Sooty terns as large-scale bioindicators of mercury contamination in marine ecosystems: A pantropical approach

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Supplementary material
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I- Supplementary tables

Table S1. Geographical coordinates of sampling sites and collaborators involved in feather sampling of sooty terns (*Onychoprion fuscatus*) across the 28 sites (following the colour code from the figures).

Sites	Coordinates	Collaborators and/or contact persons
Pacific Ocean		
Midway Atoll, USA	28°13'41" N, 177°23'20" W	Laura Brazier
Lisianski Island, USA	26°3'45" N, 173°57'59" W	Daniel Link
Laysan Island, USA	25°46'15" N, 171°44'15" W	Daniel Link
Johnston Atoll, USA	16°43'44" N, 169°32'1" W	Kate Toniolo
Palmyra Atoll, USA	5°52'56" N, 162°4'30" W	Kate Toniolo
Rose Atoll, USA	14°32'45" S, 168°9' W	Brian Peck
Motu Oa, Ua Pou, Marquises	9°28'47" S, 140°2'49" W	Thomas Ghestemme, Tehani Withers
Phillip Island, Norfolk Island	29°7'2" S, 167°56'35" E	Nicholas Carlile
Lord Howe Island, Australia	31°31'24" S, 159°3'49" E	Terence O'Dwyer
Atlantic Ocean		
Azores	37°51'24" N, 25°47'2" W	Veronica Costa Neves
Dry Tortugas, Florida	24°38'56" N, 82°52'18" W	Stuart Pimm
Felipe de Barlovento cay, Cuba	22°36'41" N, 78°37'47" W	Antonio Garcia-Quintas
Paredón de Lado cay, Cuba	22°28'43" N, 78°12'47" W	Antonio Garcic-Quintas
Culebra, Puerto Rico	18°18'11" N, 65°18'" W	Ana Roman, Eduardo Ventosa
Dog Island, Anguilla	18°16'40" N, 63°14'56" W	Louise Soanes
Tinhosa Grande, São Tomé et Príncipe	1°20'32" N, 7°17'31" E	Nina Darocha, Estrela Matilde
Fernando de Noronha, Brazil	3°51'16" S, 32°25'4" W	Leandro Bugoni, Patricia Mancini
Rocas Atoll, Brazil	3°51'21" S, 33°49'3" W	Leandro Bugoni, Patricia Mancini
Ascension Island	7°56'30" S, 14°21'45" W	Laura Shearer

Table S1. (following)

Sites	Coordinates	Collaborators and/or contact persons
Indian Ocean		
Bird Island, Seychelles	3°43' S, 55°12' E	Chris Feare
Aride Island, Seychelles	4°13' S, 55°40' E	Gerard Rocamora
Etoile Cay, Seychelles	5°53' S, 53°19' E	Matthew Morgan
African Banks, Seychelles	4°54' S, 53°20' E	Matthew Morgan
Desnoeuf Island, Seychelles	6°14' S, 53°32' E	Matthew Morgan
Cosmoledo Grande, Seychelles	9°42' S, 47°34' E	Matthew Morgan, Pierre-Andre Adam
Goëlettes Island, Seychelles	10°11' S, 51°07' E	Matthew Morgan
Juan de Nova, Mozambic Channel	17° 3' 17" S, 42° 43' 28" E	Sébastien Jaquemet
Europa Island, Mozambic Channel	22°21'1" S, 40°21'34" E	Charlie Bost, Sébastien Jaquemet
Rat Island, Houtman Abrolhos	28°42'56" S, 113°47'2" E	Nic Dunlop

Table S2. Certified reference materials (NRC Canada) used for total Hg analyses in feathers of sooty terns (*Onychoprion fuscatus*): certified (theoretical) and measured concentrations, and recoveries (calculated as measured/certified value). Sample sizes (n) for each reference material and values are mean ± SD (min–max).

Reference Material	n	Certified value ($\mu g \cdot g^{-1}$ dw)	Measured value ($\mu g \cdot g^{-1}$ dw)	Recovery (%)
DOLT-5 *Fish liver*	16	0.44 ± 0.18 (0.26–0.62)	0.42 ± 0.01 (0.41–0.43)	96.6 ± 1.4 (94.3–98.6)
TORT-3 *Lobster hepatopancreas*	101	0.29 ± 0.02 (0.27–0.31)	0.30 ± 0.01 (0.27–0.31)	101.3 ± 2.4 (94.1–107.7)

Table S3. Literature review of stable isotope values measured in feathers of sooty terns (*Onychoprion fuscatus*) sampled across three ocean basins. Values are mean ± SD (min–max).

Sites	Year	Stage	n	Bulk $\delta^{13}C$ (‰)	Bulk $\delta^{15}N$ (‰)	References
Pacific Ocean						
Midway Atoll	2021	Adult	30	–15.9 ± 0.4 (–16.6, –14.5)	14.7 ± 2.1 (10.5–17.6)	This study
		Chick	30	–16.4 ± 0.2 (–16.7, –16.1)	9.5 ± 0.3 (8.9–10.5)	This study
Lisianski Island	2021	Adult	6	–16.3 ± 1.3 (–18.8, –15.3)	13.2 ± 2.6 (10.0–16.9)	This study
Laysan Island	2021	Adult	2	–16.1 ± 0.1 (–16.2, –16.1)	16.0 ± 1.9 (14.6–17.3)	This study
Johnston Atoll	2021	Adult	30	–15.7 ± 0.4 (–16.2, –14.9)	14.5 ± 2.2 (8.1–17.0)	This study
Palmyra Atoll	2021	Adult	31	–15.6 ± 0.3 (–16.5, –14.7)	15.1 ± 2.5 (8.8–19.5)	This study
		Chick	30	–15.6 ± 0.2 (–16.0, –15.2)	16.4 ± 1.6 (12.8–18.3)	This study
Rose Atoll	2021	Adult	34	–14.9 ± 0.3 (–15.7, –14.3)	17.2 ± 2.7 (12.3–23.5)	This study
		Chick	34	–14.7 ± 0.2 (–15.4, –14.4)	14.4 ± 0.4 (13.3–15.1)	This study
Motu Oa, Ua Pou	2021/2022	Adult	4	–15.7 ± 0.5 (–16.4, –15.2)	11.7 ± 2.0 (9.1–13.5)	This study
Phillip Island, Norfolk Island	2020	Adult	30	–15.1 ± 0.2 (–15.5, –14.5)	15.3 ± 2.9 (9.9–21.9)	This study
	2021	Chick	30	–17.2 ± 0.2 (–17.5, –16.7)	11.9 ± 0.9 (10.8–12.6)	This study
Lord Howe Island	2020	Adult	30	–15.6 ± 0.4 (–16.4, –14.8)	14.8 ± 1.6 (12.5–17.7)	This study
		Chick	30	–17.2 ± 0.2 (–17.7, –17.0)	14.6 ± 0.3 (13.9–15.2)	This study
Atlantic Ocean						
Azores	2021	Adult	1	–16.3	13.2	This study
		Chick	1	–18.4	11.9	This study
Dry Tortugas, Florida	2021	Adult	24	–16.0 ± 0.4 (–16.7, –15.2)	10.7 ± 1.2 (8.6–12.9)	This study
Felipe de Barlovento and Paredón de Lado cays, Cuba		Chick	6	–15.8 ± 0.4 (–16.4, –15.4)	9.3 ± 0.4 (8.9–9.7)	This study
Culebra, Puerto Rico	2021	Adult	12	–16.4 ± 0.5 (–16.8, –15.3)	12.0 ± 1.4 (8.0–13.1)	This study
		Chick	4	–15.3 ± 0.1 (–15.4, 15.1)	9.2 ± 0.3 (8.9–9.4)	This study
Dog Island, Anguilla	2021	Adult	11	–16.3 ± 0.6 (–16.9, –14.8)	10.8 ± 1.6 (8.3–13.1)	This study
		Chick	13	–15.3 ± 0.1 (–15.6, –15.2)	8.4 ± 0.4 (7.7–8.9)	This study
Tinhosa Grande	2021	Adult	27	–16.1 ± 0.2 (–16.5, –15.3)	11.9 ± 0.2 (11.3–12.3)	This study

		Chick	25	–16.2 ± 0.2 (–16.6, –16.0)	12.8 ± 0.2 (12.4–13.3)	This study
Fernando de Noronha	2011	Adult	18	–16.0 ± 0.3 (–16.6, –15.5)	10.8 ± 0.6 (10.0–13.0)	This study
Rocas Atoll	2010	Adult	44	–16.0 ± 0.3 (–16.7, –15.4)	10.9 ± 0.7 (8.0–12.8)	This study
Ascension Island	2020	Adult	5	–15.7 ± 0.3 (–16.1, –15.2)	11.4 ± 0.8 (10.1–12.1)	This study
		Chick	30	–15.5 ± 0.2 (–15.7, 15.3)	11.8 ± 0.1 (11.8–11.9)	This study
	2021	Adult	30	–16.5 ± 0.2 (–16.8, –16.0)	13.2 ± 0.7 (11.6–14.2)	This study
		Chick	15	–16.3 ± 0.2 (–16.5, –16.2)	12.6 ± 0.1 (12.5–12.8)	This study
Indian Ocean						
Bird Island	2021	Adult	31	– 15.9 ± 0.2 (–16.3, –15.4)	13.7 ± 0.8 (12.4–15.3)	This study
	2021	Chick	33	–16.5 ± 0.2 (–16.8, –16.2)	13.9 ± 0.3 (13.1–14.5)	This study
Aride Island	2021	Adult	30	–15.9 ± 0.2 (–16.4, –15.4)	13.8 ± 0.9 (11.5–15.4)	This study
	2021	Chick	25	–16.6 ± 0.2 (–17.0, –16.3)	14.9 ± 0.2 (14.5–15.3)	This study
Etoile Cay	2021	Adult	1	–16.0	13.1	This study
African Banks	2021	Adult	3	–15.9 ± 0.3 (–16.2, –15.7)	13.5 ± 1.1 (12.5–14.6)	This study
Desnoeuf Island	2021	Adult	10	–15.9 ± 0.2 (–16.2, –15.7)	13.8 ± 0.8 (12.5–15.2)	This study
Cosmoledo Grande	2021	Adult	30	–15.9 ± 0.3 (–16.8, –15.5)	14.0 ± 0.7 (12.3–15.2)	This study
Goelette Island	2021	Adult	30	–15.8 ± 0.5 (–16.7, –13.6)	13.5 ± 1.3 (8.0–15.3)	This study
	2021	Chick	30	–15.8 ± 0.2 (–16.1, –15.5)	13.7 ± 0.3 (13.0–14.3)	This study
Europa Island	2003	Adult	18	–16.4 ± 0.4 (–17.0, –15.9)	12.4 ± 0.4 (11.9–13.2)	Cherel et al. (2008)
	2003	Chick	15	–16.6 ± 0.2 (–16.9, –16.3)	13.7 ± 0.3 (13.2–14.2)	Cherel et al. (2008)
	2021	Chick	16	–17.3 ± 0.2 (–17.5, –17.0)	13.0 ± 0.4 (12.4–13.6)	This study
Juan de Nova	2003	Adult	10	–16.4 ± 0.5 (–17.2, –15.6)	12.5 ± 0.6 (11.5–13.7)	Jaquemet et al. (2008)
	2003	Chick	10	–16.9 ± 0.3 (–17.5, –16.5)	11.7 ± 0.4 (11.1–12.3)	Jaquemet et al. (2008)
Rat Island, Houtman Abrolhos	2020	Adult	32	–16.2 ± 0.4 (–17.2, –15.6)	13.3 ± 0.4 (12.1–13.8)	This study
	2020	Chick	30	–18.4 ± 0.2 (–18.9, –18.2)	12.4 ± 0.2 (12.2–12.7)	This study

Table S4. Feather $\delta^{15}N$ values of two amino acids (AA) – glutamic acid (trophic AA) and phenylalanine (source AA) – and resulting estimated trophic position (see **Material and Methods** for further details), in feathers of adult sooty terns (*Onychoprion fuscatus*) in 19 sites across three ocean basins. Values are mean ± SD (min–max).

Ocean, Site	Year	n	Amino-acid $\delta^{15}N$ values (‰)		Trophic position
			Glutamic acid	Phenylalanine	
Pacific Ocean					
Laysan Island	2021	2	25.6 ± 1.7 (24.4–26.8)	6.1 ± 1.3 (5.2–7.0)	4.0 ± 0.1 (4.0–4.1)
Midway Atoll	2021	5	22.4 ± 2.6 (18.9–24.7)	4.0 ± 1.9 (2.0–6.6)	3.9 ± 0.2 (3.6–4.1)
Johnston Atoll	2021	5	21.9 ± 3.1 (17.4–25.5)	4.0 ± 1.6 (2.5–6.4)	3.8 ± 0.3 (3.3–4.0)
Palmyra Atoll	2021	5	22.5 ± 3.9 (18.0–28.2)	4.7 ± 2.5 (2.1–7.4)	3.7 ± 0.4 (3.4–4.3)
Motu Oa	2022	4	20.8 ± 1.9 (18.3–22.4)	2.9 ± 1.7 (0.8–4.9)	3.8 ± 0.2 (3.6–4.0)
Rose Atoll	2021	5	19.8 ± 0.7 (19.1–20.7)	3.3 ± 0.8 (2.2–4.5)	3.6 ± 0.1 (3.4–3.7)
Phillip Island	2020	5	21.7 ± 5.2 (17.5–30.3)	6.1 ± 4.5 (1.0–12.4)	3.4 ± 0.5 (2.6–3.8)
Lord Howe Island	2020	5	23.3 ± 2.8 (20.4–26.0)	5.6 ± 1.9 (3.8–8.3)	3.8 ± 0.3 (3.5–4.3)
		36			
Atlantic Ocean					
Azores	2021	1	21.4	4.0	3.7
Dog Island	2021	5	19.0 ± 2.7 (14.6–22.0)	3.4 ± 1.0 (2.4–5.0)	3.4 ± 0.4 (2.8–3.8)
Dry Tortugas	2021	5	18.8 ± 1.1 (17.4–20.3)	3.1 ± 0.8 (2.1–4.2)	3.4 ± 0.1 (3.3–3.6)
Culebra	2021	5	19.4 ± 2.1 (16.2–21.5)	2.9 ± 1.7 (0.6–4.8)	3.6 ± 0.2 (3.4–3.8)
Fernando de Noronha	2011	4	18.8 ± 1.4 (17.3–20.5)	1.9 ± 1.3 (0.6–3.5)	3.6 ± 0.1 (3.5–3.7)
Ascension Island	2020	5	20.4 ± 1.2 (19.0–22.0)	3.4 ± 0.4 (2.9–3.8)	3.6 ± 0.2 (3.4–3.8)
	2021	5	21.3 ± 1.3 (20.0–23.3)	4.6 ± 0.3 (4.0–4.9)	3.6 ± 0.2 (3.3–3.9)
Tinhosas Grande	2021	5	19.8 ± 0.7 (19.1–20.7)	3.3 ± 0.8 (2.3–4.5)	3.6 ± 0.1 (3.4–3.7)
		36			
Indian Ocean					
Aride Island	2021	5	22.2 ± 1.3 (20.6–23.9)	4.3 ± 1.1 (3.5–6.2)	3.8 ± 0.1 (3.7–3.9)
Europa Island	2003	5	21.4 ± 0.6 (20.8–22.1)	3.4 ± 0.6 (2.7–4.0)	3.8 ± 0.1 (3.7–3.8)
Juan de Nova	2003	5	21.2 ± 0.8 (19.9–22.0)	3.1 ± 0.6 (2.4–3.7)	3.8 ± 0.1 (3.7–4.0)
Rat Island	2020	5	21.5 ± 3.4 (17.5–26.9)	4.1 ± 0.7 (3.2–5.0)	3.7 ± 0.5 (3.0–4.4)
		20			
Total		**91**			**3.7 ± 0.3 (2.6–4.4)**

II- Supplementary figures

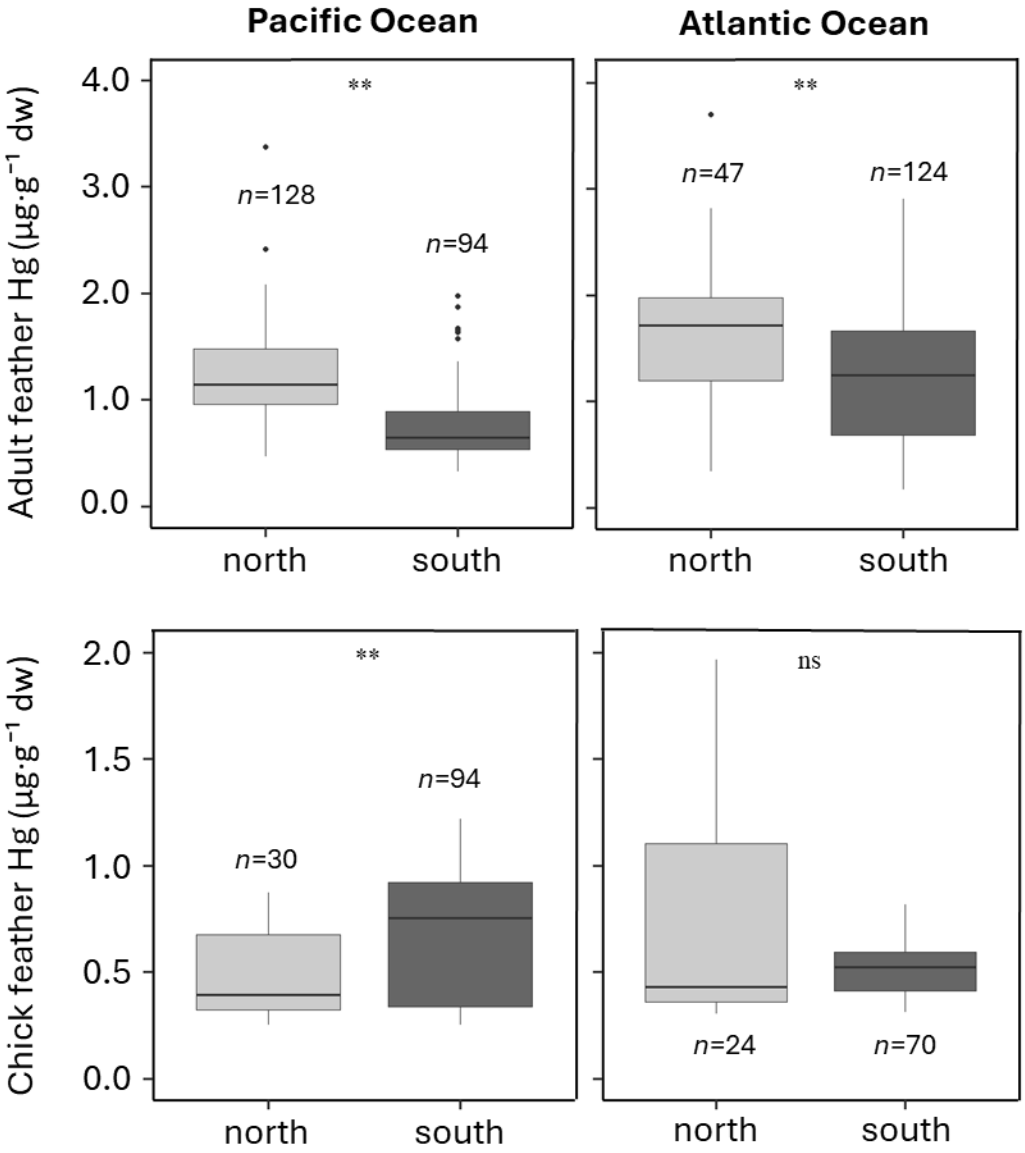

Fig. S1. Hemispheric Hg concentrations (µg·g^{-1} dw) in sooty tern (*Onychoprion fuscatus*; global subset, cf. **Materials and Methods**) adults and chicks, from two different tropical oceans: the Pacific (left) and Atlantic (right) Oceans. Comparisons were made between the Northern and the Southern Hemispheres. n indicates sample sizes. ** indicates statistical difference when detected (Wilcoxon rank sum test). ns refers to non-significant difference detected. Boxplots indicate median values (midlines), errors bars (whiskers) and outliers (black dots).

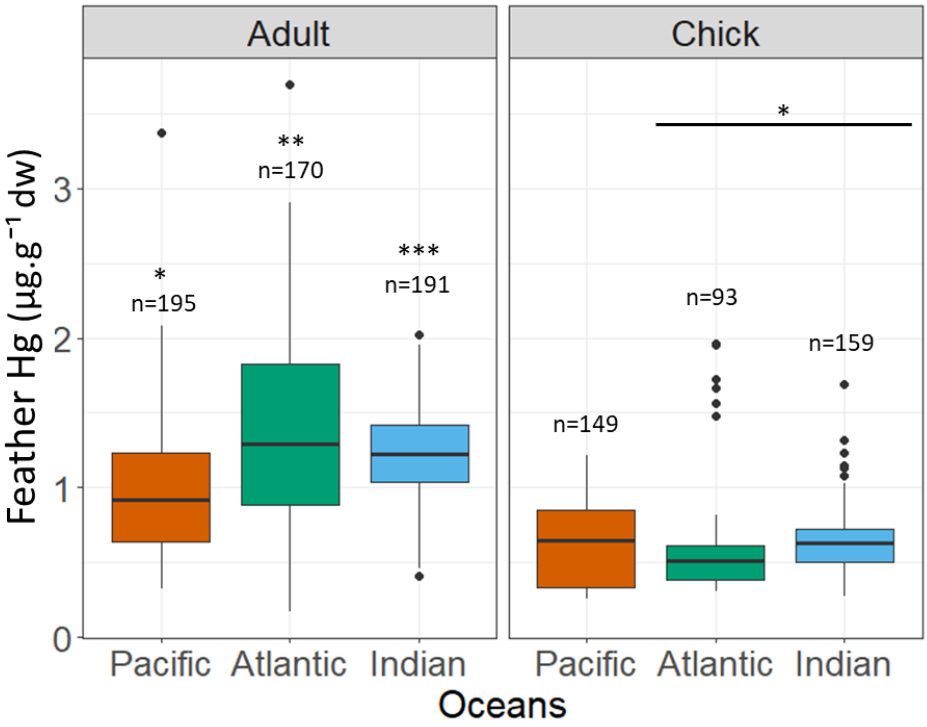

Fig. S2. Ocean comparison of feather Hg concentrations (µg·g^{-1} dw) in sooty tern (*Onychoprion fuscatus*) adults (left) and chicks (right) (global subset, only includes sites where n>4). n indicates sample sizes. * indicates when statistical difference was detected (Kruskal-Wallis test): (i) for adults, three different groups were detected, as identified by *, ** and ***; (ii) for chicks, only one statistical difference was detected between two oceans (identified by the line). Boxplots indicate median values (midlines), errors bars (whiskers) and outliers (black dots).

Statistical results

For the CSIA subset (n=88), feather Hg concentrations were different between colonies (Kruskal-Wallis, $\chi^2(17) = 43.1$, p=0.0005; Figure S3.A) and ocean basins (Kruskal-Wallis, $\chi^2(2) = 12.6$, p=0.002; Figure S4), with higher concentrations in the Atlantic Ocean (1.51 ± 0.78, n=34) compared to the Pacific (1.04 ± 0.52, n=36) and Indian (1.01 ± 0.38, n=20) Oceans (Figure S3.A).

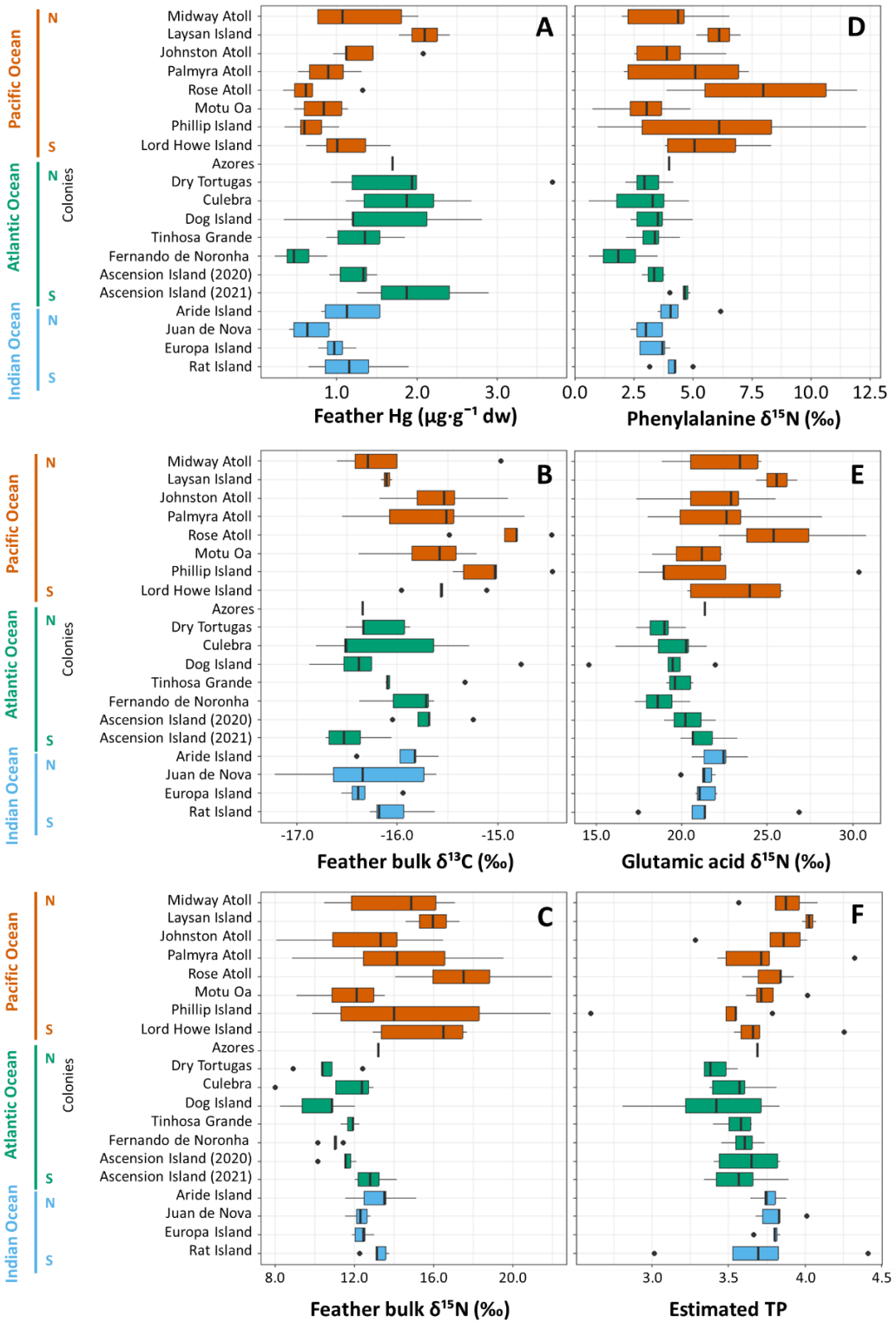

Fig. S3. Feather **(A)** Hg concentrations (µg·g^{-1} dw) and stable isotope values (‰) of adult sooty terns (*Onychoprion fuscatus*; n=91) in tropical oceans (*i.e.,* 19 sites), including bulk **(B)** δ^{13}C and **(C)** δ^{15}N values, and **(D)** Phenylalanine and **(E)** Glutamic acid δ^{15}N values, as well as **(F)** estimated trophic position (TP). Boxplots indicate median values (midlines), errors bars (whiskers) and outliers (black dots).

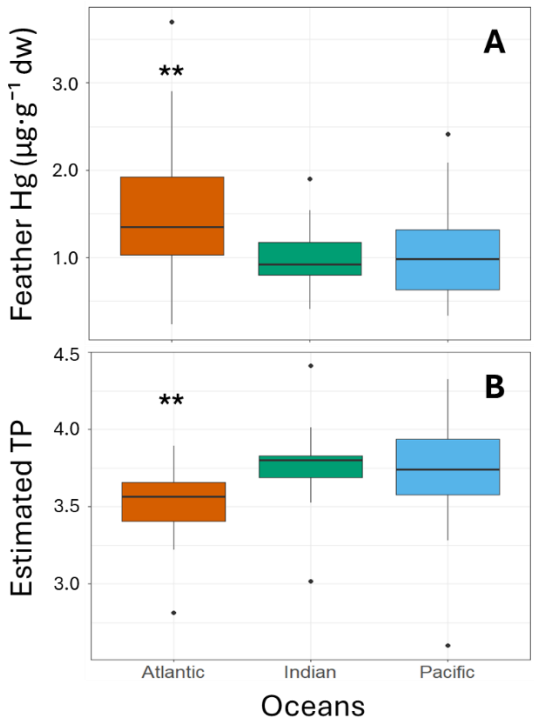

Fig. S4. Difference between ocean basins in feather **(A)** Hg concentrations (µg·g^{-1} dw), **(B)** estimated trophic position (TP; calculated from δ^{15}N values of glutamic acid and phenylalanine; cf. **Material and Methods**) from adult sooty terns (n=91; CSIA subset). The symbol ** indicates when an ocean was statistically different to all others. Boxplots indicate median values (midlines), errors bars (whiskers) and outliers (black dots).

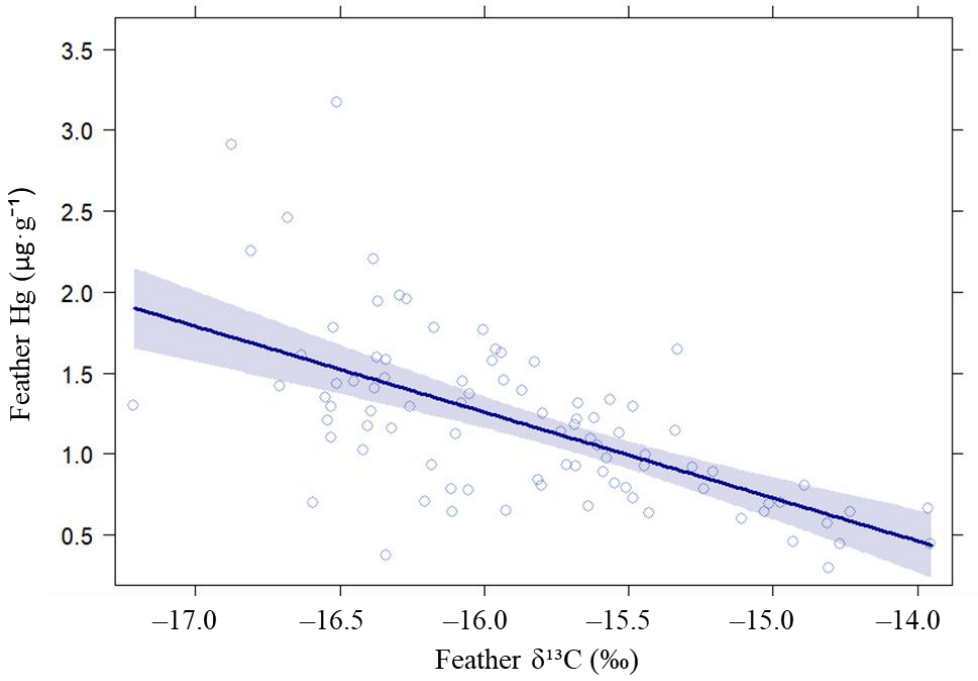

Fig. S5. Relationship (regression and confidence interval) between feather Hg concentrations (µg·g^{-1} dw) and bulk δ^{13}C values (‰) in adult sooty terns (CSIA subset; n=88), resulting from the extraction of partial residuals of the best Generalized Linear Model (GLM; see Table 2 and Material and Methods for further details). Individual data are represented in light blue (open circle).

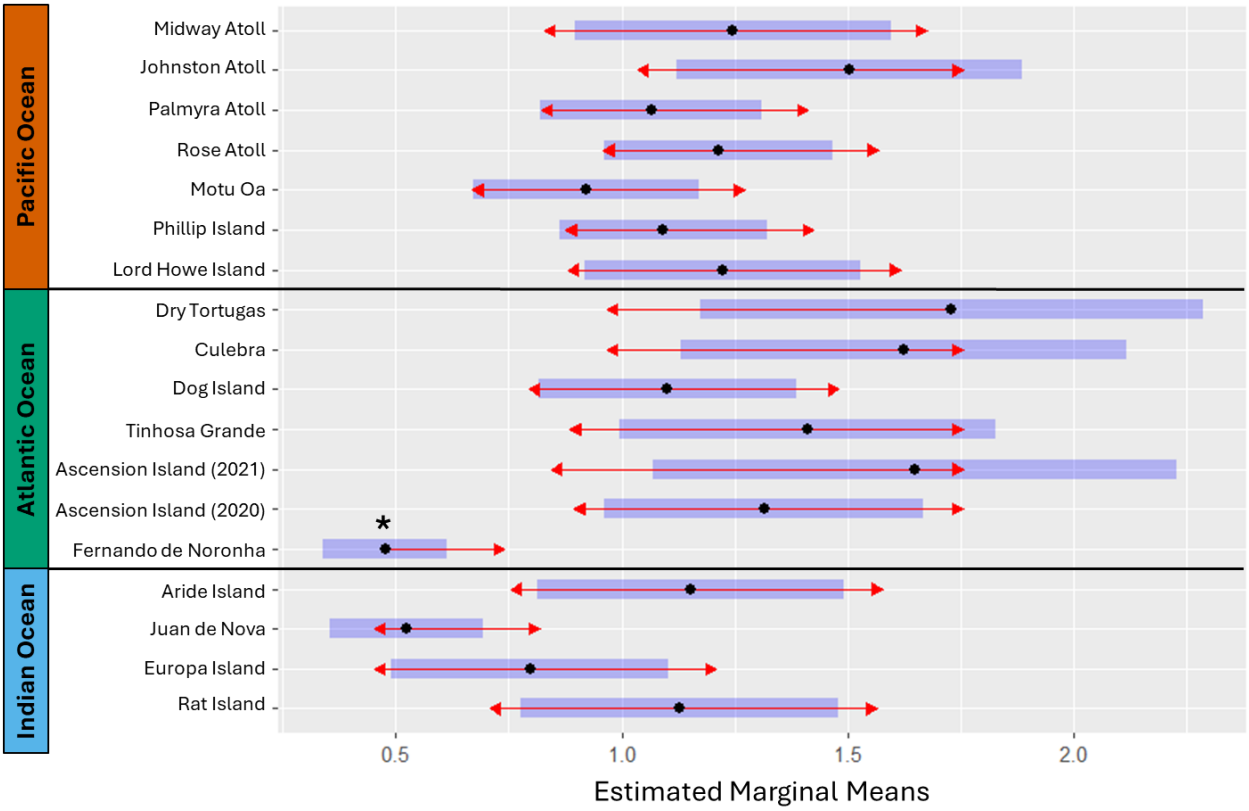

Fig. S6. Estimated Marginal Means (EMM) feather Hg concentrations for adult sooty terns (*Onychoprion fuscatus*; n=88) sampled across 17 colonies in three ocean basins (Pacific, Atlantic and Indian Oceans). Estimates were derived from the best-ranked generalized linear model (GLM with Gamma distribution and identity link-function) defined as follows: Hg ~ $\delta^{13}C$ + Colony (see **Table 2** for further details). Differences were considered significant (*) when confidence intervals (red arrows) do not overlap.