

Supplementary Material for "Evolution of causal relationships under climate change : controls of Net Primary Productivity in the North Atlantic Subpolar Gyre"

Germain BÉNARD, Marion GEHLEN, Mathieu VRAC

September 23, 2025

Contents

- Additional Information on the Earth System Models selected
- Supplementary Figures

S1 Additional information on biogeochemical models

We chose a set of Earth system models featuring biogeochemical components of comparable complexity to investigate the diversity of causal relationships linking atmospheric dynamics to net primary productivity. The selected biogeochemical models incorporate a minimum of 2 phytoplankton functional types (PFT) along with model-specific representations of PFT interactions and nutrient constraints on phytoplankton growth. To avoid redundancy, we ensured that each ocean-biogeochemistry coupling was represented only once, resulting in the final selection of 5 Earth System Models detailed in Table S1. Despite this approach, some overlap remains in our ensemble, with 3 ESMs utilizing the same oceanic component (NEMO-OPA 3.6).

Table S1: Overview of the 5 Earth System Models used in this study, showing their oceanic and atmospheric components with corresponding grid resolutions, along with their associated biogeochemical models and primary references.

ESM model	Oceanic model	Oceanic grid	Atmospheric model	Atmospheric grid	Biogeochemical model	ESM reference
IPSL-CM6A-LR	NEMO-OPA 3.6	$1^\circ \times 1^\circ$ with 75 levels	LMDZ	$1.3^\circ \times 2.5^\circ$ with 79 levels	PISCES-v2	Boucher et al. (2020)
CESM2	POP2	$1^\circ \times 1.125^\circ$ with 60 levels	CAM6	$0.9^\circ \times 1.25^\circ$ with 32 levels	MARBL	Danabasoglu et al. (2020)
CMCC-ESM2	NEMO-OPA 3.6	$1^\circ \times 1^\circ$ with 50 levels	CAM5.3	$0.9^\circ \times 1.25^\circ$ with 30 levels	BFM5.1	Lovato et al. (2022)
CanESM5-CanOE	CanNEMO 3.4.1	$1^\circ \times 1^\circ$ with 45 levels	CanAM5	isotropic triangular 2.8° grid with 49 levels	CanOE	Swart et al. (2019); Christian et al. (2021)
UKESM1-0-LL	NEMO-OPA 3.6	$1^\circ \times 1^\circ$ with 75 levels	MetUM-HadGEM3-GA7.1	$1.25^\circ \times 1.88^\circ$ with 85 levels	MEDUSA-2.0	Sellar et al. (2019); Yool et al. (2021)

S2 Supplementary Figures

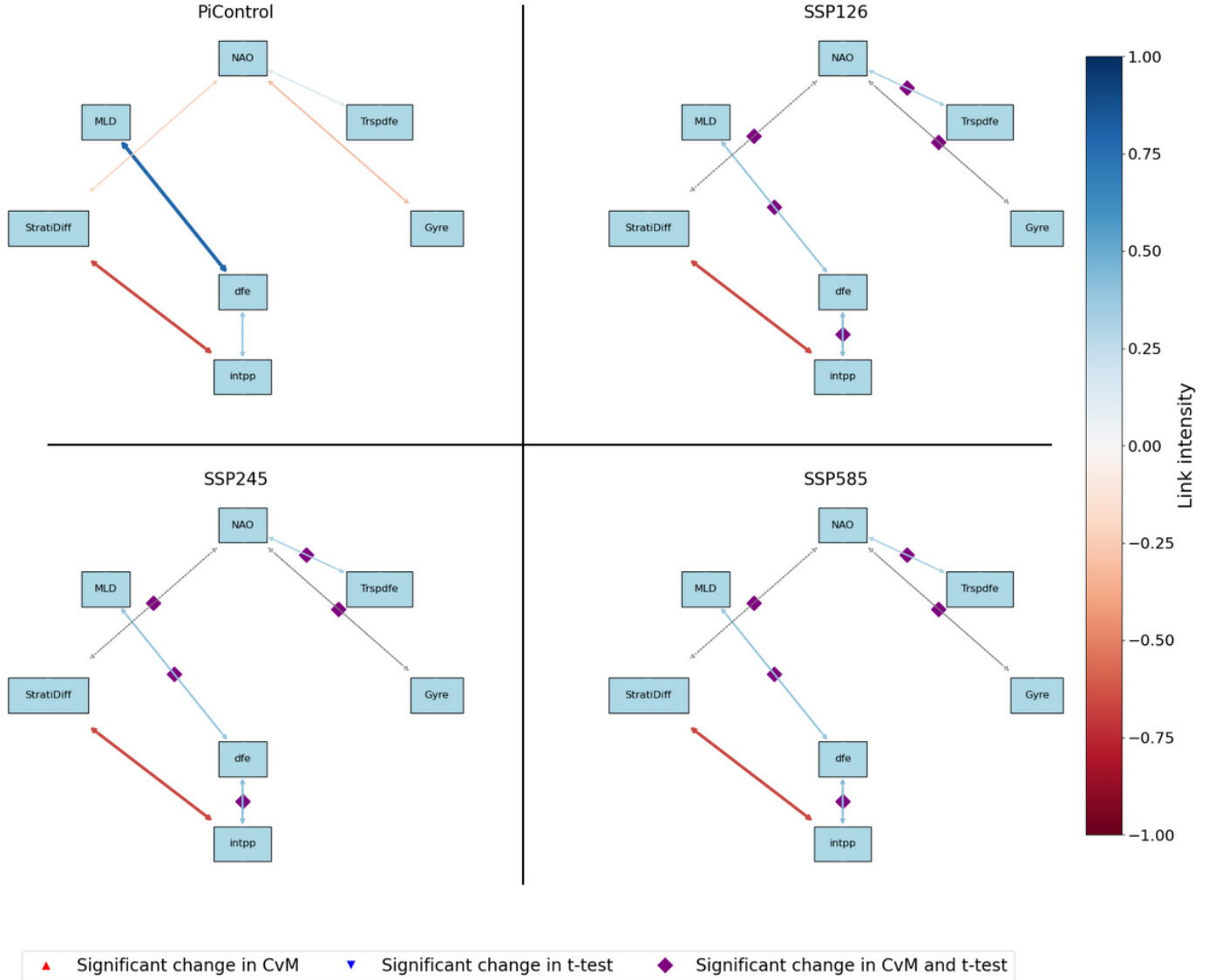


Figure S1: Mean causal graph (over the 35 last sliding windows) according to each scenario for IPSL-CM6A-LR. The colorbar indicates the intensity of the strength of the link. Only links with a strength above 0.31 (the average minimum significant strength) are displayed. Grey color indicates a link that existed in pre-industrial simulation and disappeared under SSP scenario. The statistical significance of changes is assessed using both the Cramer-von Mises test (Anderson, 1962) for distributional changes and t-tests (Kim, 2015) for shifts in mean values. MLD: Mixed layer Depth ; StratiDiff: Stratification ; dFe: Iron ; intpp: NPP ; Gyre: Gyre index; TrspDfE: Iron Transport

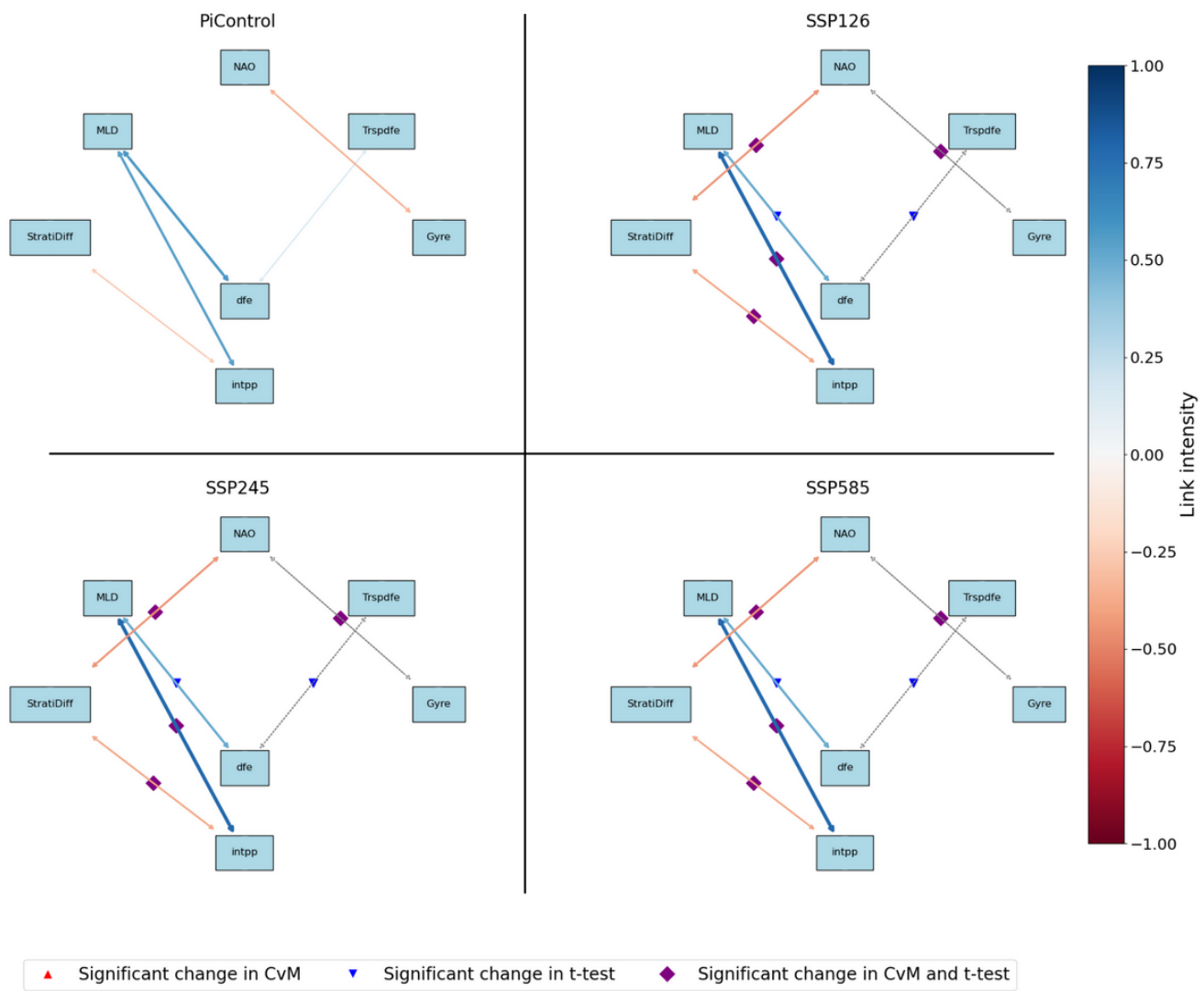


Figure S2: Similar to Fig S1 but for CMCC-ESM2.

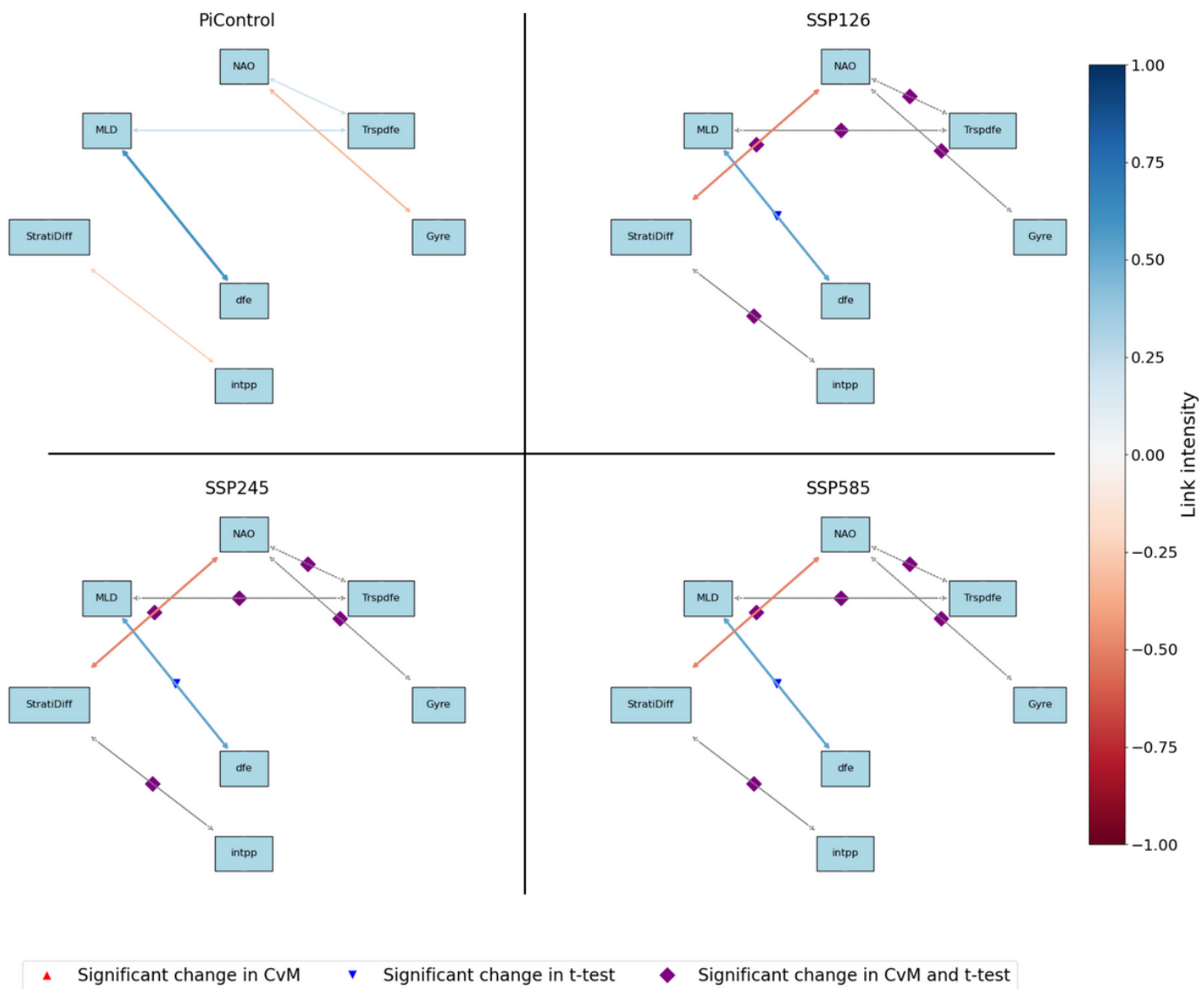


Figure S3: Similar to Fig S1 but for CSM2.

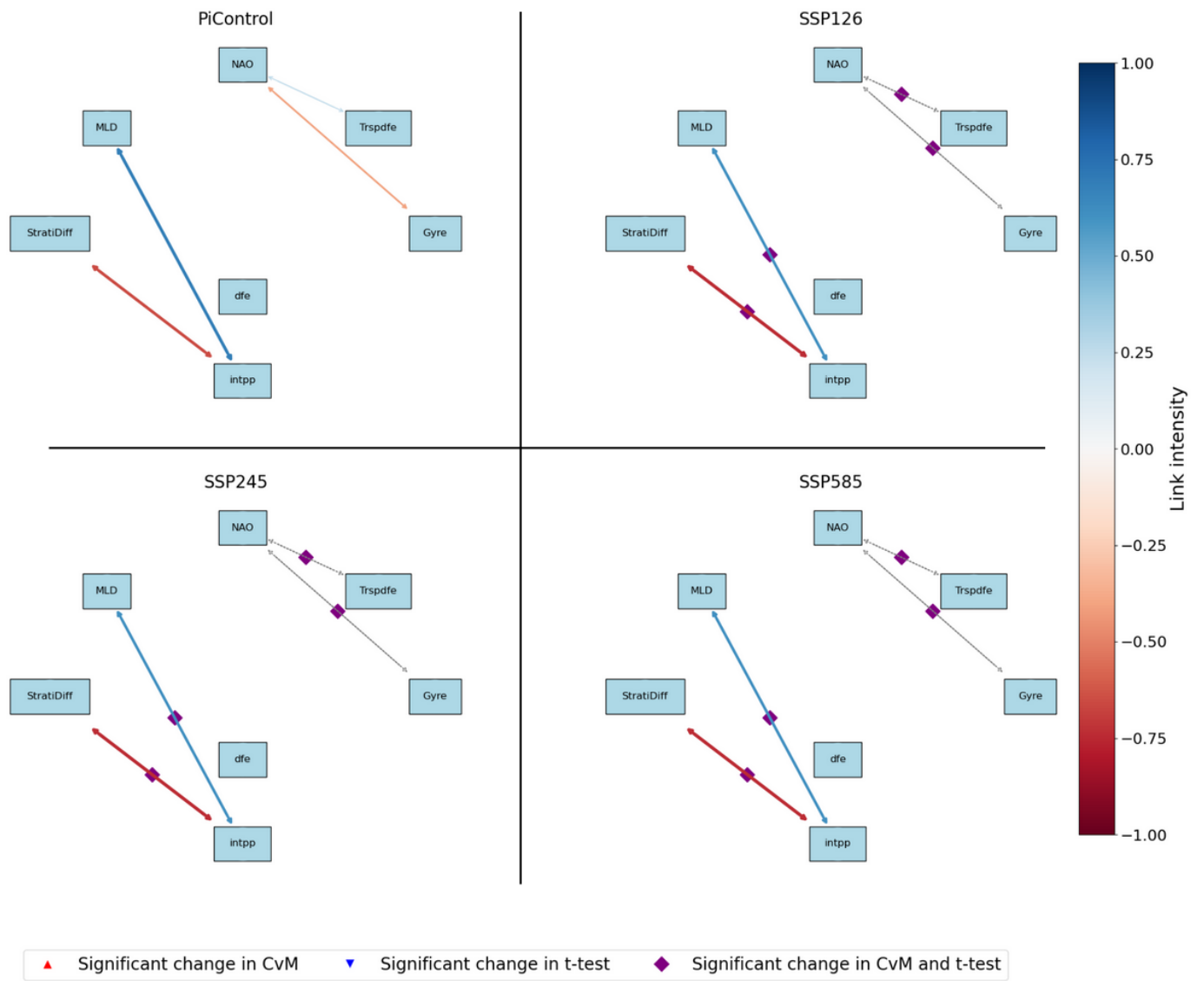


Figure S4: Similar to Fig S1 but for UKESM1-0-LL.

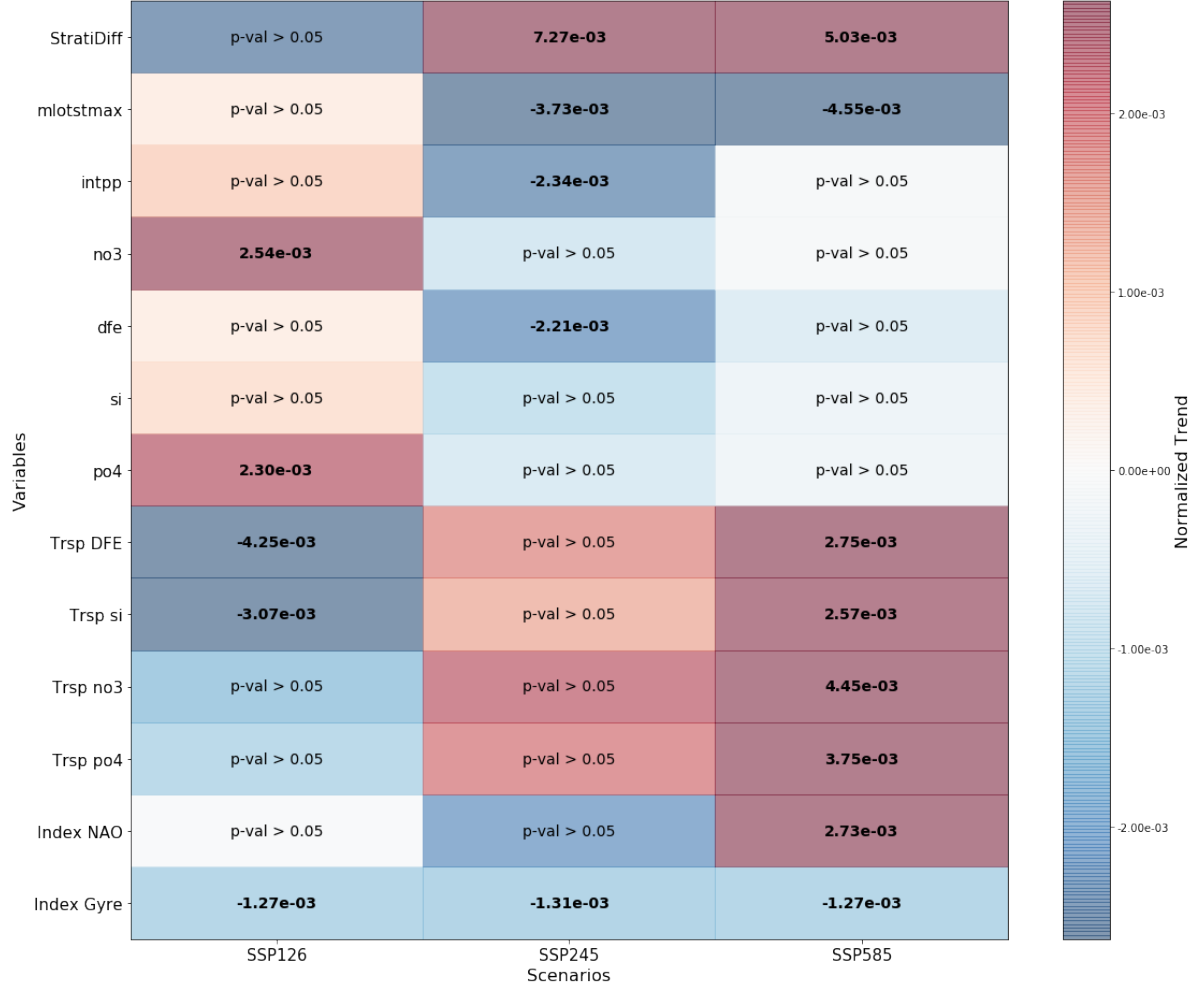


Figure S5: Normalized trends by variable and scenario for IPSL-CM6A-LR. The colorbar displays standardized trend coefficients for the variables studied in the main article across three SSP scenarios (SSP126, SSP245, SSP585). Color intensity represents the intensity of normalized trends, with red indicating positive trends, blue indicating negative trends, and white indicating minimal change. Significant trend values are shown in bold, while non-significant trends are marked as "p-val > 0.05". Variables include: StratiDiff (stratification), mlostmix (winter mixed layer depth), intpp (NPP), no3 (nitrate), dfe (dissolved iron), si (silicate), po4 (phosphate), Trsp DFE (iron transport), Trsp si (silicate transport), Trsp no3 (nitrate transport), Trsp po4 (phosphate transport), Index NAO (North Atlantic Oscillation index), and Index Gyre (gyre circulation index).

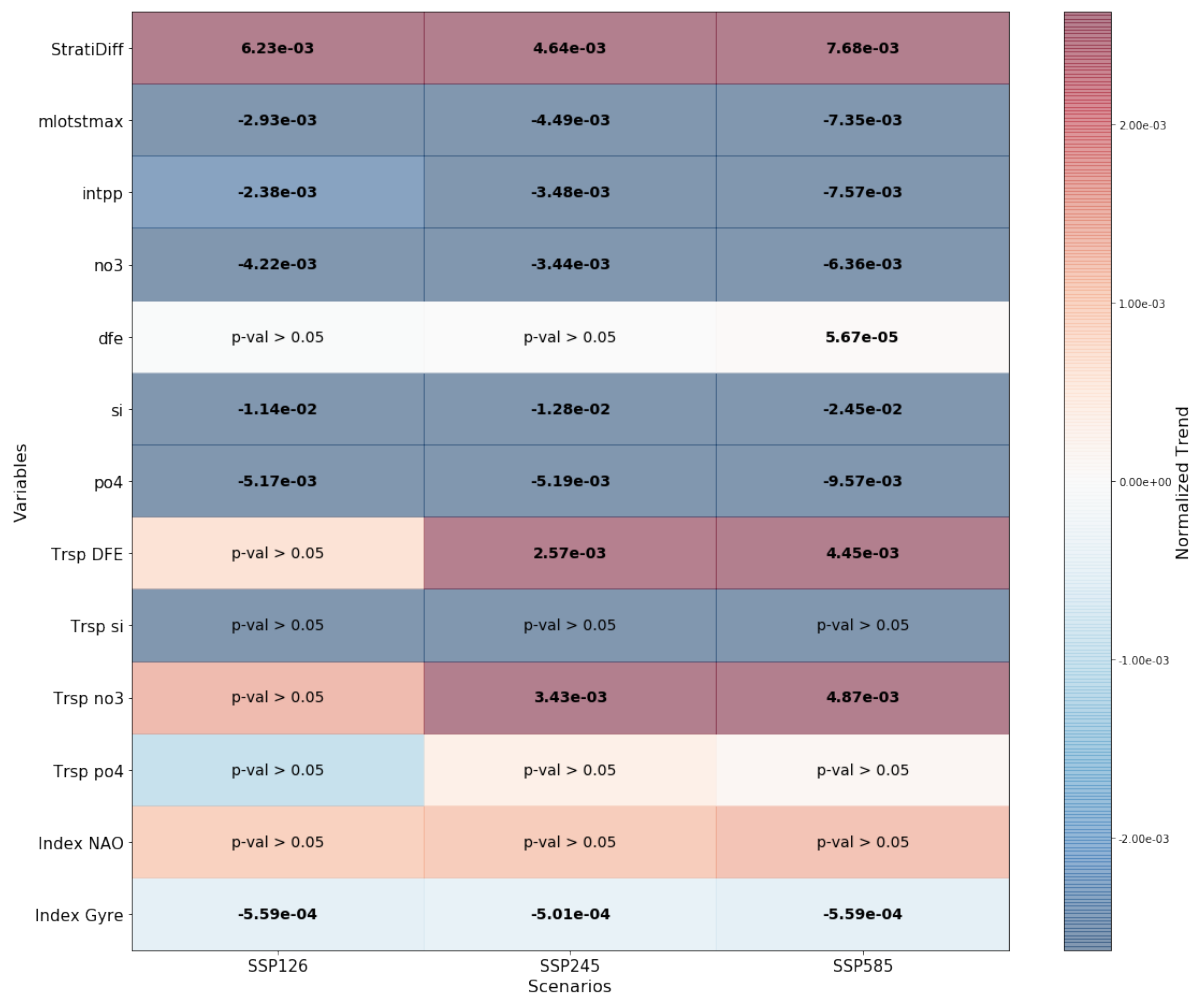


Figure S6: Similar to Fig S5 but for CMCC-ESM2

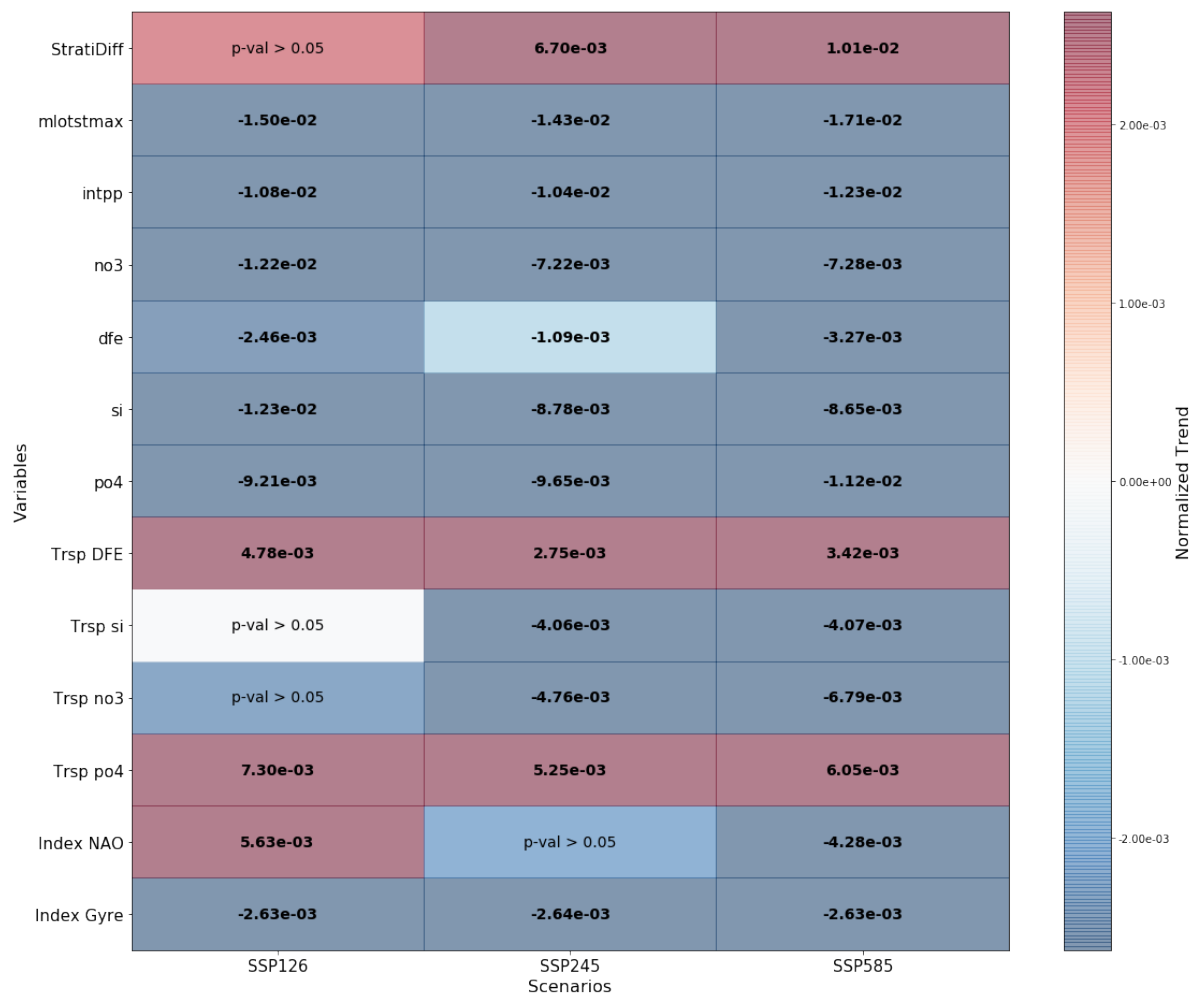


Figure S7: Similar to Fig S5 but for CESM2.

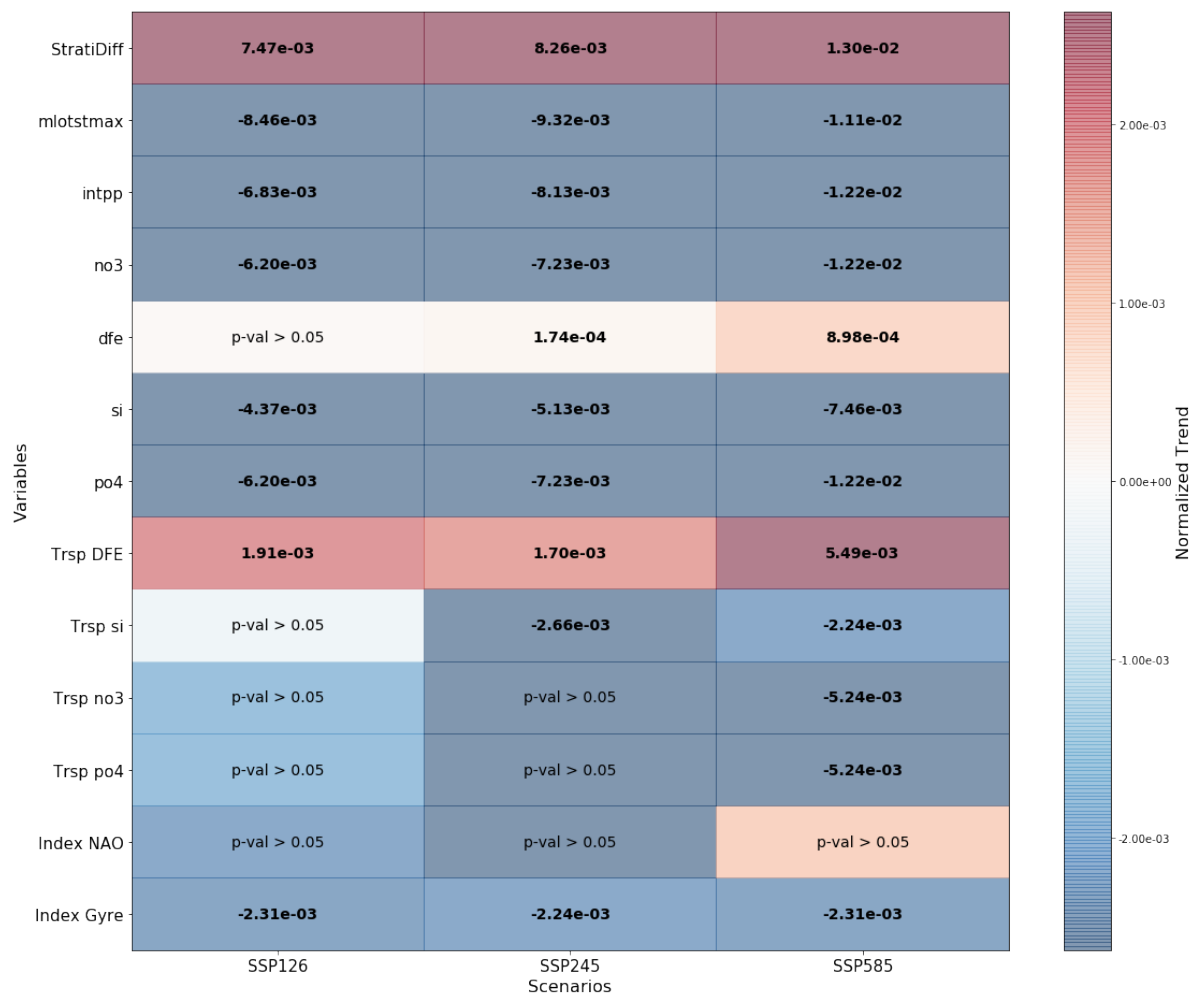


Figure S8: Similar to Fig S5 but for UKESM1-0-LL.

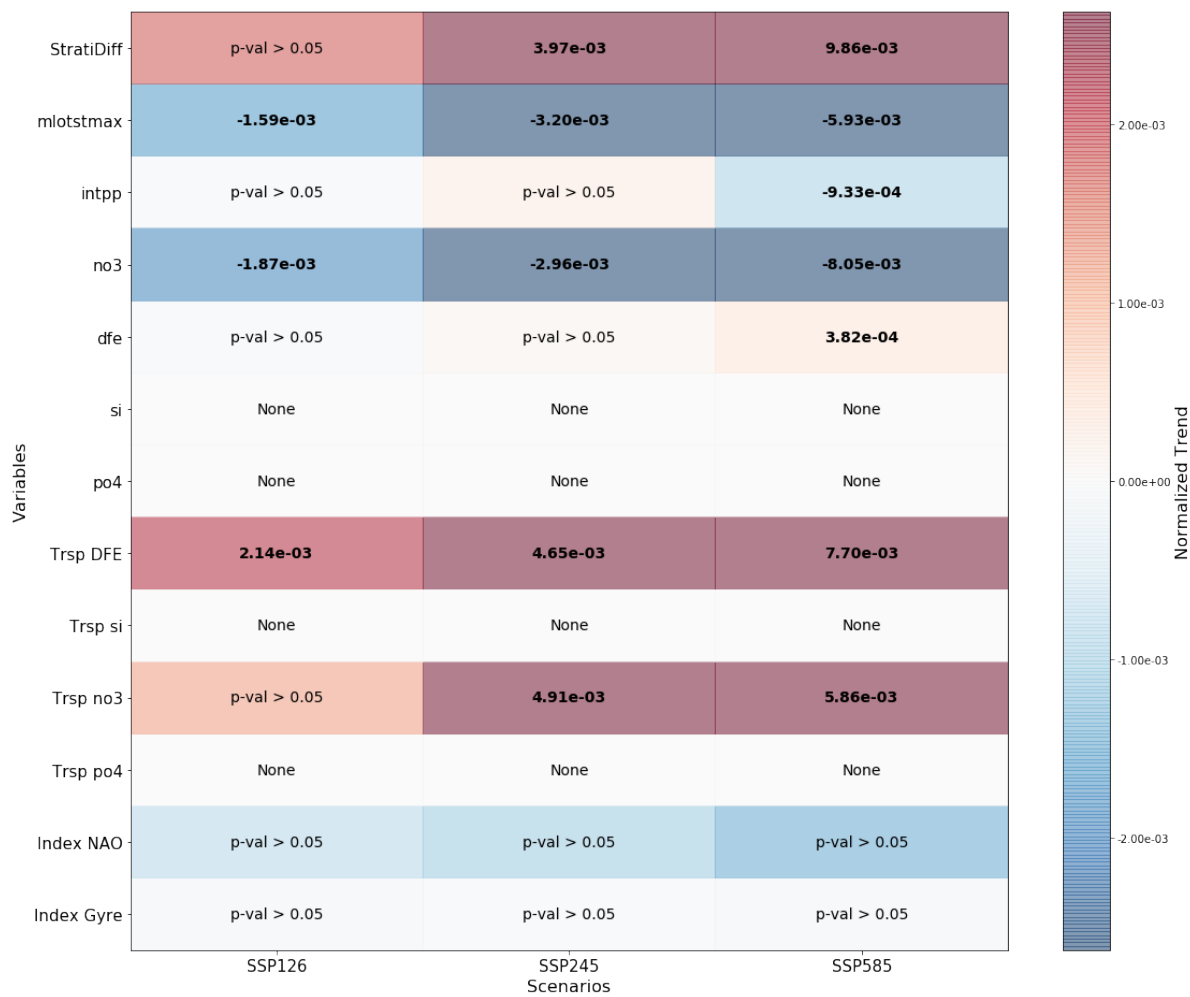


Figure S9: Similar to Fig S5 but for CanESM5-CanOE.

References

- Anderson, T. W.: On the distribution of the two-sample Cramer-von Mises criterion, *The Annals of Mathematical Statistics*, pp. 1148–1159, 1962.
- Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastyrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D’Andrea, F., Davini, P., de Lavergne, C., Denvil, S., Deshayes, J., Devilliers, M., Ducharne, A., Dufresne, J.-L., Dupont, E., Éthé, C., Fairhead, L., Falletti, L., Flavoni, S., Foujols, M.-A., Gardoll, S., Gastineau, G., Ghattas, J., Grandpeix, J.-Y., Guenet, B., Guez, Lionel, E., Guilyardi, E., Guimberteau, M., Hauglustaine, D., Hourdin, F., Idelkadi, A., Joussaume, S., Kageyama, M., Khodri, M., Krinner, G., Lebas, N., Levavasseur, G., Lévy, C., Li, L., Lott, F., Lurton, T., Luyssaert, S., Madec, G., Madeleine, J.-B., Maignan, F., Marchand, M., Marti, O., Mellul, L., Meurdesoif, Y., Mignot, J., Musat, I., Ottlé, C., Peylin, P., Planton, Y., Polcher, J., Rio, C., Rochetin, N., Rousset, C., Sepulchre, P., Sima, A., Swingedouw, D., Thiéblemont, R., Traore, A. K., Vancoppenolle, M., Vial, J., Vialard, J., Viovy, N., and Vuichard, N.: Presentation and Evaluation of the IPSL-CM6A-LR Climate Model, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS002 010, <https://doi.org/10.1029/2019MS002010>, 2020.
- Christian, J. R., Denman, K. L., Hayashida, H., Holdsworth, A. M., Lee, W. G., Riche, O. G., Shao, A. E., Steiner, N., and Swart, N. C.: Ocean biogeochemistry in the canadian earth system model version 5.0. 3: CanESM5 and CanESM5-CanOE, *Geoscientific Model Development Discussions*, 2021, 1–68, 2021.
- Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., Neale, R., Oleson, K. W., Otto-Bliesner, B., Phillips, A. S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J. E., Kinnison, D., Kushner, P. J., Larson, V. E., Long, M. C., Mickelson, S., Moore, J. K., Nienhouse, E., Polvani, L., Rasch, P. J., and Strand, W. G.: The Community Earth System Model Version 2 (CESM2), *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001 916, <https://doi.org/10.1029/2019MS001916>, 2020.
- Kim, T. K.: T test as a parametric statistic, *Korean journal of anesthesiology*, 68, 540–546, 2015.
- Lovato, T., Peano, D., Butenschön, M., Materia, S., Iovino, D., Scoccimarro, E., Fogli, P., Cherchi, A., Bellucci, A., Gualdi, S., et al.: CMIP6 simulations with the CMCC Earth system model (CMCC-ESM2), *Journal of Advances in Modeling Earth Systems*, 14, e2021MS002 814, 2022.

- Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S. T., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., Andrews, M. B., Andrews, T., Archibald, A. T., Berthou, S., Burke, E., Blockley, E., Carslaw, K., Dalvi, M., Edwards, J., Folberth, G. A., Gedney, N., Griffiths, P. T., Harper, A. B., Hendry, M. A., Hewitt, A. J., Johnson, B., Jones, A., Jones, C. D., Keeble, J., Liddicoat, S., Morgenstern, O., Parker, R. J., Predoi, V., Robertson, E., Siahann, A., Smith, R. S., Swaminathan, R., Woodhouse, M. T., Zeng, G., and Zerroukat, M.: UKESM1: Description and Evaluation of the U.K. Earth System Model, *Journal of Advances in Modeling Earth Systems*, 11, 4513–4558, <https://doi.org/10.1029/2019MS001739>, 2019.
- Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., von Salzen, K., Yang, D., and Winter, B.: The Canadian Earth System Model version 5 (CanESM5.0.3), *Geoscientific Model Development*, 12, 4823–4873, <https://doi.org/10.5194/gmd-12-4823-2019>, 2019.
- Yool, A., Palmiéri, J., Jones, C. G., de Mora, L., Kuhlbrodt, T., Popova, E. E., Nurser, A. J. G., Hirschi, J., Blaker, A. T., Coward, A. C., Blockley, E. W., and Sellar, A. A.: Evaluating the physical and biogeochemical state of the global ocean component of UKESM1 in CMIP6 historical simulations, <https://doi.org/10.5194/gmd-14-3437-2021>, 2021.