Geoscientific
Model Development

Supplement of

Global simulation of dissolved ^{231}Pa and ^{230}Th in the ocean and the sedimentary ^{231}Pa$/^{230}$Th ratios with the ocean general circulation model COCO ver4.0

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Experiment	^{231}Pad	Global			^{231}Pap	Global		
		slope	R	RMSD		slope	R	RMSD
Siddall_EXP		1.57 (1.88)	5.76×10^{-1} (7.24×10^{-1})	2.51×10^{-1} (1.47×10^{-1})		9.91×10^{-2} (6.60×10^{-2})	1.91×10^{-1} (1.00×10^{-1})	1.41×10^{-2} (1.59×10^{-2})
CTRL_EXP		7.56×10^{-1} (1.04)	7.51×10^{-1} (8.98×10^{-1})	8.21×10^{-2} (4.57×10^{-2})		6.16×10^{-2} (6.15×10^{-2})	1.87×10^{-1} (1.44×10^{-1})	1.37×10^{-2} (1.43×10^{-2})
3D_EXP		1.57 (1.88)	5.76×10^{-1} (7.24×10^{-1})	2.51×10^{-1} (1.47×10^{-1})		9.91×10^{-2} (6.60×10^{-2})	1.91×10^{-1} (1.00×10^{-1})	1.41×10^{-2} (1.59×10^{-2})

	^{230}Thd	Global			^{230}Thp	Global		
		Slope	R	RMSD		Slope	R	RMSD
Siddall_EXP		3.85 (4.44)	7.10×10^{-1} (8.68×10^{-1})	1.31 (1.17)		3.50×10^{-2} (1.26×10^{-1})	1.79×10^{-1} (2.35×10^{-1})	2.45×10^{-1} (8.56×10^{-2})
KREF_EXP		6.36×10^{-1} (8.81×10^{-1})	7.00×10^{-1} (8.08×10^{-1})	2.32×10^{-1} (2.05×10^{-1})		3.57×10^{-2} (1.67×10^{-1})	2.81×10^{-1} (4.23×10^{-1})	2.43×10^{-1} (7.87×10^{-2})
CTRL_EXP		7.65×10^{-1} (9.79×10^{-1})	8.18×10^{-1} (8.41×10^{-1})	1.71×10^{-1} (1.57×10^{-1})		3.17×10^{-2} (1.65×10^{-1})	2.79×10^{-1} (4.87×10^{-1})	2.44×10^{-1} (7.82×10^{-2})
3D_EXP		1.22 (1.73)	7.31×10^{-1} (8.30×10^{-1})	2.78×10^{-1} (2.98×10^{-1})		3.59×10^{-2} (1.67×10^{-1})	2.78×10^{-1} (4.31×10^{-1})	2.43×10^{-1} (7.85×10^{-2})

	^{231}Pa/^{230}Th (sediment)	Global			^{231}Pa/^{230}Th (seawater)	Global		
		Slope	R	RMSD		Slope	R	RMSD
Siddall_EXP		2.71×10^{-1}	3.46×10^{-1}	5.03×10^{-2}		1.61×10^{-1}	2.48×10^{-1}	6.64×10^{-2}
KREF_EXP		4.21×10^{-1}	4.21×10^{-1}	5.74×10^{-2}		3.40×10^{-1}	2.11×10^{-1}	1.08×10^{-1}
CTRL_EXP		3.91×10^{-1}	4.24×10^{-1}	5.34×10^{-2}		2.50×10^{-1}	2.30×10^{-1}	8.15×10^{-2}
3D_EXP		4.73×10^{-1}	4.42×10^{-1}	5.42×10^{-2}		3.30×10^{-1}	1.71×10^{-1}	1.33×10^{-1}

Table S1. Metrics of model-data misfits about ^{231}Pa and ^{230}Th simulated in our Siddall_EXP, KREF_EXP, CTRL_EXP, and 3D_EXP: the slope of linear regression (slope), the linear correlation coefficient (R), and the root mean square deviation (RMSD) of our experiment against all of the available data from GEOTRACES Intermediate Data Product 2017 (Schlitzer et al., 2018). ^{231}Pad(^{230}Thd) and ^{31}Pap(^{230}Thp) denote dissolved ^{231}Pa (^{230}Th) and particulate ^{231}Pa (^{230}Th), respectively. Values for ^{231}Pa/^{230}Th ratios in sediments and water column are also shown in the table. For dissolved ^{231}Pa and ^{230}Th, we compared model results with the GEOTRACES data (GA02, GA03, GIPY05, GPc01 and GP16 sections). Numbers in parentheses of dissolved ^{231}Pa and ^{230}Th indicate comparisons only with the GEOTRACES GA02 data. For particulate ^{231}Pa and ^{230}Th, we compared model results with the GEOTRACES data (GA03, GIPY05, and GP16 sections). Numbers in parentheses of particulate ^{231}Pa and ^{230}Th indicate comparisons with pre-GEOTRACES data shown in Fig. S1c. For ^{231}Pa/^{230}Th ratios in seawater, we compared model results with the GEOTRACES data (GA03, GIPY05, and GP16 sections). For ^{231}Pa/^{230}Th ratios in sediment, the model results are compared with the sedimentary data shown in Fig. S1b.

Experiment	^{231}Pa	^{230}Th
Siddall_EXP	211	89
KREF_EXP	103	18
CTRL_EXP	103	21
3D_EXP	211	28

Table S2. The residence time of ^{231}Pa and ^{230}Th (year) simulated in our Siddall_EXP, KREF_EXP, CTRL_EXP, and 3D_EXP are displayed.
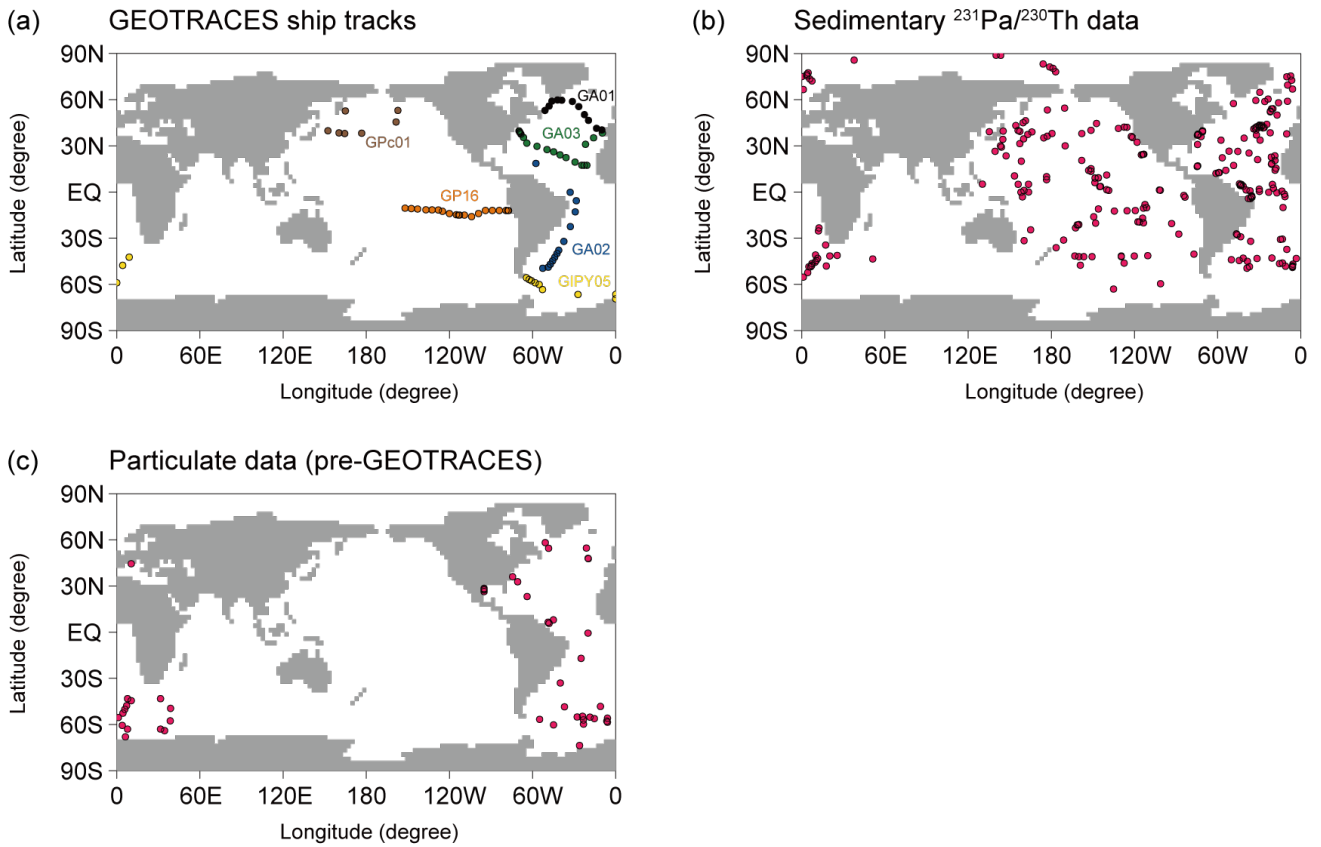
Figure S1. (a) Ship tracks of GEOTRACES data used in this study. (b) Sedimentary ^{231}Pa/^{230}Th data obtained in pre-GEOTRACES studies (Mangianini & Sonntag, 1977; Müller & Mangini, 1980; Anderson et al., 1983; Shimmield et al., 1986; Schmitz et al., 1986; Yang et al., 1986; Shimmield & Price, 1988; Lao et al., 1992; François et al., 1993; Frank et al., 1994; Frank, 1996; Bradtmiller et al., 2014, and their supplemental data). (c) Particulate ^{231}Pa and ^{230}Th data obtained in pre-GEOTRACES studies (Cochran et al., 1987; Colley et al., 1995; Guo et al., 1995; Moran et al., 1997, 2001, 2002; Rutgers van der Loeff and Berger, 1993; Vogler et al., 1998; Walter et al., 1997).

Figure S2. (a) Dissolved ^{231}Pa, (b) dissolved ^{230}Th, (c) particulate ^{231}Pa, (d) particulate ^{230}Th, and (f) particulate ^{231}Pa/^{230}Th ratios along 30 °W in the Atlantic Ocean in 1D_EXP. (e) Sedimentary ^{231}Pa/^{230}Th ratios normalized by the production ratio of 0.093 in 1D_EXP.
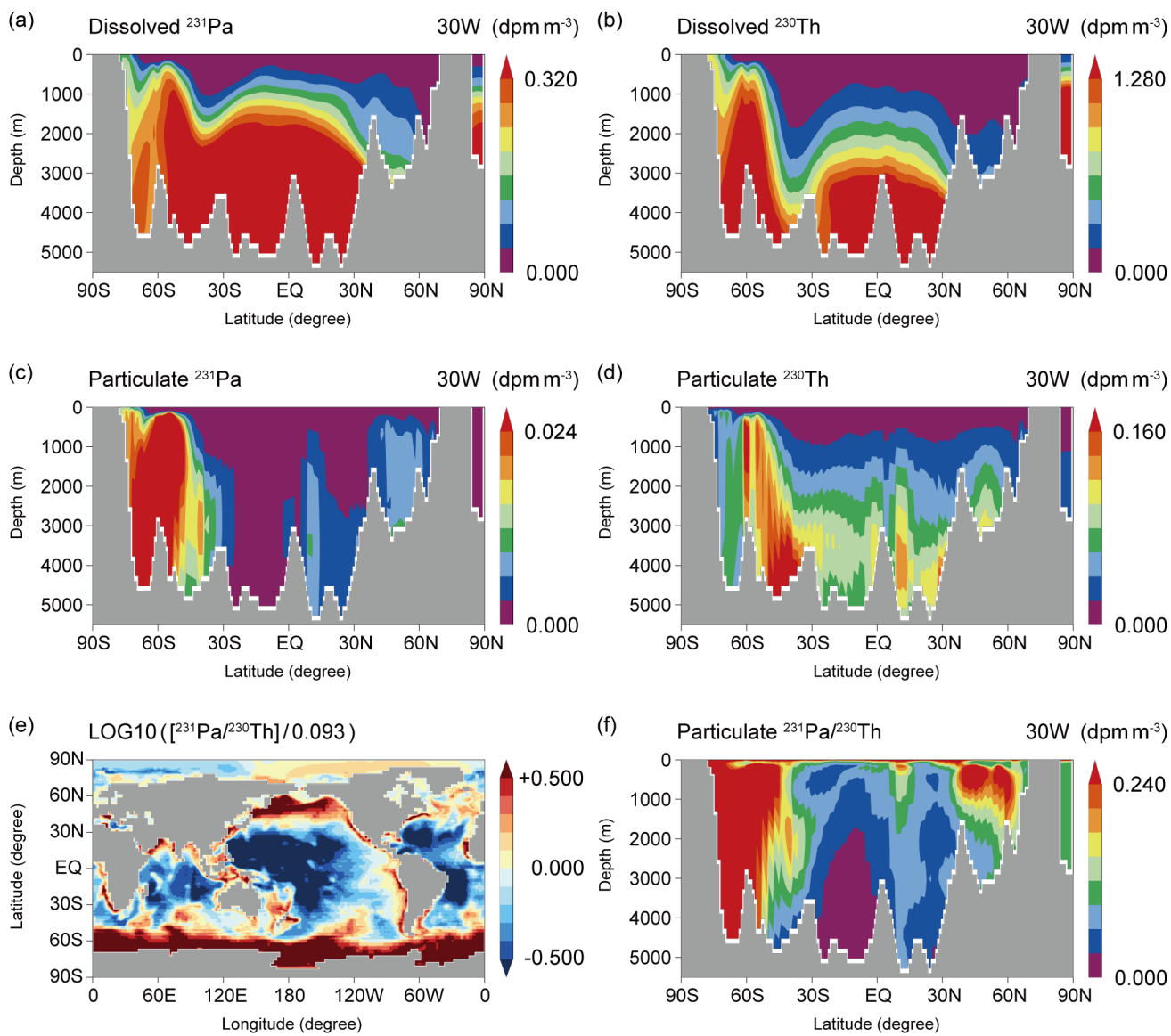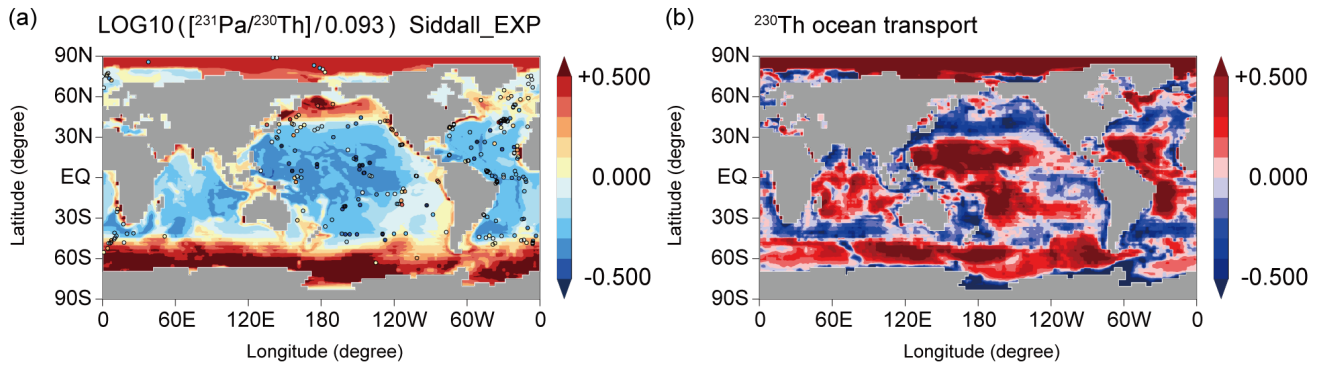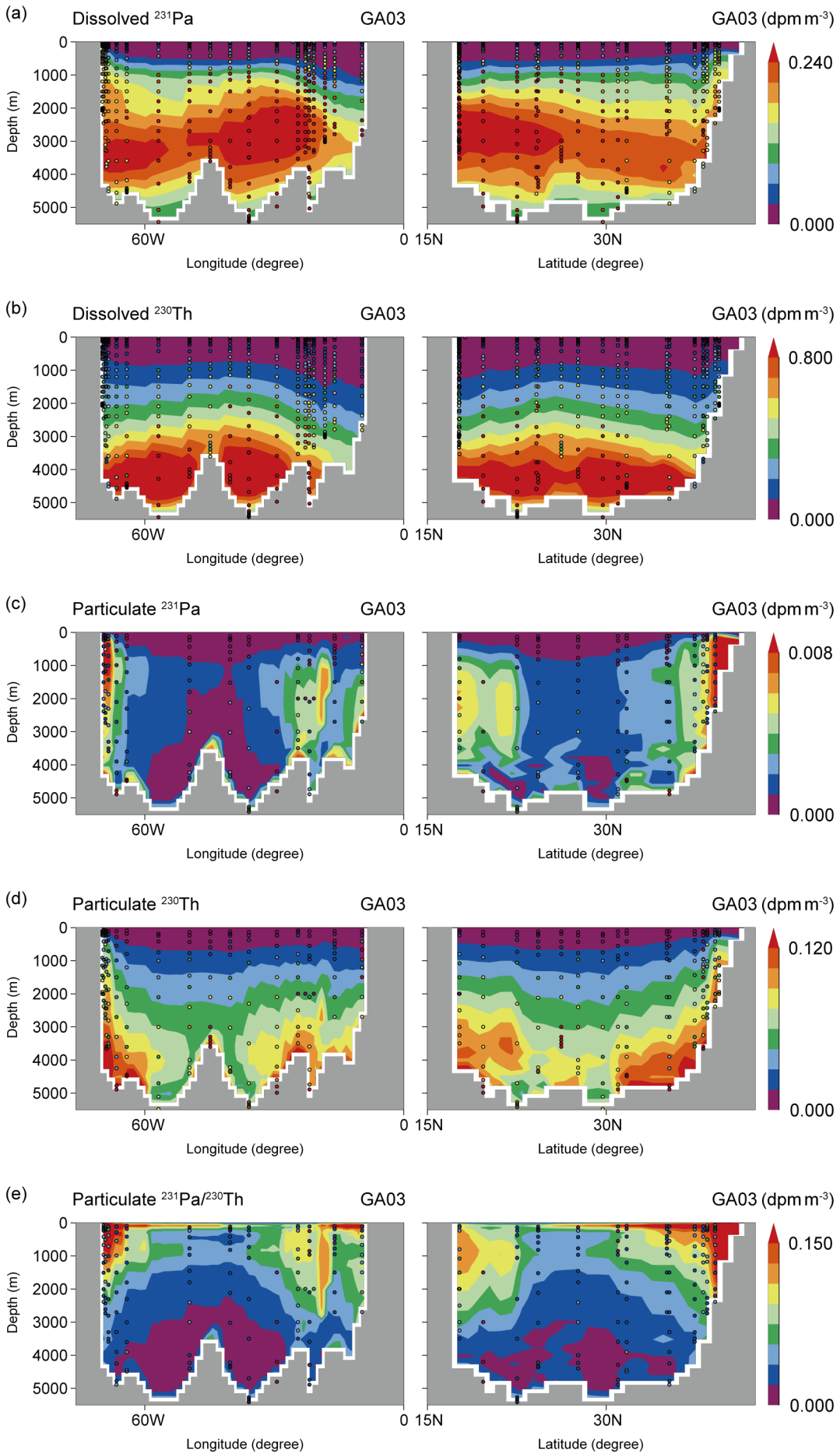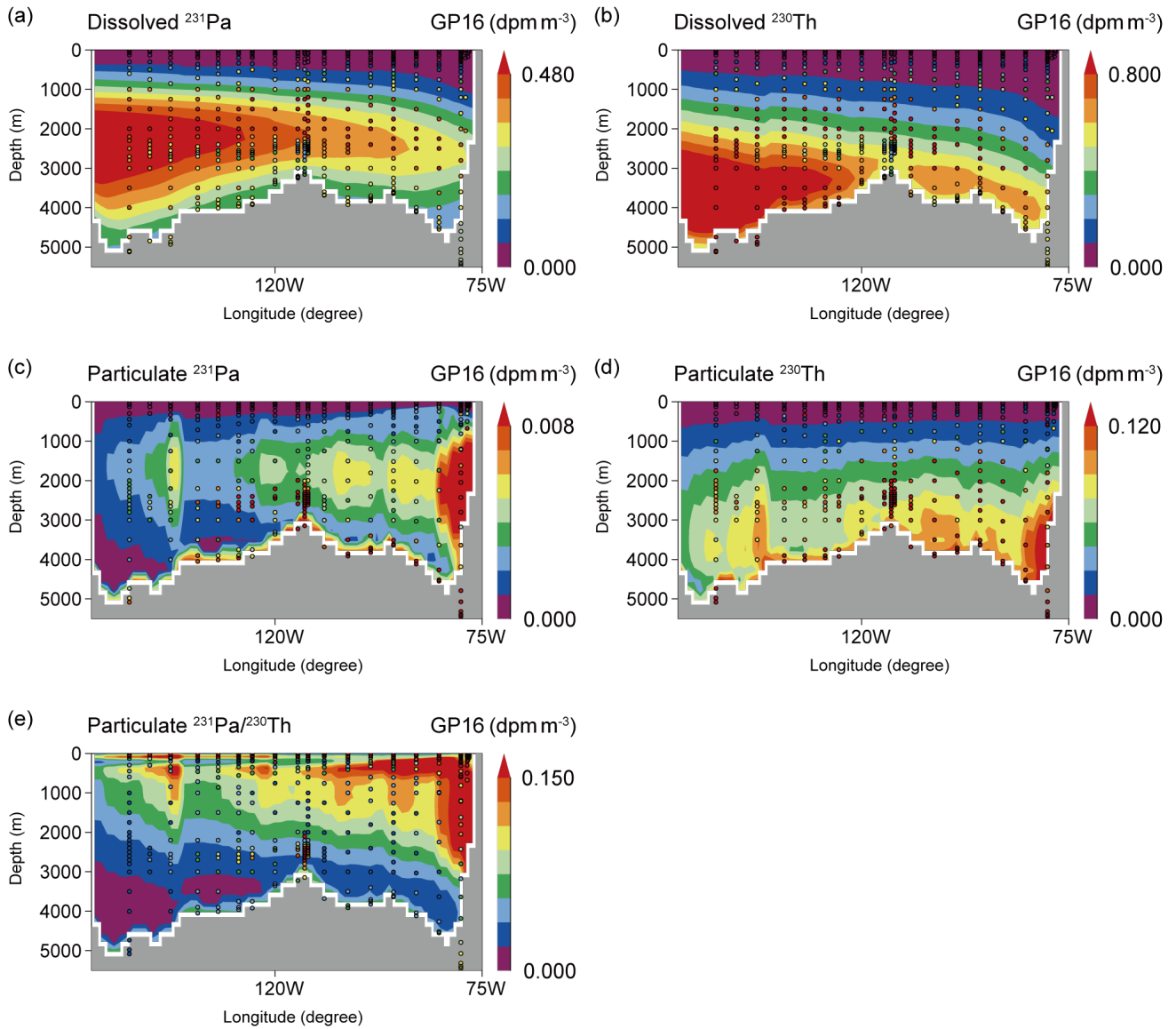
Figure S3. The same as Fig. S2 except for 3D_EXP.

Figure S4. (a) Sedimentary ^{231}Pa/^{230}Th ratios normalized by the production ratio of 0.093 in Siddall_EXP. (b) Contributions to the sedimentary ^{231}Pa/^{230}Th ratios of Siddell_EXP from ocean transport solely from ^{230}Th (i.e., ^{231}Pa(1D)/^{230}Th(Siddall)).

(a) Dissolved ²³¹Pa   GA03   GA03 (dpm m⁻³)

(b) Dissolved ²³⁰Th   GA03   GA03 (dpm m⁻³)

(c) Particulate ²³¹Pa   GA03   GA03 (dpm m⁻³)

(d) Particulate ²³⁰Th   GA03   GA03 (dpm m⁻³)

(e) Particulate ²³¹Pa/²³⁰Th GA03   GA03 (dpm m⁻³)

7

Figure S5. (a) Dissolved ^{231}Pa, (b) dissolved ^{230}Th, (c) particulate ^{231}Pa, (d) particulate ^{230}Th, and (e) particulate ^{231}Pa/^{230}Th ratios along the Atlantic GEOTRACES GA03 transect in CTRL_EXP. The coloured circles represent the GEOTRACES data (GA03; Hayes et al., 2015).
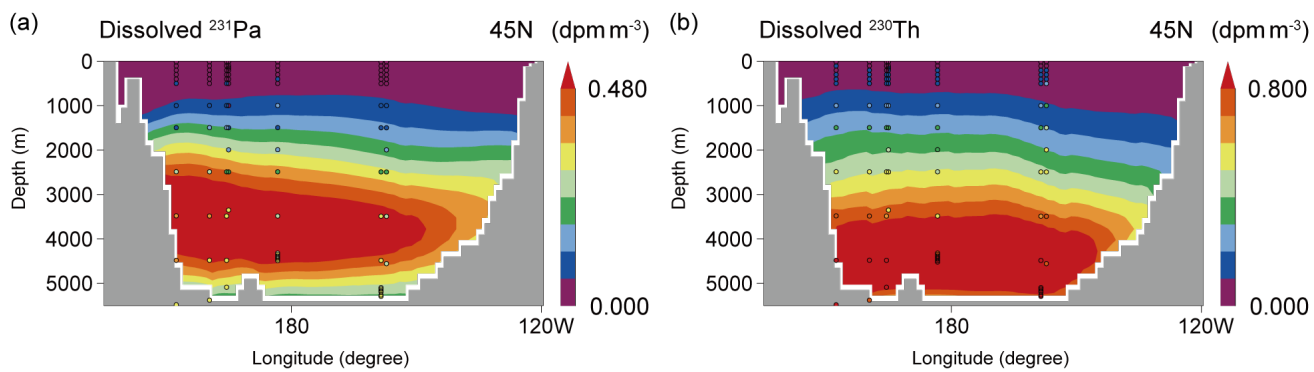
Figure S6. (a) Dissolved ^{231}Pa, (b) dissolved ^{230}Th, (c) particulate ^{231}Pa, (d) particulate ^{230}Th, and (e) particulate ^{231}Pa/^{230}Th ratios along the Pacific GEOTRACES GP16 transect in CTRL_EXP. The coloured circles represent the GEOTRACES data (GP16; Pavia et al., 2018).

Figure S7. (a) Dissolved ²³¹Pa and (b) dissolved ²³⁰Th along 45°N in the Pacific in CTRL_EXP. The coloured circles represent the GEOTRACES data (GPc01; Hayes et al., 2013).

Figure S8. (a) Dissolved ^{231}Pa and (b) dissolved ^{230}Th along the Atlantic GEOTRACES GA01 transect in CTRL_EXP. The coloured circles represent the GEOTRACES data (GA01; Deng et al., 2018).
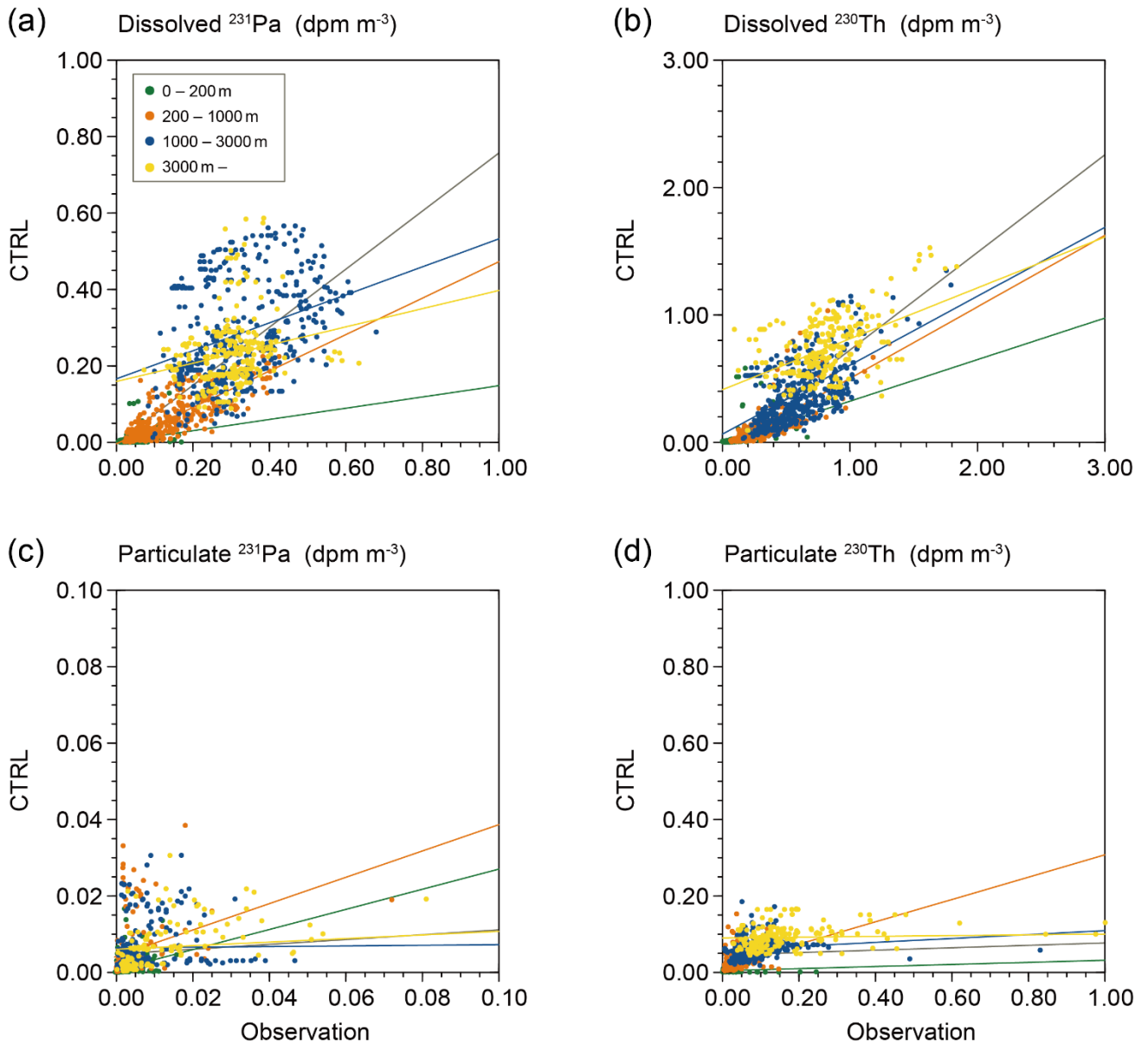
Figure S9. The scatter plot of (a) dissolved ^{231}Pa, (b) dissolved ^{230}Th, (c) particulate ^{231}Pa, and (d) particulate ^{230}Th between CTRL_EXP and available GEOTRACES data (unit: dpm m^{-3}). Plots from different ocean depth ranges are drawn with different colors: green for 0–200 m, orange for 200–1000 m, blue for 1000–3000m and yellow for deeper than 3000 m. The regression lines are also shown. The gray line represents the linear regression line for all depth ranges. For dissolved ^{231}Pa and ^{230}Th, the data from GEOTRACES GA02, GA03, GIPY05, GPc01 and GP16 sections are used. For particulate ^{231}Pa and ^{230}Th, the data from GEOTRACES GA03, GIPY05, and GP16 sections are used.
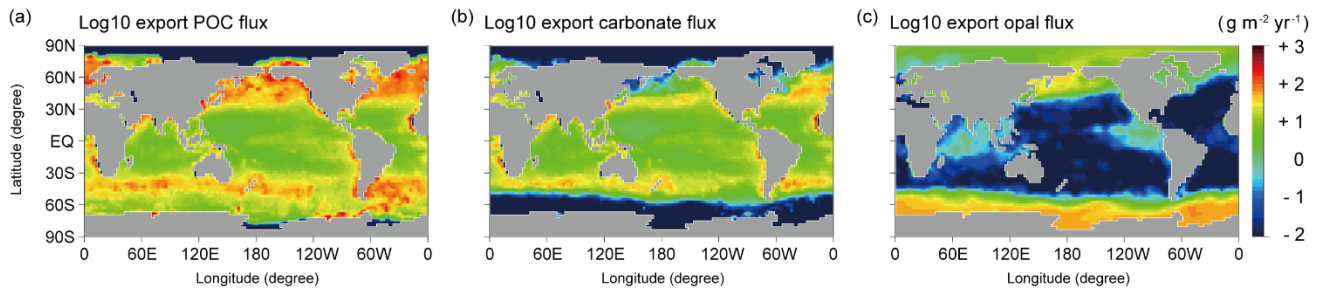
Figure S10. Surface particle fluxes (unit: g m^{-2} yr^{-1}) of (a) particulate organic carbon, (b) calcium carbonate, and (c) opal.
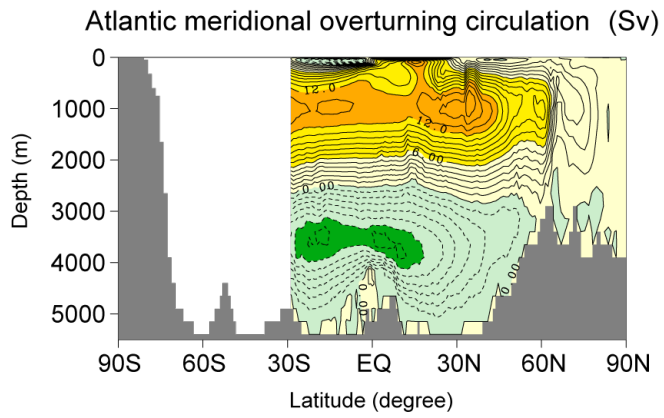
Figure S11. Atlantic meridional overturning circulation (AMOC) simulated in the OGCM COCO under modern conditions. The contour interval is 1 Sv (1 Sv = 10^6 m^3 s^{-1}).

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