— Revisiting Miocene Climatic Optimum (MCO) —

Addressing the MCO warmth conundrum with equilibrated isotope-enabled CESM simulations

Feng Zhu[1], Jiang Zhu[1], Weimin Si[2], Jared E. Nirenberg[2], Timothy Herbert[2], Jessica E. Tierney[3], R. Paul Acosta[4], Natalie J. Burls[4]

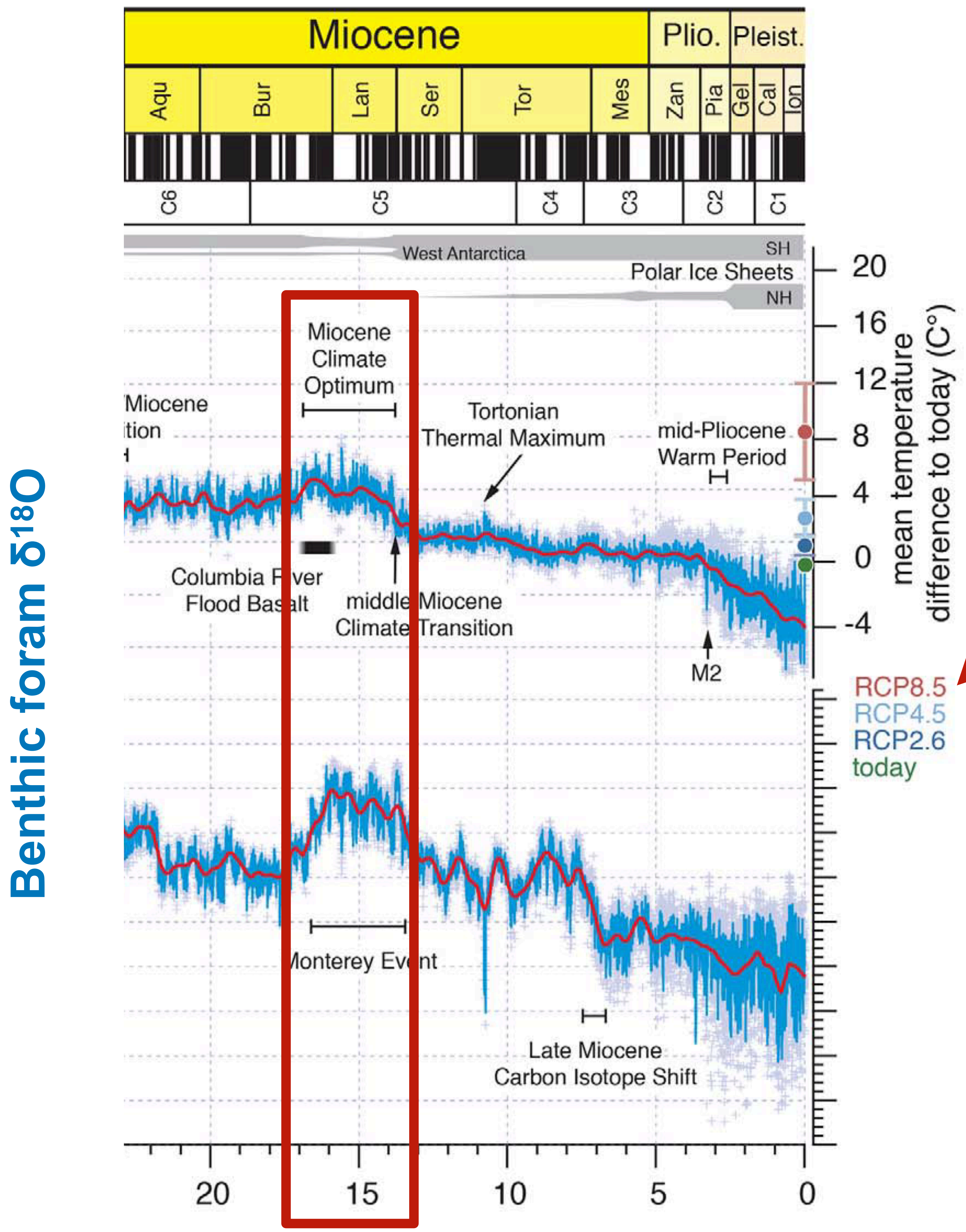
1. NSF NCAR 2. Brown University 3. University of Arizona 4. George Mason University

Jan 29, 2025
CESM Paleoclimate Working Group Meeting

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

▣ Miocene Climate Optimum (MCO): an analog for future climate

Westerhold et al. (2020, Science)

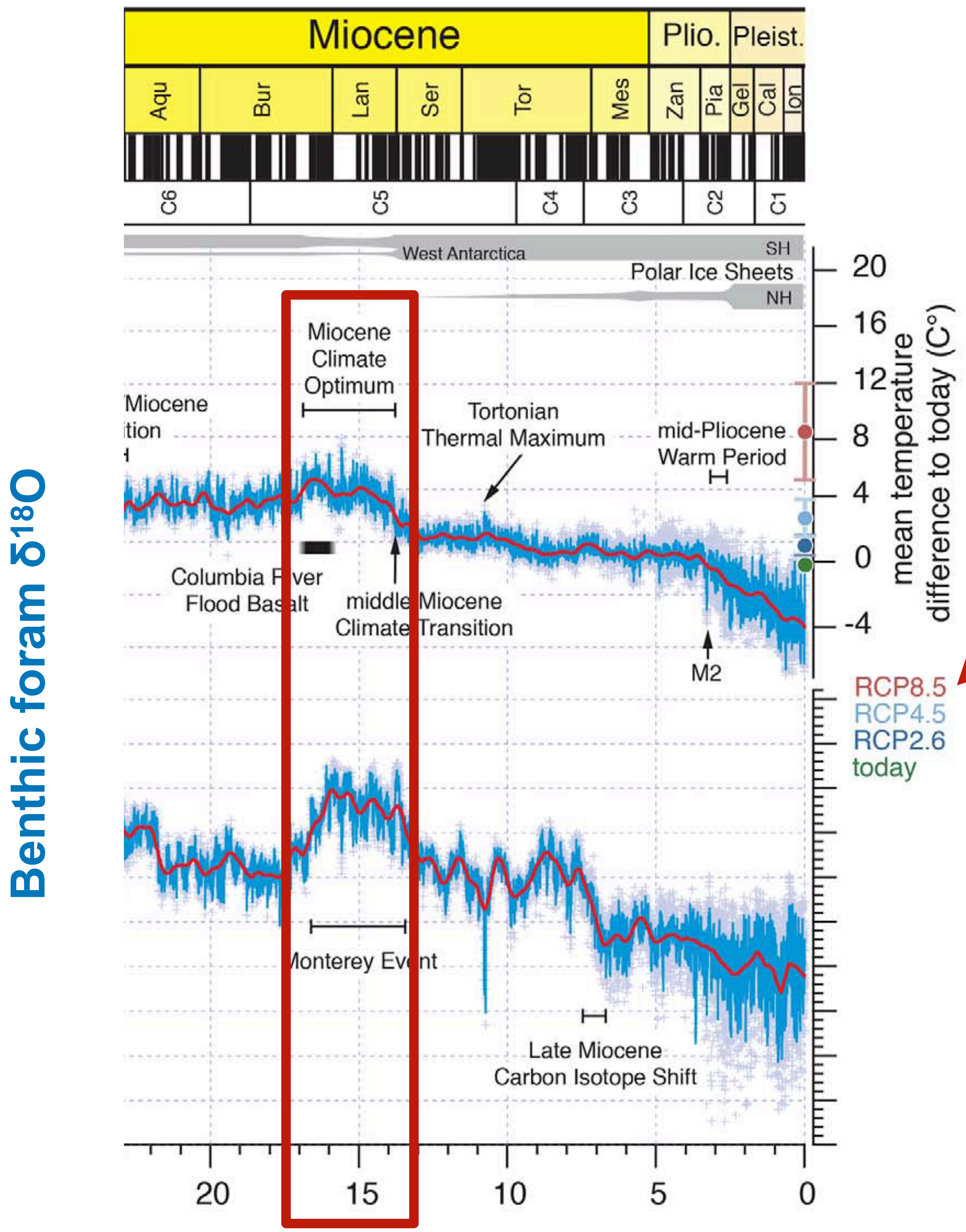


Middle Miocene Optimum (MCO, ~15 Ma) is of great scientific interests:

- ► Warm climate insights
- ► Global climate and carbon cycle
- ► Ocean circulation and ice sheets
- ► Climate models validation

Miocene Climate Optimum (MCO): an analog for future climate

Westerhold et al. (2020, Science)

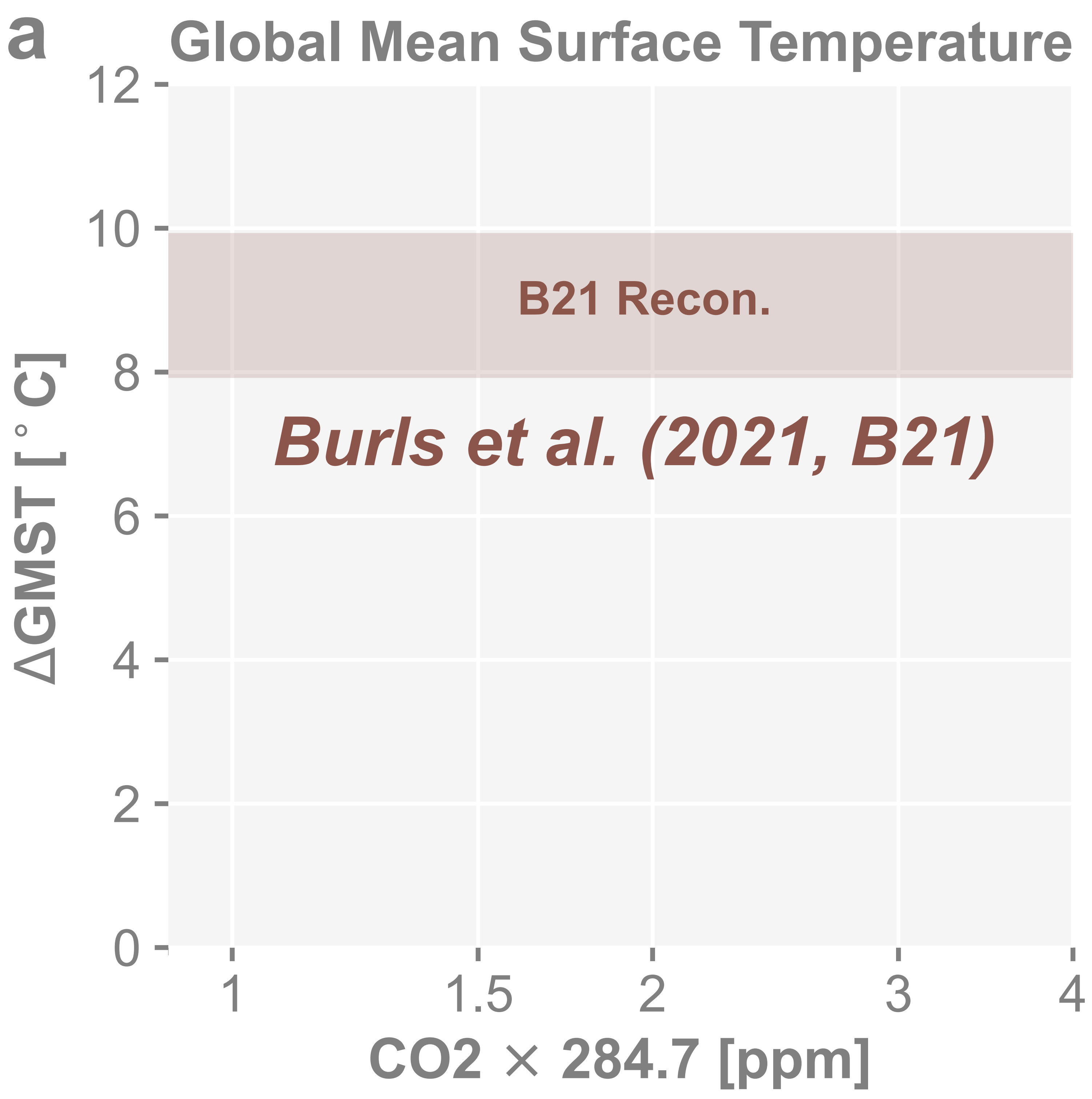


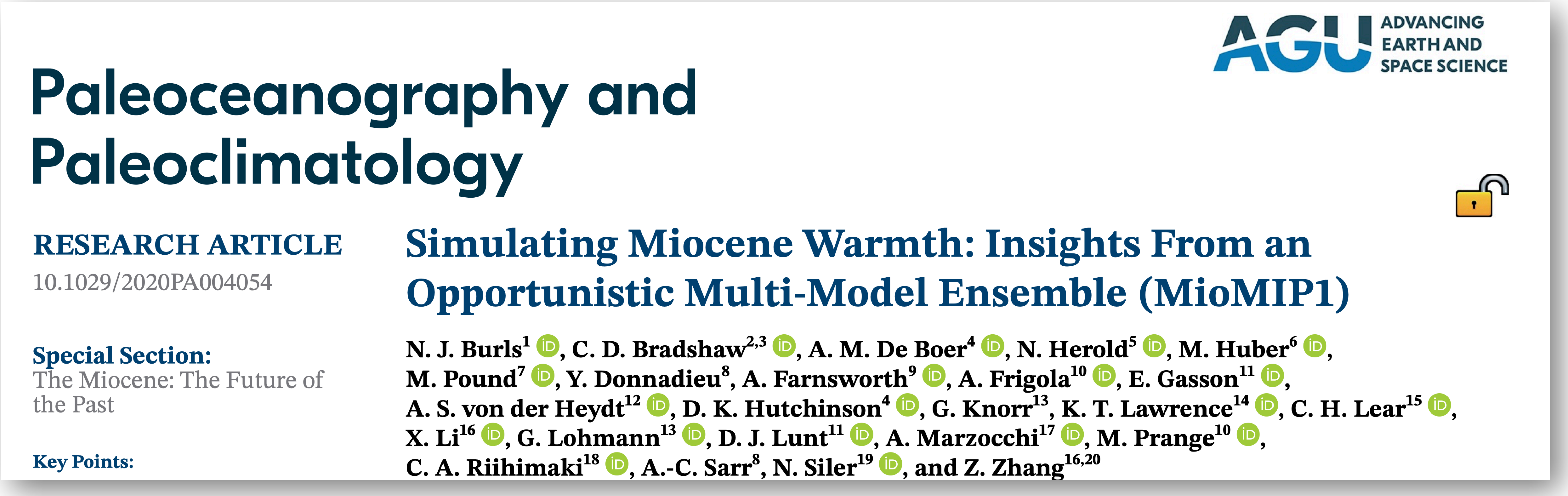
Middle Miocene Optimum (MCO, ~15 Ma) is of great scientific interests:

- ► Warm climate insights
- ► Global climate and carbon cycle
- ► Ocean circulation and ice sheets
- ► Climate models validation

How warm was MCO?

The MCO warmth conundrum in GMST




AGU ADVANCING EARTH AND SPACE SCIENCE

Paleoceanography and Paleoclimatology

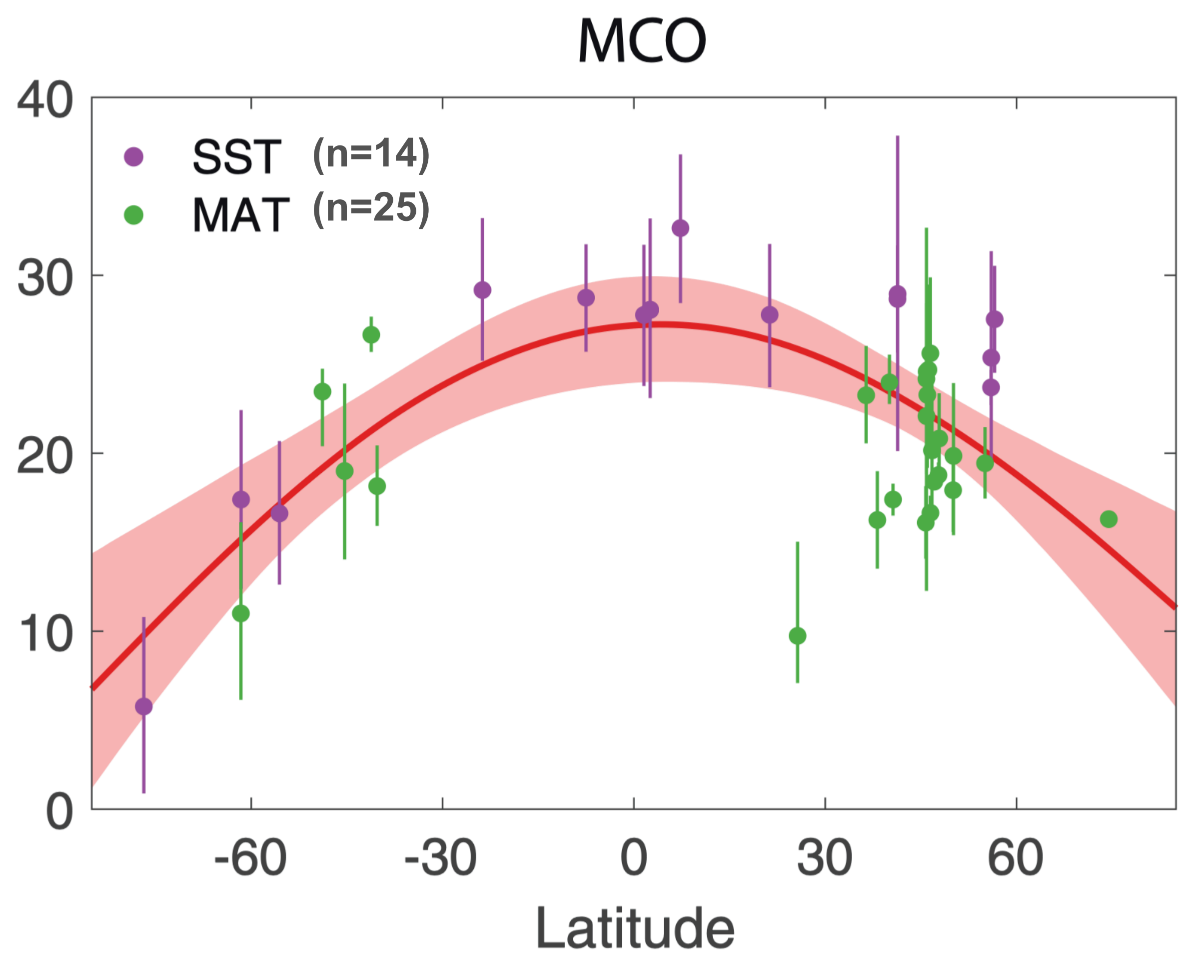
RESEARCH ARTICLE
10.1029/2020PA004054

Special Section:
The Miocene: The Future of the Past

Key Points:

Simulating Miocene Warmth: Insights From an Opportunistic Multi-Model Ensemble (MioMIP1)

N. J. Burls[1], C. D. Bradshaw[2,3], A. M. De Boer[4], N. Herold[5], M. Huber[6], M. Pound[7], Y. Donnadieu[8], A. Farnsworth[9], A. Frigola[10], E. Gasson[11], A. S. von der Heydt[12], D. K. Hutchinson[4], G. Knorr[13], K. T. Lawrence[14], C. H. Lear[15], X. Li[16], G. Lohmann[13], D. J. Lunt[11], A. Marzocchi[17], M. Prange[10], C. A. Riihimaki[18], A.-C. Sarr[8], N. Siler[19], and Z. Zhang[16,20]

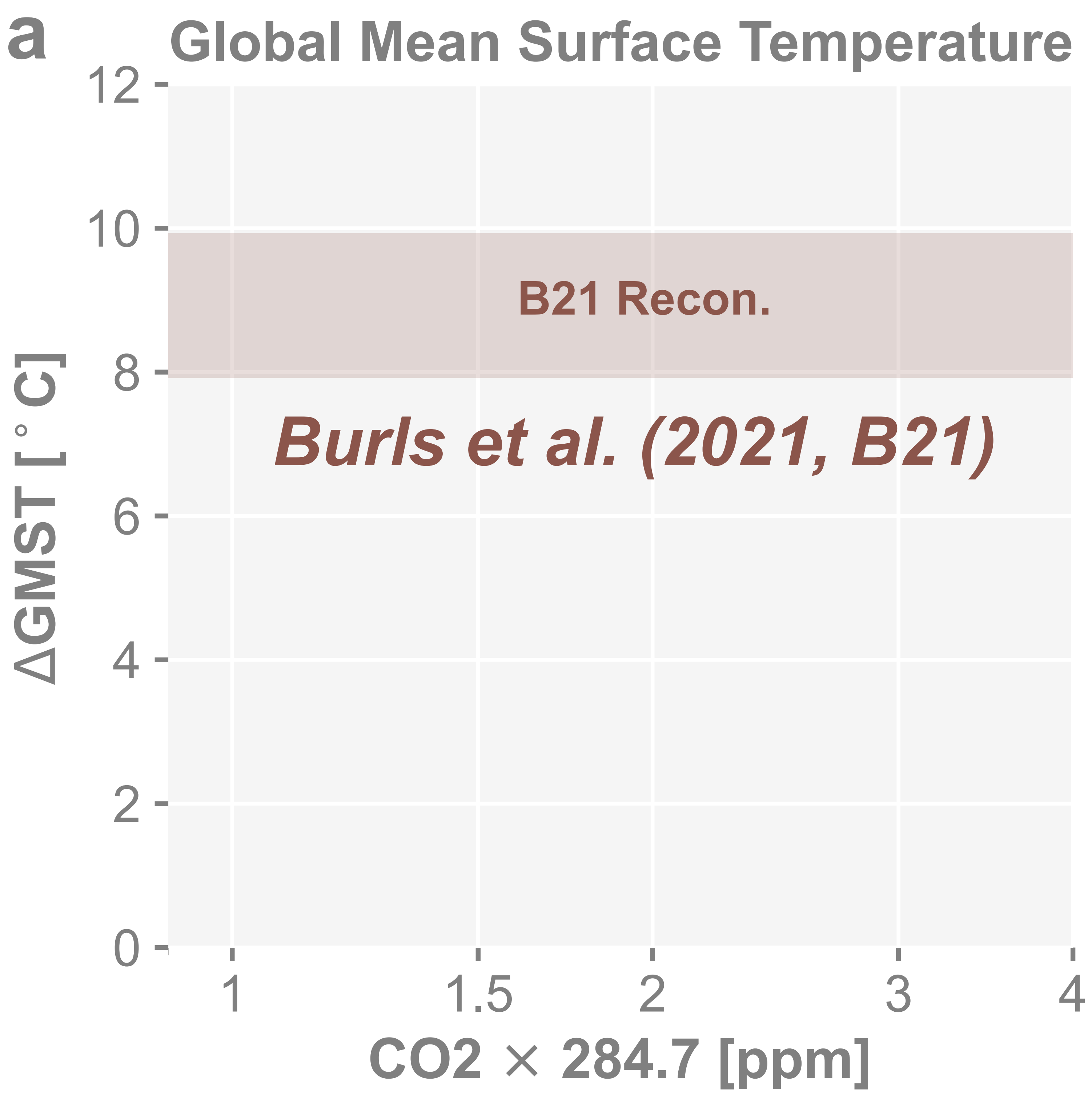


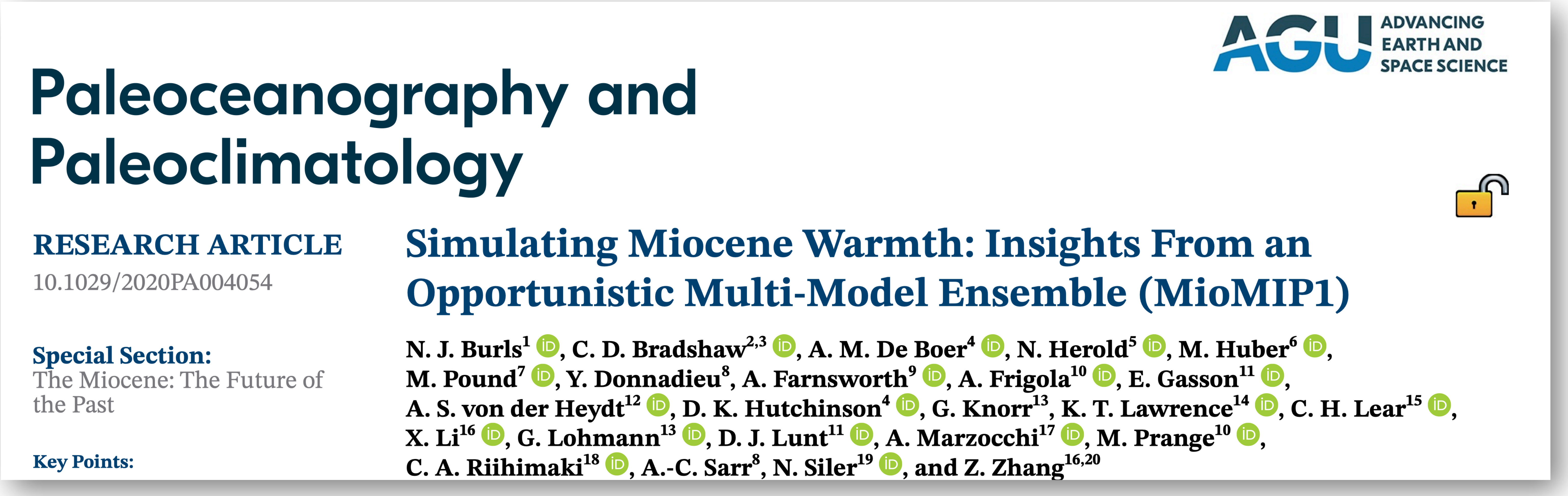
Fitting zonal mean temperature profile against surface temperature records:

$$T(\theta) \approx a + b\theta + c\cos\theta$$

Inglis et al. (2020)

The MCO warmth conundrum in GMST





AGU ADVANCING EARTH AND SPACE SCIENCE

Paleoceanography and Paleoclimatology

RESEARCH ARTICLE

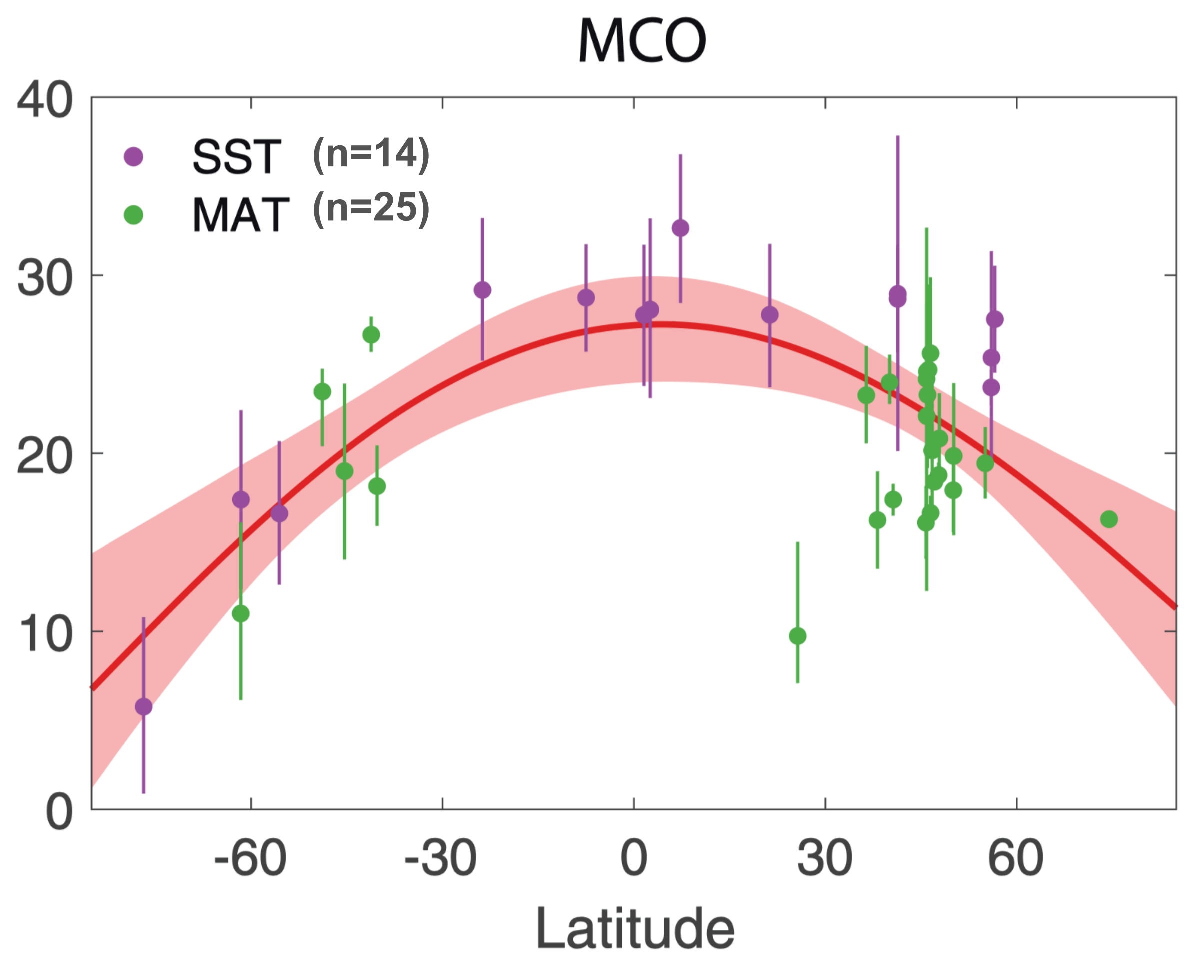
10.1029/2020PA004054

Special Section:
The Miocene: The Future of the Past

Key Points:

Simulating Miocene Warmth: Insights From an Opportunistic Multi-Model Ensemble (MioMIP1)

N. J. Burls[1], C. D. Bradshaw[2,3], A. M. De Boer[4], N. Herold[5], M. Huber[6], M. Pound[7], Y. Donnadieu[8], A. Farnsworth[9], A. Frigola[10], E. Gasson[11], A. S. von der Heydt[12], D. K. Hutchinson[4], G. Knorr[13], K. T. Lawrence[14], C. H. Lear[15], X. Li[16], G. Lohmann[13], D. J. Lunt[11], A. Marzocchi[17], M. Prange[10], C. A. Riihimaki[18], A.-C. Sarr[8], N. Siler[19], and Z. Zhang[16,20]



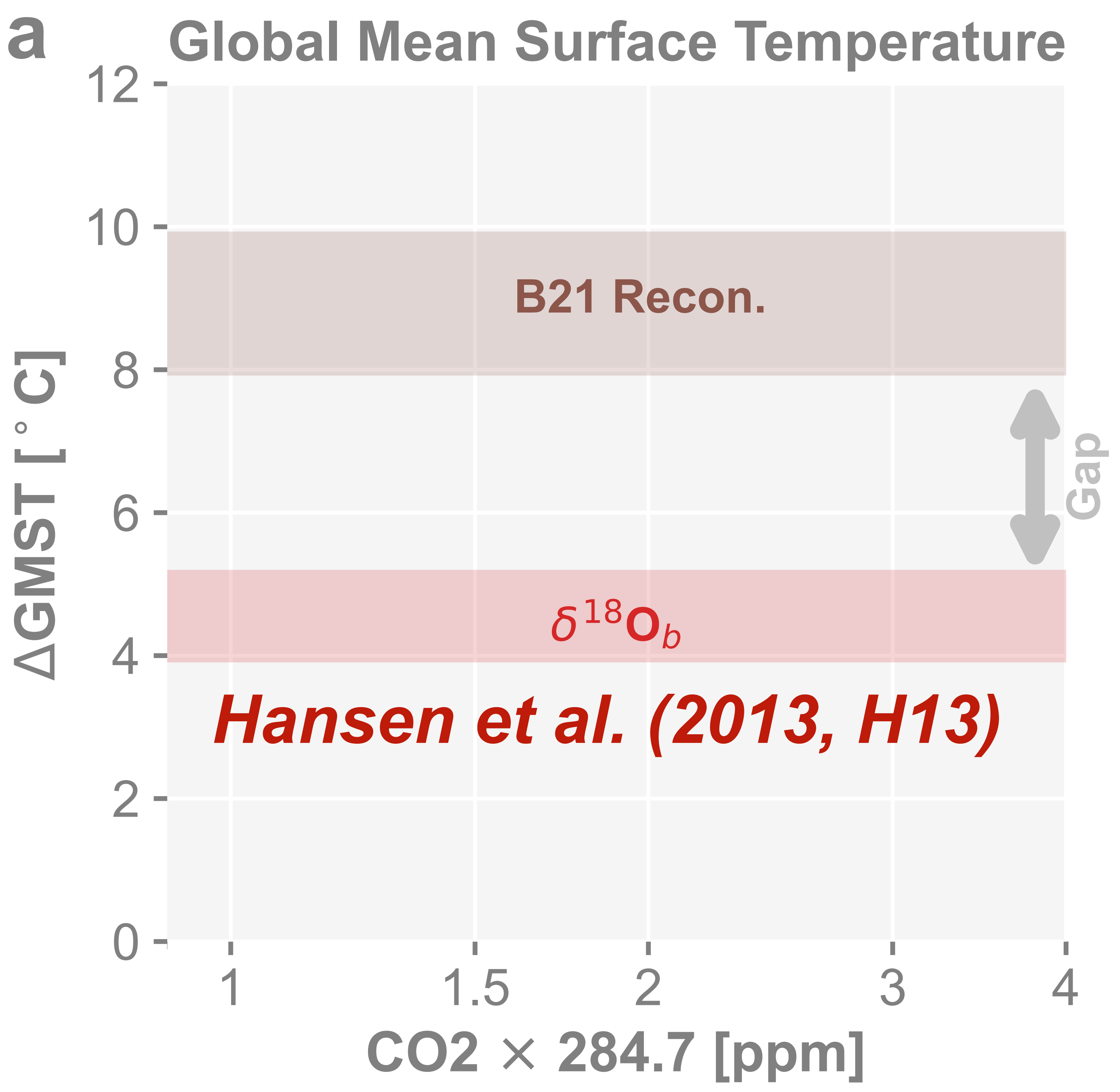
Fitting zonal mean temperature profile against surface temperature records:

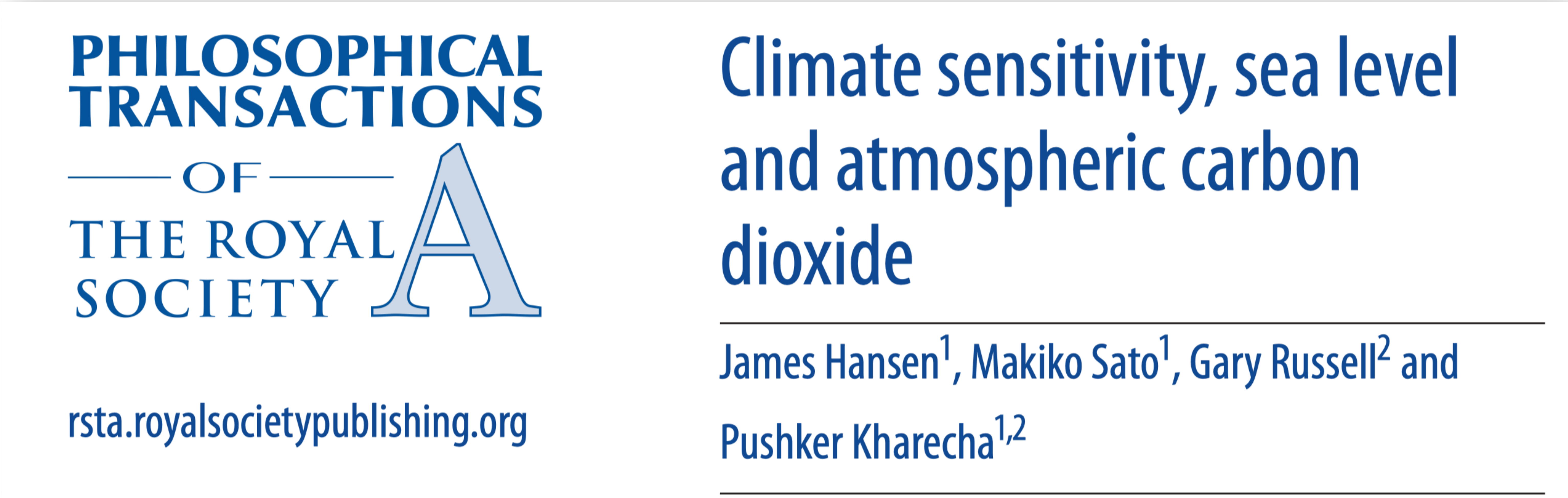
$$T(\theta) \approx a + b\theta + c\cos\theta$$

Inglis et al. (2020)

Spatial Heterogeneity

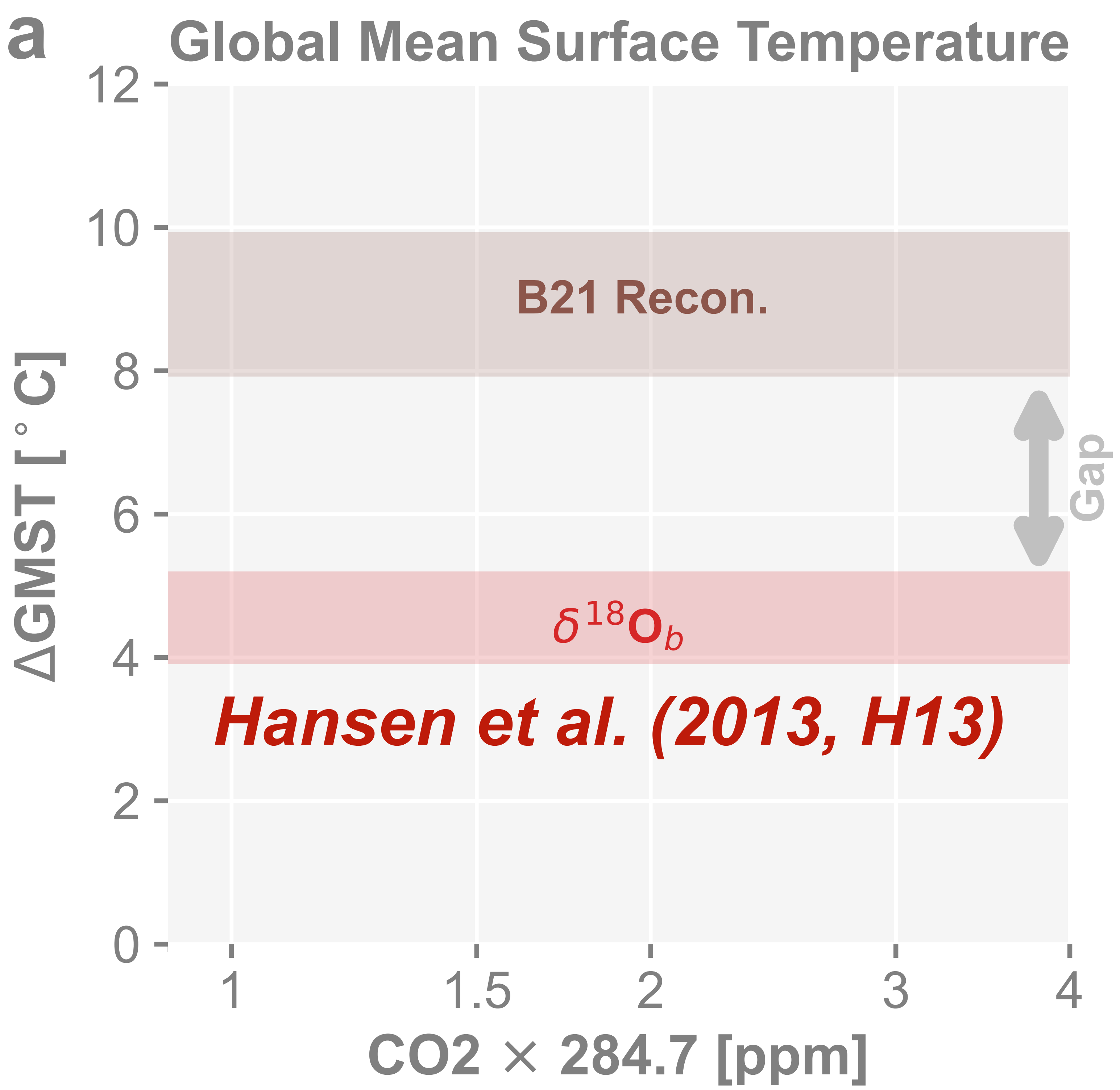
The MCO warmth conundrum in GMST

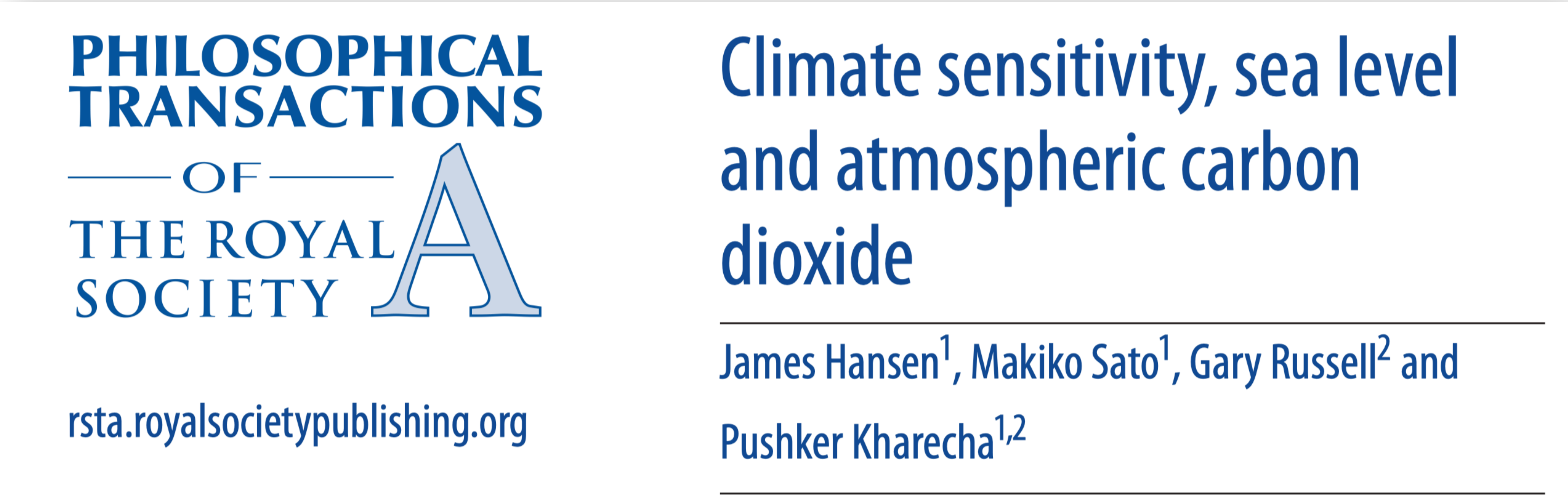




Benthic foram δ18O ⇨ **Bottom Water Temperature** ⇨ **GMST**

The MCO warmth conundrum in GMST





PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

rsta.royalsocietypublishing.org

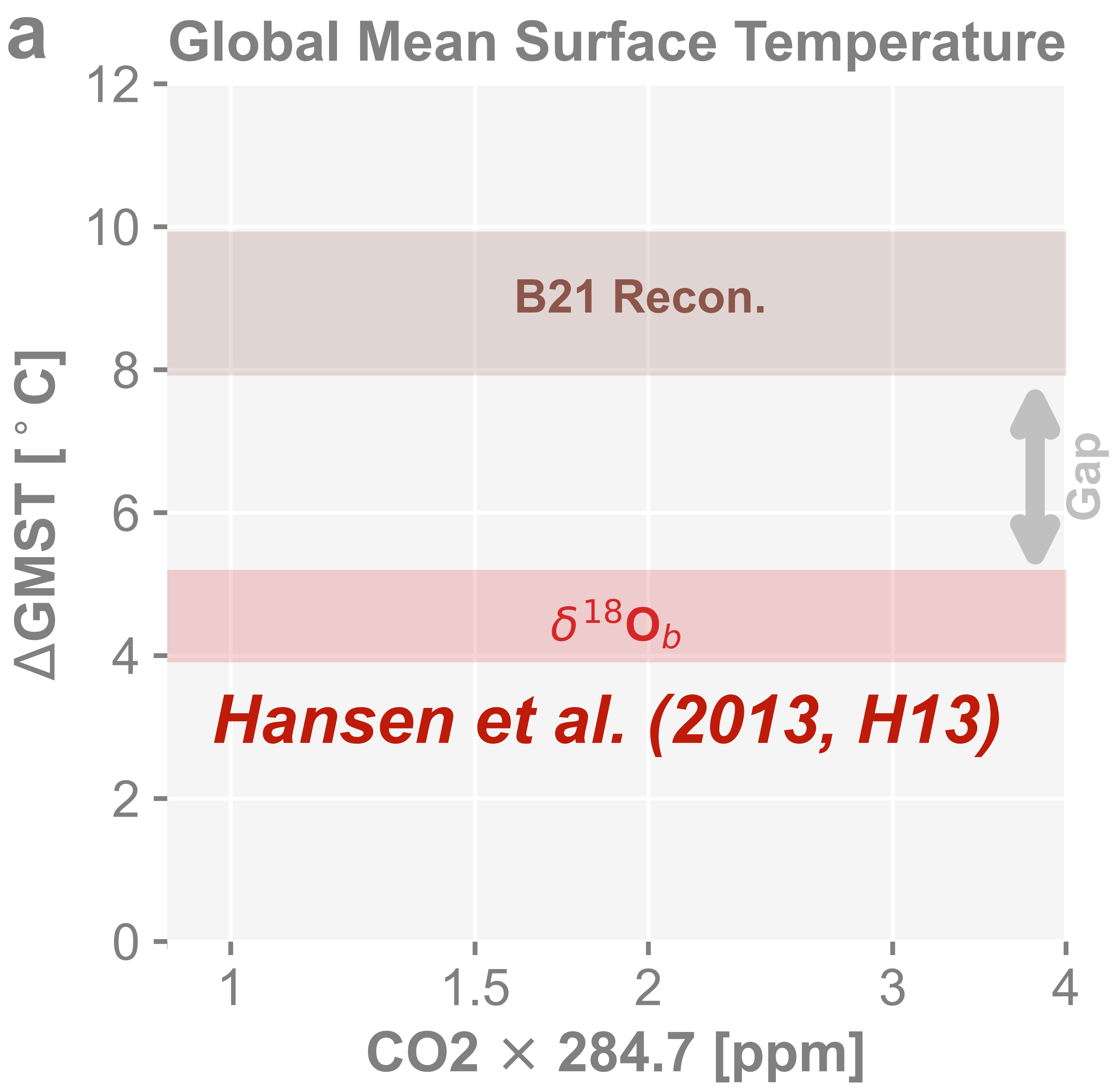
Climate sensitivity, sea level and atmospheric carbon dioxide

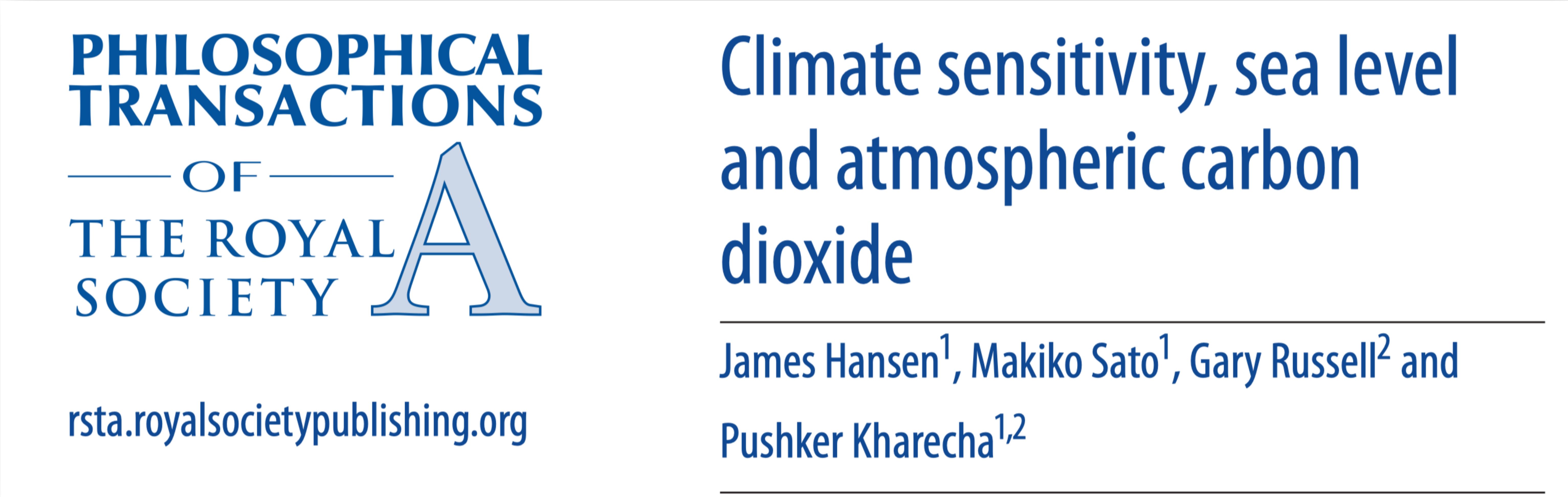
James Hansen[1], Makiko Sato[1], Gary Russell[2] and Pushker Kharecha[1,2]

Benthic foram $\delta^{18}O$ → Bottom Water Temperature → GMST

- Global Ice Volume
- Seawater Chemistry

The MCO warmth conundrum in GMST




PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

rsta.royalsocietypublishing.org

Climate sensitivity, sea level and atmospheric carbon dioxide

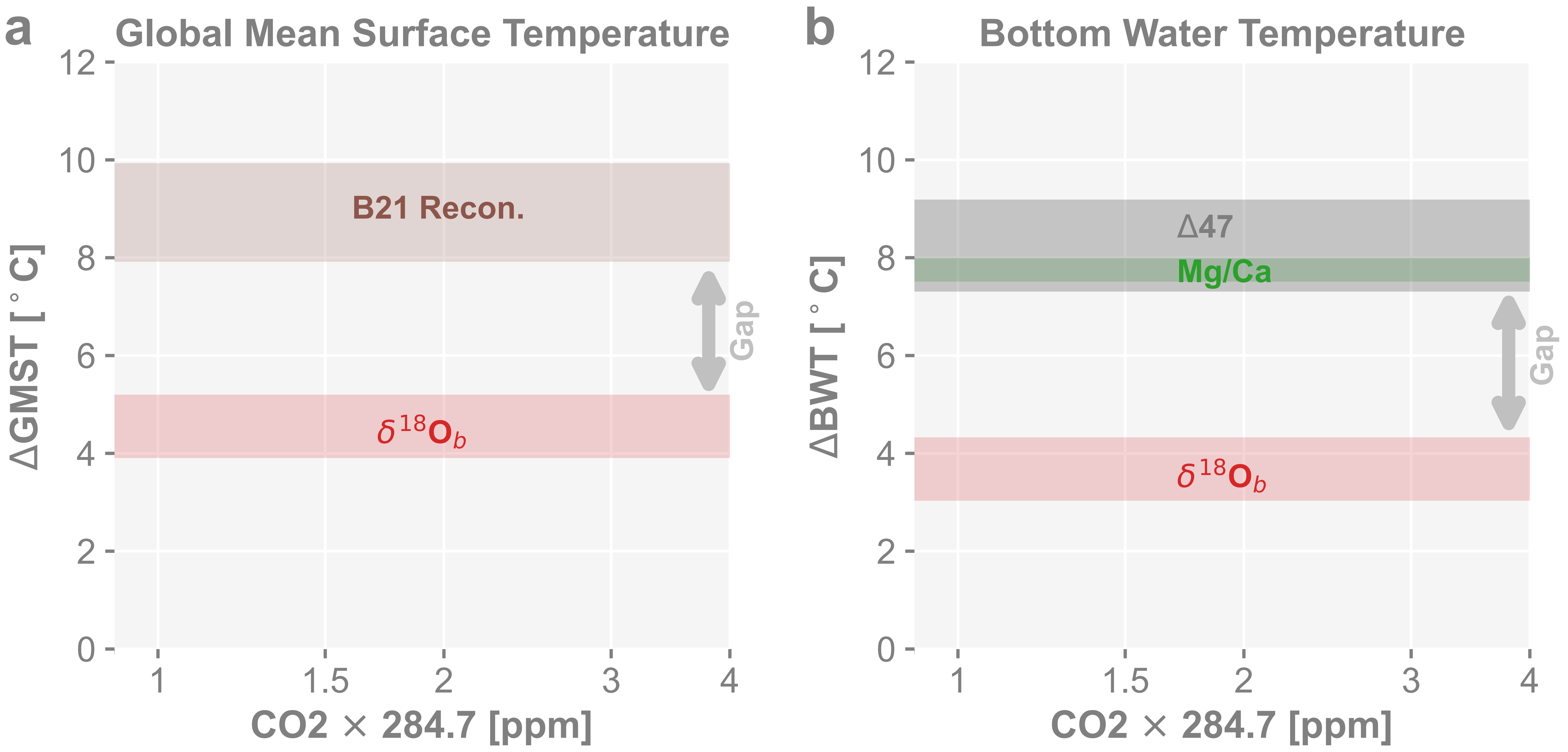
James Hansen[1], Makiko Sato[1], Gary Russell[2] and Pushker Kharecha[1,2]

Benthic foram $\delta^{18}O$ ⇨ **Bottom Water Temperature** ⇨ **GMST**

- Global Ice Volume
- Seawater Chemistry

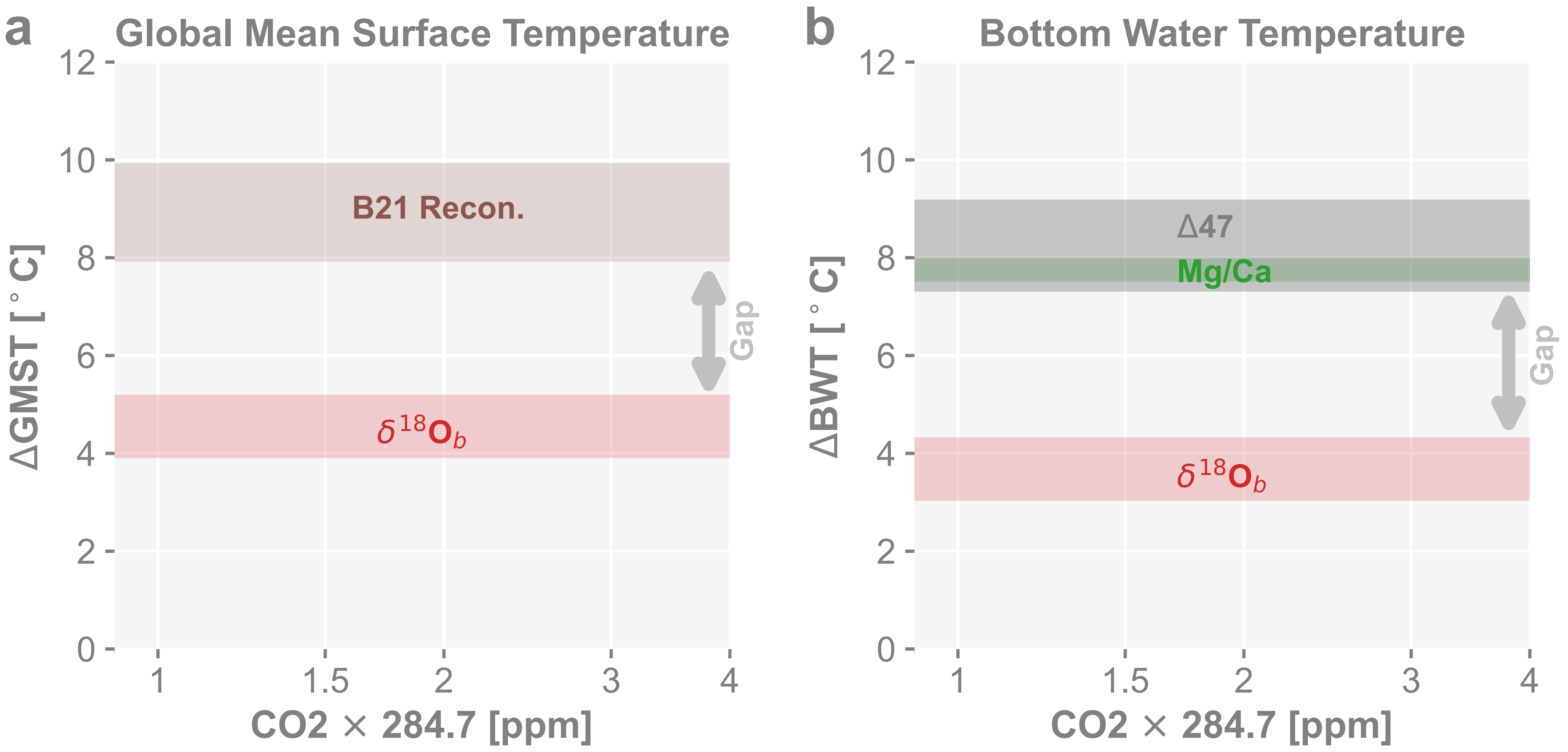
- Surface-deep Ocean Relationship

The MCO warmth conundrum in BWT



- **Global Ice Volume**
- **Seawater Chemistry**

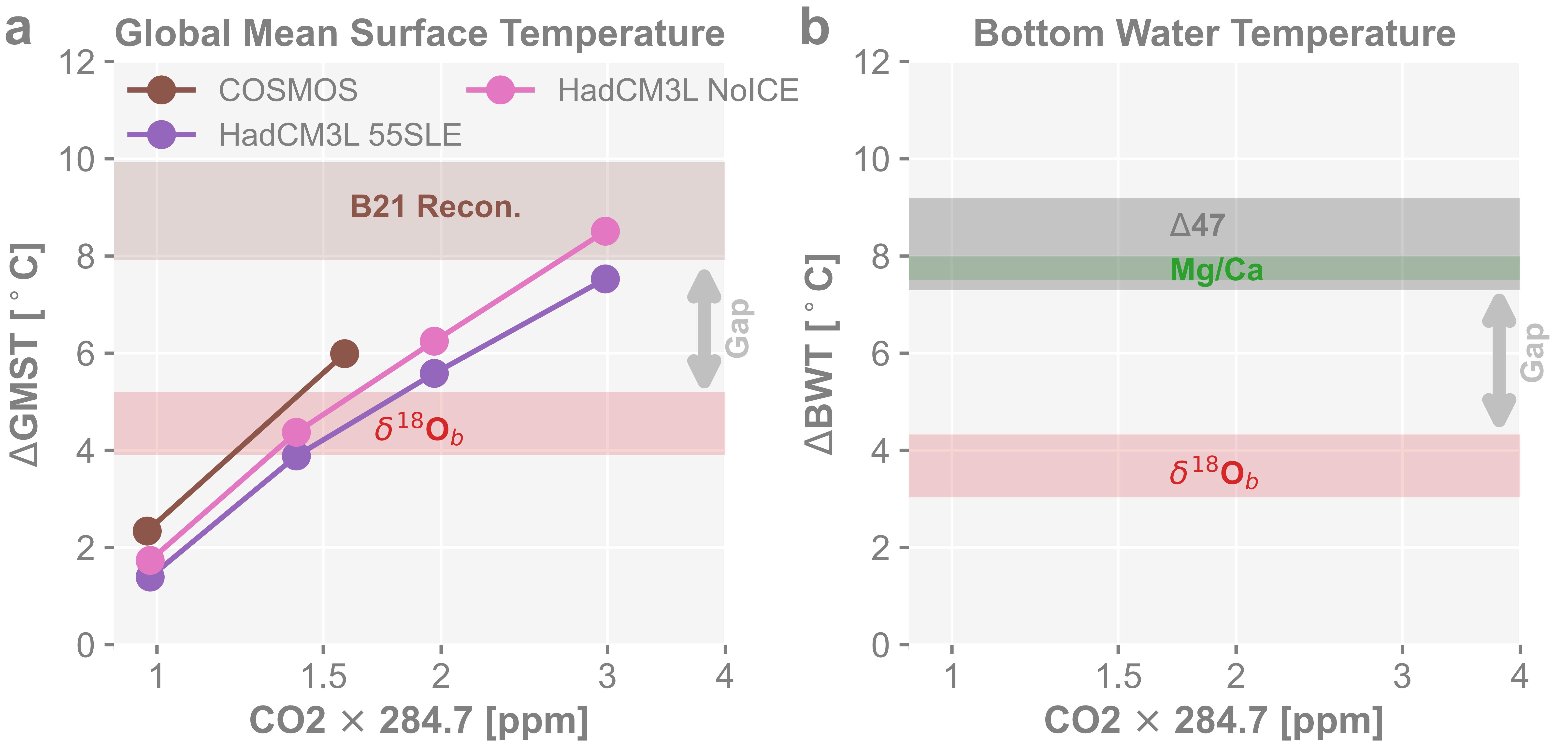
The MCO warmth conundrum in BWT



- Global Ice Volume
- Seawater Chemistry

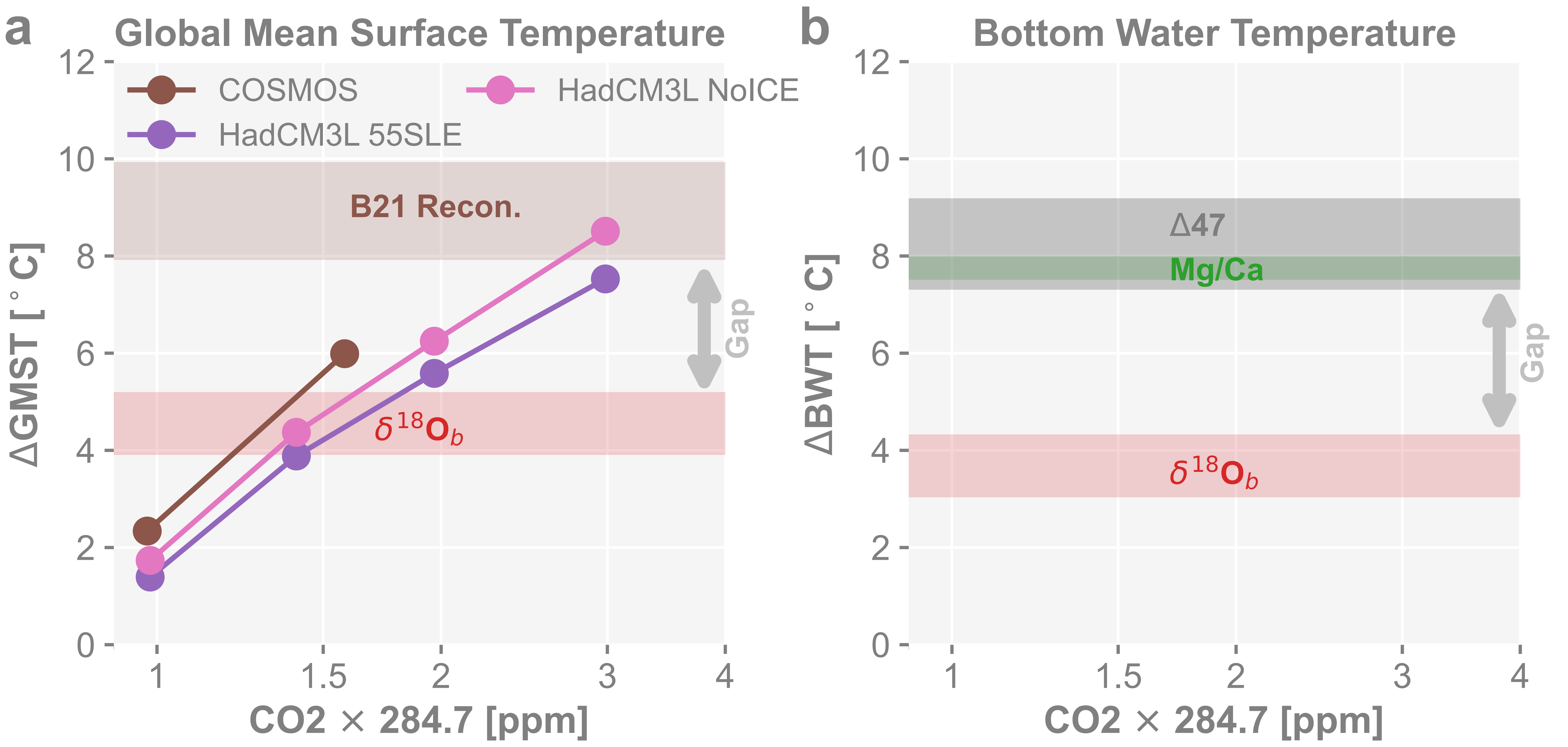
Proxies show a significant MCO warmth gap.
Can model-data comparison be helpful?

Model-data comparison is inconclusive in the *GMST* space



- **Global Ice Volume**
- **Seawater Chemistry**

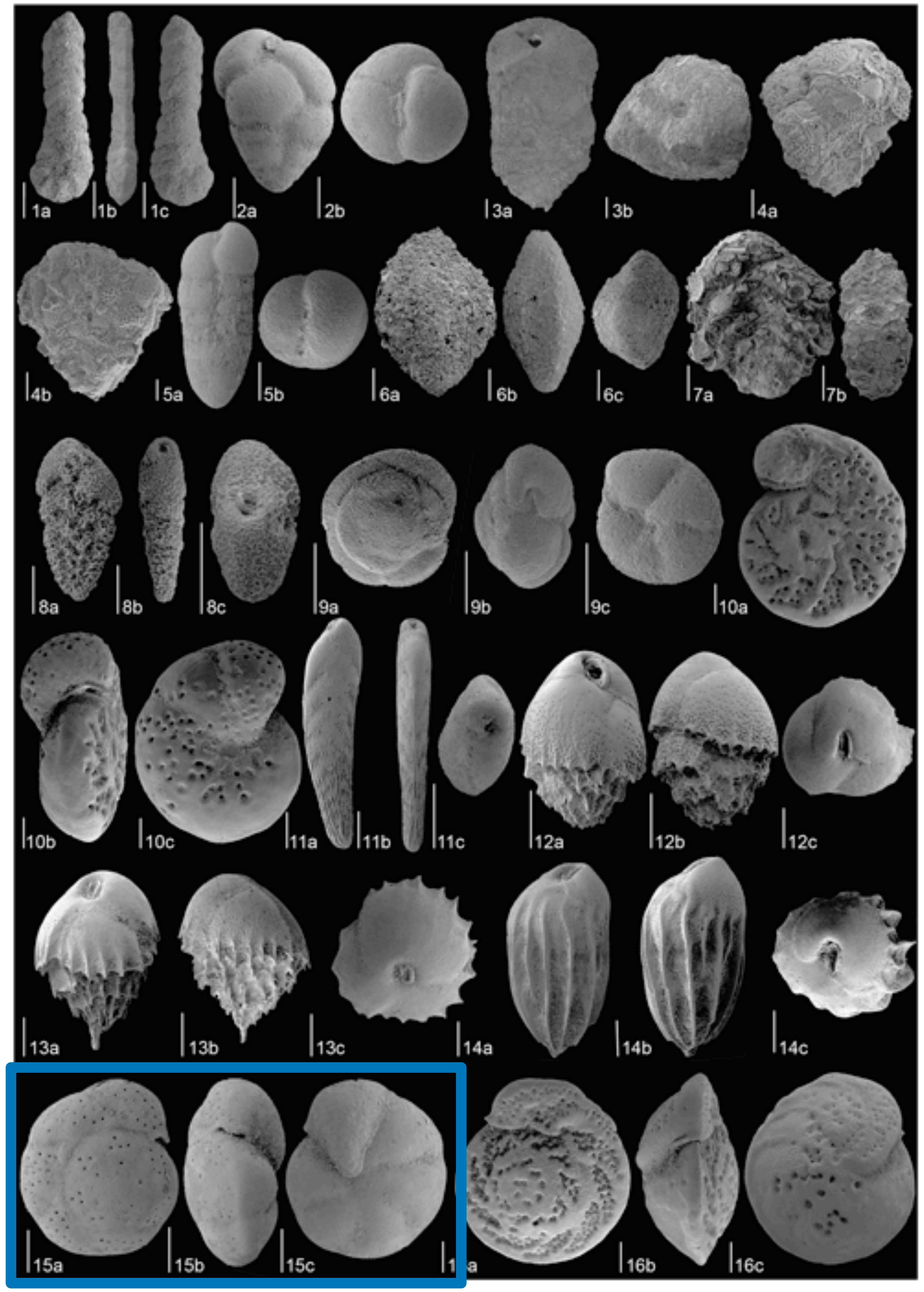
Model-data comparison is inconclusive in the *GMST* space



- **Global Ice Volume**
- **Seawater Chemistry**

Our strategy: model-data comparison in the *benthic foram δ¹⁸O* space

A direct comparison with benthic foram $\delta^{18}O$



Gastaldello, M. E., Agnini, C., and Alegret, L.: Late Miocene to Early Pliocene benthic foraminifera from the Tasman Sea (International Ocean Discovery Program Site U1506), J. Micropalaeontol., 43, 1–35, https://doi.org/10.5194/jm-43-1-2024, 2024.

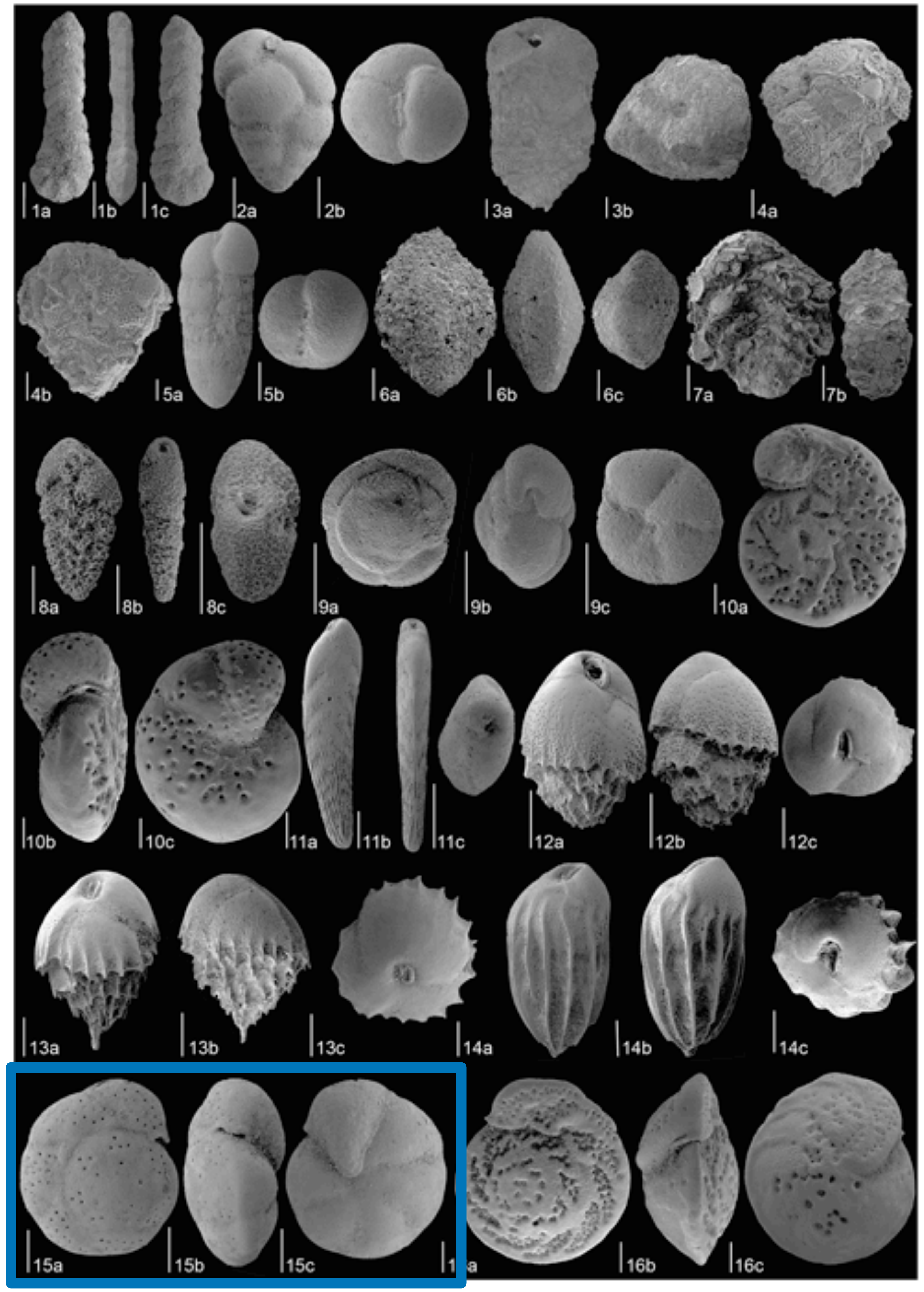
Benthic foraminifera $\delta^{18}O$:

- **well-preserved in a stable environment**
- **representative of the global mean**

Comparison in the proxy space: more reliable than the comparison in the temperature space when nonlinearity and/or multiple environmental variables are involved

- **Inverse modeling:** temperature $= f(\delta^{18}O_b, \cdots)$
- **Forward modeling:** $\delta^{18}O_b = f(\text{temperature}, \cdots)$

A direct comparison with benthic foram $\delta^{18}O$



Gastaldello, M. E., Agnini, C., and Alegret, L.: Late Miocene to Early Pliocene benthic foraminifera from the Tasman Sea (International Ocean Discovery Program Site U1506), J. Micropalaeontol., 43, 1–35, https://doi.org/10.5194/jm-43-1-2024, 2024.

Benthic foraminifera $\delta^{18}O$:

- **well-preserved in a stable environment**
- **representative of the global mean**

Comparison in the proxy space: more reliable than the comparison in the temperature space when nonlinearity and/or multiple environmental variables are involved

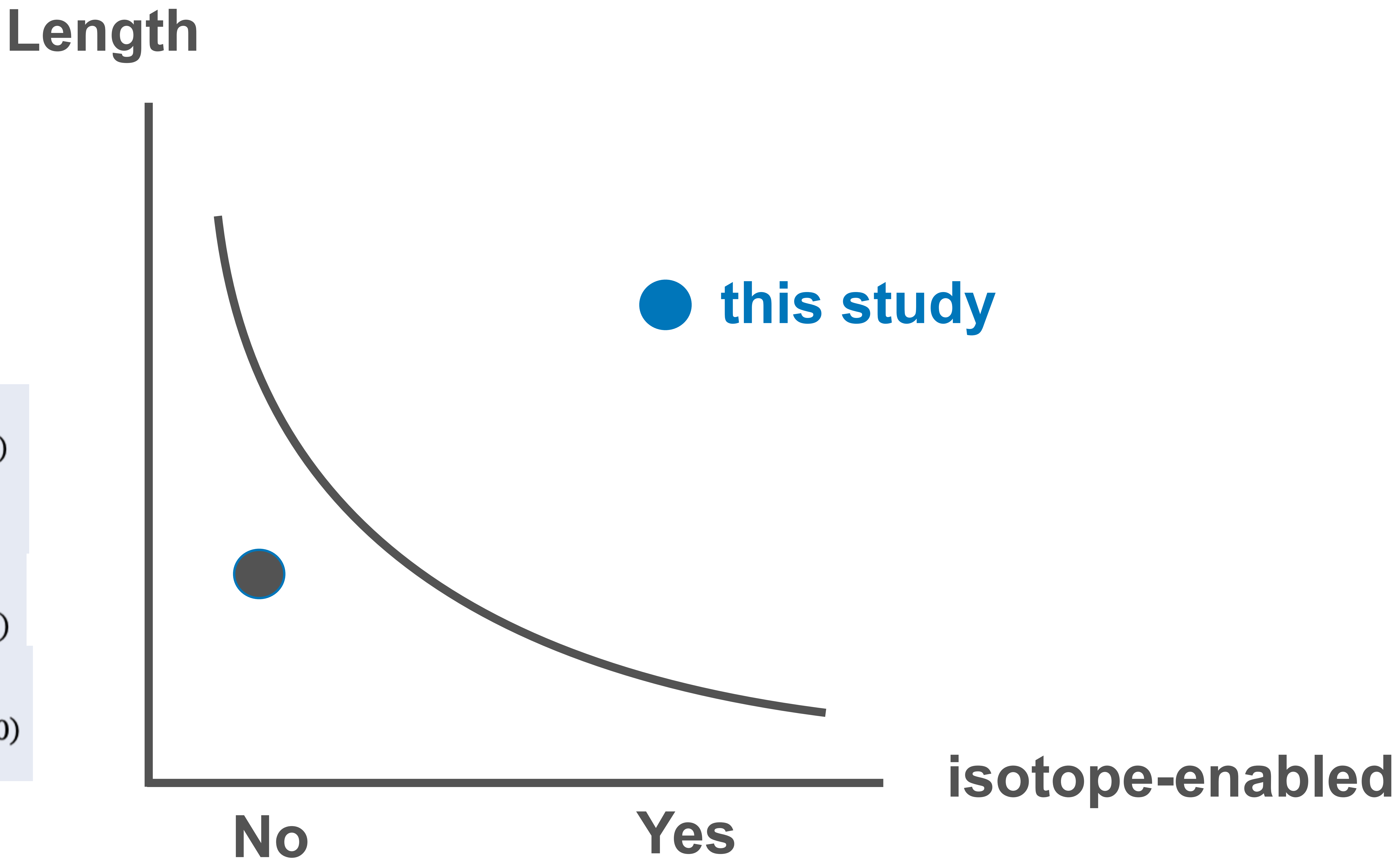
- **Inverse modeling:** temperature $= f(\delta^{18}O_b, \cdots)$
- **Forward modeling:** $\delta^{18}O_b = f(\text{temperature}, \cdots)$

1. equilibrated deep ocean
2. isotope-enabled simulations

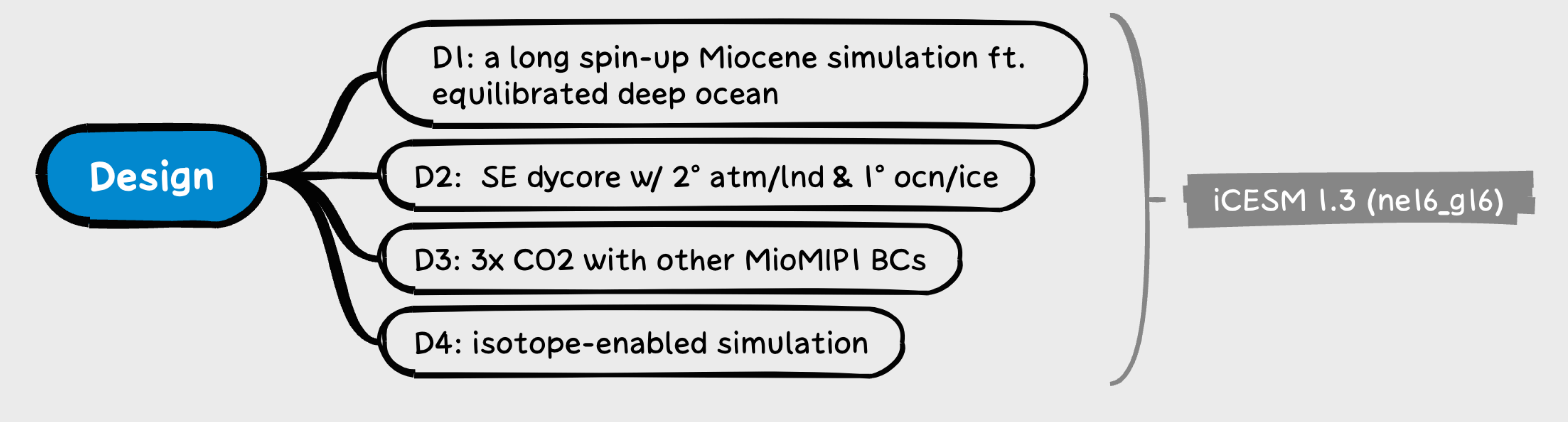
Isotope-enabled simulations ft. equilibrated deep ocean are *RARE*

MioMIP1 MCO Simulations
(Burls et al., 2021)

COSMOS T31	Middle Miocene (Herold ~20–14)	3.75° × 3.75° /~3°	2,000 (last 100)
HadCM3L - Bradshaw	Mid Miocene	3.75° × 2.5° /3.75° × 2.5°	2,000 (last 50)
CCSM3 T42 (MARUM)	MMCO	T42–2.8°/1°	1,500 (last 100)



iCESM1.3 MCO configuration



Model

isotope-enabled CESM (iCESM) 1.3_hires

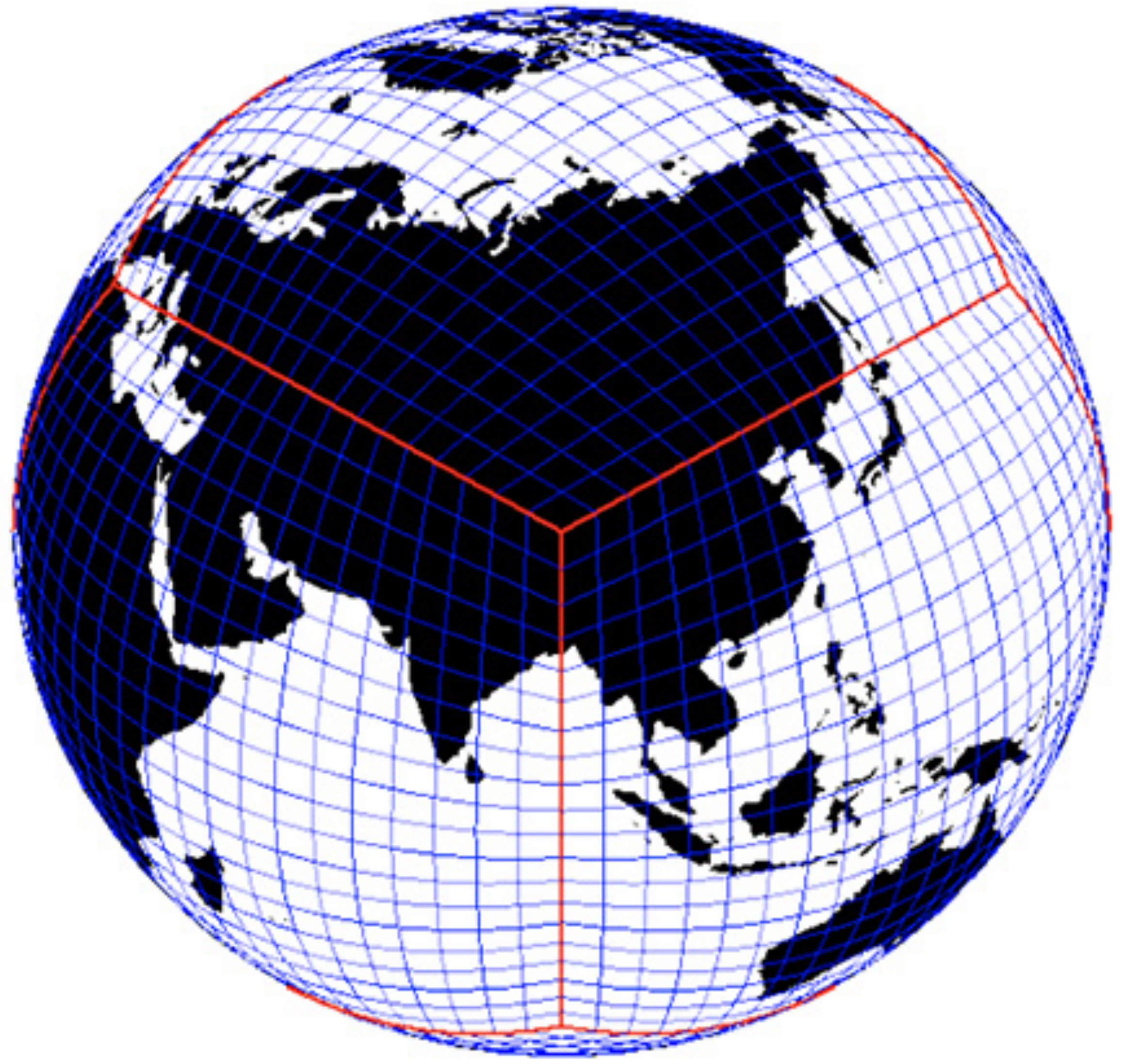
Brady et al. (2019)
Otto-Bliesner et al. (in prep)

One of the best models simulating the preset-day observations and the past extreme cold and warm conditions

Zhu et al. (2019)
Chang et al. (2020)
Kageyama et al. (2020)
Lunt et al. (2021)

Dynamical Core

Spectral Element (ne16)



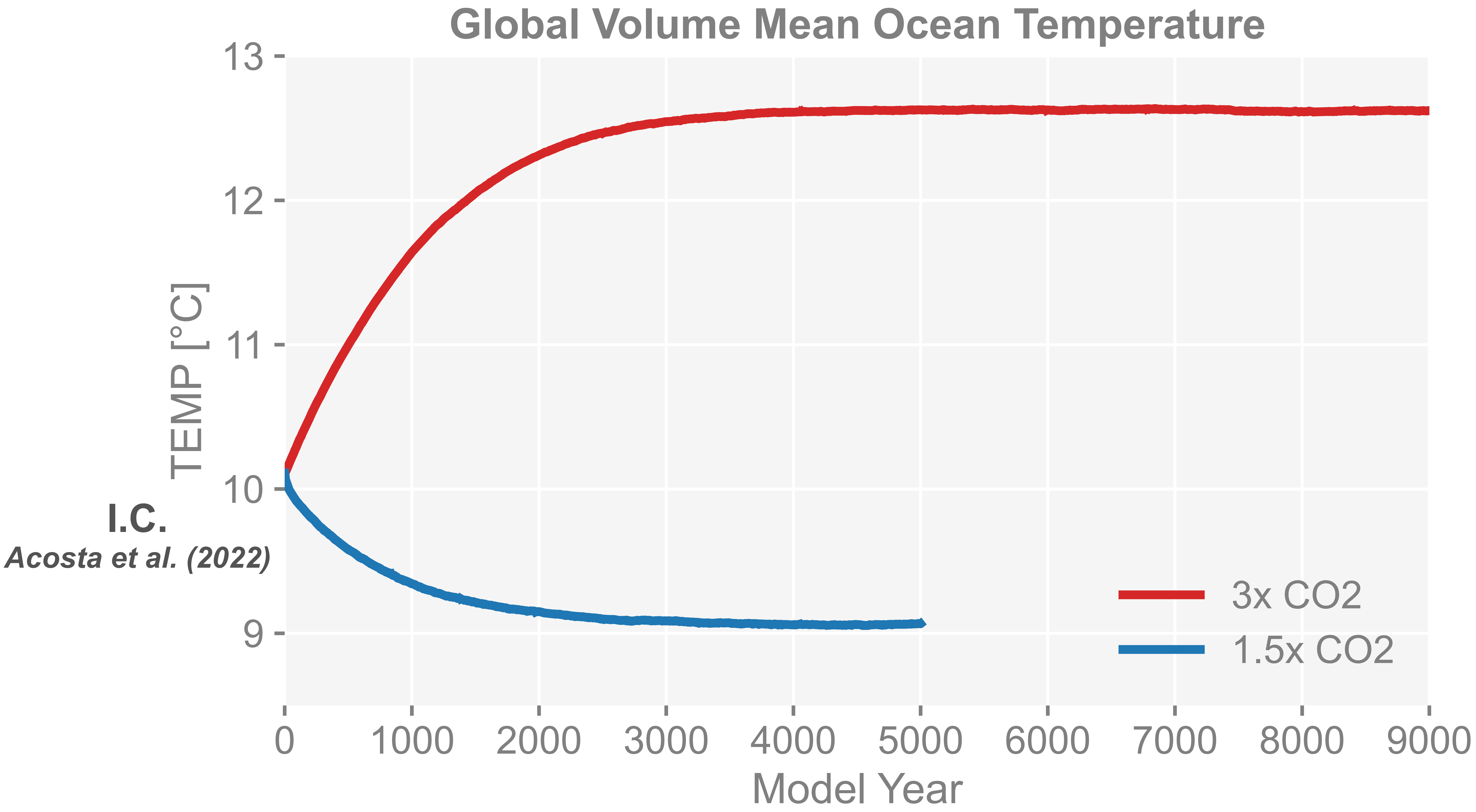
Initial Conditions

Acosta et al. (2022)

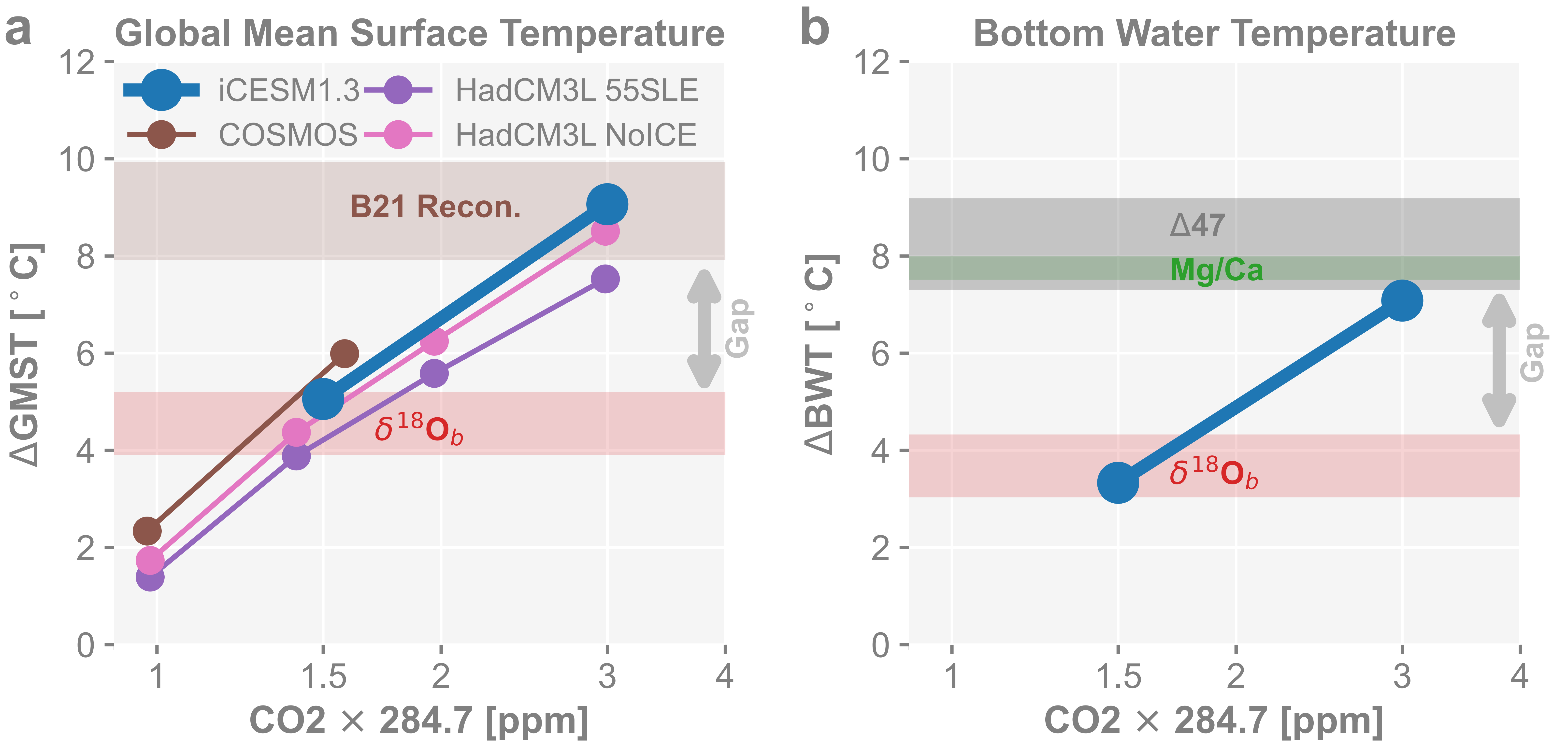
Boundary Conditions

- **The MioMIP1 setup**
- **3xCO2, 1.5xCO2**

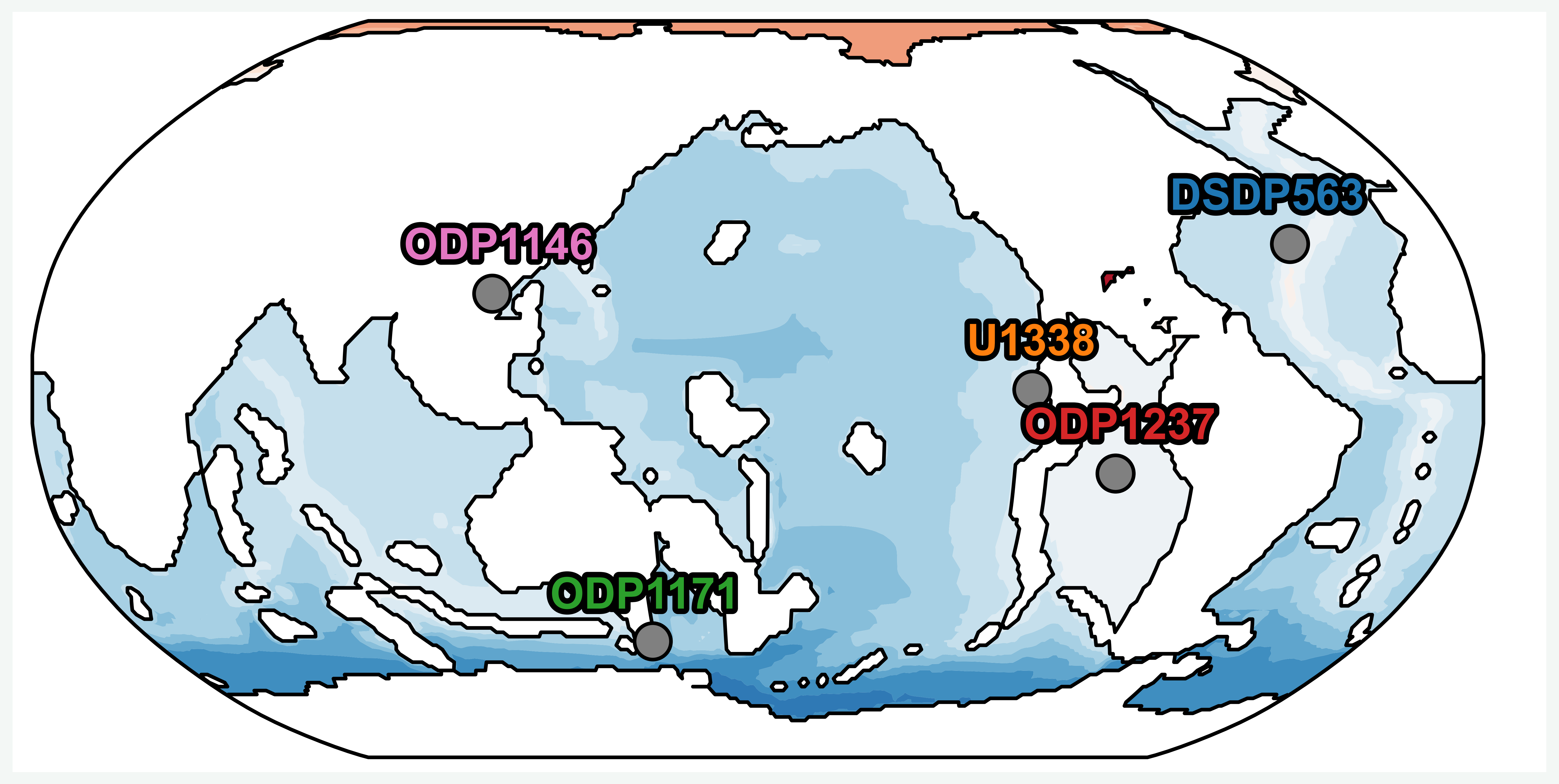
Deep ocean equilibrium achieved after 5 kyrs

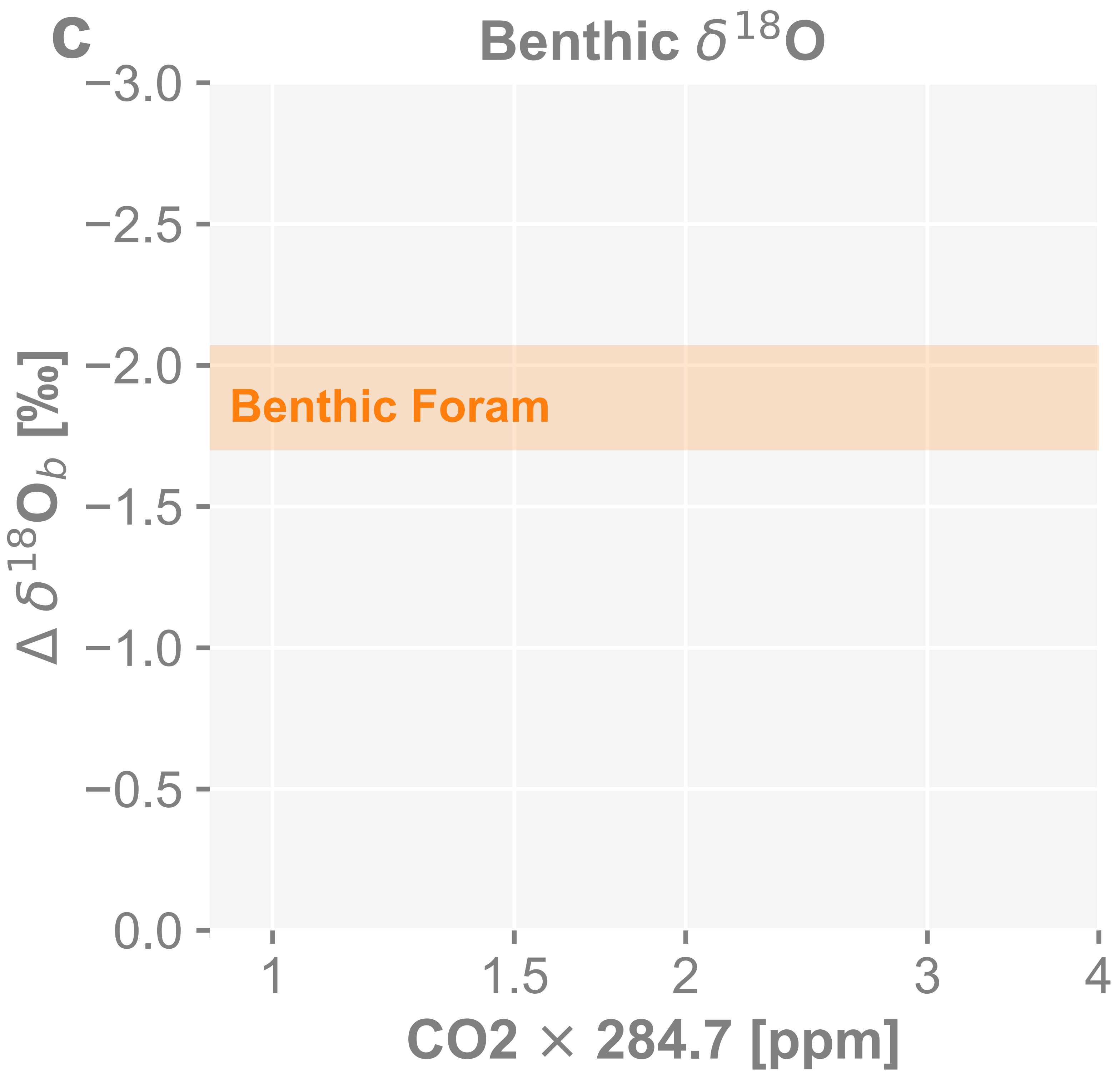


Addressing the MCO warmth conundrum

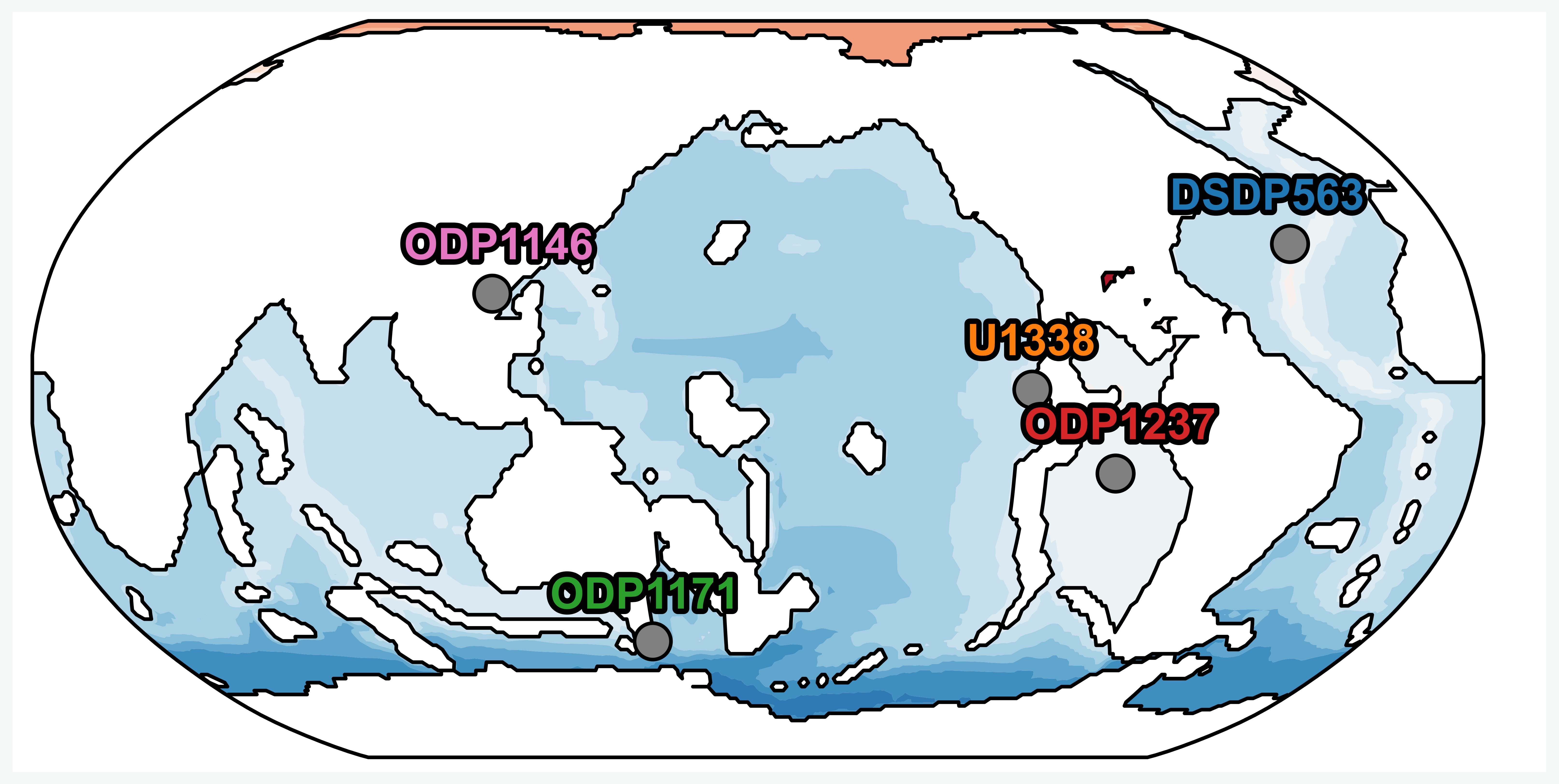


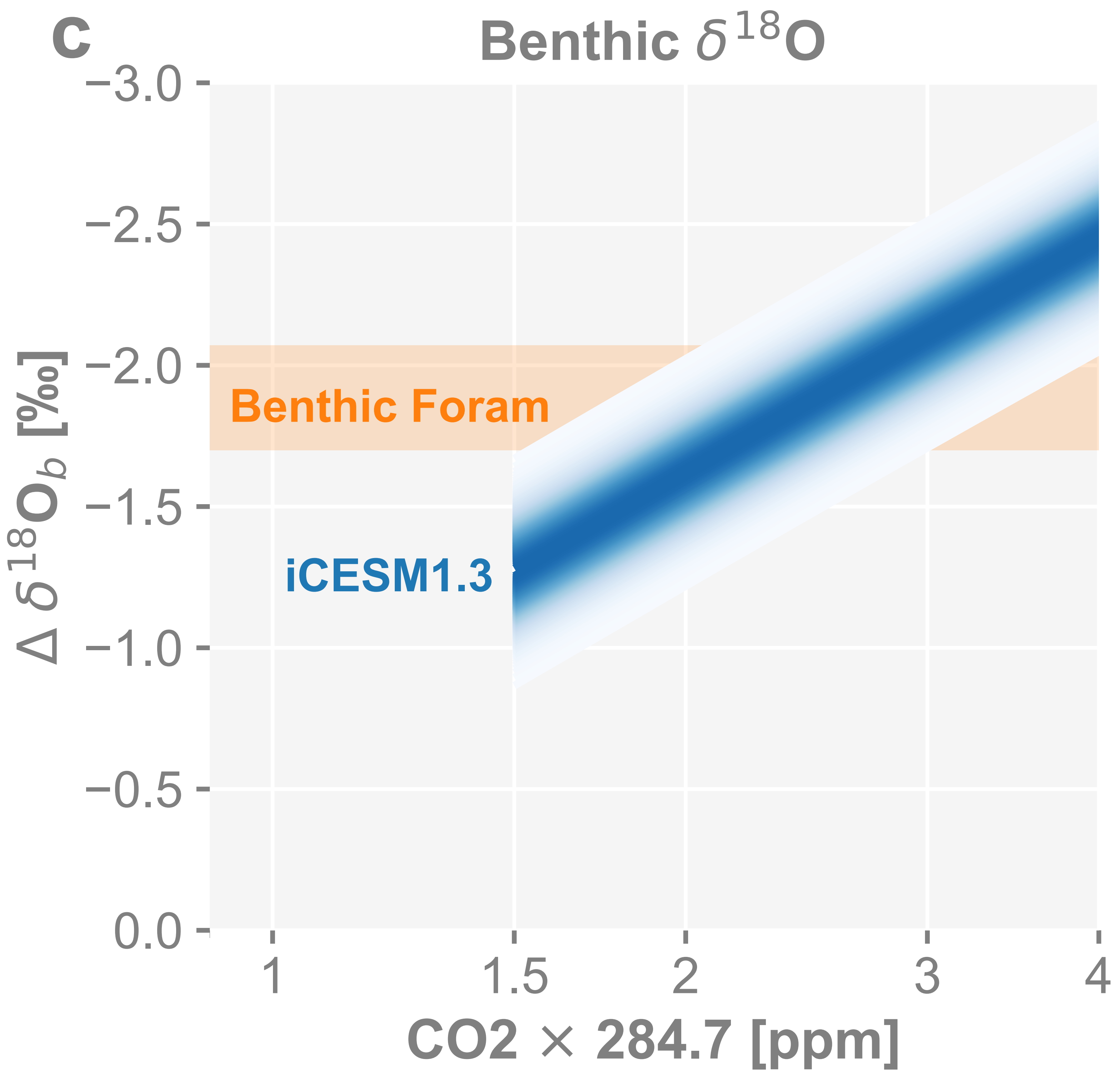
Addressing the MCO warmth conundrum





Addressing the MCO warmth conundrum





$$\delta^{18}O_b = \delta^{18}O_{mdl} + (-0.245T_{mdl} + 0.0011T_{mdl}^2 + 3.58) + \delta^{18}O_{ice\text{-}vol} + 1.5435(7.8 - pH)$$

Marchitto et al. (2014)

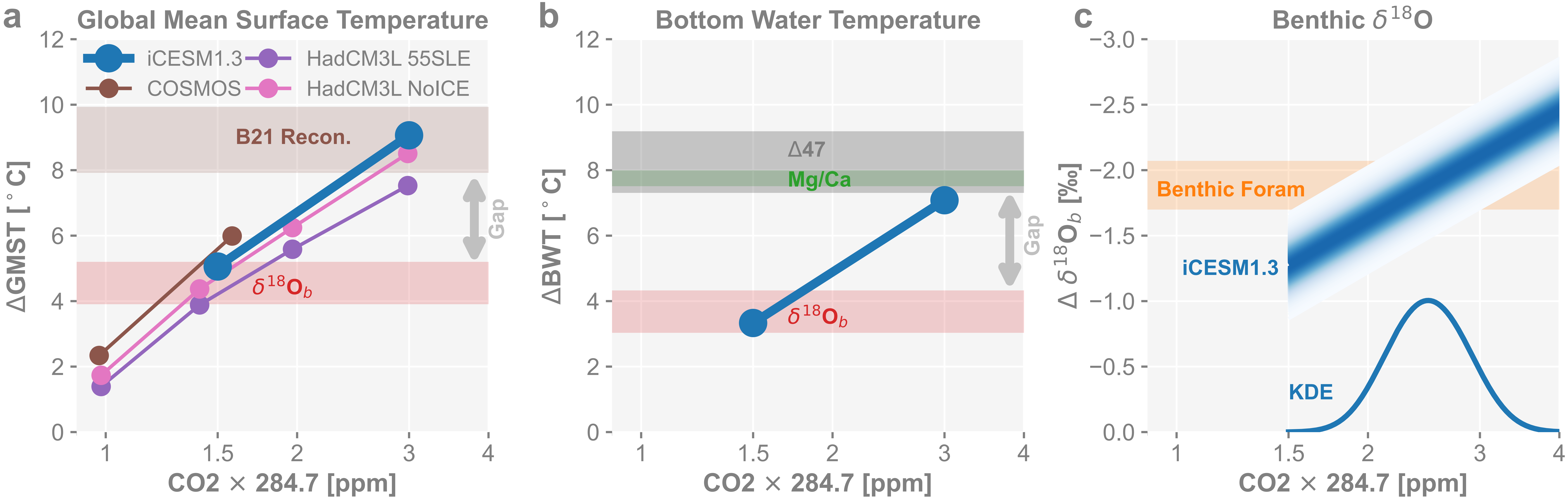
$\delta^{18}O_{ice\text{-}vol} \sim \mathcal{N}(-0.4,\ 0.1^2)$

Cramer et al. (2011)
Lear et al. (2015)

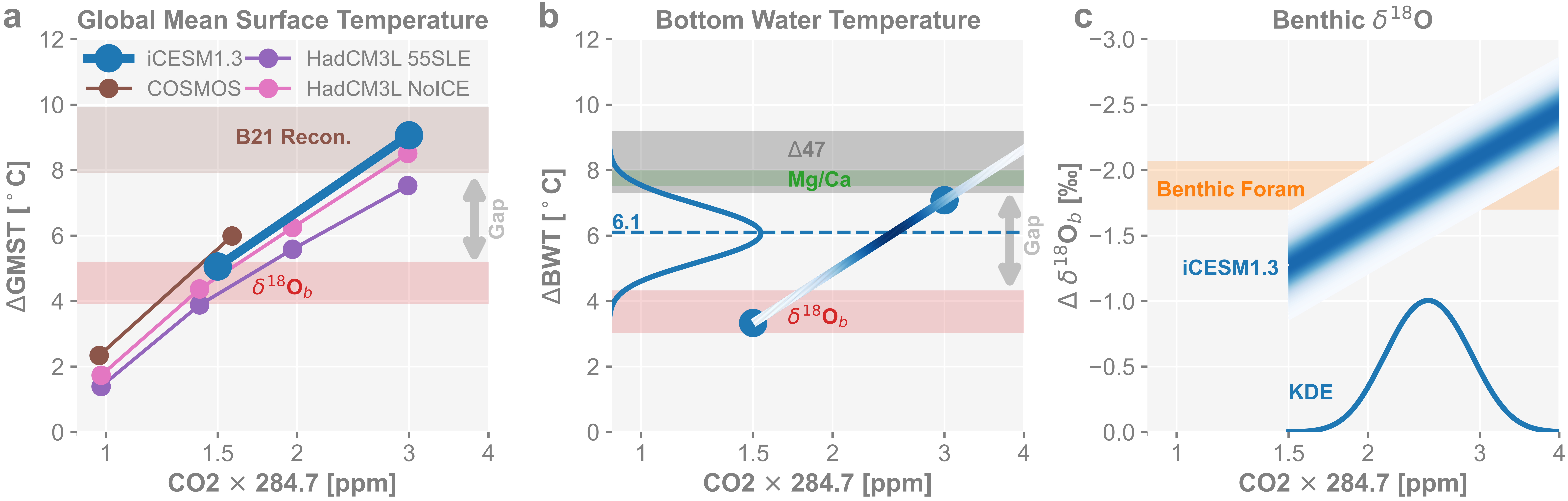
$pH \sim \mathcal{N}(7.7,\ 0.05^2)$

Zeebe et al. (2007)
Tierney et al. (2020)

Addressing the MCO warmth conundrum

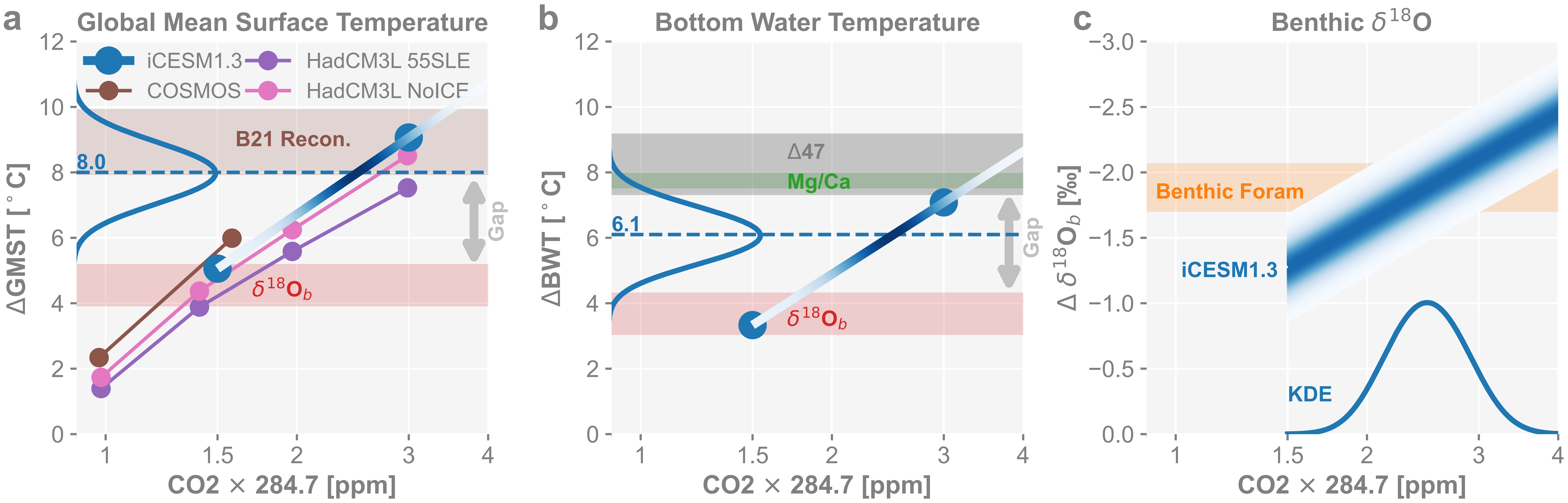


Bri Addressing the MCO warmth conundrum



► **MCO ΔBWT:** 6.1 ± 0.8°C

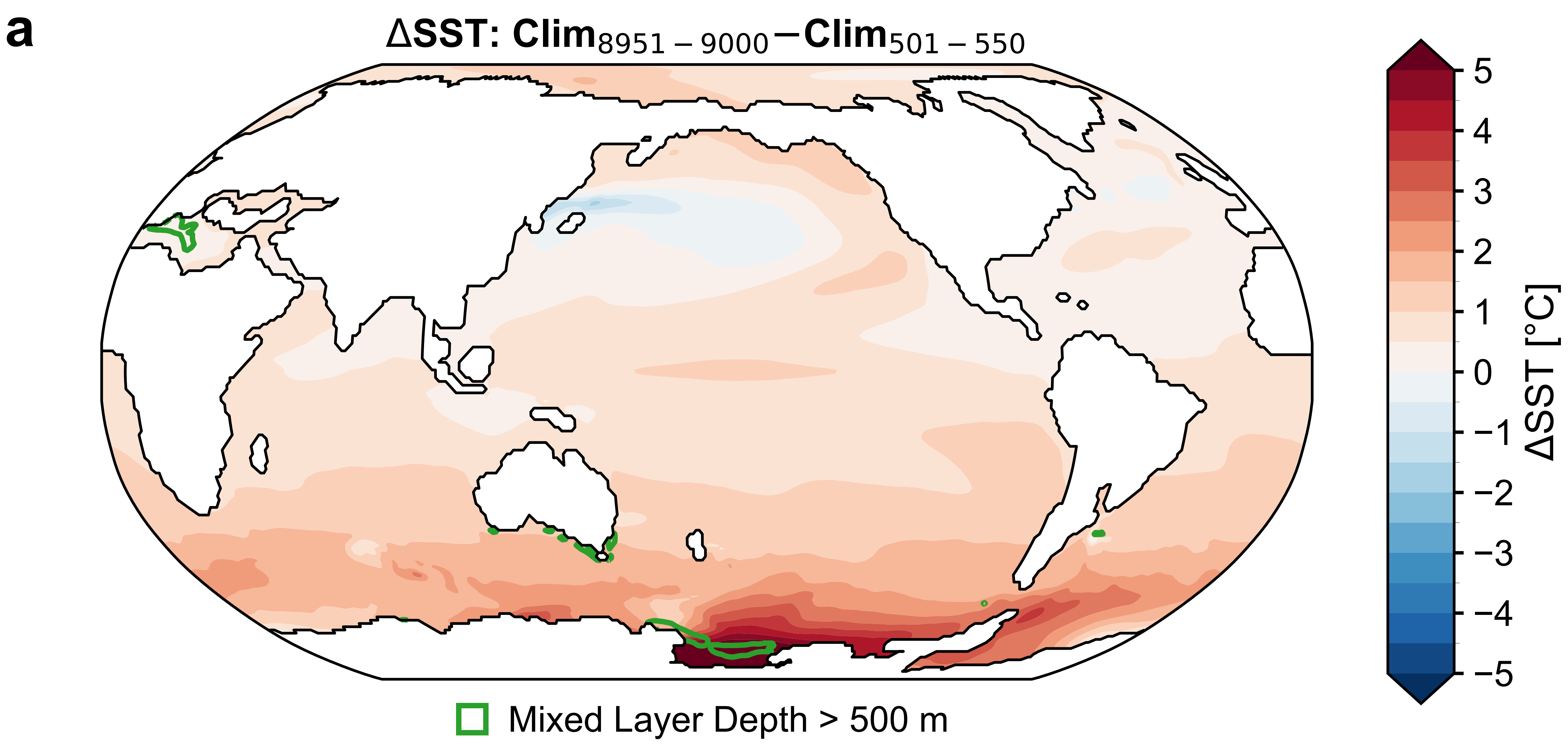
Addressing the MCO warmth conundrum

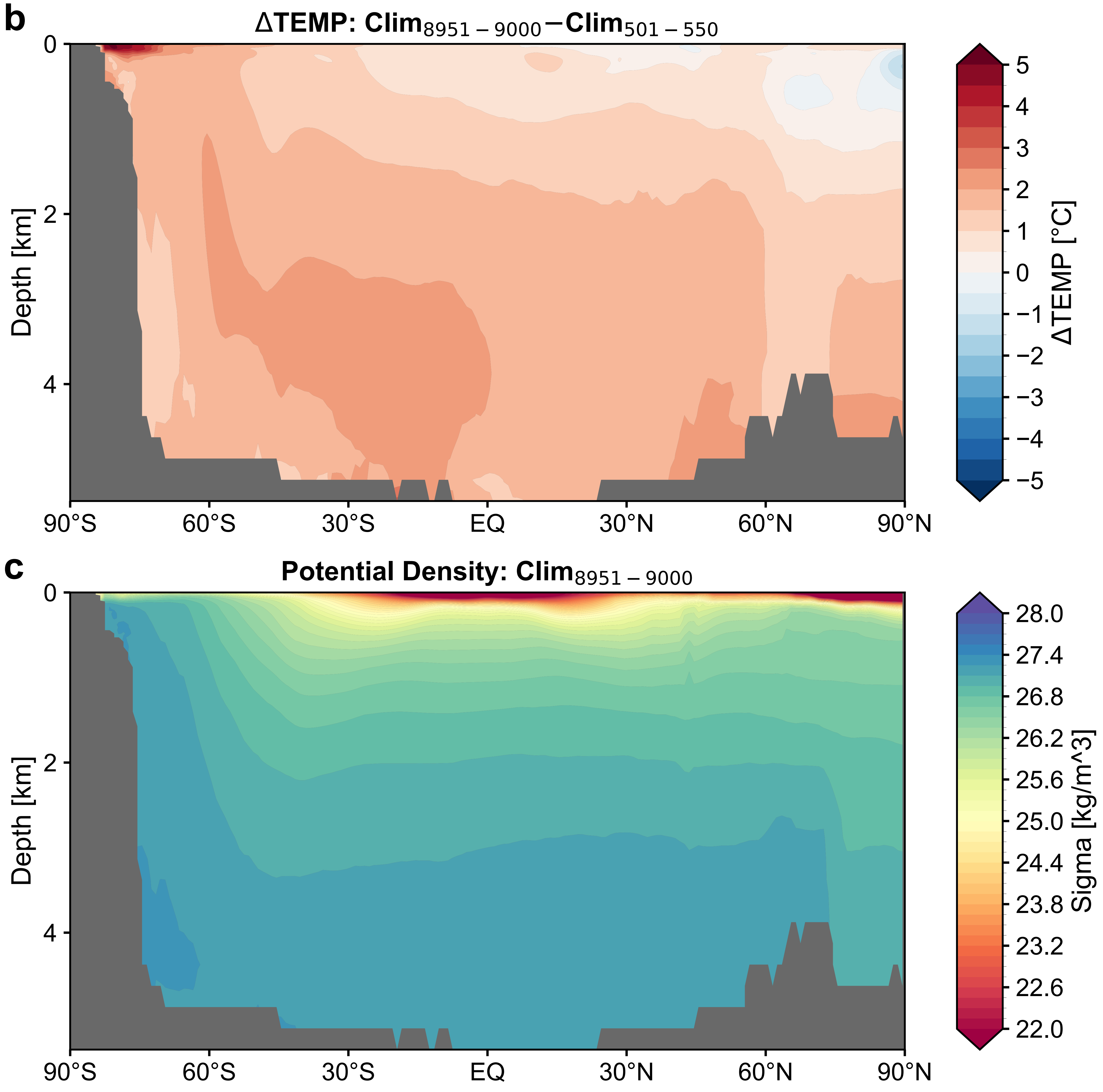


▶ **MCO ΔGMST:** 8.0 ± 0.9°C

▶ **MCO ΔBWT:** 6.1 ± 0.8°C

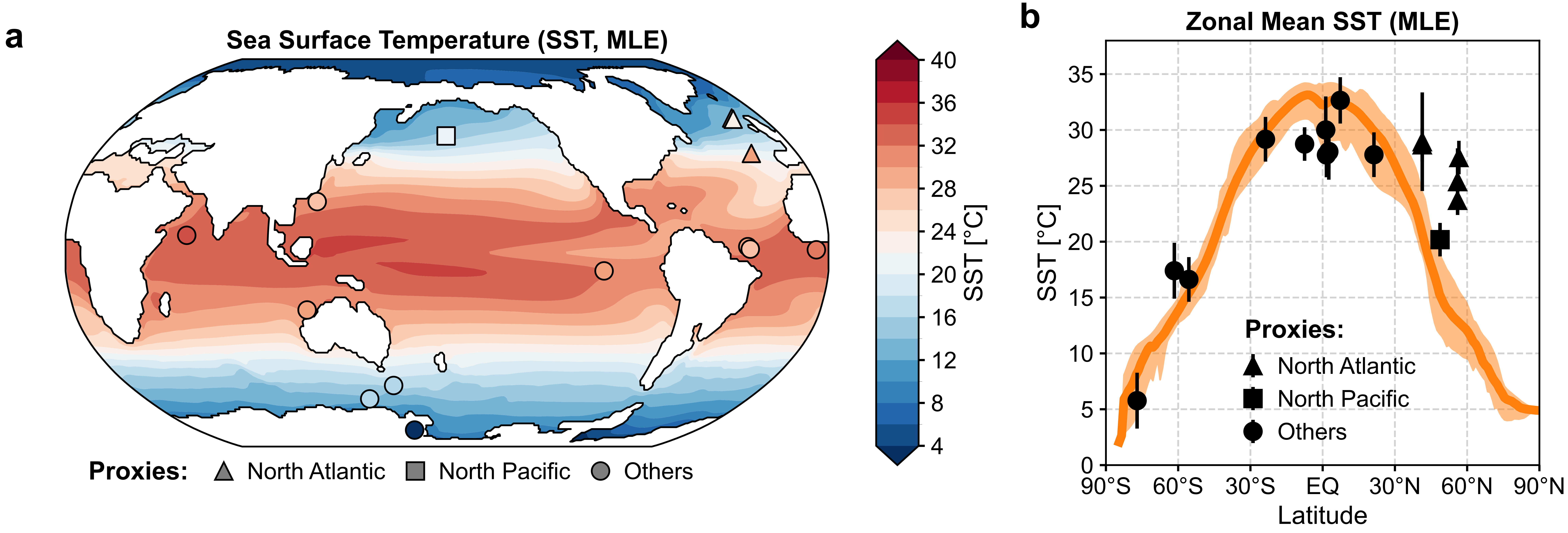
Deep ocean equilibrium impacts the southern ocean surface



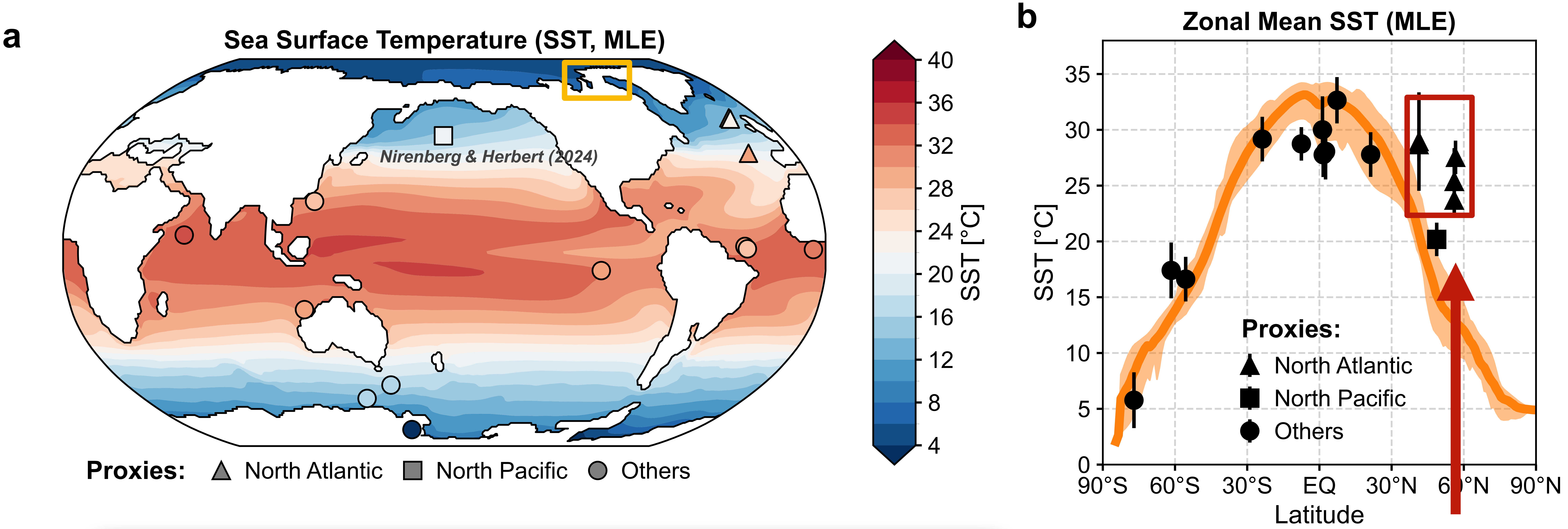


- **Deep Water Formation in the southern ocean**
- **No AMOC**

A good agreement with independent SST records



▣ A good agreement with independent SST records



Geophysical Research Letters®

RESEARCH LETTER
10.1029/2024GL109159

Key Points:

- Opening an Arctic Ocean gateway in Miocene climate simulations generates a strong Atlantic Meridional Overturning Circulation (AMOC) and increases northward ocean heat transport

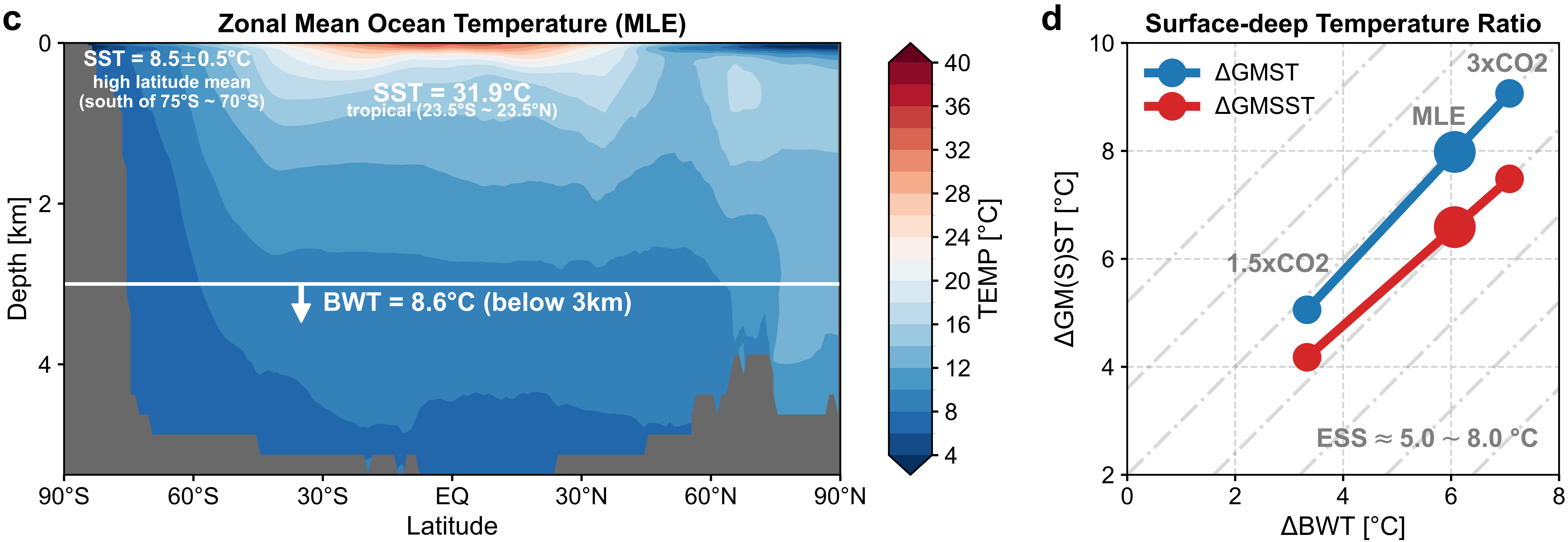
Atlantic Meridional Overturning Circulation Influence on the Annual Mean Intertropical Convergence Zone Location in the Miocene

Xiaoqing Liu[1], Nicholas Herold[2], and Matthew Huber[1]

[1]Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, IN, USA, [2]School of Life and Environmental Sciences, The University of Sydney, Sydney, NSW, Australia

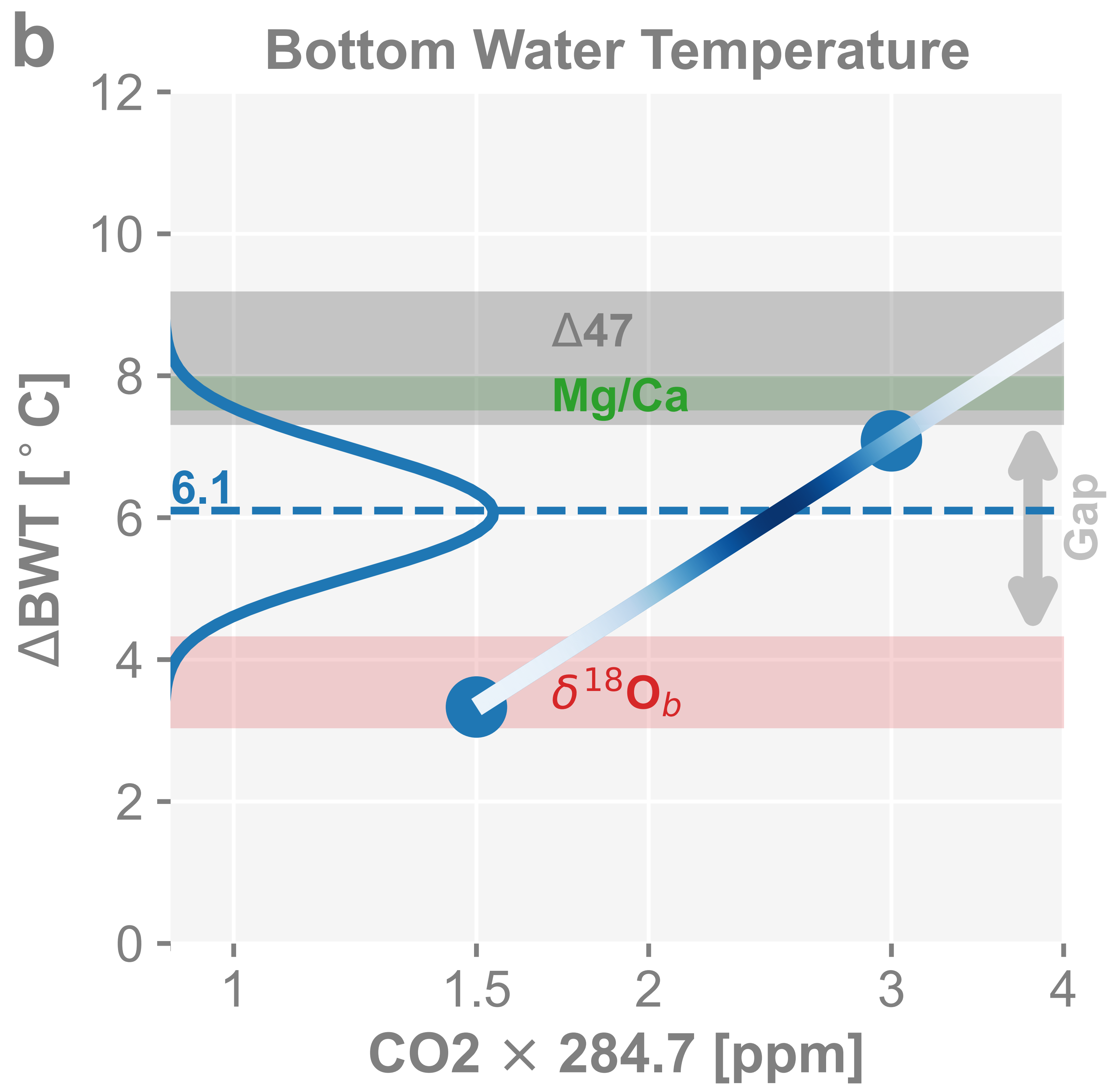
- **still an open question**
- **"a vigorous AMOC increases northward Atlantic Ocean heat transport" — *Liu et al. (2024)***

The 1:1 surface-deep ocean relationship during warm climates



The deep ocean and the high latitude southern ocean is inherently linked, which leads to a 1:1 surface-deep ocean relationship during warm climates, confirming *Hansen et al. (2013)* and *Evans et al. (2024)*.

Attributions of the discrepancy: H13 vs MLE (this study)



	H13	MLE	Δ
BWT [°C]	4.27	6.1	1.83

Hansen et al. (2013, H13)

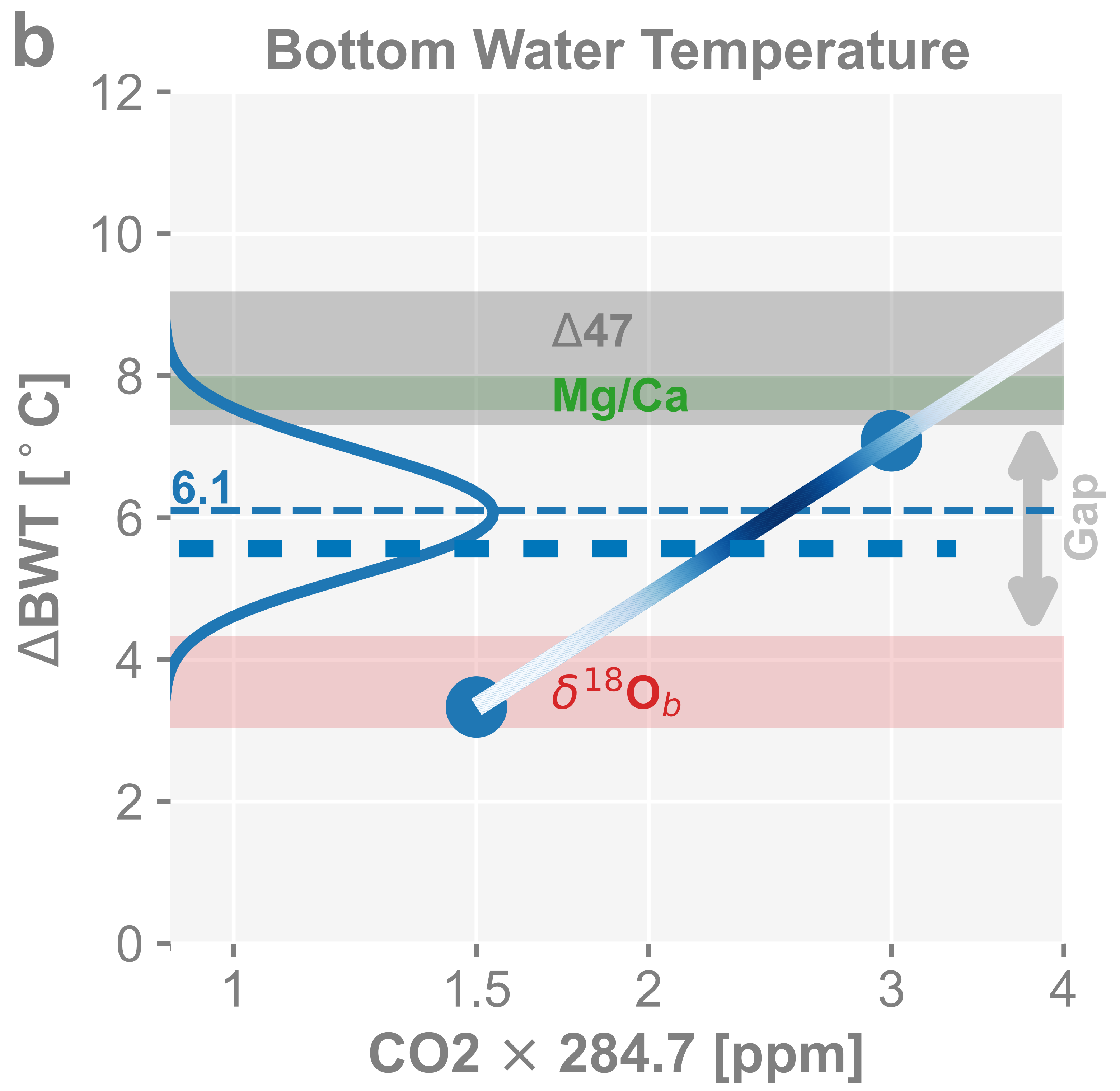
$$T_{do}\,(°C) = 5 - 8\frac{\delta^{18}O - 1.75}{3}$$

$$\delta^{18}O_b = -0.375T_{mdl} + 3.625$$

$$\delta^{18}O_b = \delta^{18}O_{mdl} + (-0.245T_{mdl} + 0.0011T_{mdl}^2 + 3.58) + \delta^{18}O_{ice\text{-}vol} + 1.5435(7.8 - pH)$$

$\delta^{18}O_{ice\text{-}vol} \sim \mathcal{N}(-0.4,\, 0.1^2)$ $pH \sim \mathcal{N}(7.7,\, 0.05^2)$

Attributions of the discrepancy: H13 vs MLE (this study)



	H13	MLE	Δ
BWT [°C]	4.27	6.1	1.83
⊖ pH correction	N/A	5.4	0.7 (38%)

Hansen et al. (2013, H13)

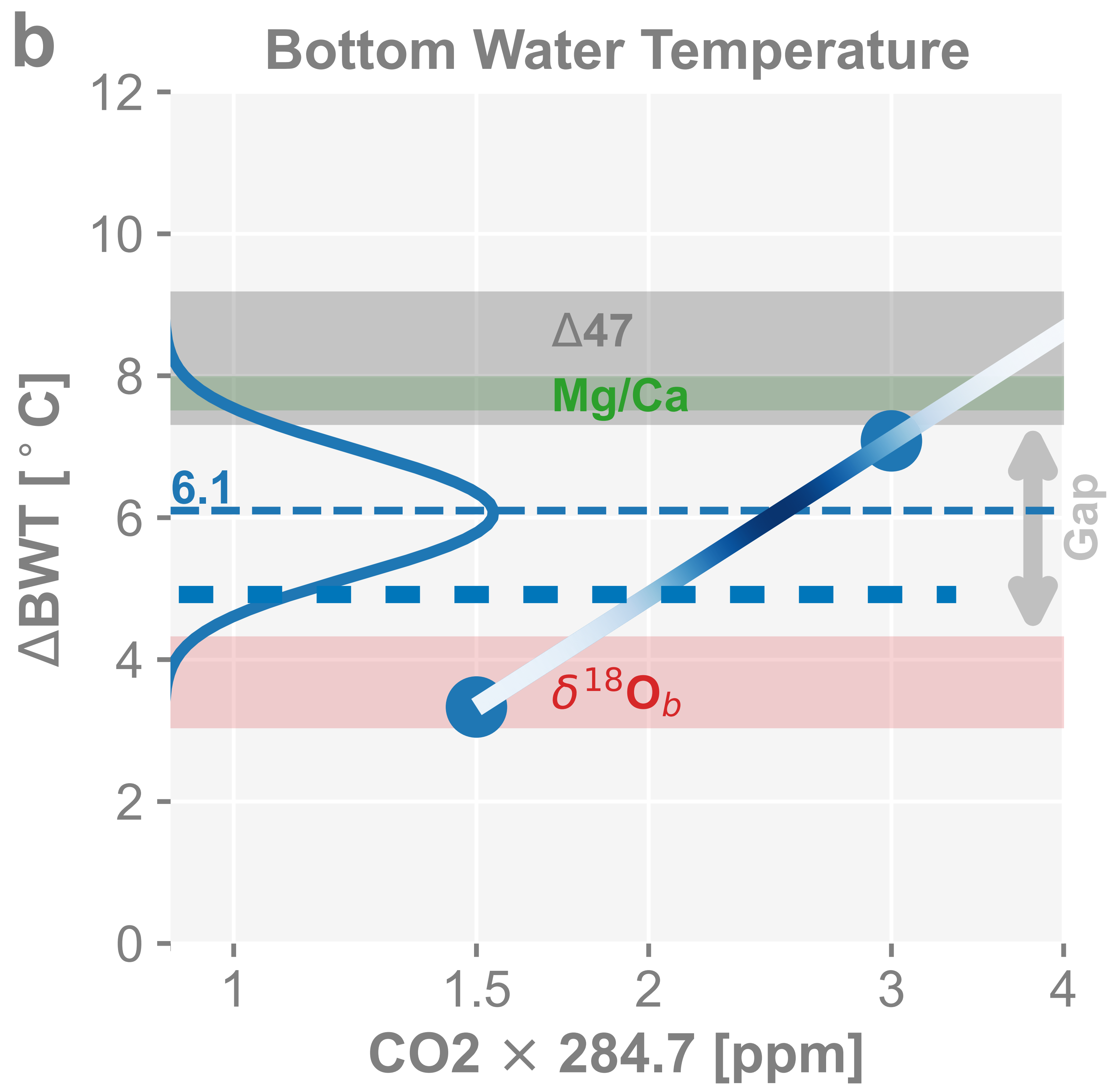
$$T_{do}\ (°C) = 5 - 8\frac{\delta^{18}O - 1.75}{3}$$

$$\delta^{18}O_b = -0.375T_{mdl} + 3.625$$

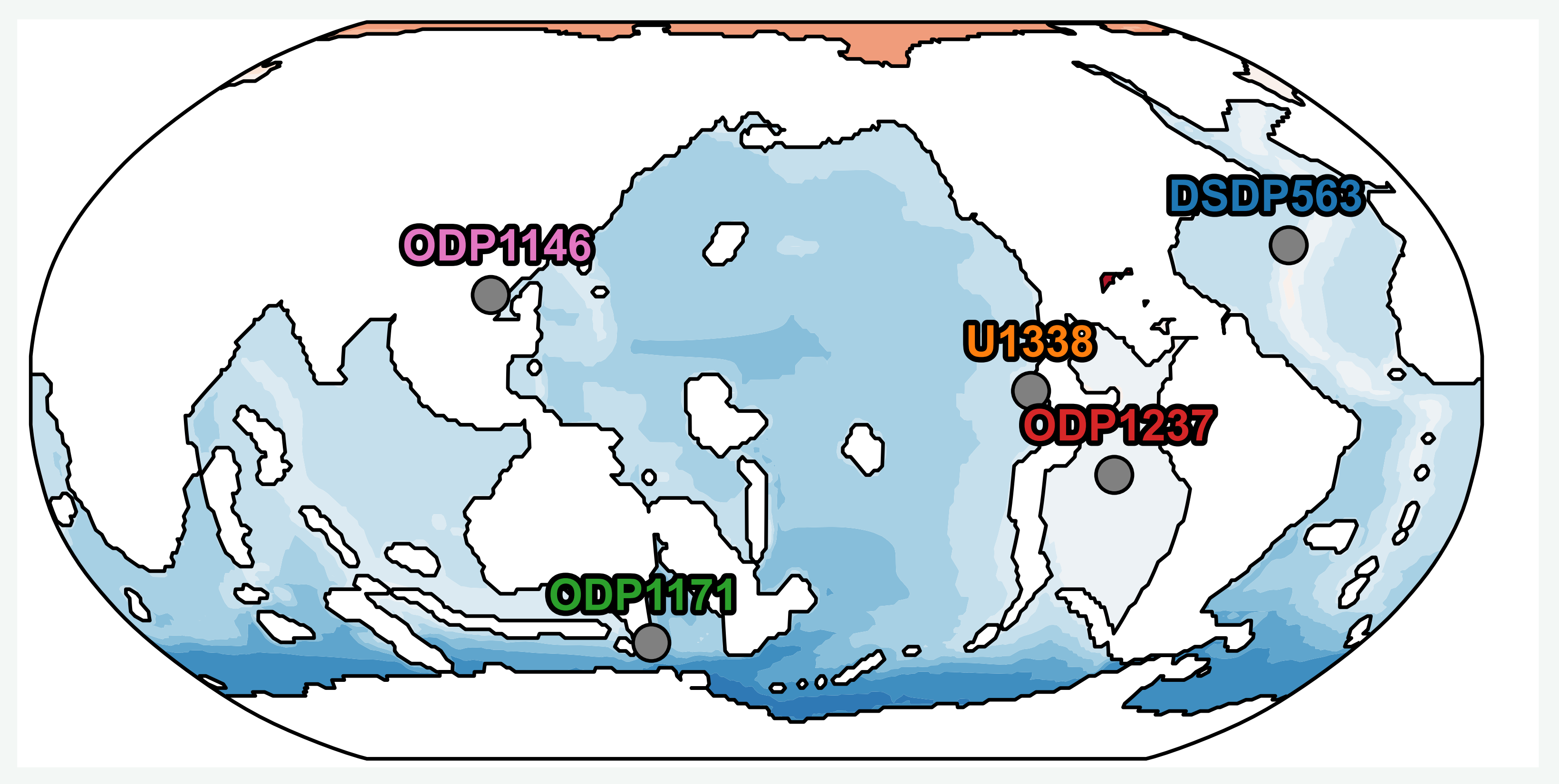
$$\delta^{18}O_b = \delta^{18}O_{mdl} + (-0.245T_{mdl} + 0.0011T_{mdl}^2 + 3.58) + \delta^{18}O_{ice\text{-}vol}$$

$$\delta^{18}O_{ice\text{-}vol} \sim \mathcal{N}(-0.4,\ 0.1^2)$$

Attributions of the discrepancy: H13 vs MLE (this study)



	H13	MLE	Δ
BWT [°C]	4.27	6.1	1.83
⊖ pH correction	N/A	5.4	0.7 (38%)
⊖ spatial representativeness	N/A	4.9	0.5 (27%)

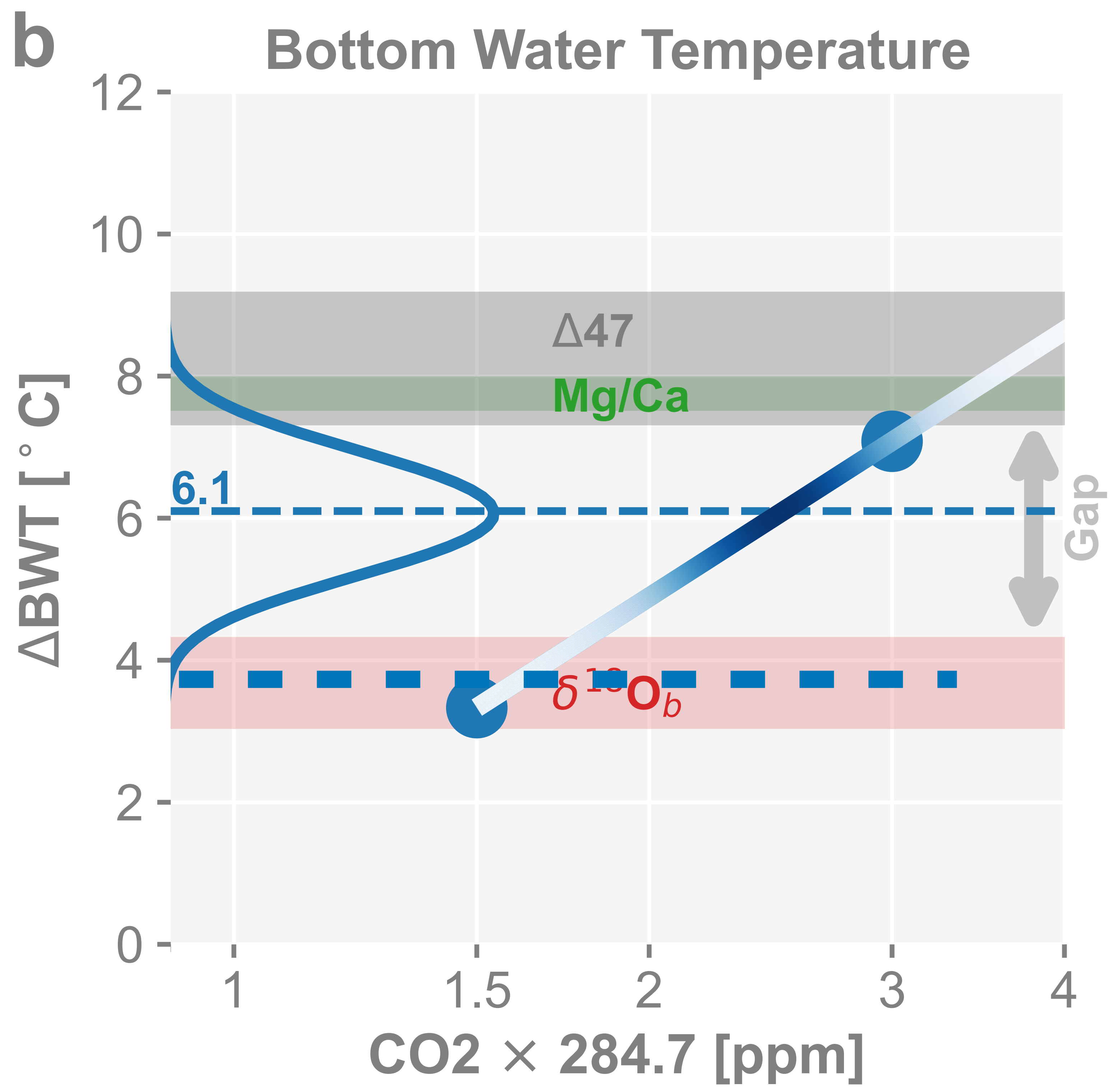


- H13 (U1338): 1.335‰
- MLE (avg.): 1.449‰

$$\delta^{18}O_b = \delta^{18}O_{mdl} + (-0.245T_{mdl} + 0.0011T_{mdl}^2 + 3.58) + \delta^{18}O_{ice\text{-}vol}$$

$\delta^{18}O_{ice\text{-}vol} \sim \mathcal{N}(-0.4,\ 0.1^2)$

Attributions of the discrepancy: H13 vs MLE (this study)

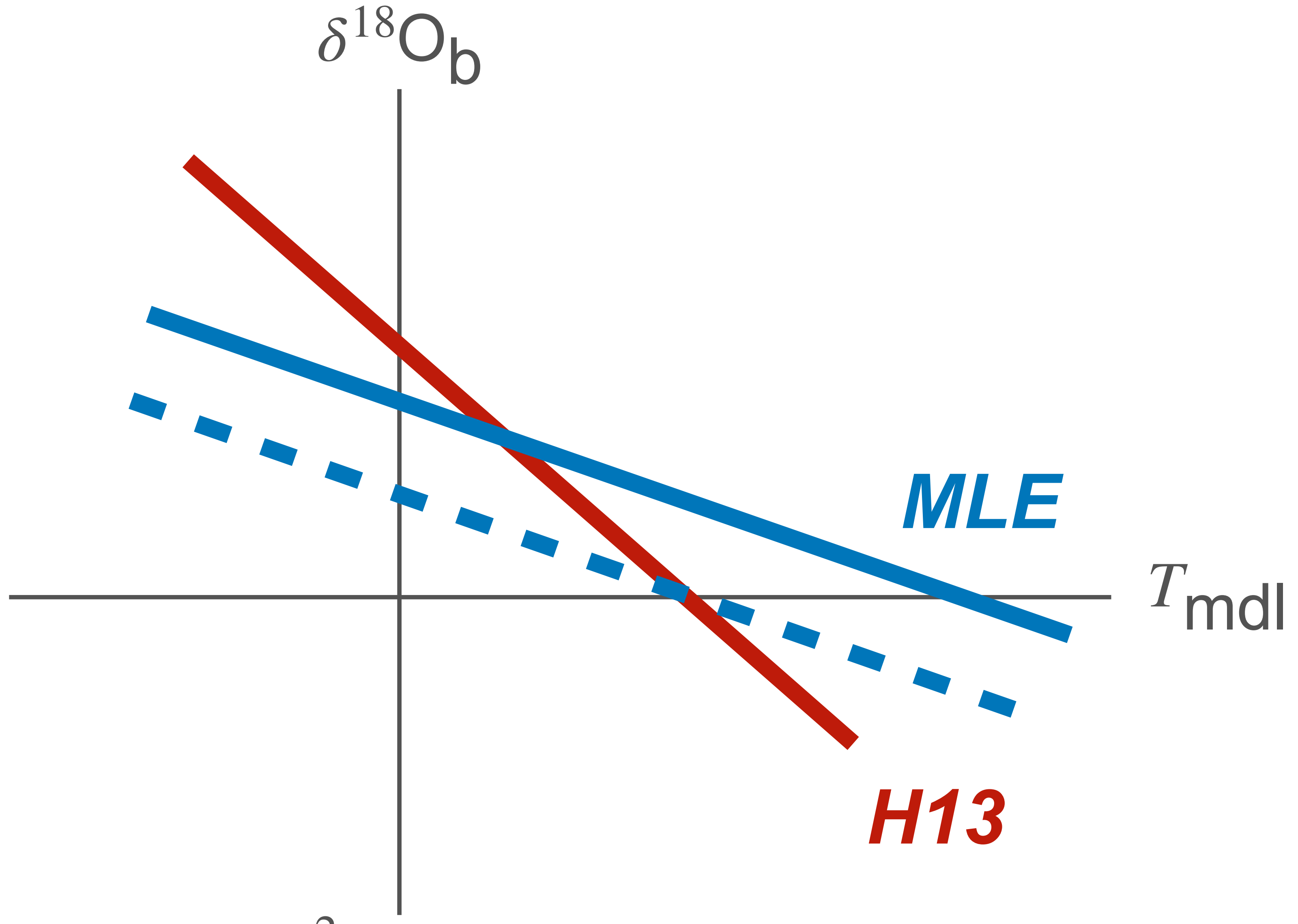


	H13	MLE	Δ
BWT [°C]	4.27	6.1	1.83
⊖ pH correction	N/A	5.4	0.7 (38%)
⊖ spatial representativeness	N/A	4.9	0.5 (27%)
⊖ ice volume effect	N/A	4.3	0.6 (33%)

Hansen et al. (2013, H13)

$$T_{do}\ (°C) = 5 - 8\frac{\delta^{18}O - 1.75}{3}$$

$$\delta^{18}O_b = -0.375T_{mdl} + 3.625$$



$$\delta^{18}O_b = \delta^{18}O_{mdl} + (-0.245T_{mdl} + 0.0011T_{mdl}^2 + 3.58) + \delta^{18}O_{ice\text{-}vol}$$

$$\delta^{18}O_{ice\text{-}vol} \sim \mathcal{N}(-0.53,\ 0.1^2)$$

Summary

- The first long-run isotope-enabled MCO simulations ft. full equilibrium in deep ocean; critical for an accurate estimate of the southern ocean surface.
- A novel analytical probabilistic approach to infer posterior ΔGMST and ΔBWT integrating model and benthic foram data.
- MCO ΔGMST: 8.0 ± 0.9°C, ΔBWT: 6.1 ± 0.8°C, warmer than *Westerhold et al. (2020, Science)*.
- SST estimation in good agreement with independent proxies.
- 1:1 surface-deep ocean relationship during warm climates.
- Our estimation suggests equivalently a pathway of RCP8.5.
  If we end up with RCP8.5 by 2100, we will physically revisit MCO: highly reduced Antarctic ice sheet, higher sea level, global ecosystem/hydroclimate changes, etc.

Research supported by

Thank you!

(fengzhu@ucar.edu)

Feng Zhu[1], *Jiang Zhu*[1], *Weimin Si*[2], *Jared E. Nirenberg*[2], *Timothy Herbert*[2], *Jessica E. Tierney*[3], *R. Paul Acosta*[4], *Natalie J. Burls*[4]

1. NSF NCAR 2. Brown University 3. University of Arizona 4. George Mason University

Jan 29, 2025
CESM Paleoclimate Working Group Meeting

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.