Supplementary Information

Title: Regional restructuring in planktic foraminifera communities through Pliocene-early Pleistocene climate variability

Authors: Ekaterina Larina[1*], Adam Woodhouse[2,3,4], Anshuman Swain[5,6,7], Christopher M. Lowery[2], Rowan C. Martindale[1], and Corinne E. Myers[8]

Affiliations

[1] Department of Earth and Planetary Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, 78712, USA

[2] University of Texas Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, 78758, U.S.A.

[3] School of Earth Sciences, University of Bristol, Bristol, BS8 1 RJ, United Kingdom

[4] School of Earth and Environmental Sciences, Cardiff University, Cardiff, CF10 3AT, UK

[5] Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA

[6]Museum of Paleontology, University of Michigan, Ann Arbor, MI 48109, USA

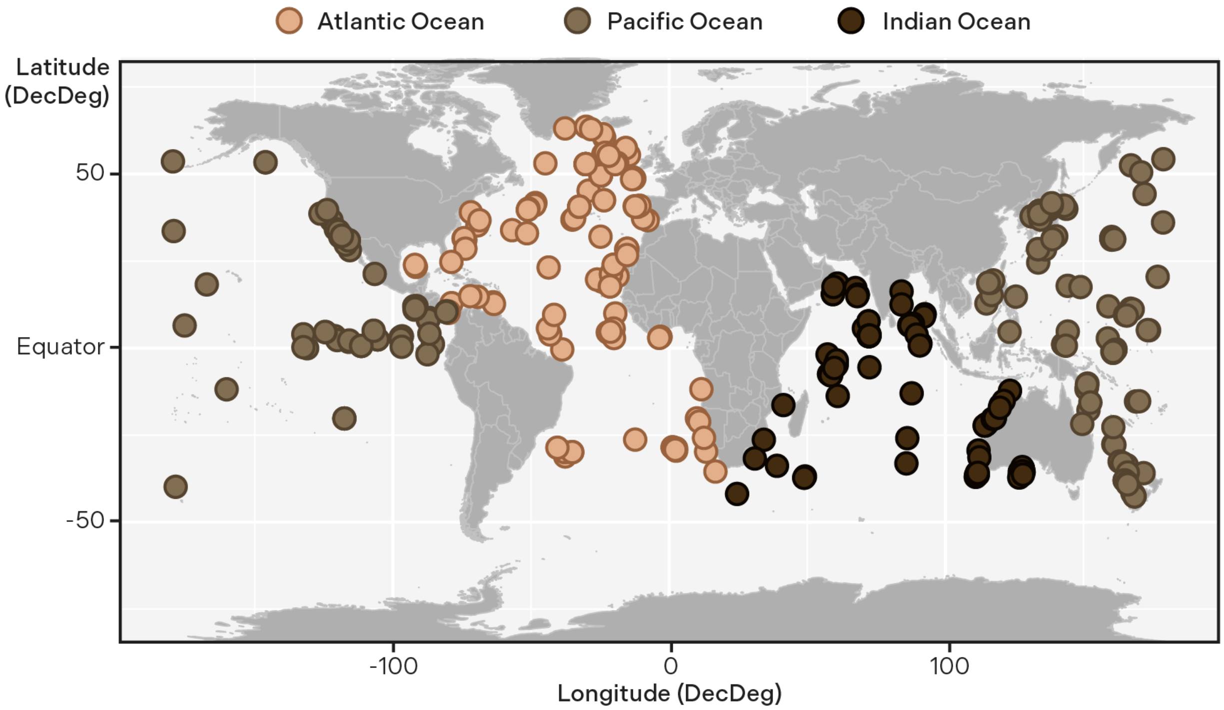
[7]Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138, USA

[8]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, U.S.A.

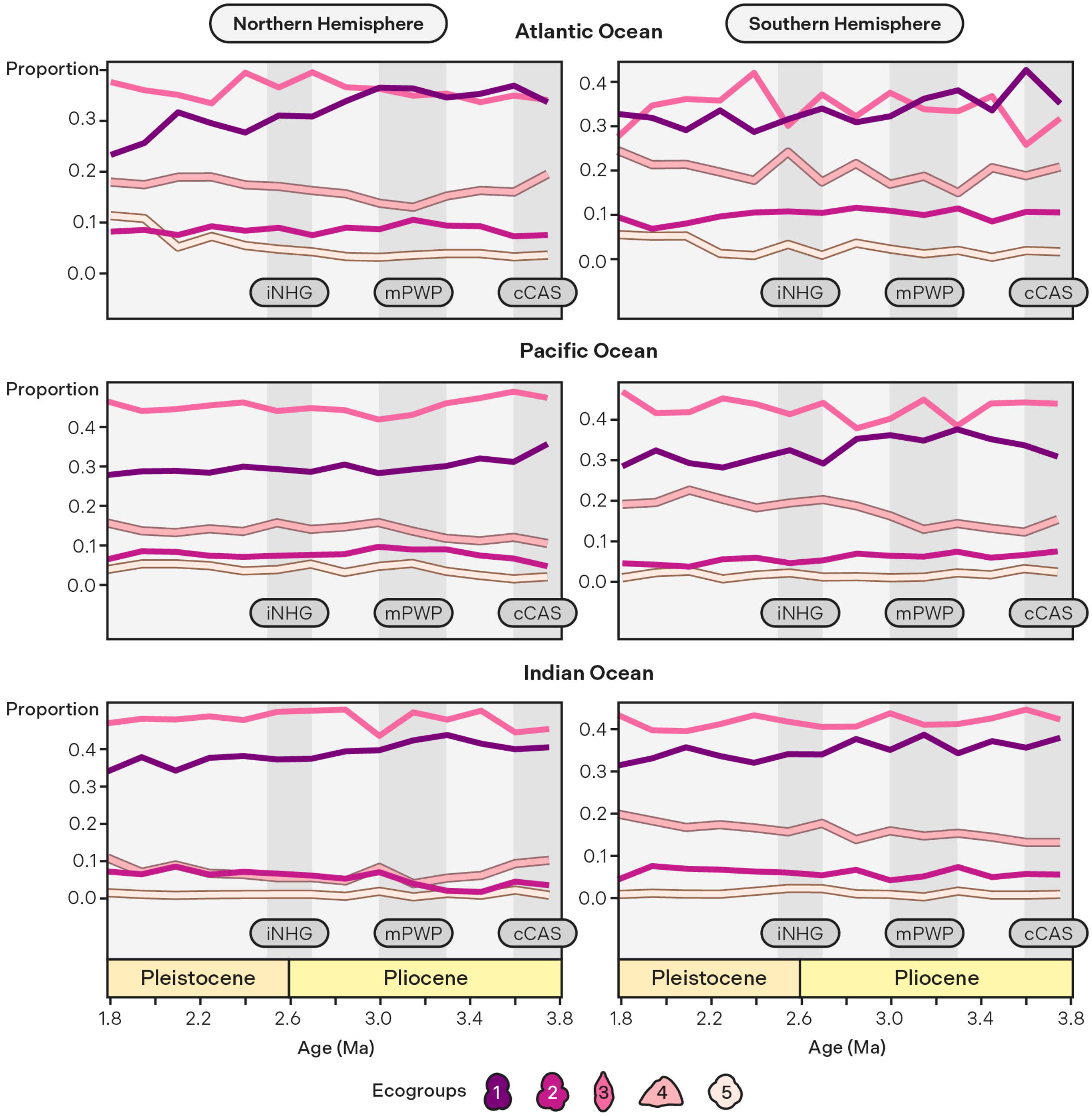
Correspondence: elarina@jsg.utexas.edu

Code availability

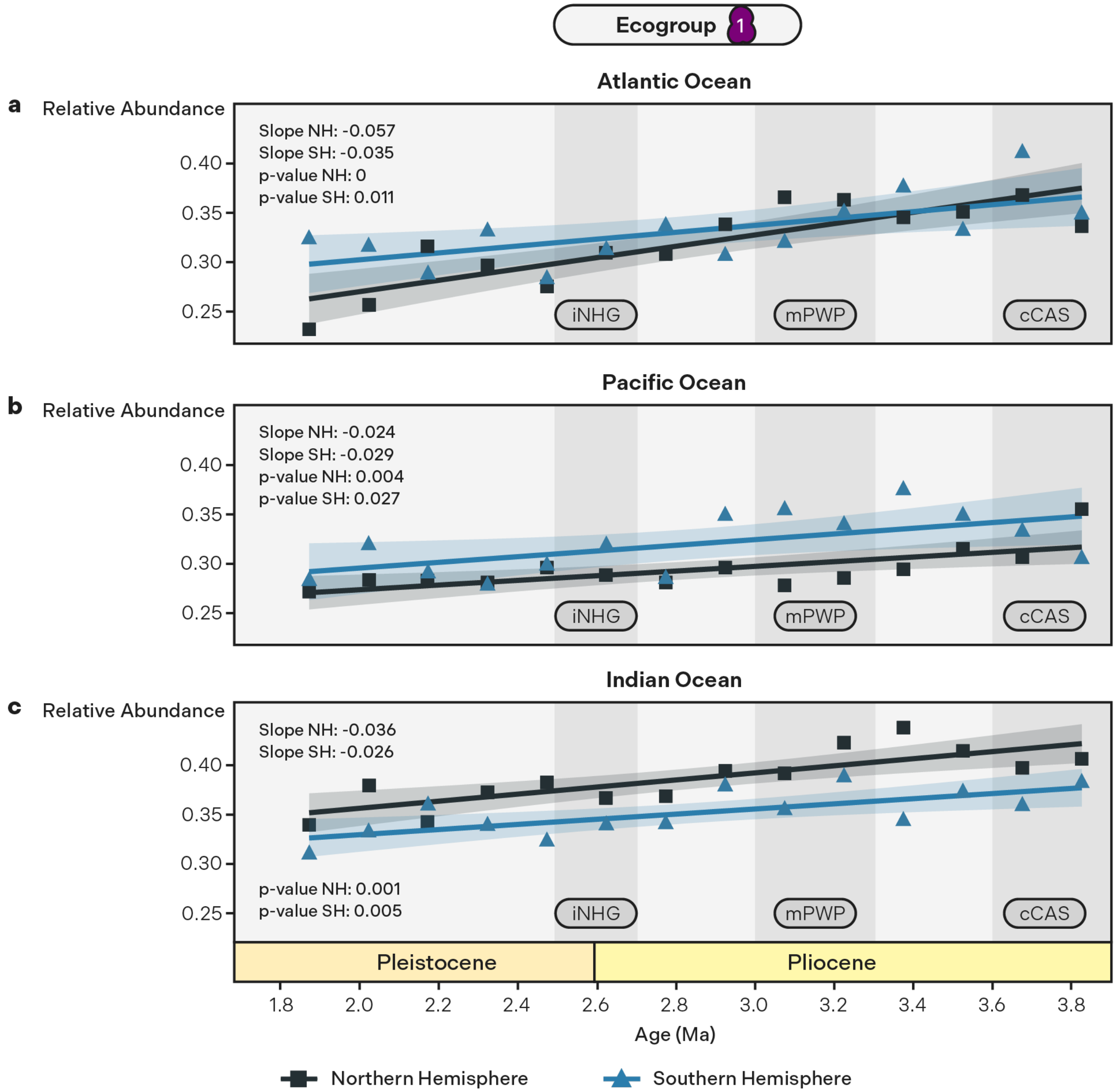
Code is available at https://github.com/ekatlarina/forams-ecogroups.



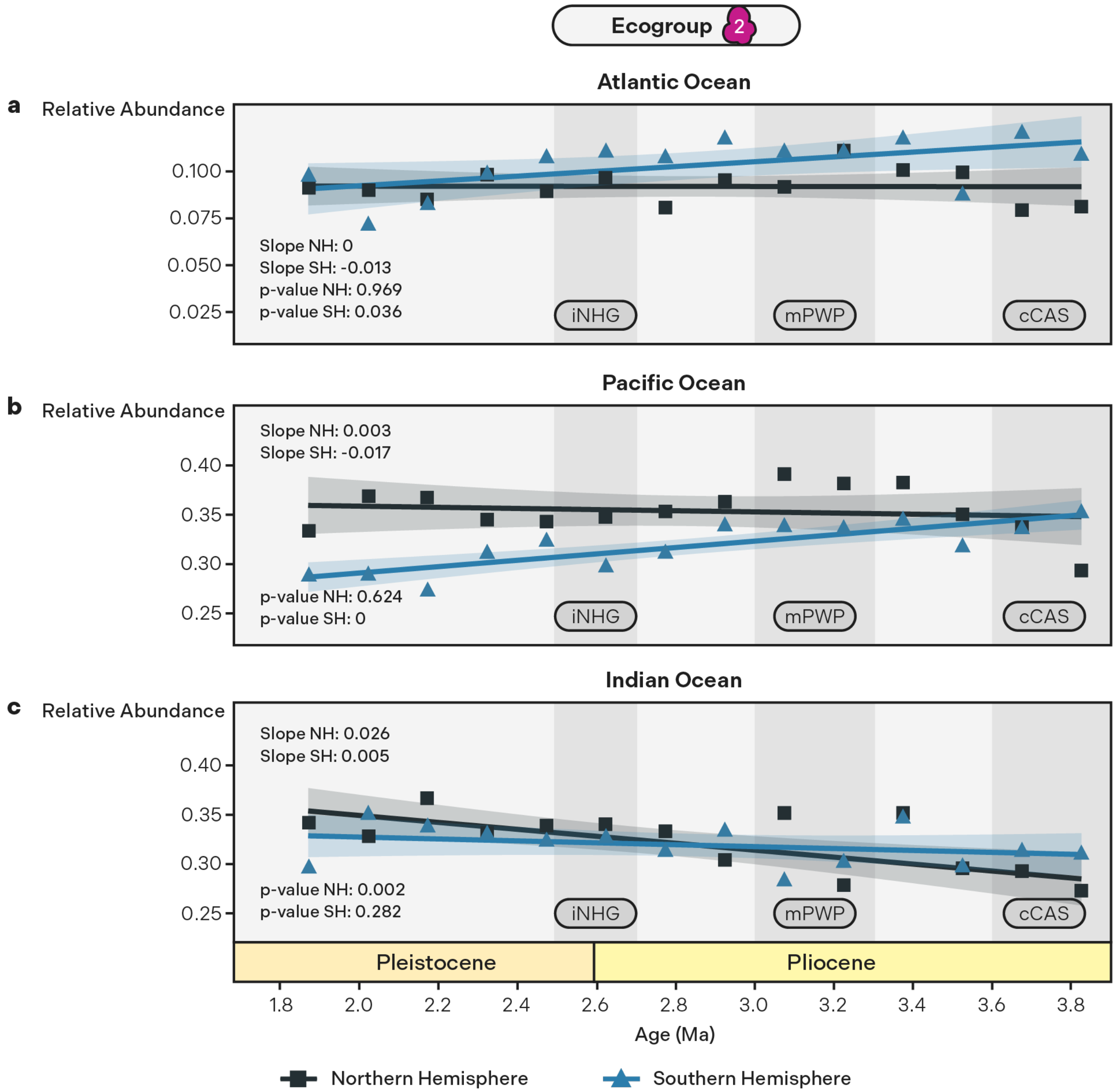
Supplementary Figure 1. Location of sediment cores (n = 370) used in this study from 1.8 to 3.9 Ma. Atlantic Ocean (n = 127), Pacific (n = 156), and Indian (n = 87). Source data are available at https://zenodo.org/records/15344269.



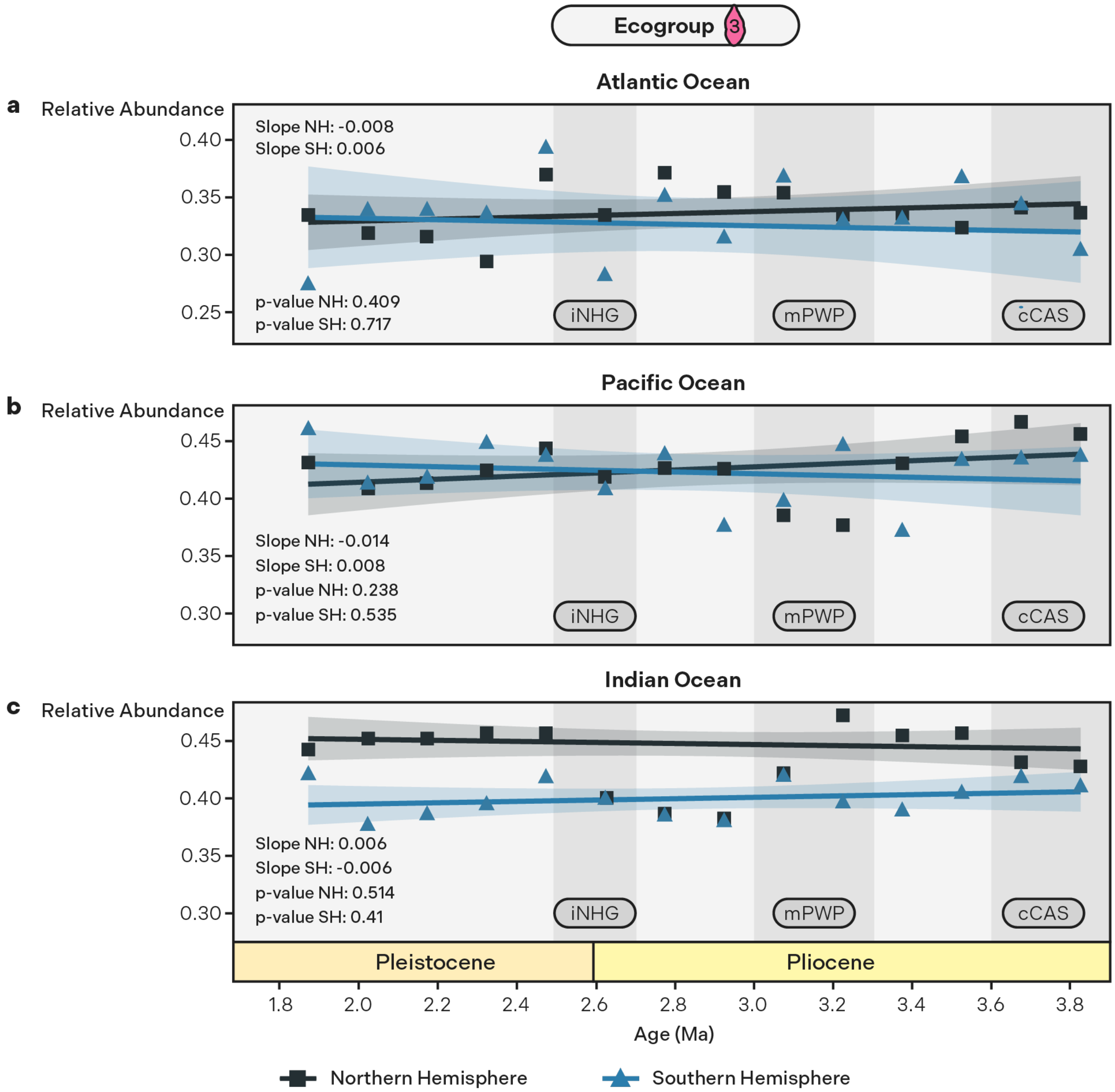
Supplementary Figure 2. Temporal trends in ecogroup relative abundance across the Pliocene - early Pleistocene in the Atlantic, Pacific, and Indian Oceans in the Northern and Southern Hemispheres. The reconfiguration of ecogroup distribution - particularly among high-latitude dwellers (ecogroup 5) and warm-water symbiotic dwellers (ecogroup 1) in the Atlantic's Northern Hemisphere - and the increased abundance of subthermocline taxa (ecogroup 4) across all ocean basins, with a significant presence in the South Pacific, coincide with the onset of iNHG. cCAS = closure of the Central American Seaway; mPWP = the mid-Pliocene Warm Period; iNHG = the intensification of the Northern Hemisphere Glaciation. Ecogroup 1 - open ocean surface mixed layer (SML) tropical/subtropical dwellers with algal photosymbionts. Ecogroup 2 - open ocean SML tropical/subtropical dwellers without algal photosymbionts. Ecogroup 3 - open ocean thermocline dwellers. Ecogroup 4 - open ocean sub-thermocline dwellers. Ecogroup 5 - high-latitude dwellers. Source data are available at https://zenodo.org/records/15344269.



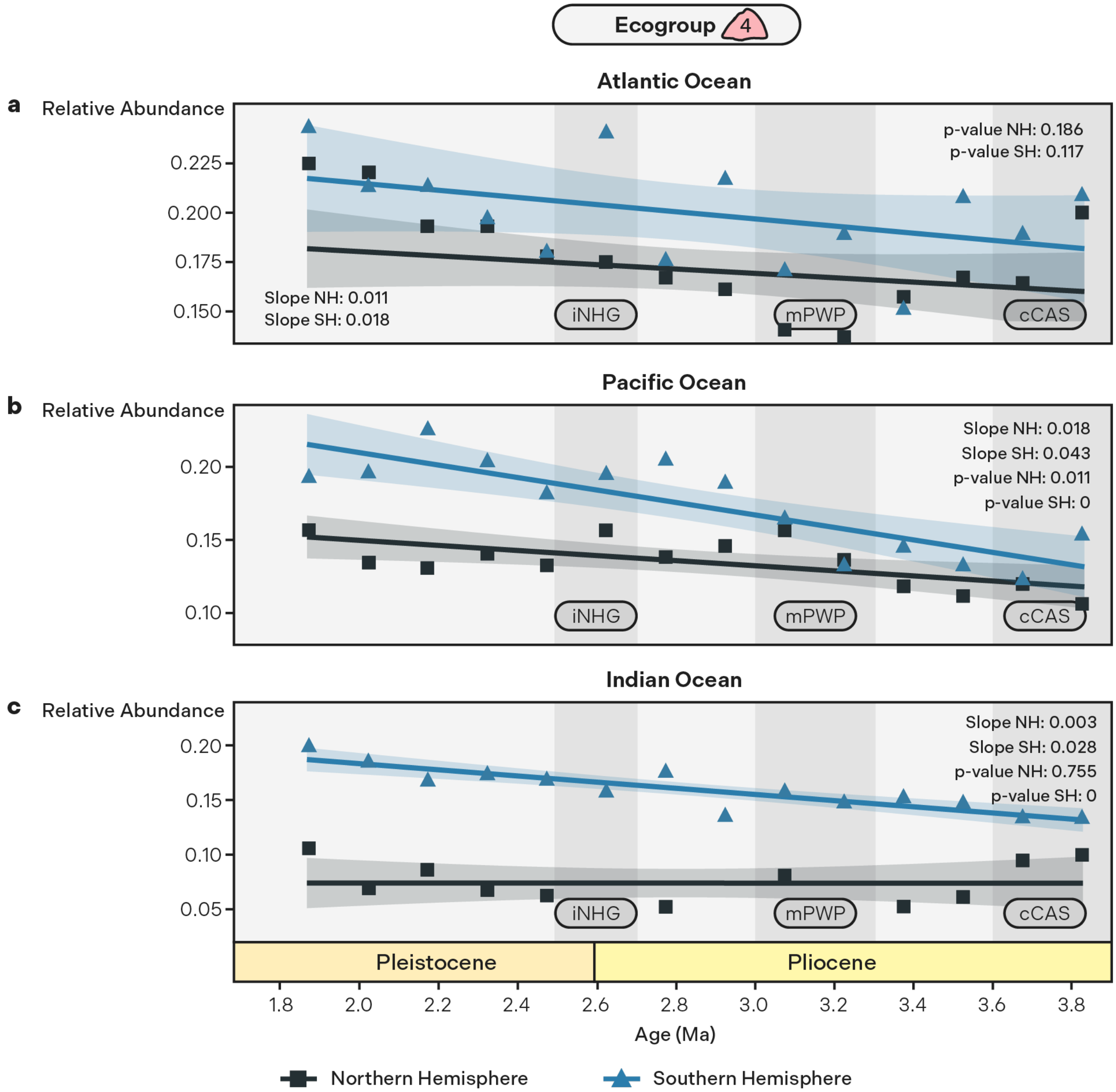
Supplementary Figure 3. Fitted linear models of ecogroup 1 relative abundances by hemisphere across the Atlantic (a), Pacific (b), and Indian (c) Oceans. The slopes of these fitted linear models were calculated to quantify the rates of change in the relative abundance of ecogroup 1 across hemispheres and basins. A positive slope indicates an increase in the number of ecogroup 1 dwellers since 3.9 Ma, while a negative slope indicates a decrease. The number of ecogroup 1 dwellers consistently decreased across all basins, with the highest decrease recorded in the North Atlantic. All fitted models include 95% confidence intervals in gray. cCAS = closure of the Central American Seaway; mPWP = the mid-Pliocene Warm Period; iNHG = the intensification of the Northern Hemisphere Glaciation. NH = Northern Hemisphere; SH = Southern Hemisphere. Source data are available at https://zenodo.org/records/15344269.



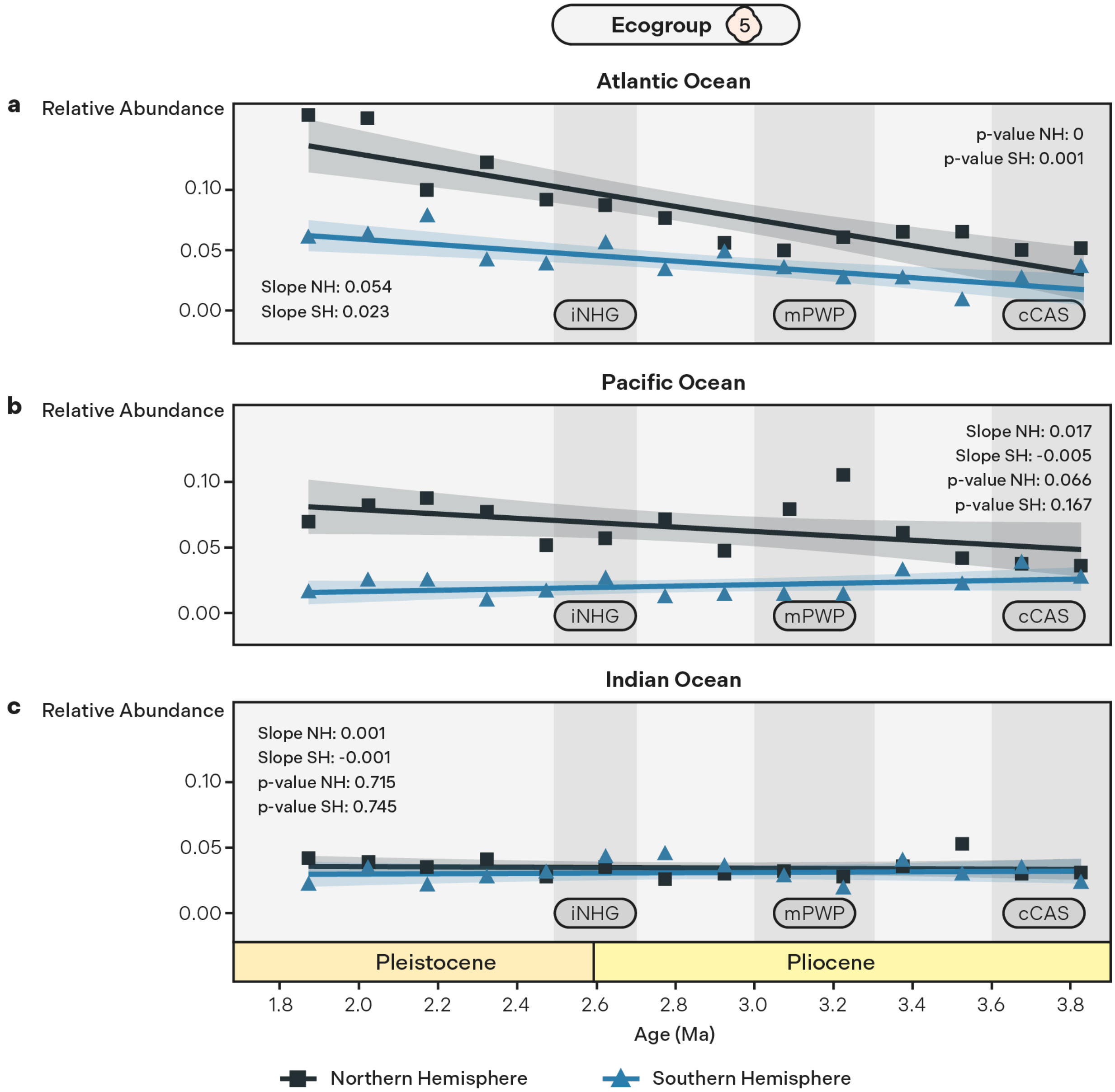
Supplementary Figure 4. Fitted linear models of ecogroup 2 relative abundances by hemisphere across the Atlantic (a), Pacific (b), and Indian (c) Oceans. The slopes of these fitted linear models were calculated to quantify the rates of change in the relative abundance of ecogroup 2 across hemispheres and basins. A positive slope indicates an increase in ecogroup 2 dwellers since 3.9 Ma, while a negative slope indicates a decrease. Ecogroup 2 populations showed moderate to no increase in the Northern Hemisphere across all basins, with a modest decline observed in the South Atlantic and South Pacific. All fitted models include 95% confidence intervals shown in gray. cCAS = closure of the Central American Seaway; mPWP = the mid-Pliocene Warm Period; iNHG = the intensification of the Northern Hemisphere Glaciation. NH = Northern Hemisphere; SH = Southern Hemisphere. Source data are available at https://zenodo.org/records/15344269.



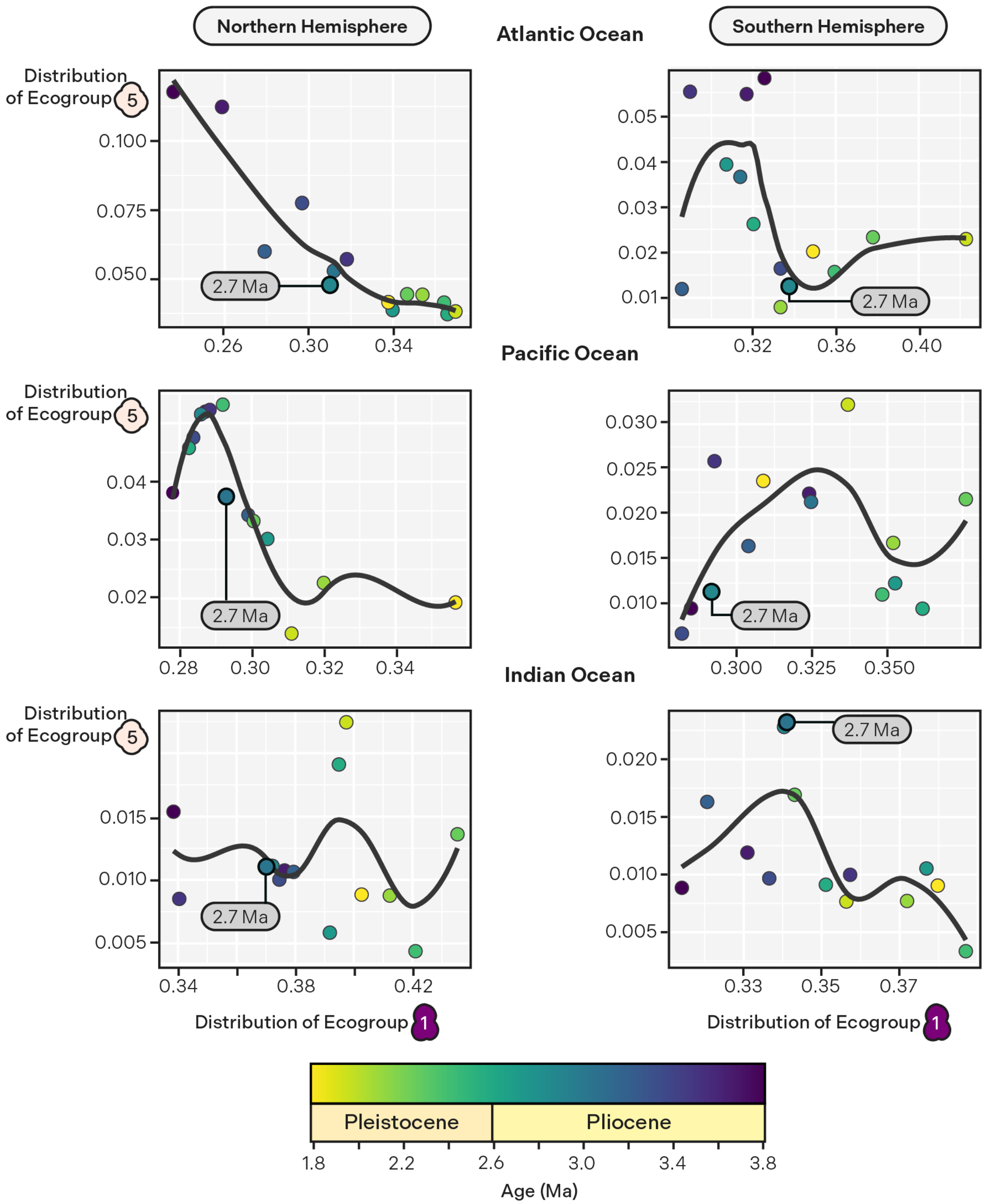
Supplementary Figure 5. Fitted linear models of ecogroup 3 relative abundances by hemisphere across the Atlantic (a), Pacific (b), and Indian (c) Oceans. The slopes of these fitted linear models were calculated to quantify the rates of change in the relative abundance of ecogroup 3 across hemispheres and basins. A positive slope indicates an increase in the number of ecogroup 3 dwellers since 3.9 Ma, while a negative slope indicates a decrease. The rate of change in the number of ecogroup 3 dwellers remained relatively consistent across the Pliocene - early Pleistocene. All fitted models include 95% confidence intervals shown in gray. cCAS = closure of the Central American Seaway; mPWP = the mid-Pliocene Warm Period; iNHG = the intensification of the Northern Hemisphere Glaciation. NH = Northern Hemisphere; SH = Southern Hemisphere. Source data are available at https://zenodo.org/records/15344269.



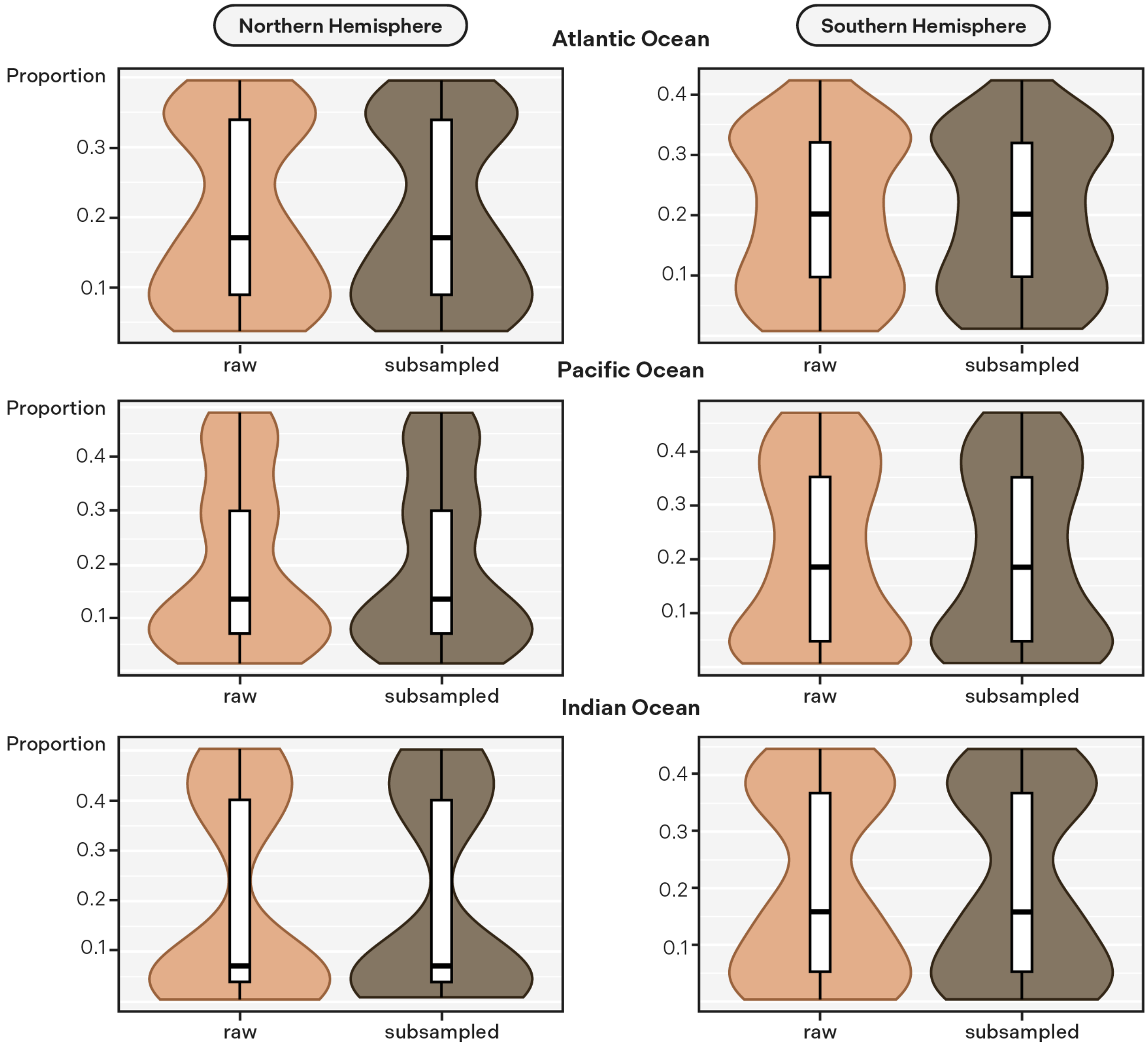
Supplementary Figure 6. Fitted linear models of ecogroup 4 relative abundances by hemisphere across the Atlantic (a), Pacific (b), and Indian (c) Oceans. The slopes of these fitted linear models were calculated to quantify the rates of change in the relative abundance of ecogroup 4 across hemispheres and basins. A positive slope indicates an increase in the number of ecogroup 4 dwellers since 3.9 Ma, while a negative slope indicates a decrease. The number of ecogroup 4 dwellers consistently increased across all basins, experiencing the highest rise in the South Pacific. The rise in the Northern Hemisphere was insignificant. All fitted models include 95% confidence intervals shown in gray. cCAS = closure of the Central American Seaway; mPWP = the mid-Pliocene Warm Period; iNHG = the intensification of the Northern Hemisphere Glaciation. NH = Northern Hemisphere; SH = Southern Hemisphere. Source data are available at https://zenodo.org/records/15344269.



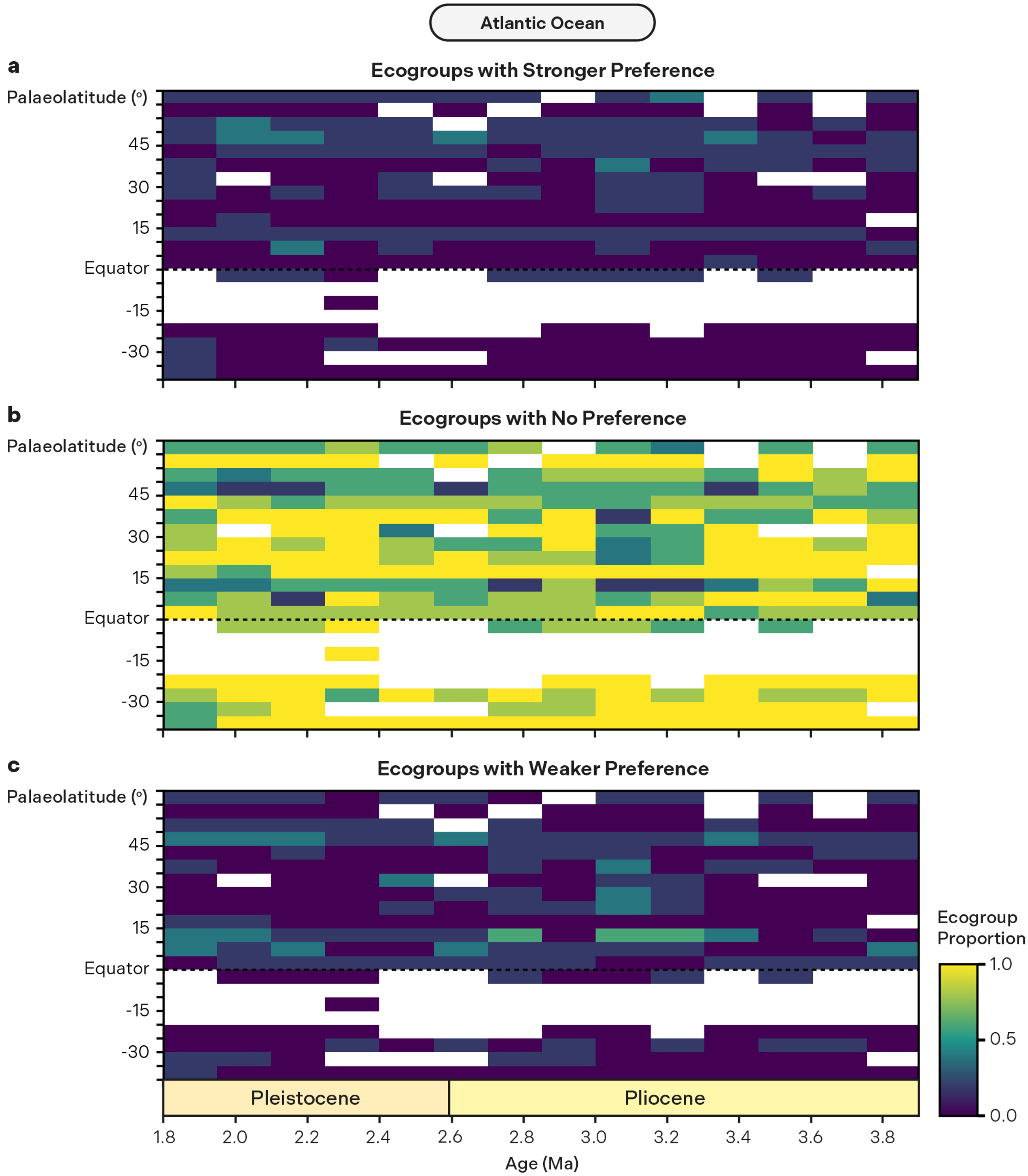
Supplementary Figure 7. Fitted linear models of ecogroup 5 relative abundances by hemisphere across the Atlantic (a), Pacific (b), and Indian (c) Oceans. The slopes of these fitted linear models were calculated to quantify the rates of change in the relative abundance of ecogroup 5 across hemispheres and basins. A positive slope indicates an increase in the number of ecogroup 5 dwellers since 3.9 Ma, while a negative slope indicates a decrease. The population of ecogroup 5 increased in the Atlantic, particularly in its Northern Hemisphere, while it remained stable in the Indian Ocean. The North Pacific exhibited a slight increase in the number of ecogroup 5 dwellers. All fitted models include 95% confidence intervals shown in gray. cCAS = closure of the Central American Seaway; mPWP = the mid-Pliocene Warm Period; iNHG = the intensification of the Northern Hemisphere Glaciation. NH = Northern Hemisphere; SH = Southern Hemisphere. Source data are available at https://zenodo.org/records/15344269.



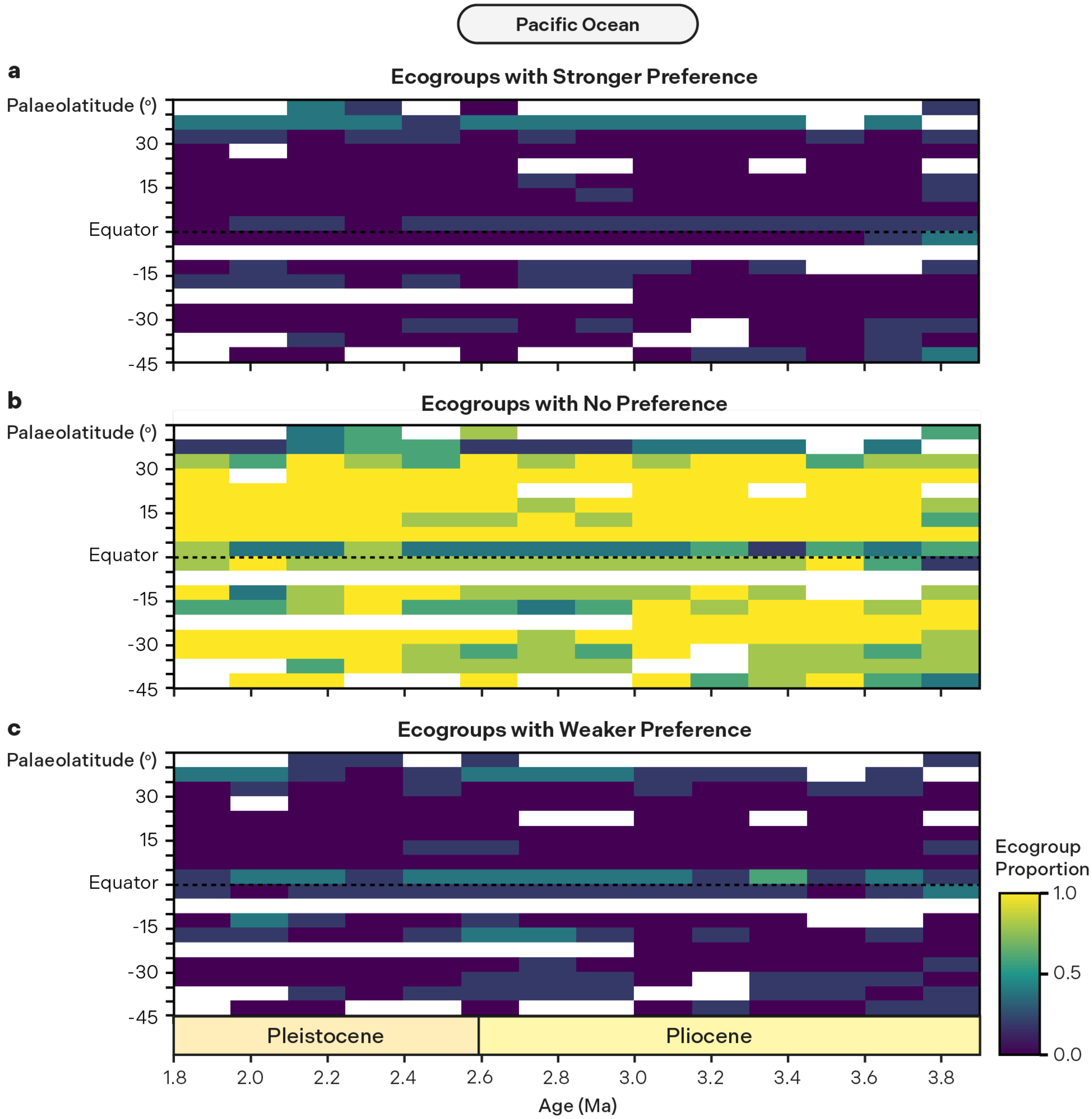
Supplementary Figure 8. Comparative analysis of ecogroup 5 (high-latitude) and ecogroup 1 (tropical/subtropical species with algal photosymbionts) dwellers' distributions across the Atlantic, Pacific, and Indian Oceans. A noticeable negative correlation between the distributions of these ecogroups emerges in the North Atlantic, coinciding with the onset of the intensification of Northern Hemisphere Glaciation at ~2.7 Ma. Scattered data smoothed using a locally estimated scatterplot smoothing (LOESS), depicted as a black line. Significant correlations between ecogroups 1 and 5 ($p < 0.05$) were observed exclusively in the Atlantic and North Pacific. Source data are available at https://zenodo.org/records/15344269.



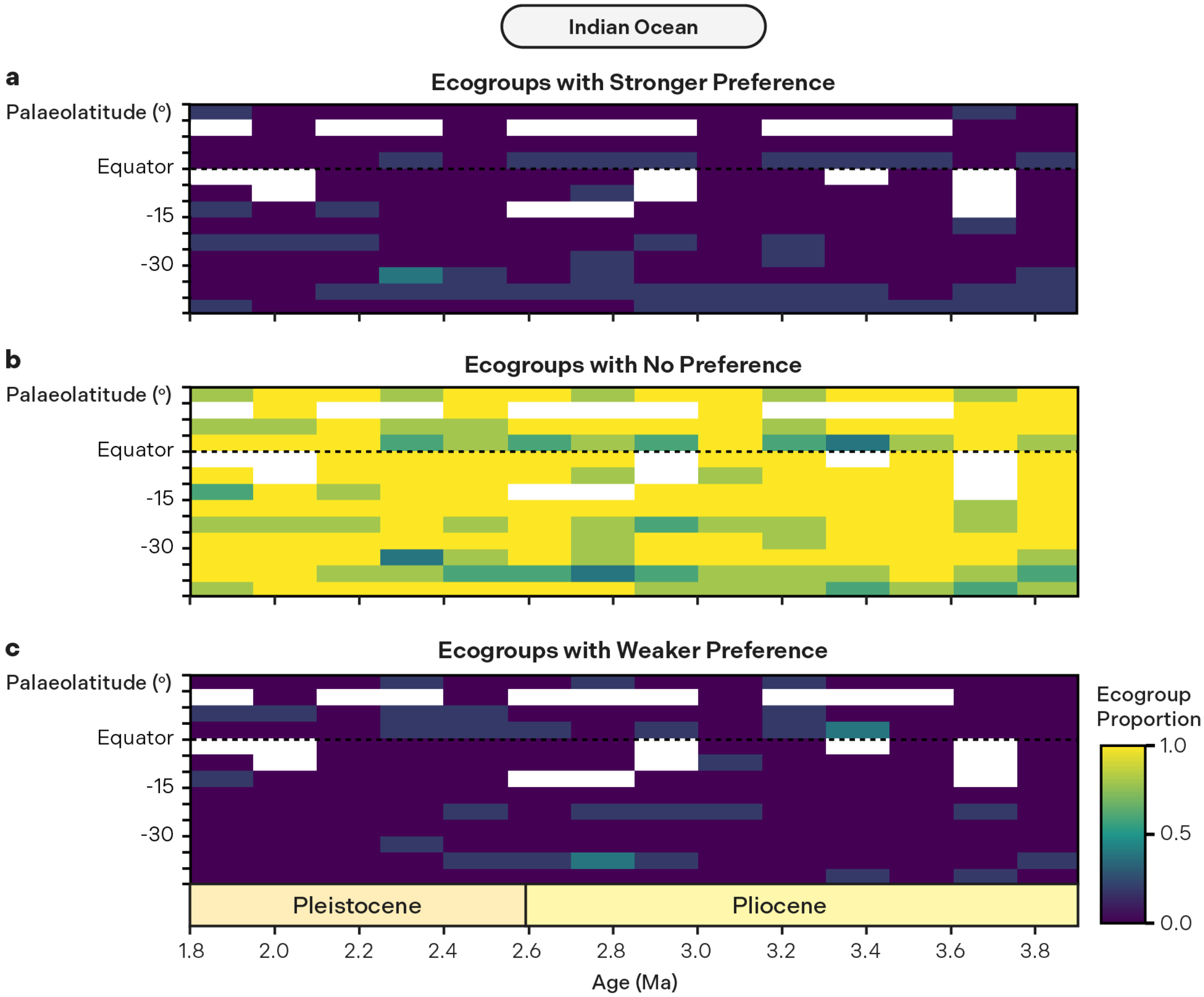
Supplementary Figure 9. Comparing ecogroup distributions from raw and subsampled data across hemispheres in the Atlantic, Pacific, and Indian Oceans. We performed resampling of ecogroup distribution data without replacement (n = 1000) for each 150-kyr time bin, matching the smallest number of cores in any 150-kyr bin. Minimum number of cores per region: Northern Atlantic = 30, Southern Atlantic = 4, Northern Pacific = 36, Southern Pacific = 11, Northern Indian = 9, Southern Indian = 17. The analysis revealed that both raw and subsampled datasets exhibit identical distributions, suggesting that the observed patterns in our study are not influenced by sampling differences or the use of raw data. Source data are available at https://zenodo.org/records/15344269.



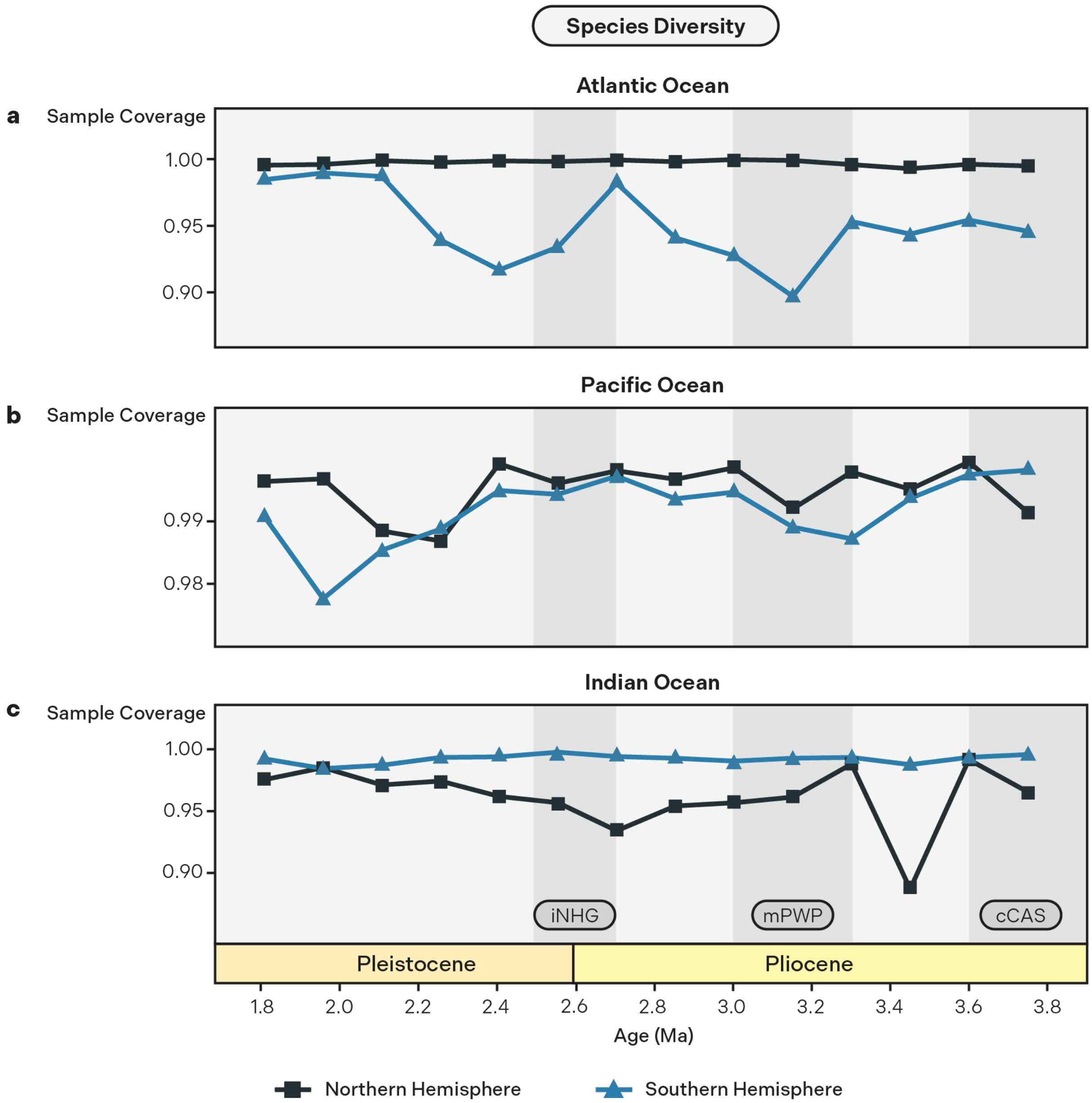
Supplementary Figure 10. The Pliocene - early Pleistocene null models and ecogroup preferences in the Atlantic Ocean. The plot shows the proportion of ecogroups in a given bin that have stronger (a), no preference (b), or weaker preference (c) as compared to their respective null models. These results reveal that the distribution of ecogroups significantly deviates from what would be expected by mere random chance. The number of resampling procedures is 500. Source data are available at https://zenodo.org/records/15344269.



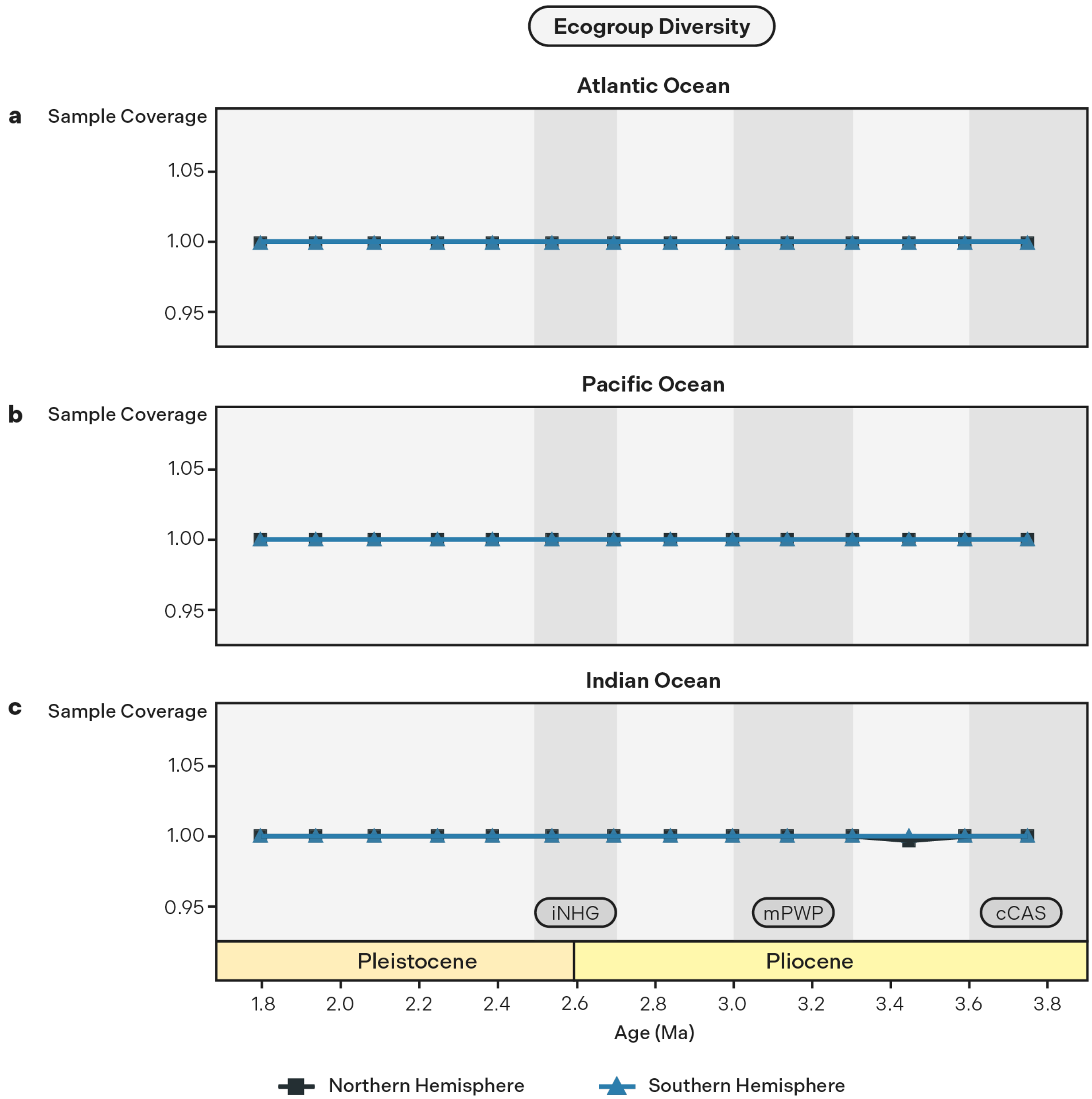
Supplementary Figure 11. The Pliocene - early Pleistocene null models and ecogroup preferences in the Pacific Ocean. The plot shows the proportion of ecogroups in a given bin that have stronger (a), no preference (b), or weaker preference (c) as compared to their respective null models. These results reveal that the distribution of ecogroups significantly deviates from what would be expected by mere random chance. The number of resampling procedures is 500. Source data are available at https://zenodo.org/records/15344269.



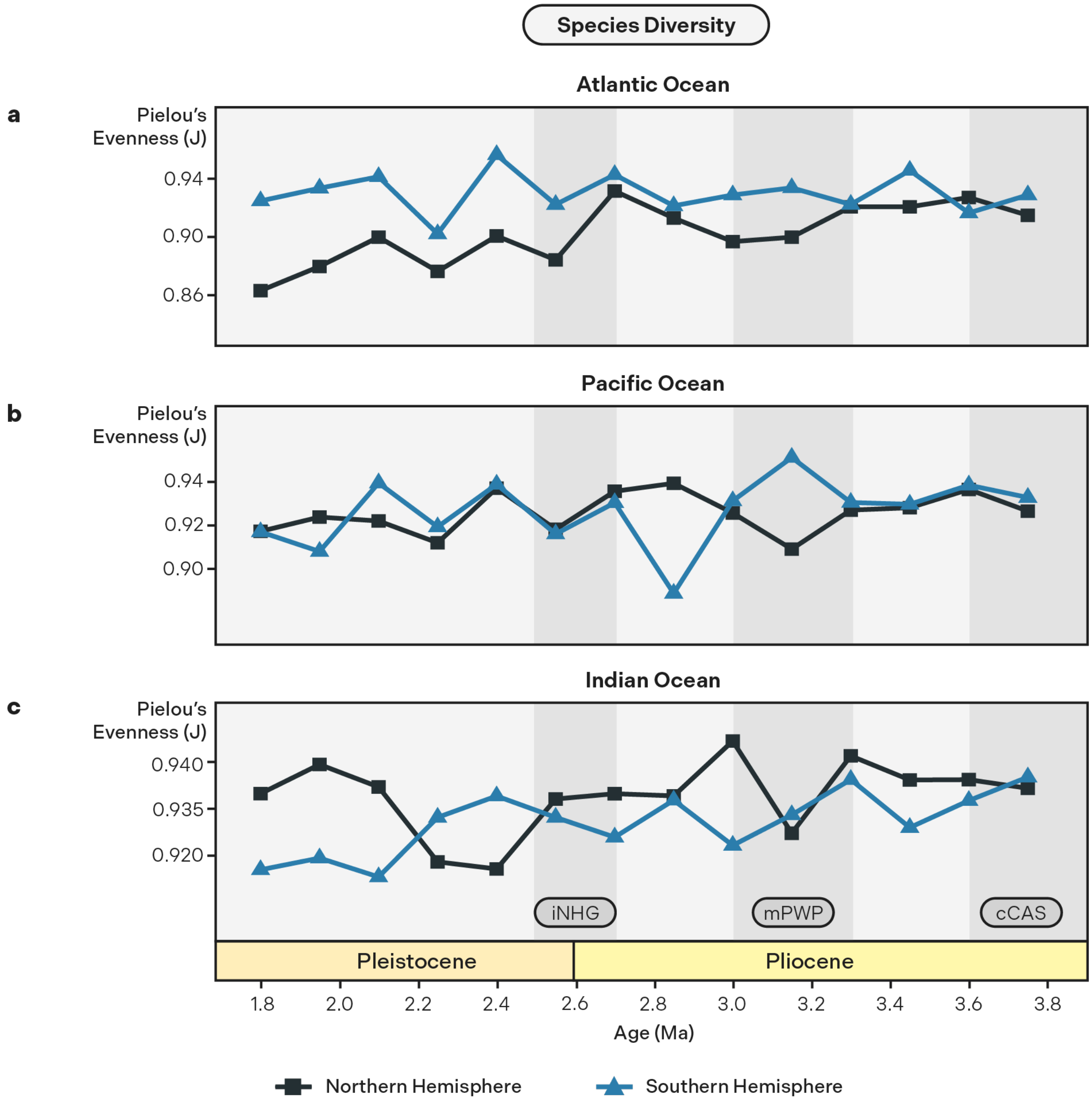
Supplementary Figure 12. The Pliocene - early Pleistocene null models and ecogroup preferences in the Indian Ocean. The plot shows the proportion of ecogroups in a given bin that have stronger (a), no preference (b) or weaker preference (c) as compared to their respective null models. These results reveal that the distribution of ecogroups significantly deviates from what would be expected by mere random chance. The number of resampling procedures is 500. Source data are available at https://zenodo.org/records/15344269.



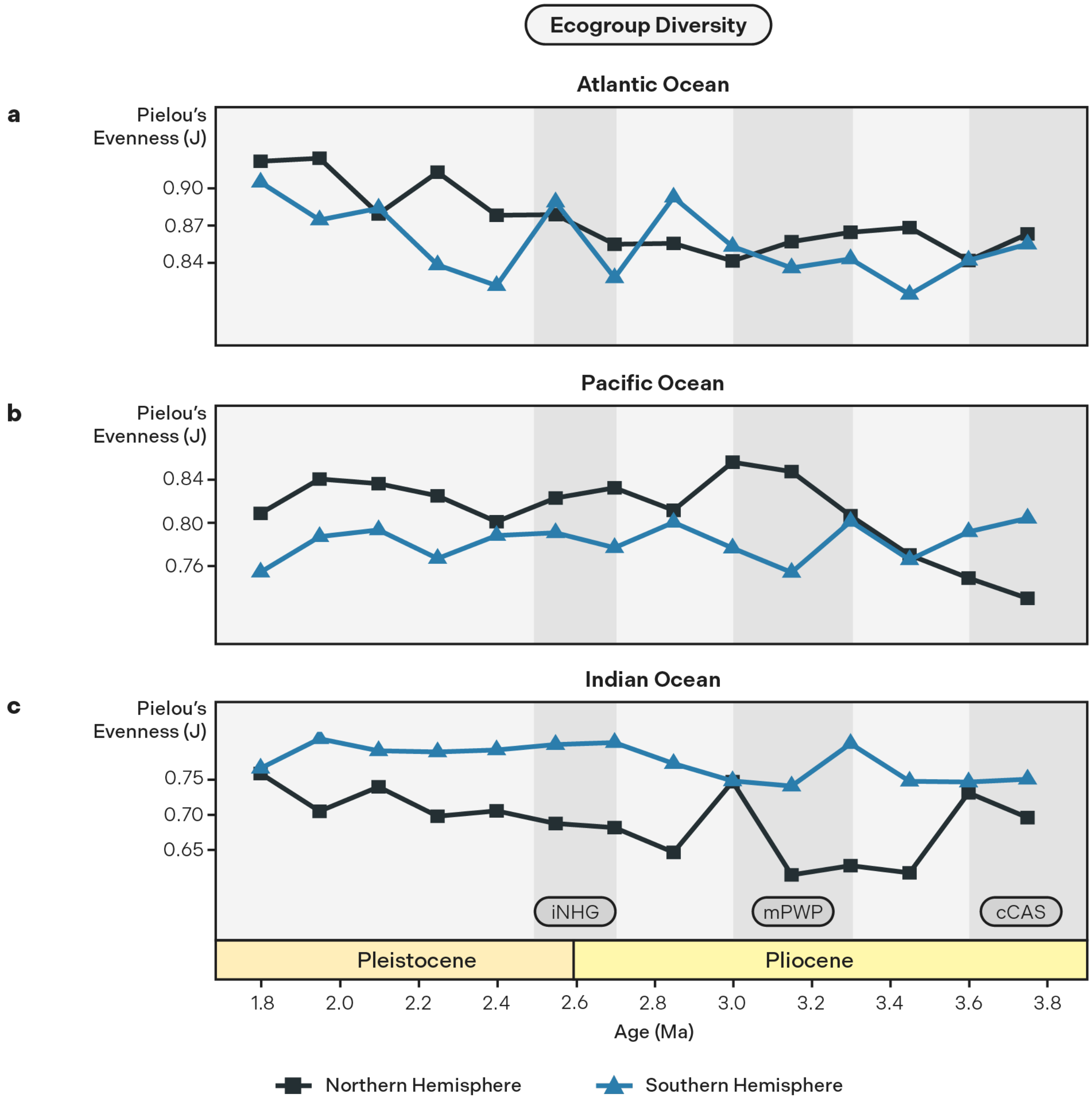
Supplementary Figure 13. Sample coverage of species diversity distribution across the Atlantic (a), Pacific (b), and Indian (c) Oceans for the Northern (tan) and Southern Hemisphere (teal) from 1.8 to 3.8 Ma. Sample coverage remains consistently high across all ocean basins, with values generally above 0.90, ensuring robust representation of species diversity. Variations in coverage are minimal, demonstrating reliable data quality for assessing temporal and regional trends. Source data are available at https://zenodo.org/records/15344269.



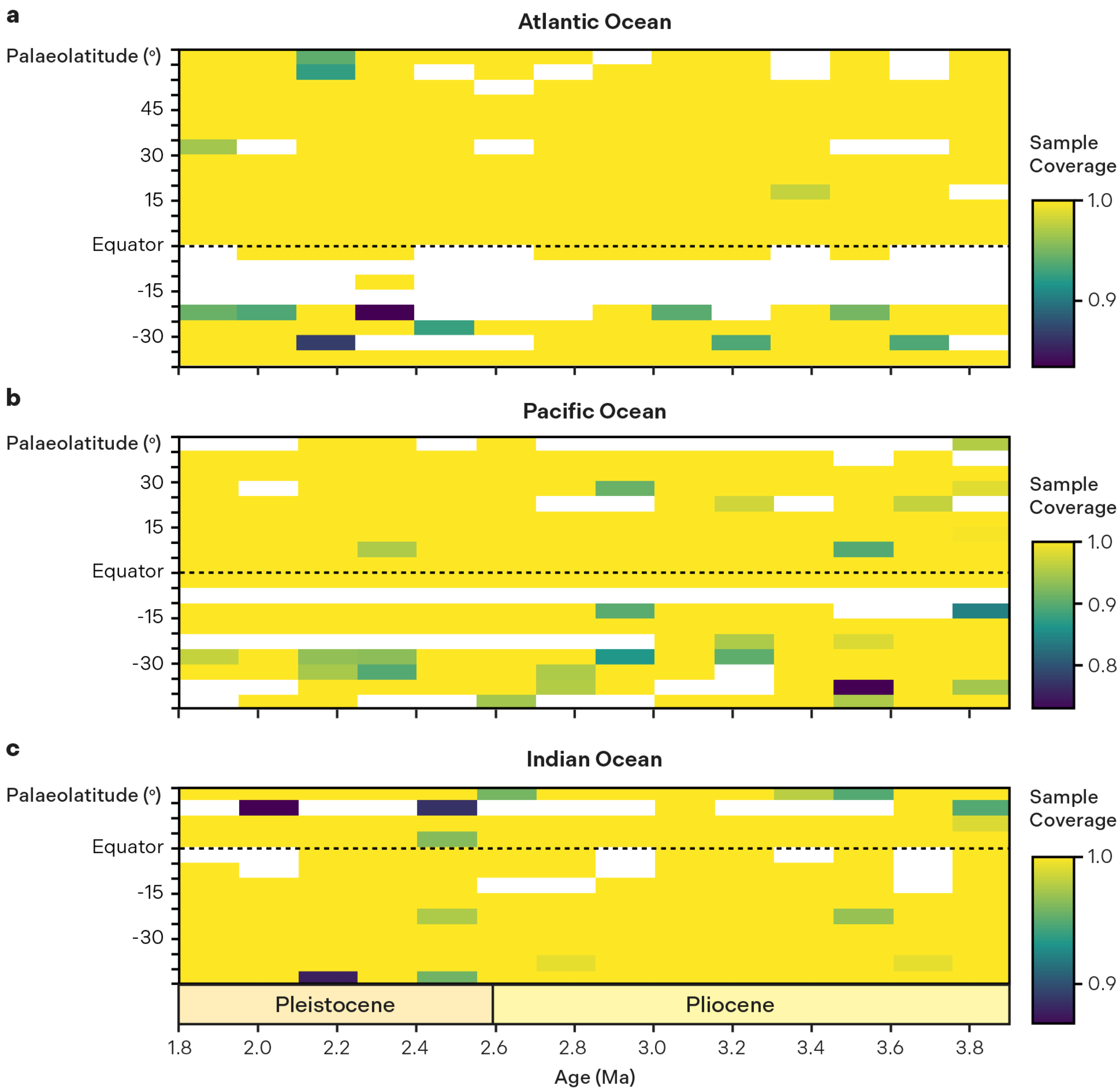
Supplementary Figure 14. Sample coverage of ecogroup diversity distribution across the Atlantic (a), Pacific (b), and Indian (c) Oceans for the Northern (tan) and Southern Hemisphere (teal) from 1.8 to 3.8 Ma. Sample coverage is exceptionally high and consistent across all basins, with values at 1.0, ensuring robust representation of ecogroup diversity over time. This high coverage indicates reliable data for analyzing ecogroup-level patterns and trends. Source data are available at https://zenodo.org/records/15344269.



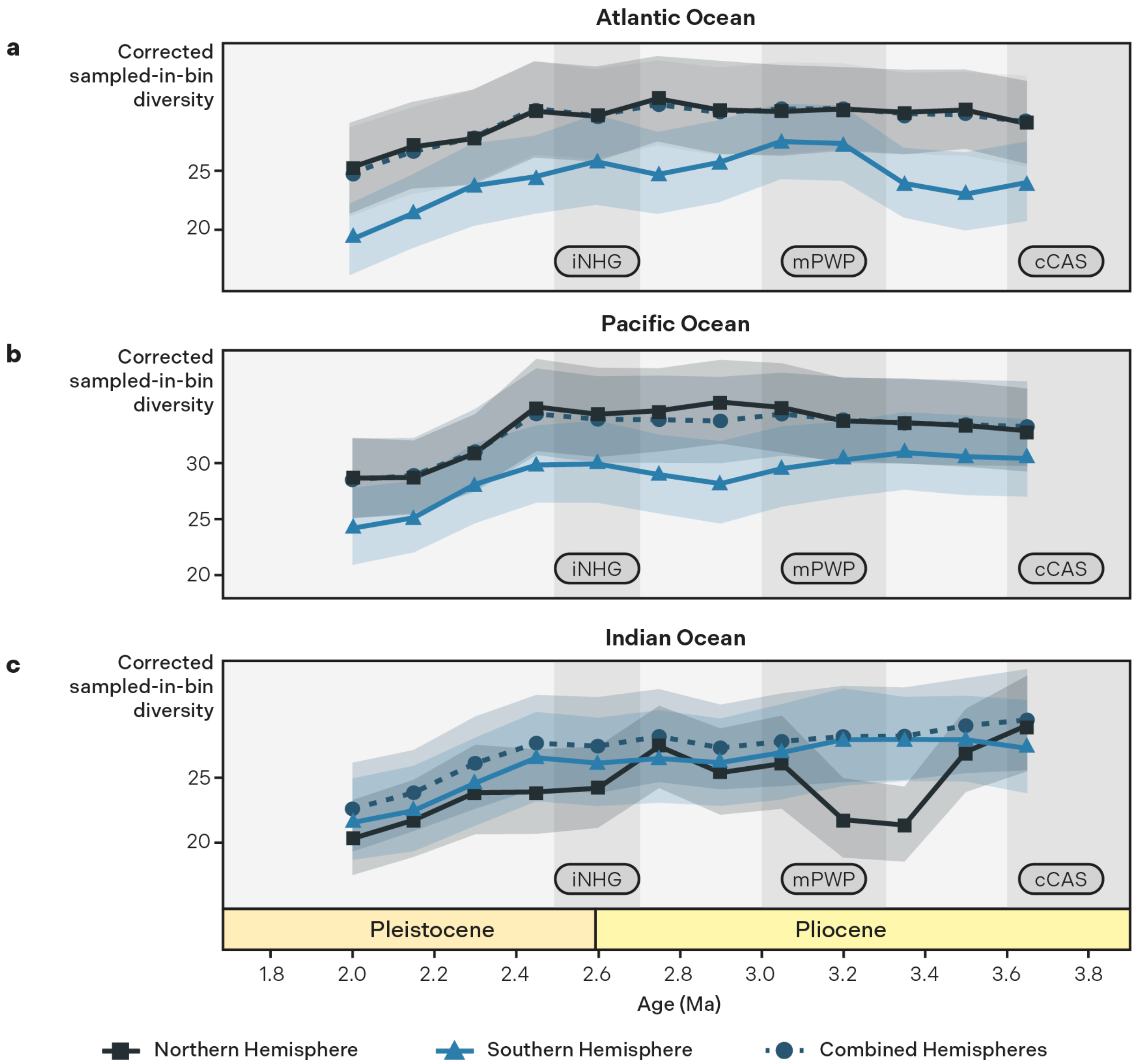
Supplementary Figure 15. **Pielou's evenness (J) of species diversity distribution across the Atlantic (a), Pacific (b), and Indian (c) Oceans for the Northern Hemisphere (tan) and Southern Hemisphere (teal) from 1.8 to 3.8 Ma.** The evenness index fluctuates over time, capturing variability in the balance of species abundances within each region. Notable differences between hemispheres are observed, particularly in the Atlantic and Pacific Oceans, where the Southern Hemisphere generally exhibits higher evenness. These results suggest proportional changes in species distributions, consistent with uniform environmental drivers across ecogroups. High evenness values also indicate robust sampling coverage and data reliability, ensuring well-represented species distributions across time bins and regions. Source data are available at https://zenodo.org/records/15344269.



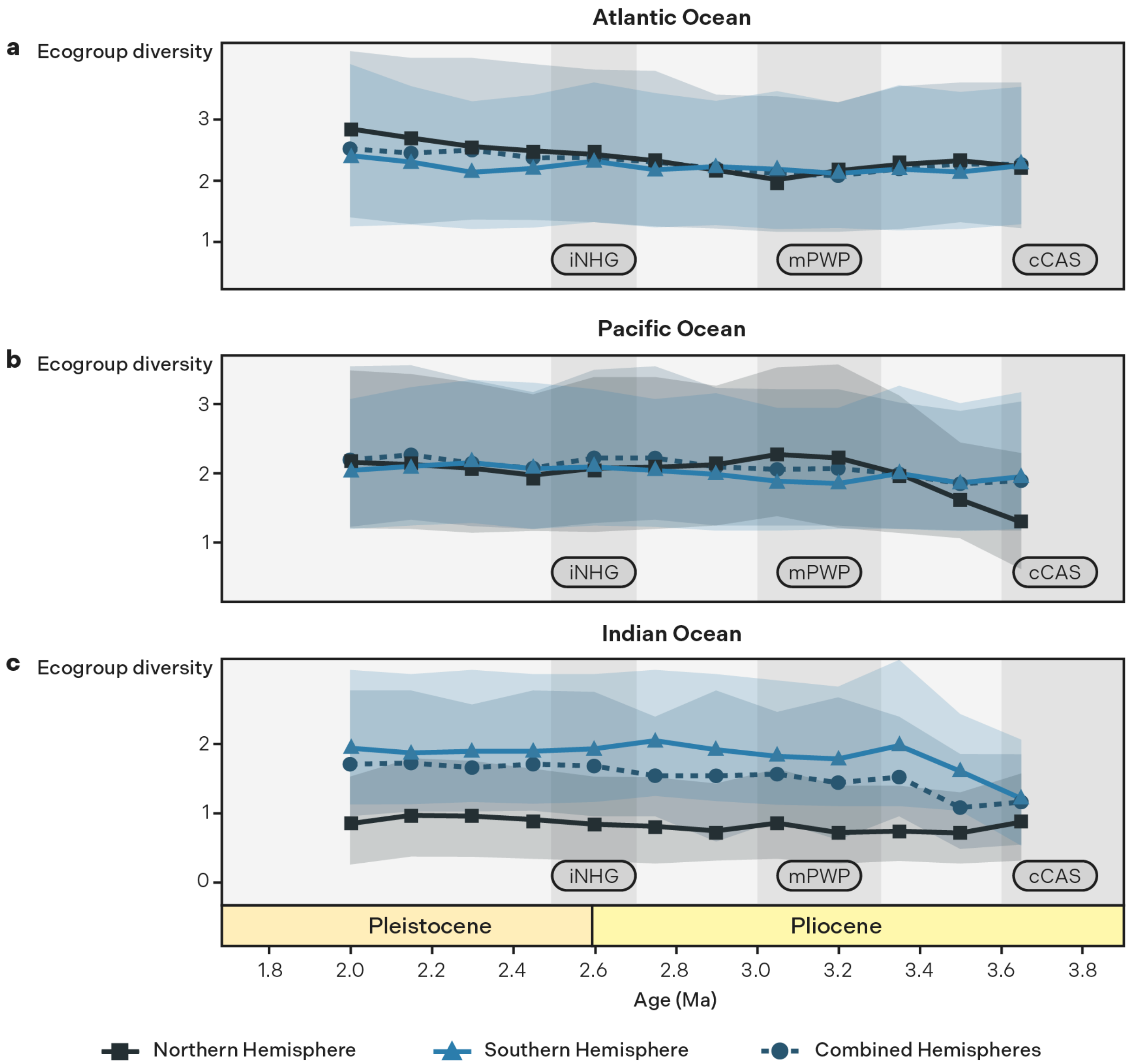
Supplementary Figure 16. **Pielou's Evenness (J) of ecogroup diversity across the Atlantic (a), Pacific (b), and Indian (c) Oceans for the Northern Hemisphere (tan) and Southern Hemisphere (teal) from 1.8 to 3.8 Ma.** Evenness reflects the balance of ecogroup abundances, with higher values indicating more even distributions. The patterns in the Atlantic and Pacific Oceans show declines in evenness over time, closely mirroring the trends in ecogroup diversity (Figure 4). This indicates proportional losses across ecogroups, consistent with uniform environmental changes impacting the system. In contrast, the Indian Ocean exhibits greater hemispheric variability, suggesting regionally distinct ecological dynamics. Source data are available at https://zenodo.org/records/15344269.



Supplementary Figure 17. Sample coverage (SC) of ecogroup distribution across the Atlantic (a), Pacific (b), and Indian (c) Oceans during the Pliocene - early Pleistocene calculated using the iNEXT package. Higher SC values (teal) indicate greater data completeness, while lower values (tan) reflect reduced coverage. White areas represent time bins excluded for not meeting completeness thresholds. These plots highlight overall high SC, ensuring robust ecogroup representation across basins and time bins. Source data are available at https://zenodo.org/records/15344269.



Supplementary Figure 18. Corrected sampled-in-bin species diversity across the Pliocene - early Pleistocene in the Atlantic (a), Pacific (b), and Indian (c) Oceans. Values are based on sample-standardized data using the shareholder quorum subsampling method with corrected sampled-in-bin diversity by species diversity. Subsampling was performed with 1000 iterations at a quorum of 0.8, with 90% confidence intervals in gray. Source data are available at https://zenodo.org/records/15344269.



Supplementary Figure 19. Corrected sampled-in-bin ecogroup diversity across the Pliocene - early Pleistocene in the Atlantic (a), Pacific (b), and Indian (c) Oceans. Values are based on sample-standardized data using the shareholder quorum subsampling method with corrected sampled-in-bin diversity by ecogroup diversity. Subsampling was performed with 1000 iterations at a quorum of 0.8, with 90% confidence intervals in gray. Source data are available at https://zenodo.org/records/15344269.

Supplementary Table 1. Species of planktic foraminifera with assigned ecogroups used in our study from Aze et al.[21] compared to ecogroups assigned by modern studies. Ecogroup 1 - open ocean surface mixed layer (SML) tropical/subtropical dwellers with algal photosymbionts. Ecogroup 2 - open ocean SML tropical/subtropical dwellers without algal photosymbionts. Ecogroup 3 - open ocean thermocline dwellers. Ecogroup 4 – open ocean sub-thermocline dwellers. Ecogroup 5 - high-latitude dwellers.

Species Names	**Extinction Status**	**Ecogroup by Aze[21]**	**Modern Studies Ecogroup**	**Modern Studies References**
Globigerina falconensis	Extant	1	1	Schiebel and Hemleben 2017
Globigerinoides conglobatus	Extant	1	1	Schiebel and Hemleben, 2017
Globigerinoides ruber	Extant	1	1	Schiebel and Hemleben, 2017
Orbulina universa	Extant	1	1	Schiebel and Hemleben, 2017
Trilobatus immaturus	Extant	1	1	Schiebel and Hemleben, 2017
Trilobatus sacculifer	Extant	1	1	Schiebel and Hemleben, 2017
Trilobatus trilobus	Extant	1	1	Schiebel and Hemleben, 2017
Turborotalita humilis	Extant	1	1	Schiebel and Hemleben, 2017
Globigerina bulloides	Extant	2	2	Schiebel and Hemleben 2017
Globoturborotalita rubescens	Extant	2	2	Schiebel and Hemleben, 2017
Globoturborotalita tenella	Extant	2	2	Schiebel and Hemleben, 2017
Turborotalita cristata	Extant	2	2	Aze et al., 2011
Globigerinella calida	Extant	3	3	Niebler et al., 1999
Globigerinella siphonifera	Extant	3	3	Schiebel and Hemleben, 2017
Globoconella inflata	Extant	3	3	Wilke et al., 2006
Globoquadrina conglomerata	Extant	3	3	Aze et al., 2011
Globorotalia tumida	Extant	3	3	Schiebel and Hemleben, 2017
Globorotalia ungulata	Extant	3	3	Birch et al., 2013
Menardella menardii	Extant	3	3	Schiebel and Hemleben, 2017
Neogloboquadrina dutertrei	Extant	3	3	Schiebel and Hemleben, 2017
Orbulina suturalis	Extant	3	3	Aze et al., 2011
Pulleniatina finalis	Extant	3	3	Woodhouse pers. comm.
Pulleniatina obliquiloculata	Extant	3	3	Schiebel and Hemleben, 2017
Sphaeroidinella dehiscens	Extant	3	3	Schiebel and Hemleben, 2017
Neogloboquadrina incompta	Extant	NA	3	Schiebel and Hemleben, 2017
Beella digitata	Extant	4	4	Schiebel and Hemleben, 2017
Globorotaloides hexagonus	Extant	4	4	Schiebel and Hemleben, 2017
Hirsutella bermudezi	Extant	4	4	Aze et al., 2011
Hirsutella hirsuta	Extant	4	4	Schiebel and Hemleben 2017
Hirsutella scitula	Extant	4	4	Birch et al., 2013
Hirsutella theyeri	Extant	4	4	Aze et al., 2011
Truncorotalia crassaformis	Extant	4	4	Schiebel and Hemleben, 2017
Truncorotalia oceanica	Extant	4	4	Aze et al., 2011
Truncorotalia truncatulinoides	Extant	4	4	Schiebel and Hemleben, 2017
Neogloboquadrina pachyderma	Extant	5	5	Schiebel and Hemleben, 2017
Turborotalita quinqueloba	Extant	5	5	Schiebel and Hemleben, 2017

Supplementary Table 2. Species of planktic foraminifera with assigned ecogroups used in our studies. The ecogroup assignment is from Aze et al.[21]. Ecogroup 1 - open ocean surface mixed layer (SML) tropical/subtropical dwellers with algal photosymbionts. Ecogroup 2 - open ocean SML tropical/subtropical dwellers without algal photosymbionts. Ecogroup 3 - open ocean thermocline dwellers. Ecogroup 4 – open ocean sub-thermocline dwellers. Ecogroup 5 - high-latitude dwellers.

Species Name	Extinction Status	Ecogroup by Aze[21]
Dentoglobigerina altispira	Extinct	1
Dentoglobigerina baroemoenensis	Extinct	1
Dentoglobigerina globosa	Extinct	1
Globigerina eamesi	Extinct	1
Globigerina umbilicata	Extinct	1
Globigerinoides bollii	Extinct	1
Globigerinoides extremus	Extinct	1
Globigerinoides obliquus	Extinct	1
Globigerinoidesella fistulosa	Extinct	1
Globoturborotalita druryi	Extinct	1
Globoturborotalita woodi	Extinct	1
Globoturborotalita apertura	Extinct	2
Globoturborotalita decoraperta	Extinct	2
Globoconella miotumida	Extinct	3
Globoconella puncticulata	Extinct	3
Globorotalia flexuosa	Extinct	3
Menardella exilis	Extinct	3
Menardella limbata	Extinct	3
Menardella miocenica	Extinct	3
Menardella multicamerata	Extinct	3
Menardella pertenuis	Extinct	3
Menardella pseudomiocenica	Extinct	3
Neogloboquadrina acostaensis	Extinct	3
Neogloboquadrina humerosa	Extinct	3
Pulleniatina praecursor	Extinct	3
Pulleniatina primalis	Extinct	3
Sphaeroidinellopsis kochi	Extinct	3
Sphaeroidinellopsis paenedehiscens	Extinct	3
Sphaeroidinellopsis seminulina	Extinct	3
Beella praedigitata	Extinct	4
Dentoglobigerina venezuelana	Extinct	4
Hirsutella margaritae	Extinct	4
Truncorotalia crassaconica	Extinct	4
Truncorotalia crassula	Extinct	4
Truncorotalia ronda	Extinct	4
Truncorotalia tenuitheca	Extinct	4
Truncorotalia tosaensis	Extinct	4
Truncorotalia viola	Extinct	4

Supplementary References

1. Schiebel, R. and Hemleben, C., 2017. *Planktic foraminifers in the modern ocean* (Vol. 358). Berlin: Springer.

2. Niebler, H.S., Hubberten, H.W. and Gersonde, R., 1999. Oxygen isotope values of planktic foraminifera: a tool for the reconstruction of surface water stratification. *Use of Proxies in Paleoceanography: examples from the South Atlantic*, pp.165-189.

3. Wilke I., Bickert T., Peeters F.J.C., 2006. The influence of seawater carbonate ion concentration [CO_3^{2-}] on the stable carbon isotope composition of the planktic foraminifera species *Globorotalia inflata*. Marine Micropaleontology. 58:243–258.

4. Birch, H., Coxall, H.K., Pearson, P.N., Kroon, D. and O'Regan, M., 2013. Planktonic foraminifera stable isotopes and water column structure: Disentangling ecological signals. *Marine Micropaleontology*, *101*, pp.127-145.