and salinity measurements throughout the world ocean

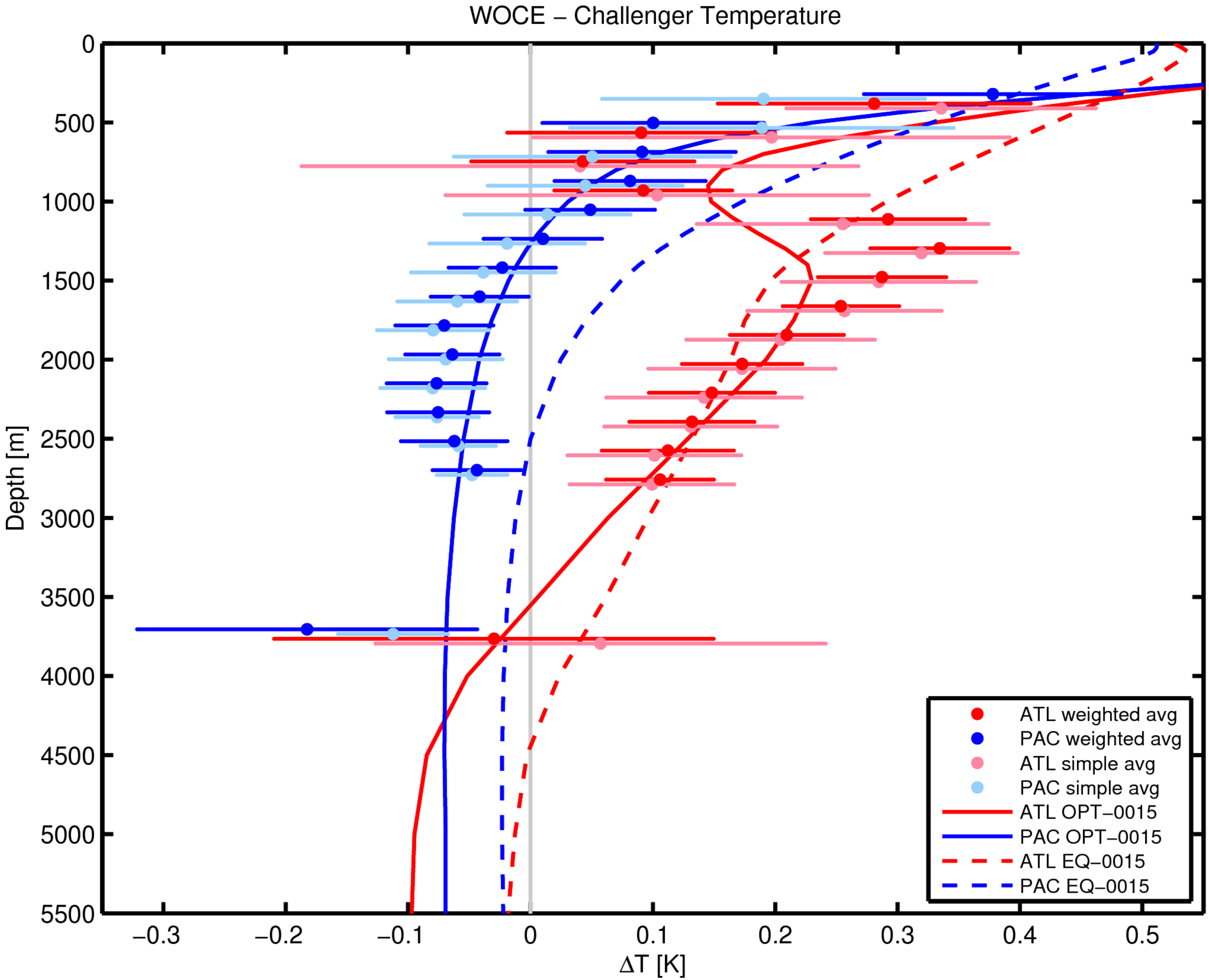
Are the predicted deep temperature trends consistent with the HMS *Challenger* (1872-1876) observations?



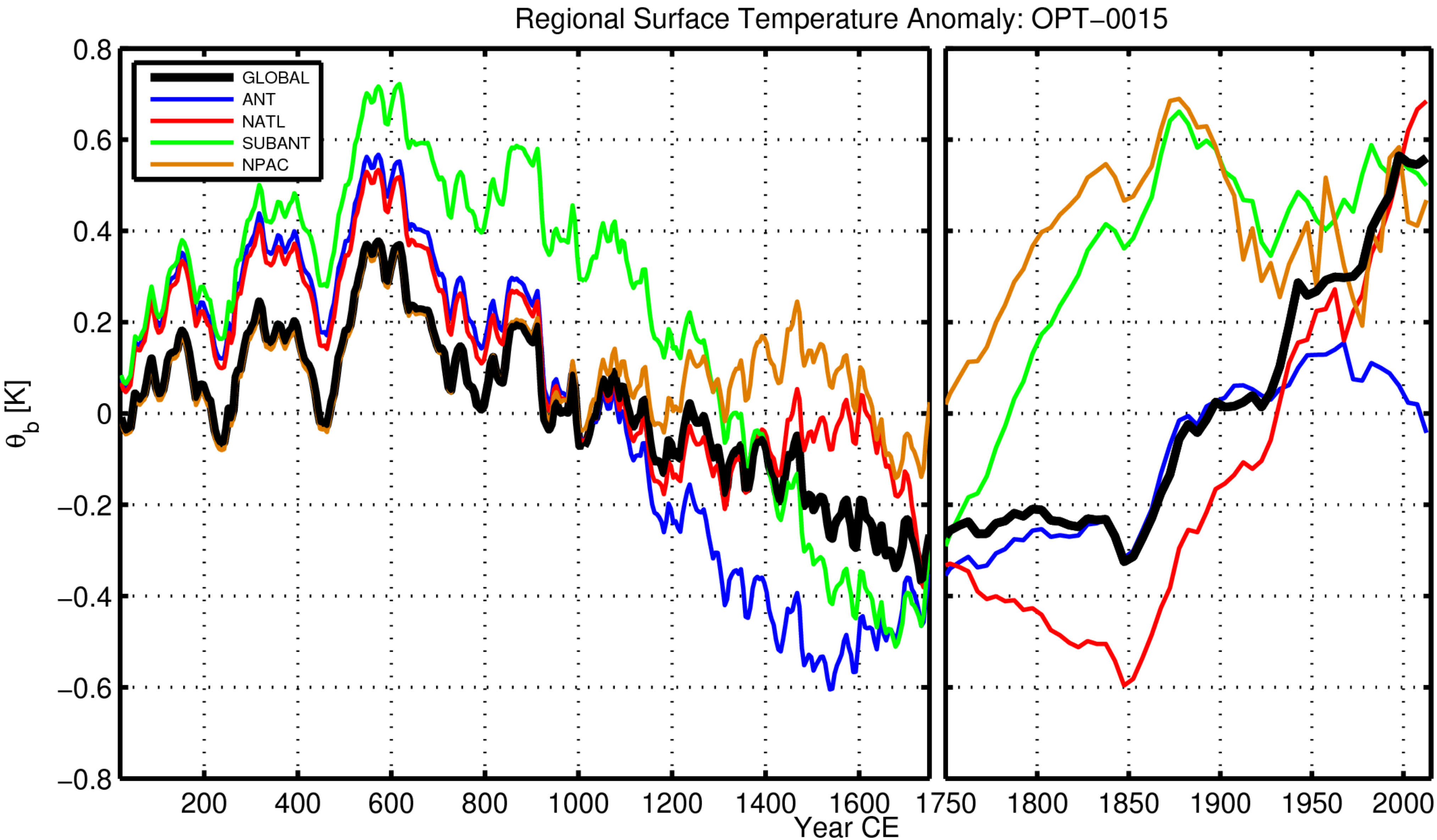
Symbols: WOCE-*Challenger* observations
Bckgrnd: Circulation model constrained by *Challenger* ("OPT-0015")

Roemmich et al. 2012

Are the temperature responses of the Atlantic and Pacific consistent with the HMS *Challenger* observations?

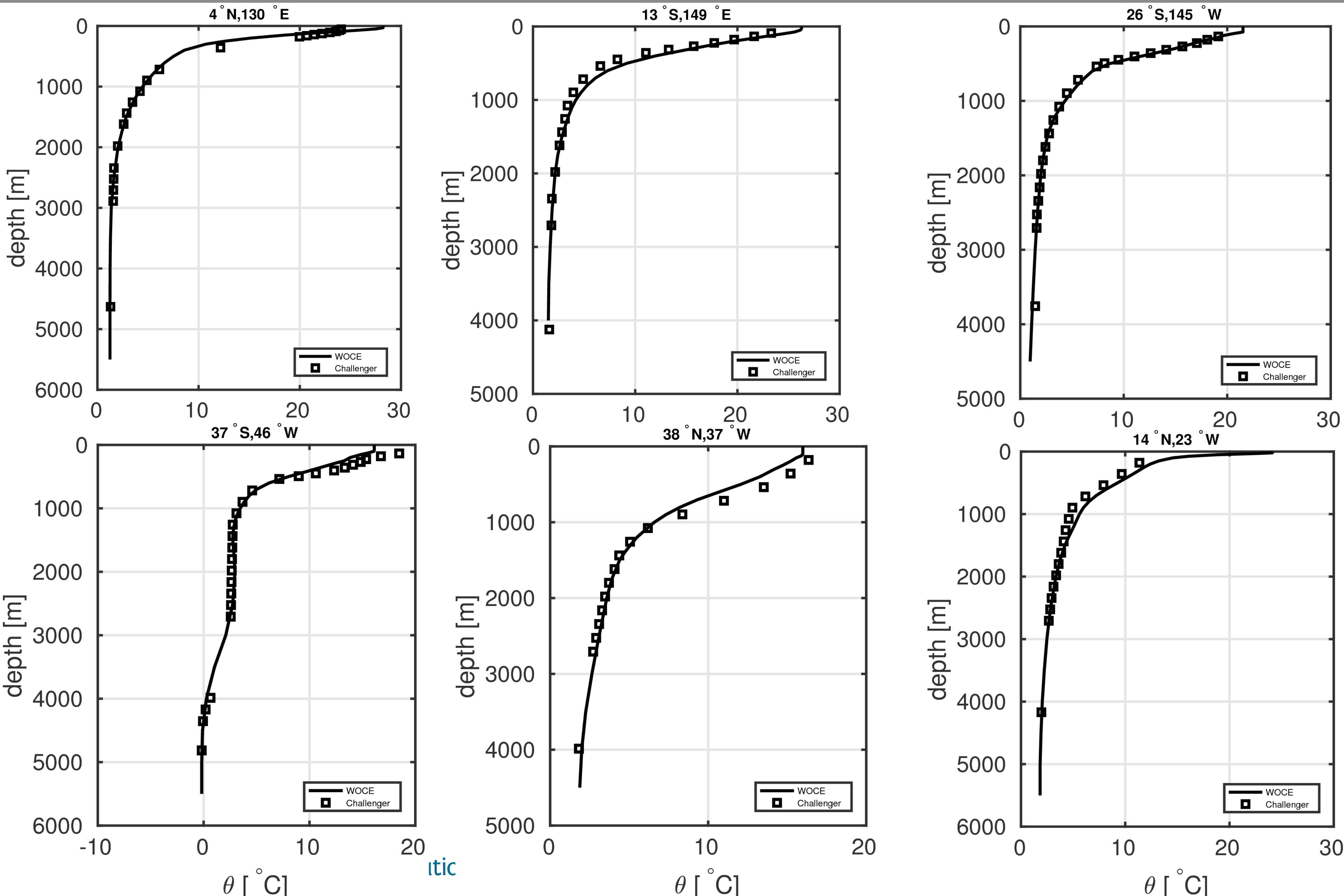


What are the implications for reconstructing Common Era surface climate?: Inverting the ocean like a borehole

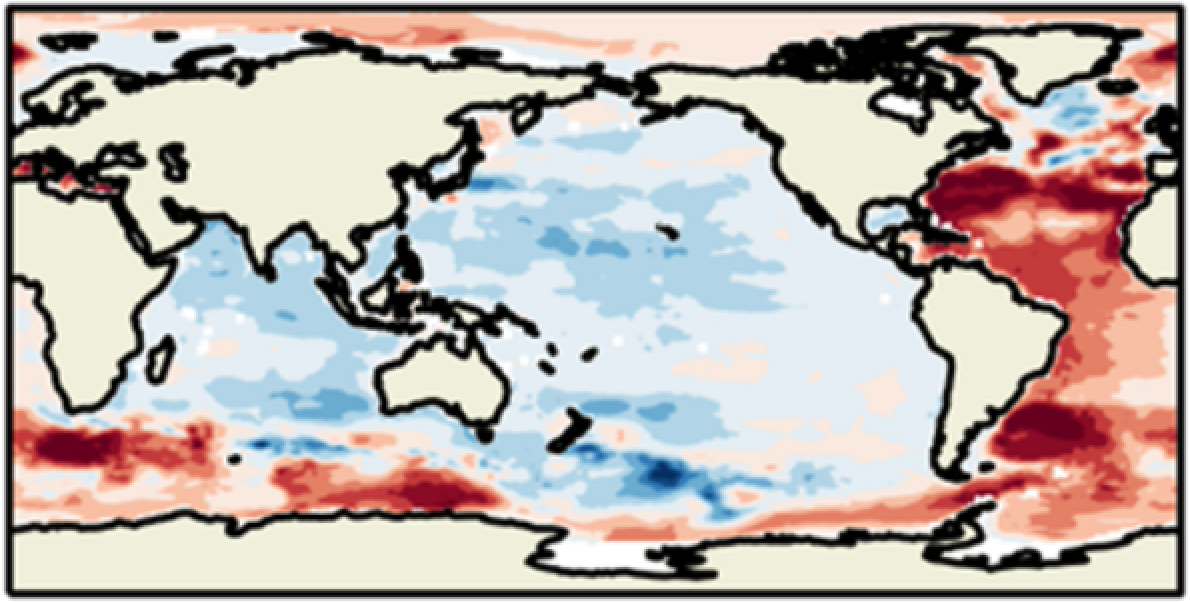


The *Challenger* data suggest a prolonged and intensified Little Ice Age in the North Atlantic.

97% of variance in HMS *Challenger* profiles is consistent with WOCE profiles.



Are there more recent observations of the deep Pacific cooling trend?

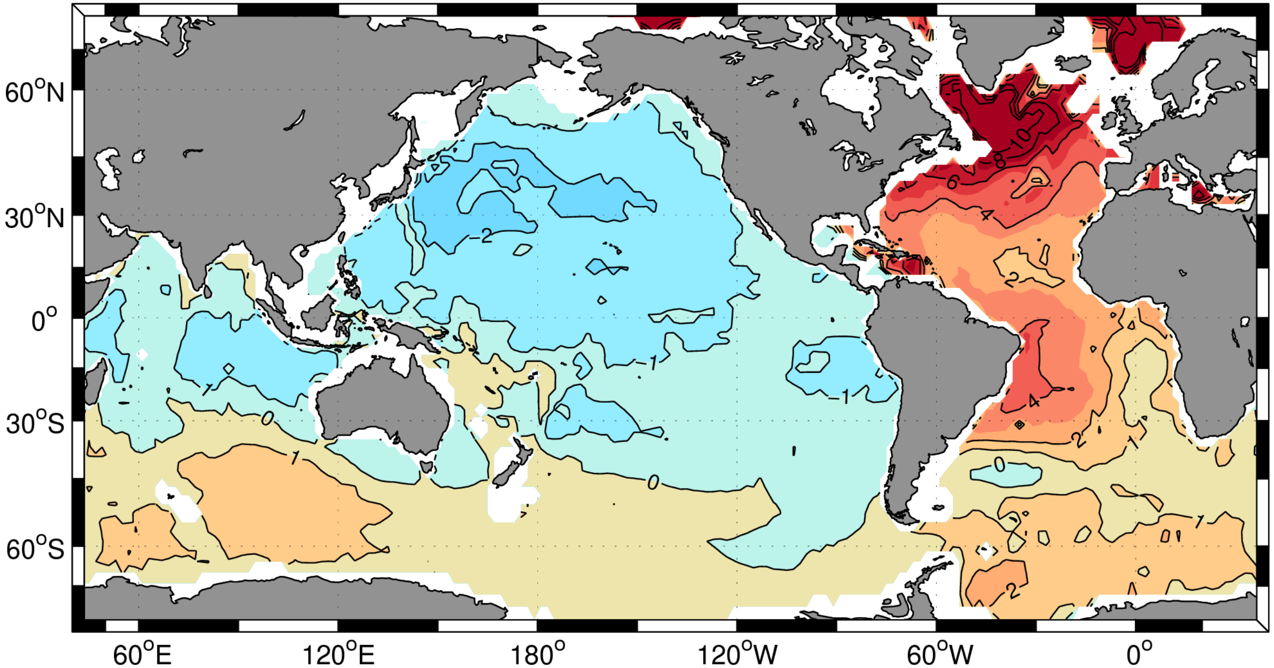


Integrated 700m-bottom temperature trend: 1970-2009 [K*m/yr]

Mean of ocean reanalyses

Palmer et al. 2017

Integrated Temperature Trend, 750–5750m, 1970–2010 [K*m/yr]: OPT–0015



Passive response model

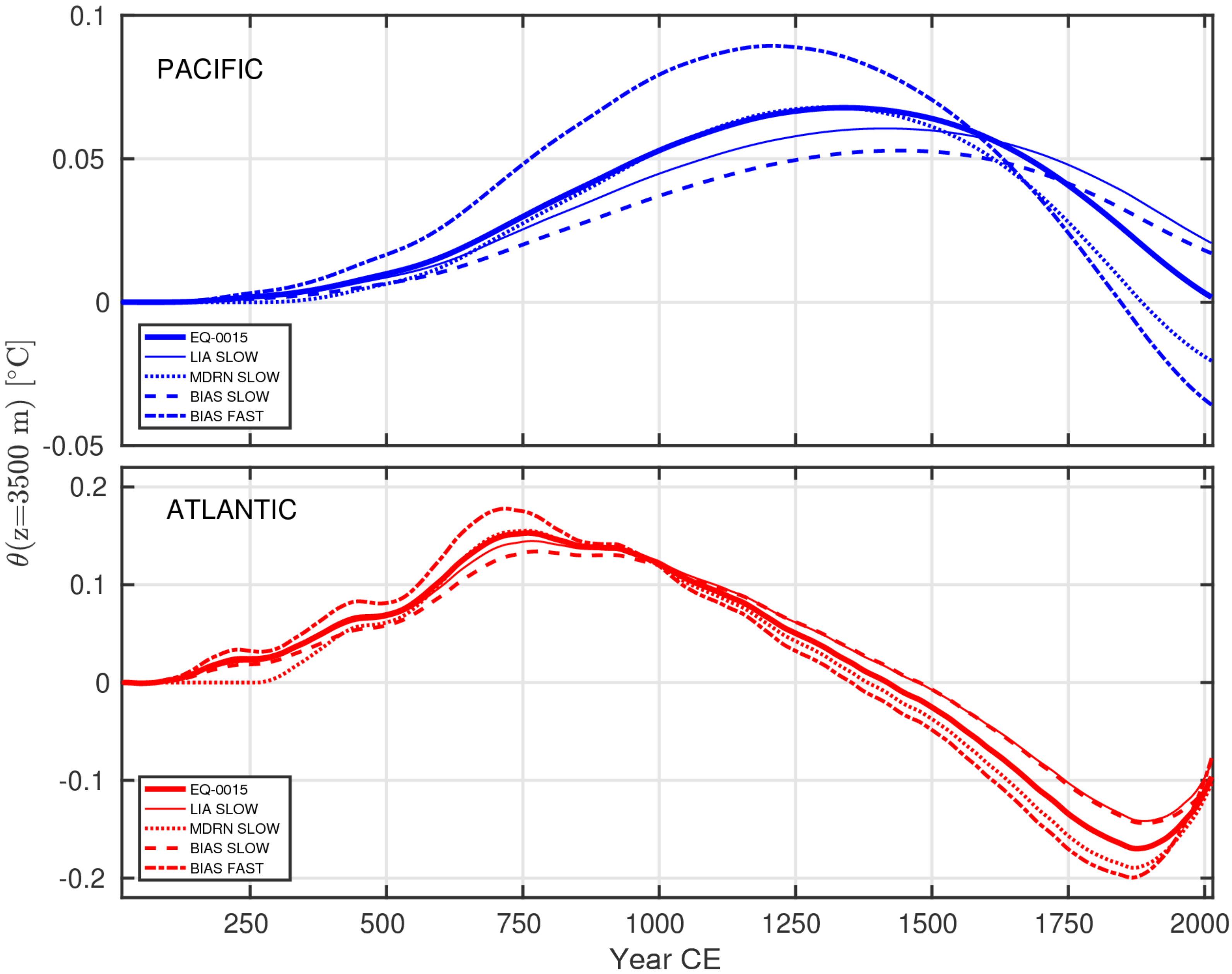
Gebbie & Huybers 2018

Pacific, 1991-2010, 2-4 km depth
Repeat hydrography: 6 ± 7 TW

Desbruyères et al. 2016

Here: – 1 TW

What is the impact of a changing circulation strength?

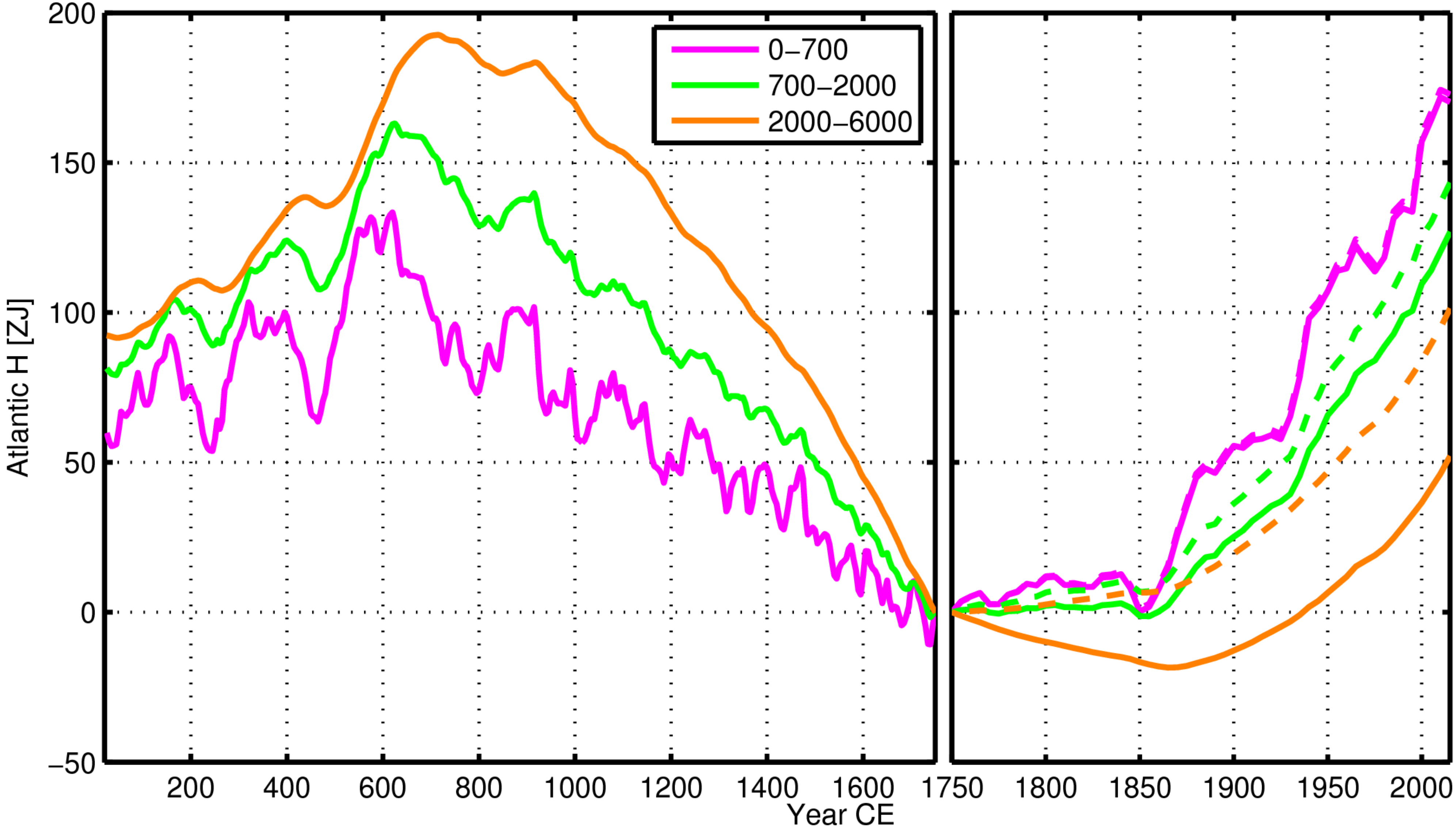


Basic pattern unchanged: Atlantic warming, Pacific cooling

Magnitude of trends affected by AMOC strength

Thornalley et al, 2018;
Lund et al., 2006

Disequilibrium Effects: Atlantic Ocean Heat Content



Deep Atlantic delay in response to surface.

Summary

Evidence from

(1) the simulated response to the surface history of marine proxies,
(2) the HMS *Challenger* hydrographic data, and
(3) ocean reanalyses over the last few decades

is consistent with a net cooling of the 20th Century deep Pacific between 1800 and 2600 meters depth.

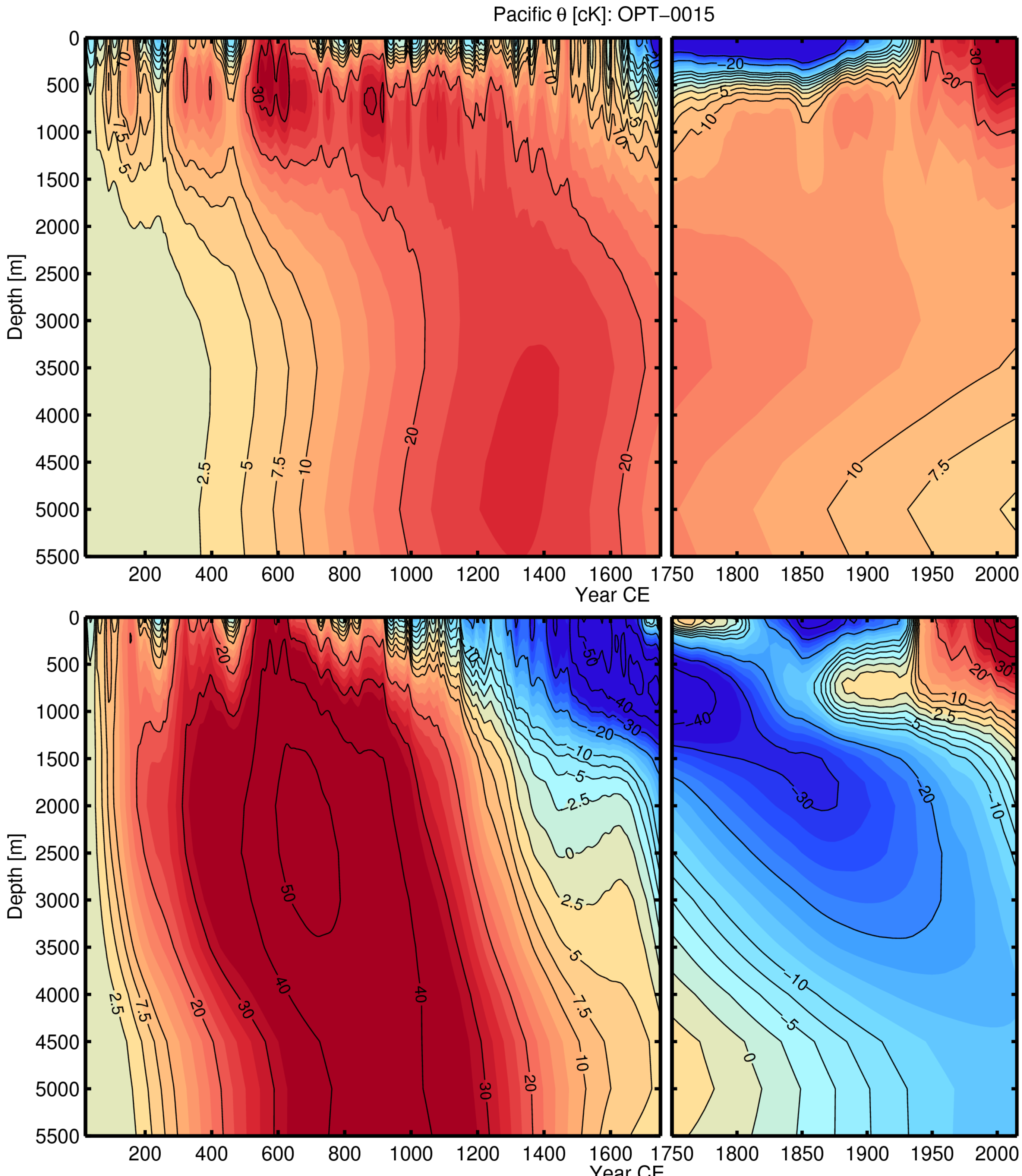
The 20th Century deep Pacific cooling trend results from the delayed response to the Medieval Warm Period to Little Ice Age transition.

Interbasin differences in the subsurface temperature response, such as deep Atlantic warming and deep Pacific cooling, are an expression of the AMOC.

Reconstructed basinwide -average temperature profiles

PACIFIC AVERAGE [cK]

ATLANTIC AVERAGE [cK]



-Data-constrained, starts at 15 C.E. ("OPT-0015")

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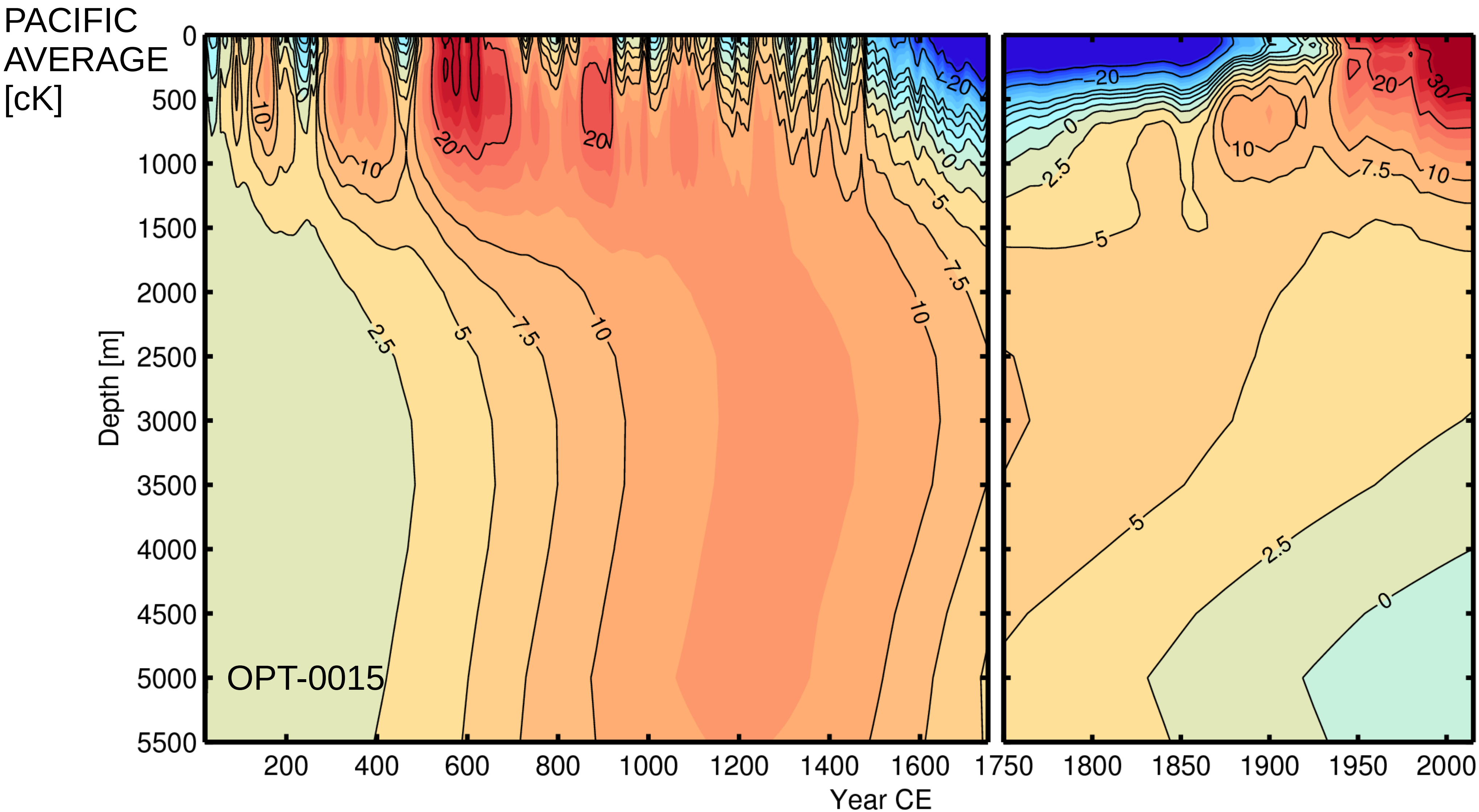
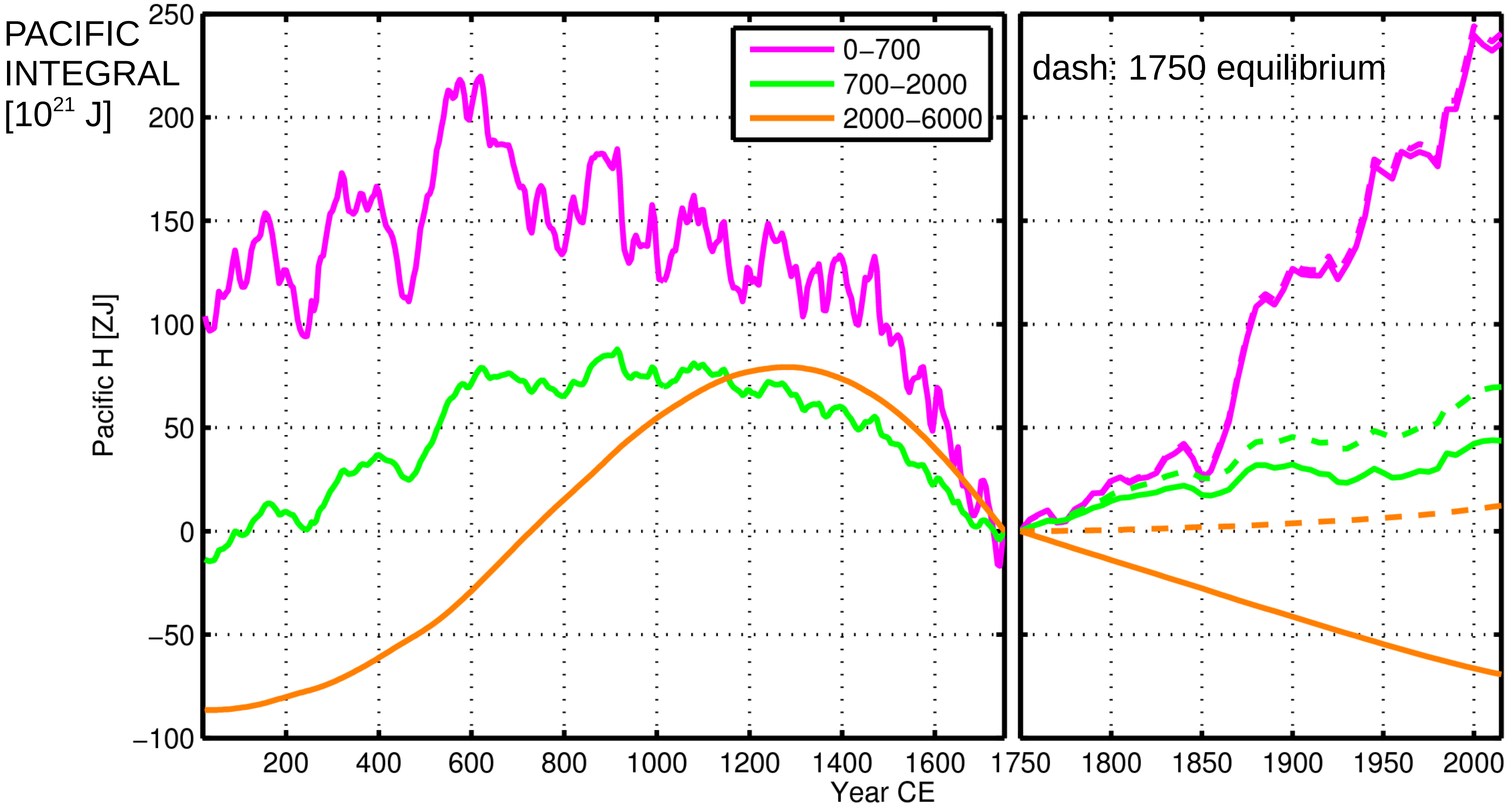
What are implications for modern-day Pacific temperature trends?



Modern deep-Pacific observations should be interpreted in the context of a long-term cooling trend of 3 cK/century.

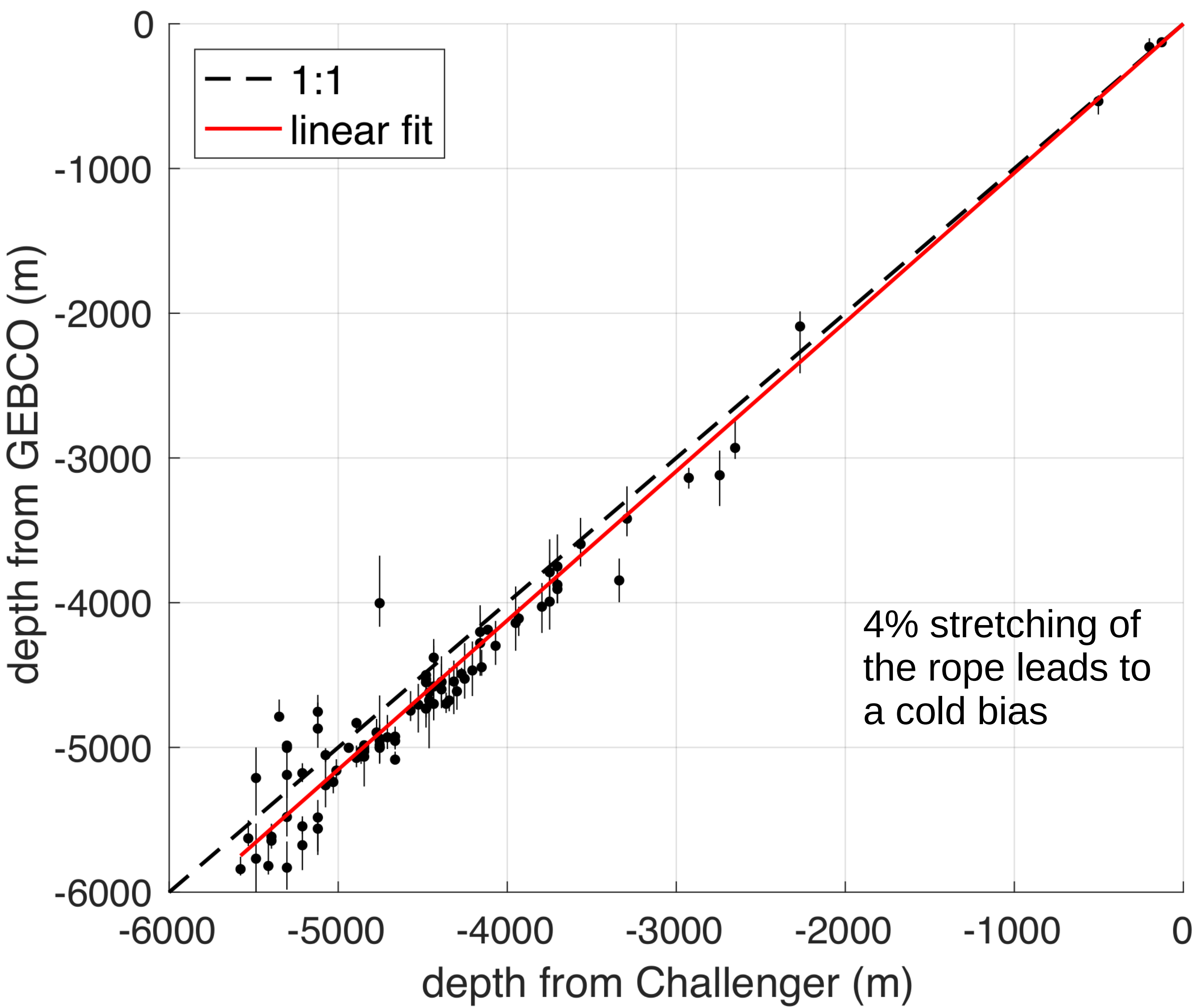
What are the implications for planetary heat balance?



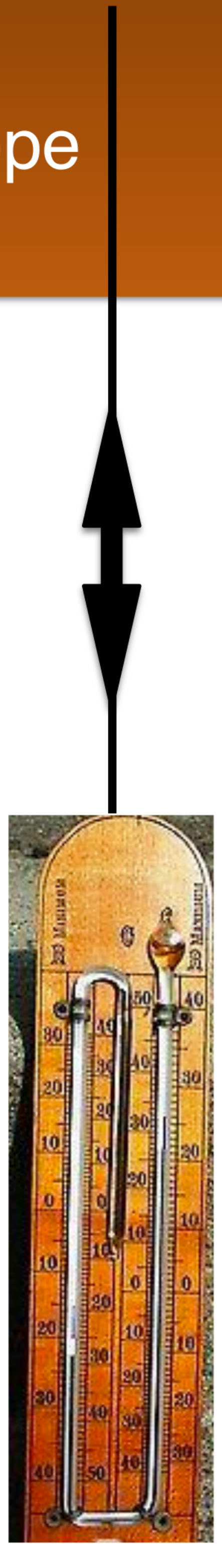
Rosenthal et al. 2017

Modest deep temperature trends are large enough to affect the global energy balance.

Challenger temperature data issues: stretching hemp rope

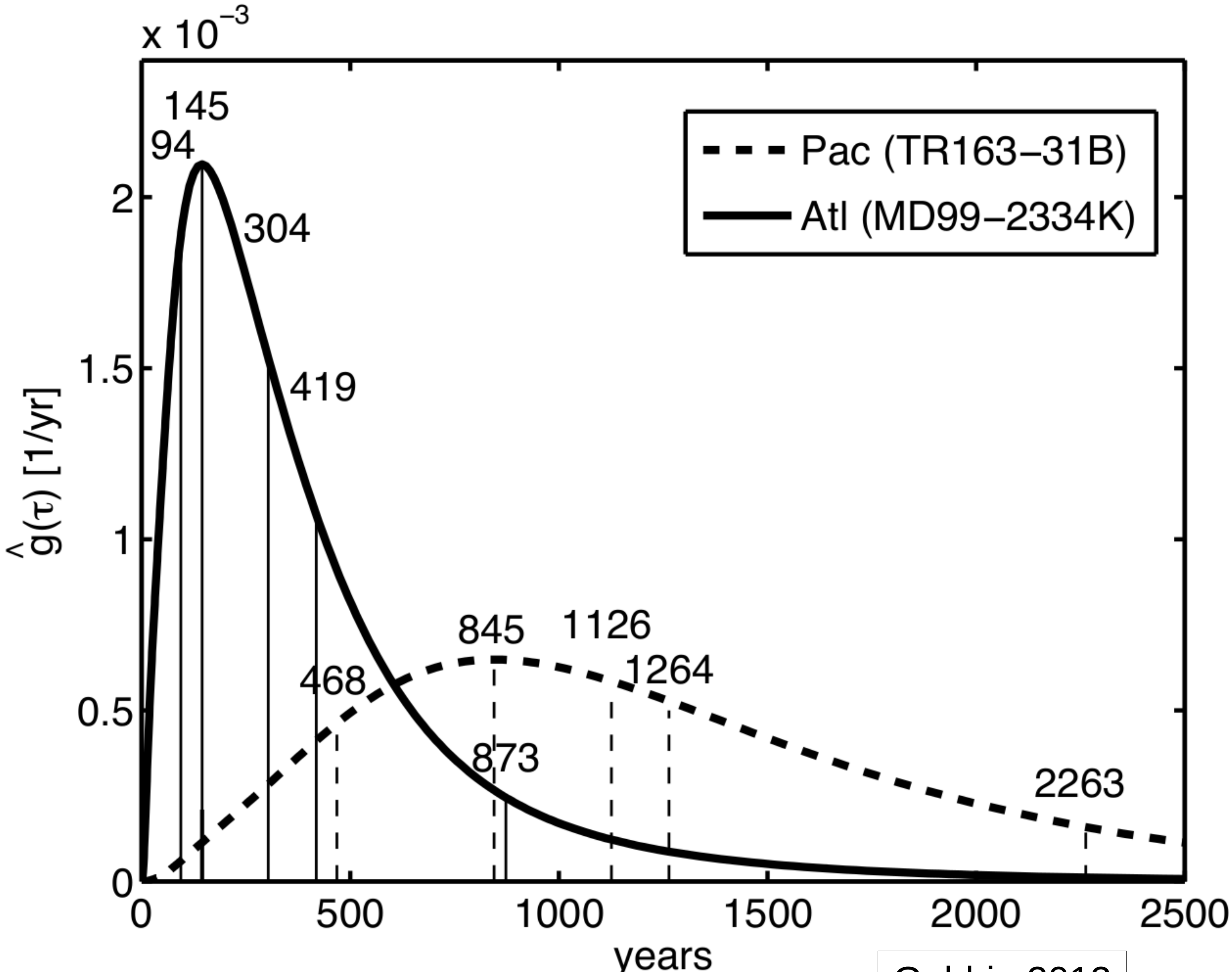


4% stretching of the rope leads to a cold bias



The interior response doesn't solely depend upon the mean or ideal age, but a distribution of timescales.

Global-response Green's functions

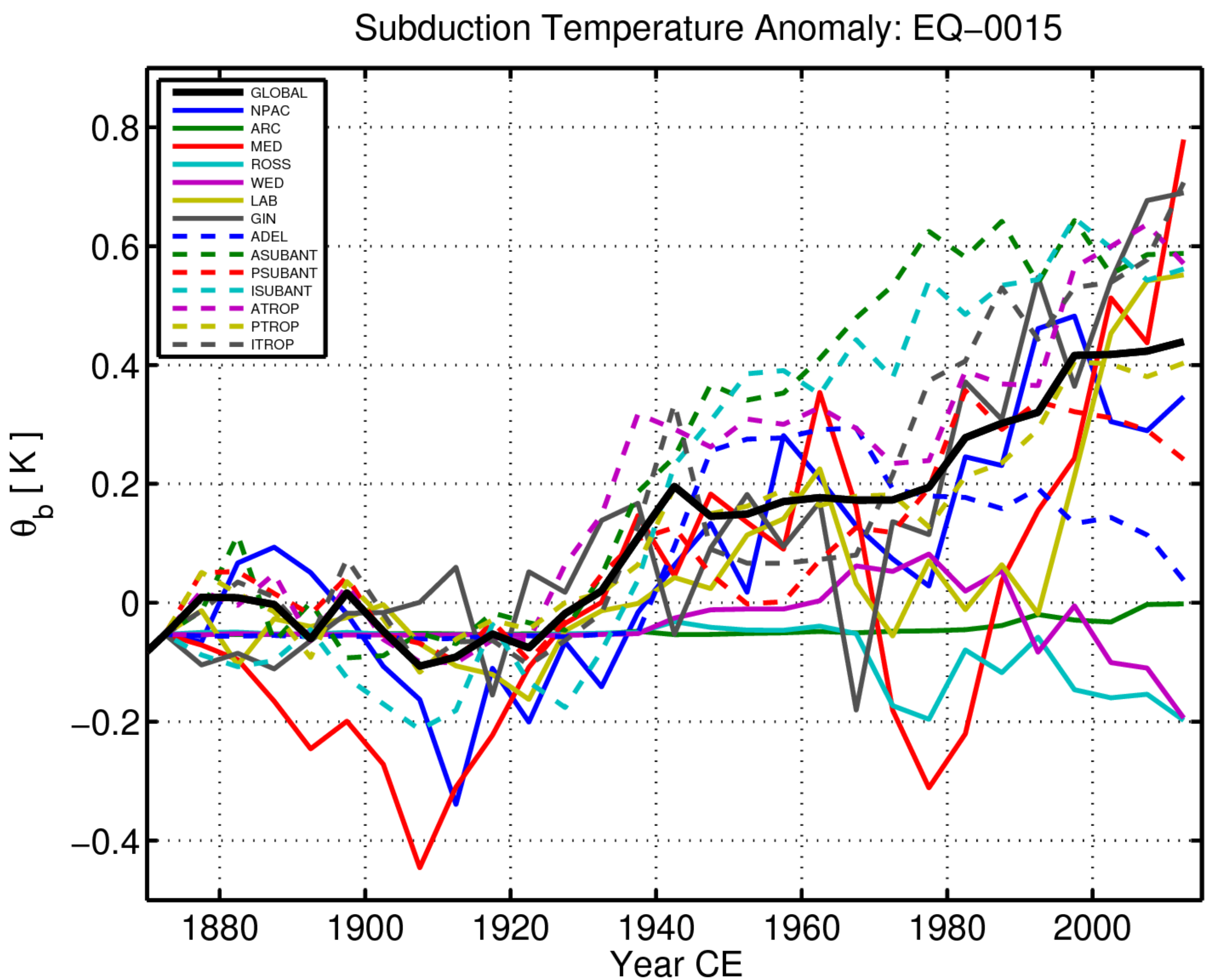


~3 km depth

Gebbie 2012

Forcing a Common Era Simulation: 1870-2015 C.E.

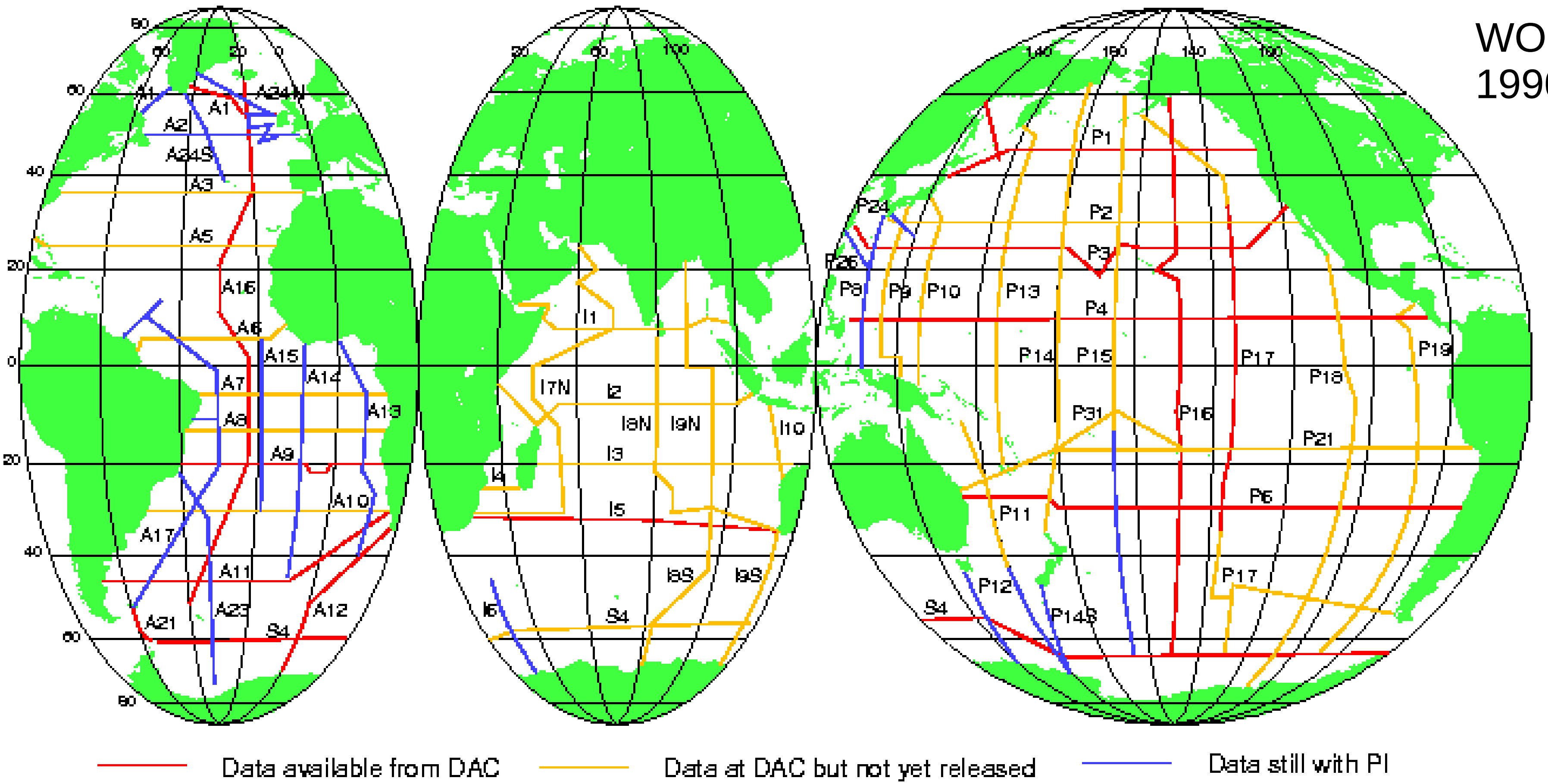
Regionally-Averaged "Subduction" Temperature Relative to 15 C.E.



$$\hat{\boldsymbol{\theta}}_b = \mathbf{V}\mathbf{b}$$

Regionally-filter HadISST 1.1:
"hat" = filtered boundary temp., V = 14 regional patches, b = temp. coefficients

The Circulation Model: Empirically based on worldwide observations of the 1990's



WOCE
1990-2002

Inverse Circulation Model (Gebbie & Huybers 2012)

- derived by inverting WOCE temperature, salinity, phosphate, nitrate, oxygen, d18O, D14C
- Global with 2 x 2 degree horizontal resolution with 33 vertical levels

Translating the WOCE circulation into a transient model

$$\boldsymbol{\theta}(t + \Delta t) = \mathbf{A}(t)\boldsymbol{\theta}(t) + \mathbf{B}\boldsymbol{\theta}_b(t + \Delta t),$$

Working hypothesis: **A**(t) = **A** from the WOCE era.

Entries of **A** are advective and diffusive fluxes between gridcells.

A: dimension 74064 x 74064

Surface boundary condition: “Subduction temperature” at maximum mixed-layer depth

Stommel 1979, Williams et al. 2015

Next slide: Response at 3500 meters depth to a globally uniform surface change of magnitude 100.

Gebbie & Huybers 2012

Common Era Simulation: Passive temperature anomalies

Working hypothesis: temperature anomalies are small enough that their evolution is well-approximated by a passive response.

$$\boldsymbol{\theta}(t) = \mathbf{A}(t_w)^N \boldsymbol{\theta}(t - N\Delta t) + \sum_{i=0}^{N-1} \mathbf{A}(t_w)^i \, \mathbf{B}\mathbf{V}\mathbf{b}\,(t - i\Delta t).$$

It is useful to simplify the timestepping equation by defining the Green's functions,

$$\mathbf{G}(i) = \mathbf{A}(t_w)^i \mathbf{B}\mathbf{V},$$

$$\boxed{\boldsymbol{\theta}(t) = \sum_{i=0}^{K-1} \mathbf{G}(i)\, \mathbf{b}(t - i\Delta t).}$$

Roemmich and Wunsch 1984, Marshall et al. 2015

Ocean variability on interannual and higher frequencies must be treated as a contaminant in the observations.

$$\Delta\theta(r_i) = \theta(t_w, r_i) - \theta(t_c, r_i)$$

$$\mathbf{y} = \begin{pmatrix} \Delta\theta(r_1) \\ \Delta\theta(r_2) \\ \vdots \\ \Delta\theta(r_3) \end{pmatrix}$$

$$\mathbf{x} = \begin{pmatrix} \Delta\theta_{pac}(z) \\ \Delta\theta_{atl}(z) \\ \Delta\theta_{sth}(z) \\ \Delta\theta_{ind}(z) \end{pmatrix}$$

$$\mathbf{y} = \mathbf{E}\mathbf{x} + [\mathbf{n}_T(t_w) - \mathbf{n}_T(t_c)] + [\mathbf{n}_S(t_w) - \mathbf{n}_S(t_c)] + [\mathbf{n}_M(t_w) - \mathbf{n}_M(t_c)]$$

$$\mathbf{y} = \mathbf{E}\mathbf{x} + \mathbf{q}$$

Temperature differences may reflect long-term changes or be contaminated by high-frequency motions due to internal waves and mesoscale eddies.

Passive temperature anomaly simulation

$$\boldsymbol{\Theta}(t+\Delta t) = \mathbf{A}(t)\boldsymbol{\Theta}(t) + \mathbf{B}\boldsymbol{\Theta}_b(t+\Delta t)$$

$$\text{Equilibrium temperature: } \boldsymbol{\Theta}_{eq} = \mathbf{A}_{eq}\boldsymbol{\Theta}_{eq} + \mathbf{B}\boldsymbol{\Theta}_b^{eq}$$

$$\text{Perturbation temperature: } \boldsymbol{\theta}(t) = \boldsymbol{\Theta}(t) - \boldsymbol{\Theta}_{eq}$$

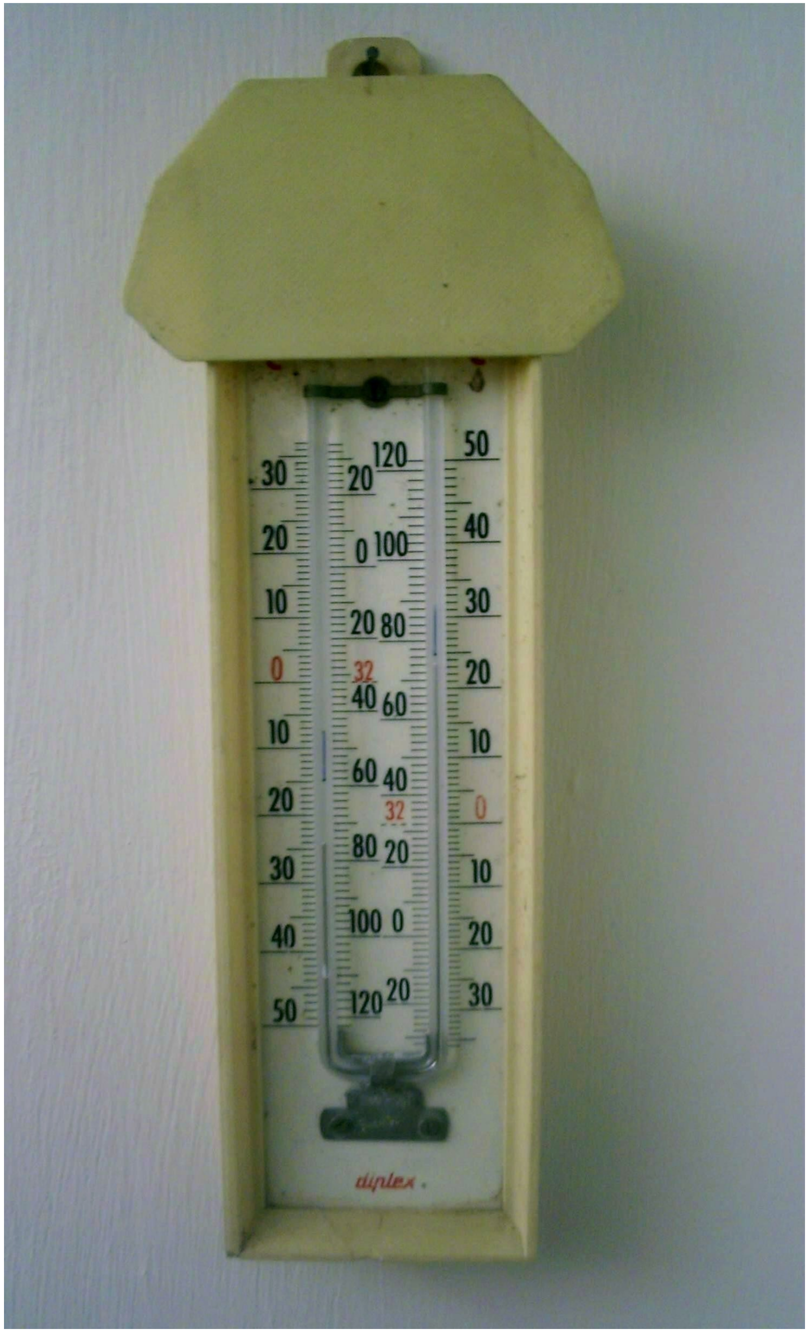
$$\boldsymbol{\theta}(t+\Delta t) = \mathbf{A}_{eq}\boldsymbol{\theta}(t) + \mathbf{B}\boldsymbol{\theta}_b(t+\Delta t) + \mathcal{O}[\mathbf{A}'(t)\boldsymbol{\theta}(t)]$$

Drop the last term, use $\mathbf{A} \equiv \mathbf{A}_{eq} = \mathbf{A}_W$, and the filtered subduction temperature:

$$\boxed{\boldsymbol{\theta}(t+\Delta t) = \mathbf{A}\boldsymbol{\theta}(t) + \mathbf{B}\mathbf{V}\mathbf{b}(t+\Delta t)}$$

Model originally developed in Gebbie 2012

Interpreting historical data



Miller-Casella (max-min or Six’s) thermometer:
Primarily used on HMS *Challenger*

Systematic errors:

1. depth taken from amount of line out

2. pressure effect on “protected” glass thermometer: +0.04 K/km as empirically determined by *Tait*

3. mounting on vulcanite frames susceptible to compressional warming and heat transfer to thermometer

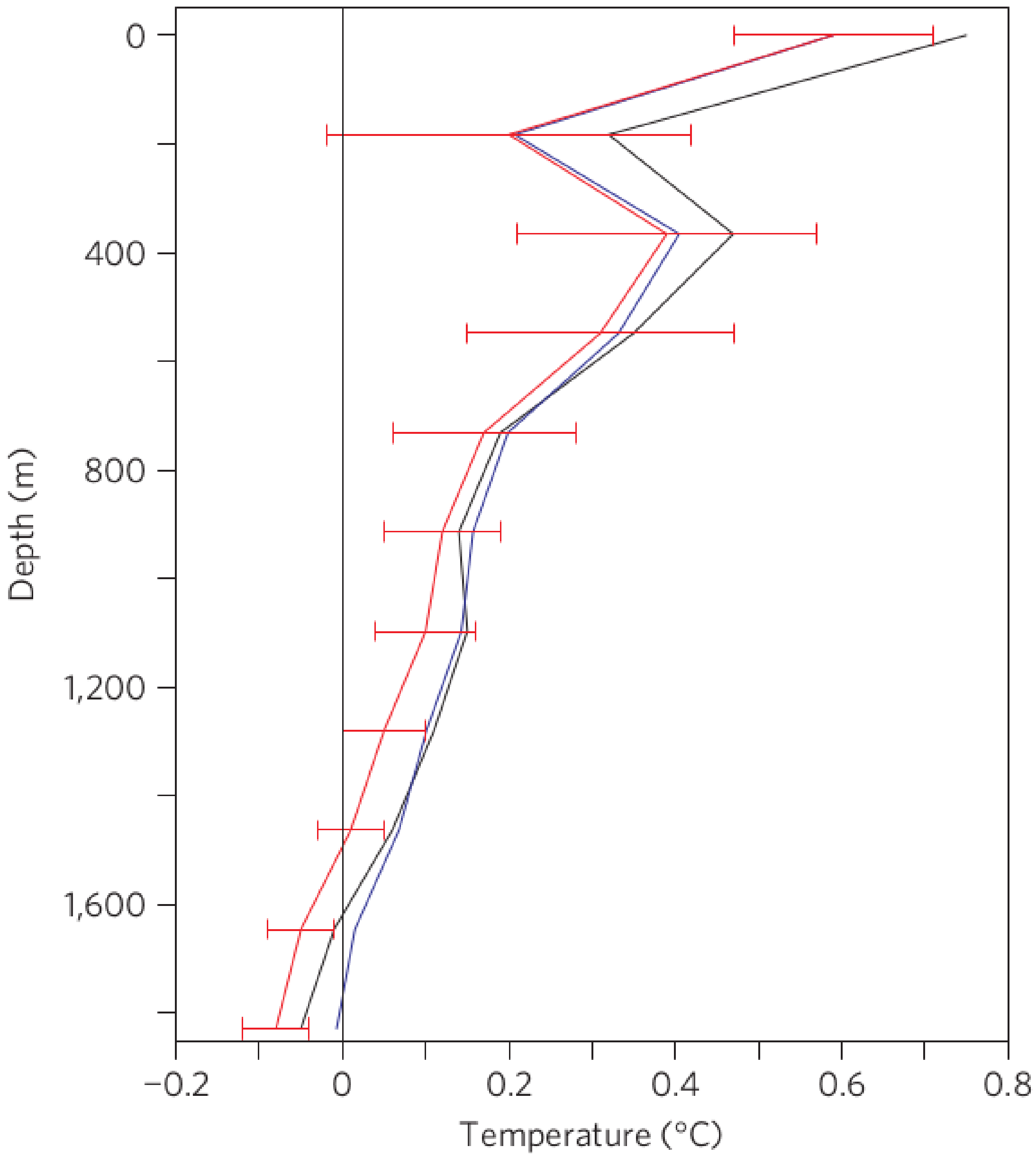
These 3 systematic errors all lead to a warm bias.

On the day of the discovery of Challenger Deep

"At 4 a.m. got up steam. At 5.15 a.m. shortened and furled sail. At 6 a.m. proceeded under steam, and sounded in 4575 fathoms. The line was checked at 4575 fathoms, and the accumulator showed that the weights were off. It must, therefore, just have got to the bottom as it was checked. To leave no doubt as to the correctness of the sounding, the line was again let go at 12.30 p.m with a weight of 4 cwts. (instead of 3 cwts. as usual), and the depth obtained amounted to 4475 fathoms, only 100 fathoms less than the first sounding."

Scientific report of the expedition of the HMS *Challenger*

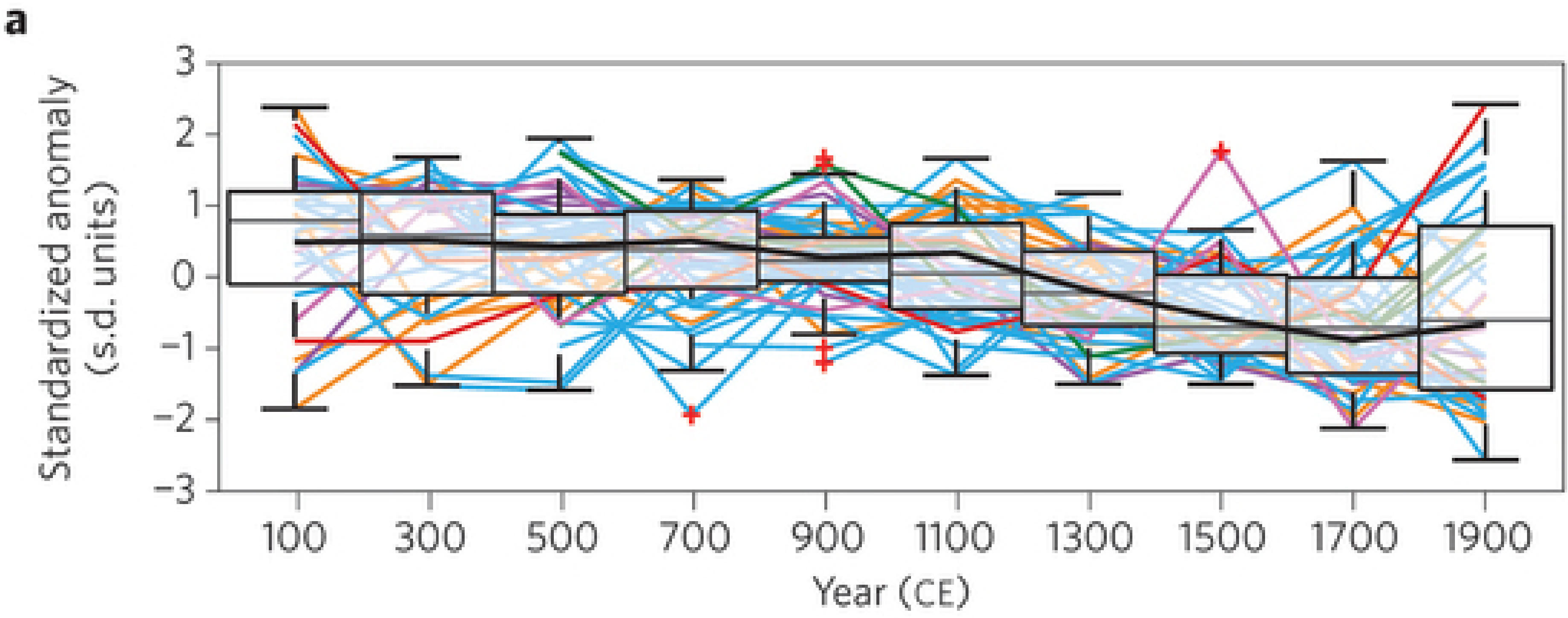
Argo-*Challenger* temperature difference



Blue: simple mean
Red: volume-averaged
Black: pressure correction

Roemmich et al. 2012

“Little Ice Age”: long-term surface cooling

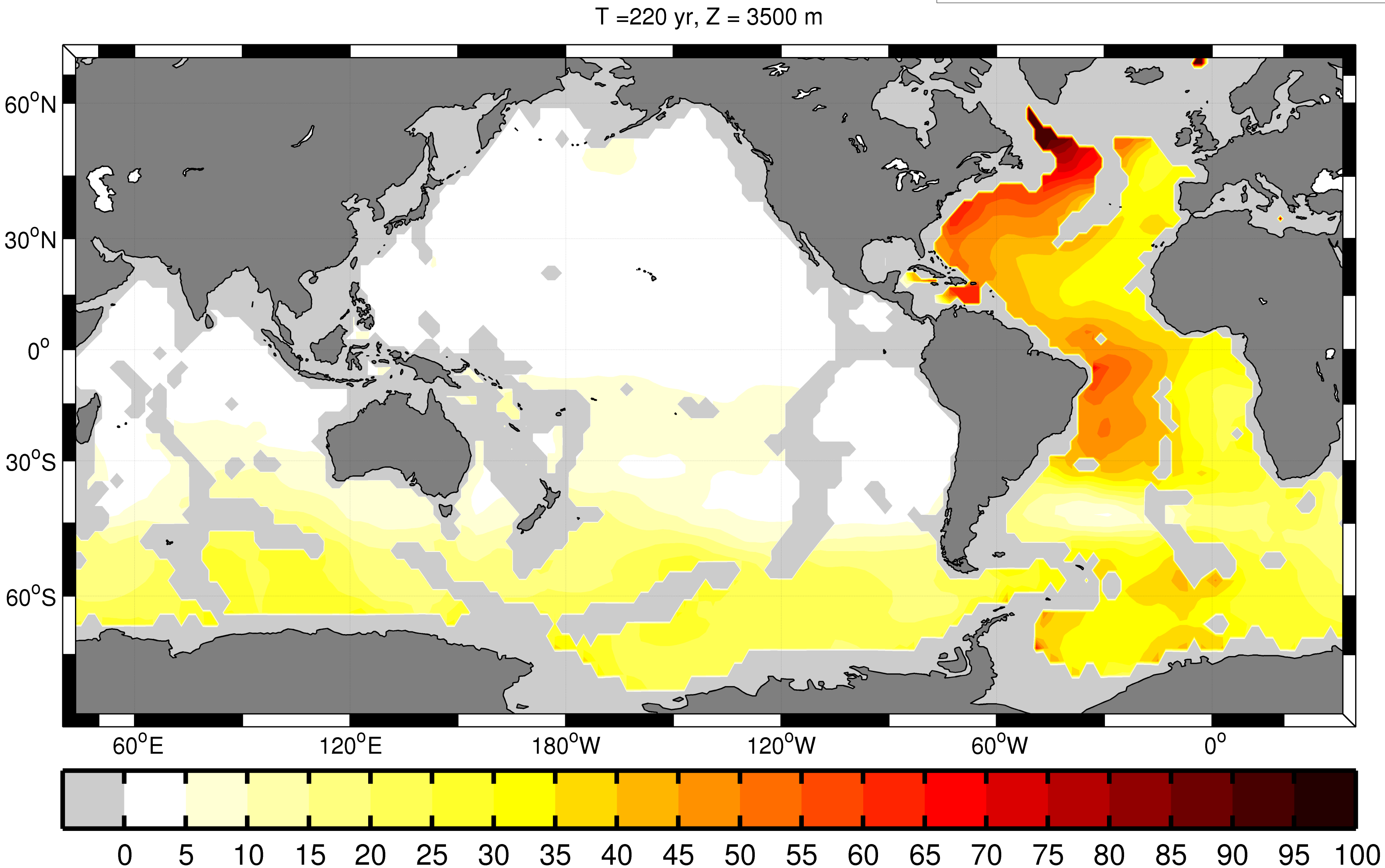


McGregor et al. 2015

Oceans 2k Project
Based on: Marine records of alkenones and
foraminiferal Mg/Ca

Our inverse-derived model simulates a deep ocean response along deep western boundary currents.

Gebbie, *Paleoceanography*, 2012



- Empirical model trained with WOCE/GLODAP T, S, PO_4, NO_3, O_2, $\delta^{18}O$, $\Delta^{14}C$
- Global with 4° x 4° horizontal resolution and 33 vertical levels

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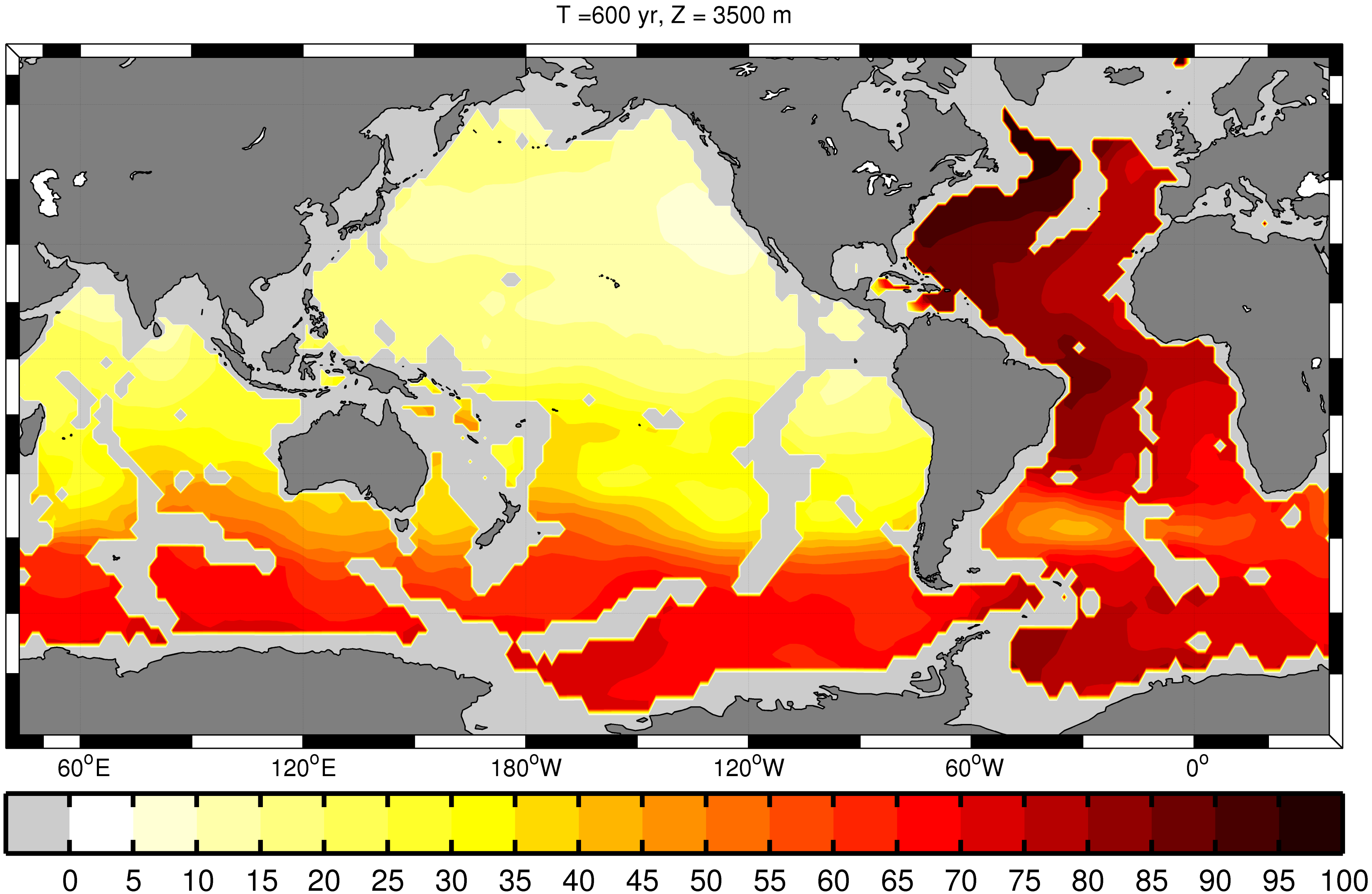

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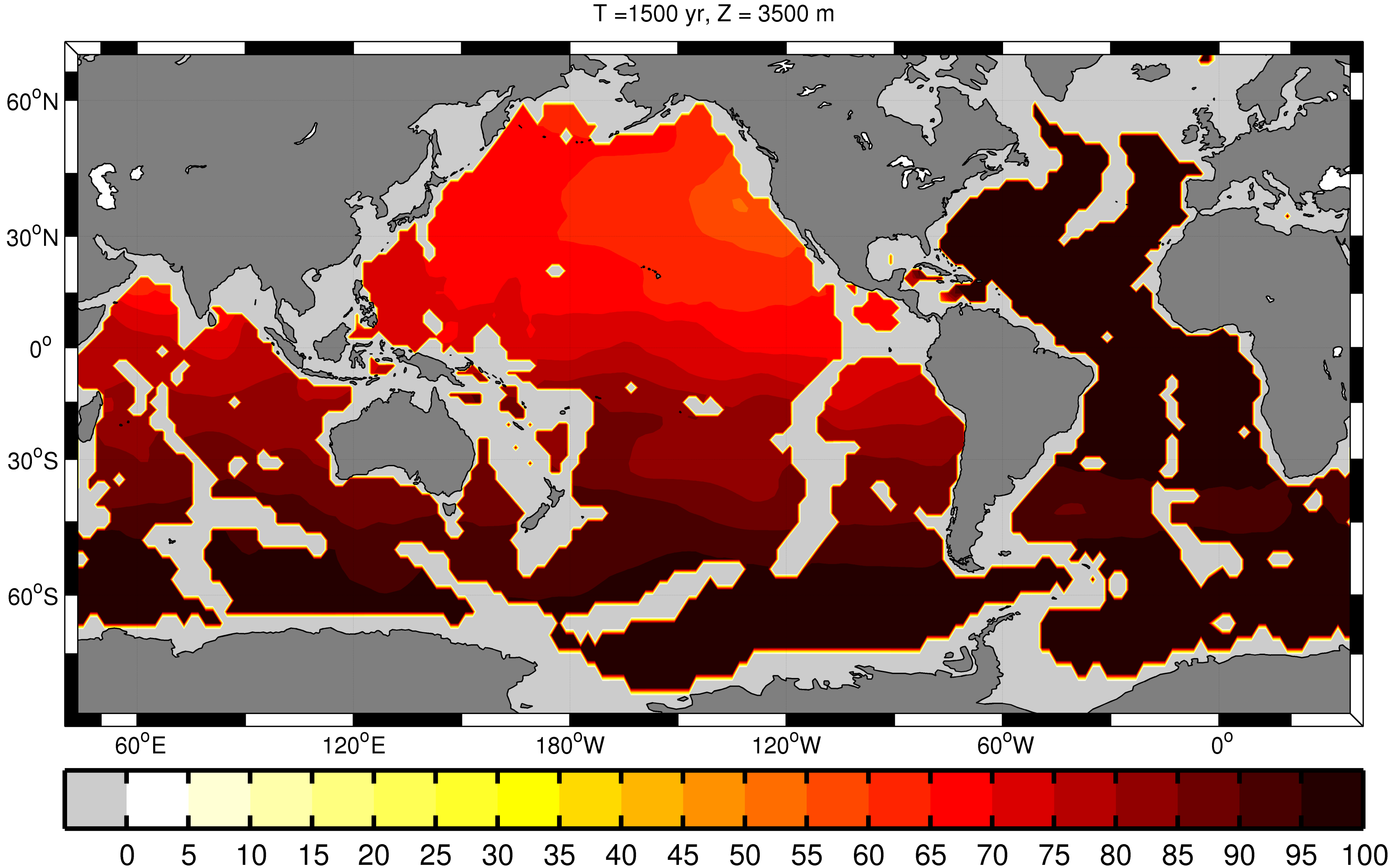

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