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Supplementary Materials for

Abrupt shifts in 21st-century plankton communities

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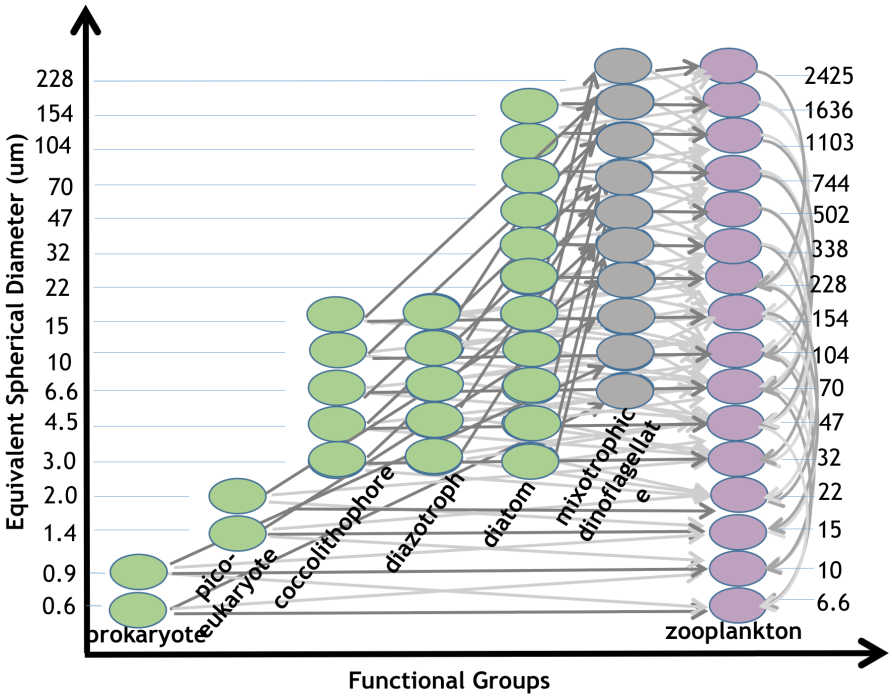

Figure S1: Schematic of model plankton by size and function.

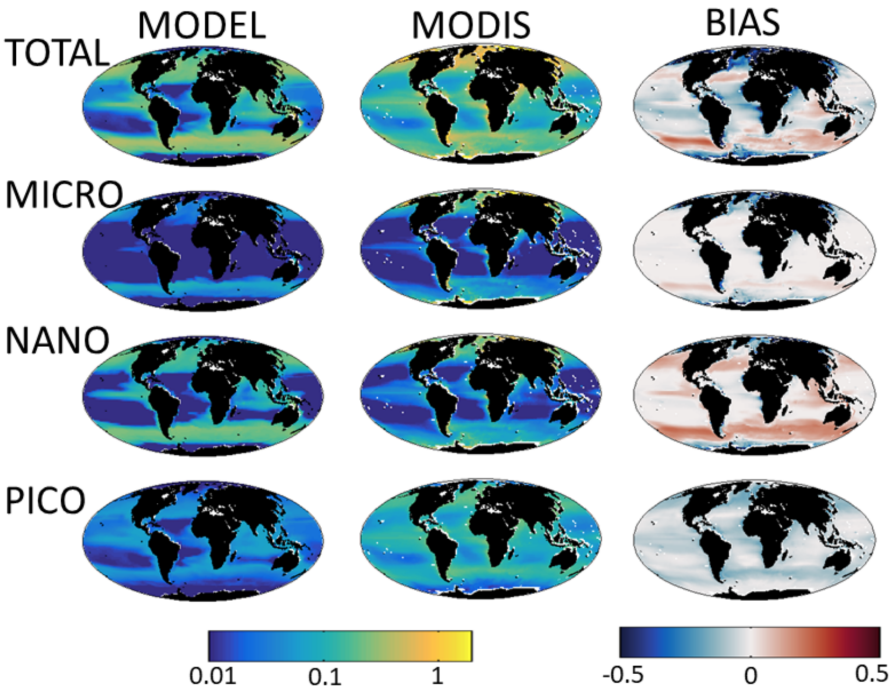

Figure S2: Comparison of Annual Mean Surface Chl-a (mg Chl / m^3). (Top row) total Chl-a; and Chl-a in size classes (Second row) micro (>20μm); (Third row) nano (2-20μm); (Bottom row) pico (<2μm). (Left column) Model 2000-2020 mean; (Middle Column) Satellite Observations, top from NASA MODIS, other three panels are the satellite-based estimates from Ref. (*19*); (Right Column) Model bias determined as model minus observations. The middle column shows mean of all available satellite measurements, with missing observations in the polar winters and under clouds; while model results are mean (0-50m).

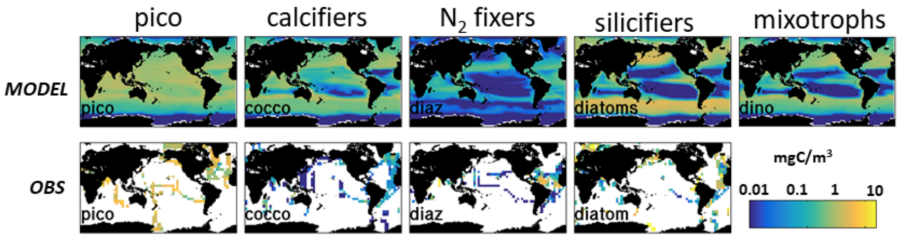

Figure S3: Comparison to Observations of Functional Groups. (top) mean from 2000-2020 from model (0-60m) and (bottom) data compilation (MAREDAT) (*20*) in carbon biomass (mg C / m^3). For the MAREDAT databases: pico-phytoplankton (*48*); coccolithophores (*44*); diazotrophs (*49*); diatoms (*50*). There was no MAREDAT dataset for dinoflagellates. We do not show biases as these would not be reasonable comparisons since MAREDAT data presented here combines all measurements regardless of time, while model show annual mean.

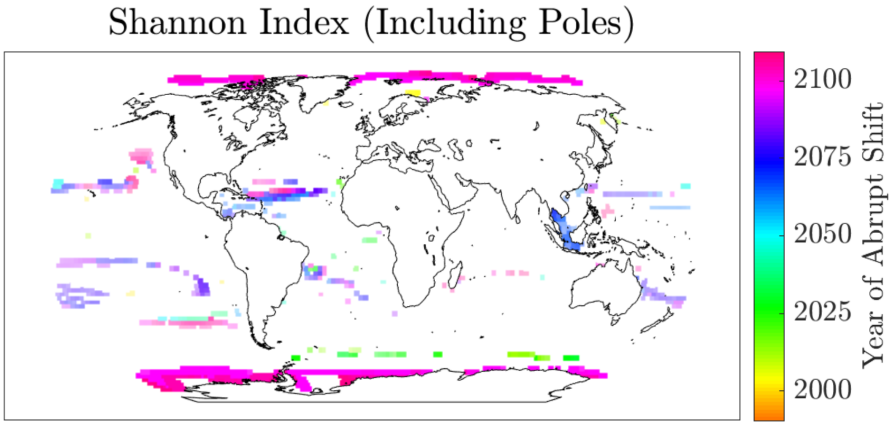

Figure S4: Same as Figure 3a but including poles.

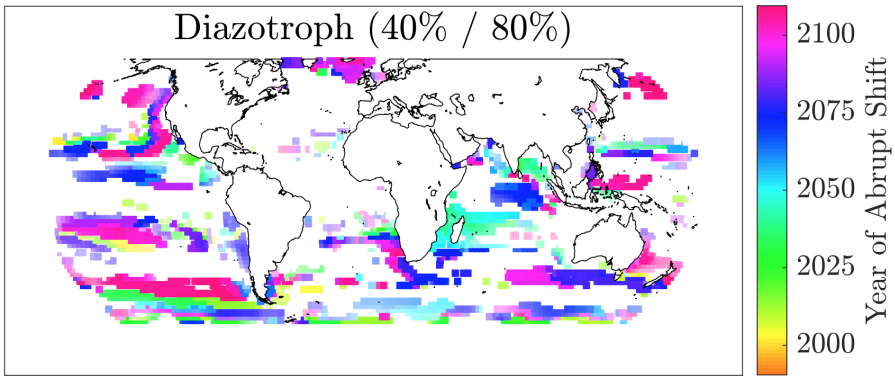

Figure S5: Same as Figures 2a-f for diazotrophs.

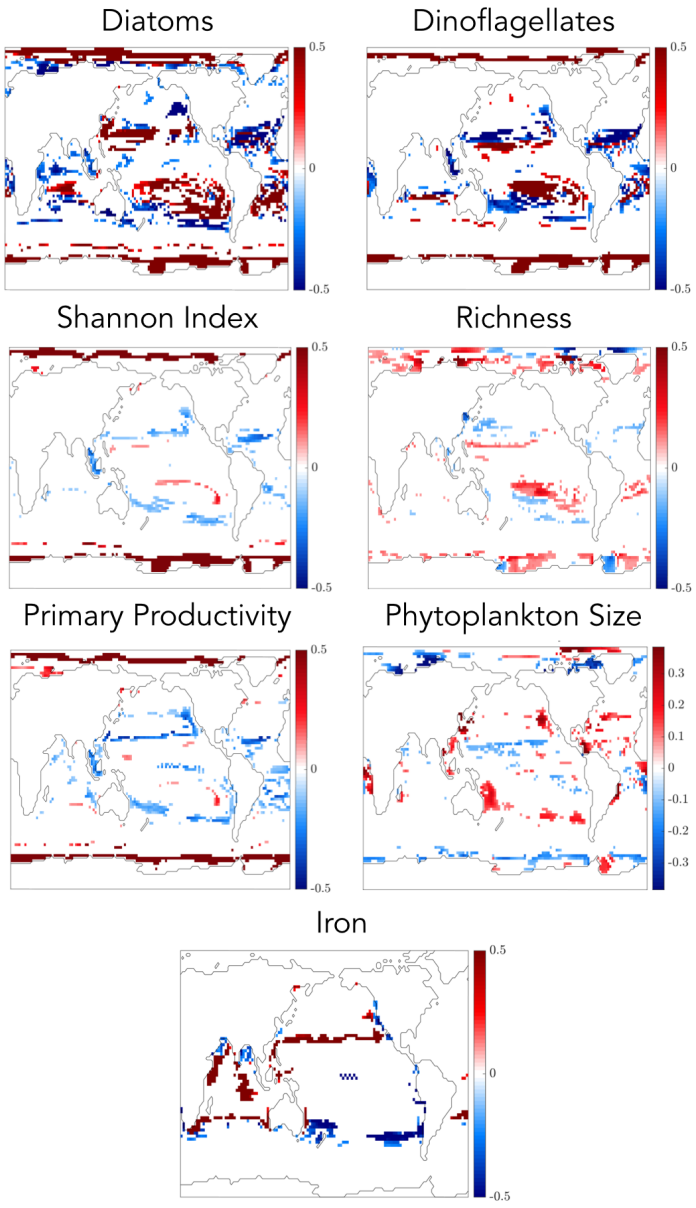

Figure S6: Same as maps in Figures 2a-f, 3a-f, S5, S6 for those properties where the sign of an abrupt change is mentioned in the text. Blue corresponds to declines and red corresponds to increases, with color intensity corresponding to the magnitude of the shift up to saturation at 50%. Red in the phytoplankton size distribution plot corresponds to a shift to smaller size classes (larger magnitude of power-law size distribution exponent).

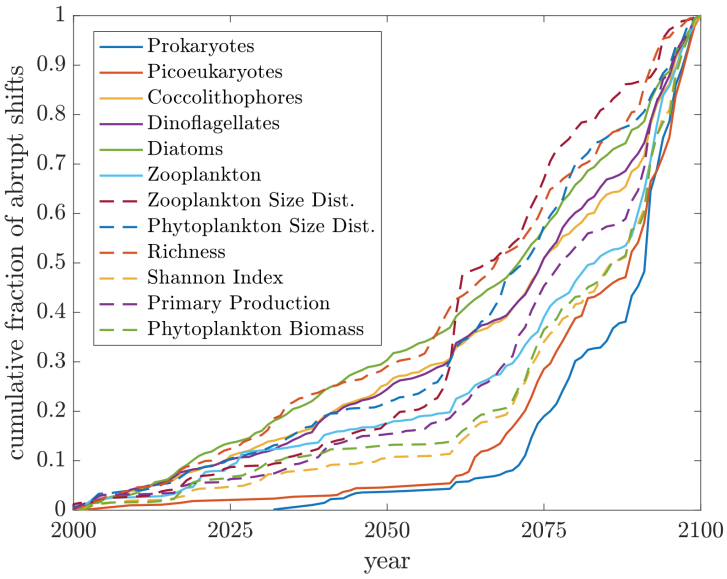

Figure S7: For each ecosystem property, the fraction of 21st-century abrupt shifts identified when analyzing model output from 1990-y as a function of end year y between 2000 and 2100. Depending on the ecosystem property, 70-96% of the abrupt shifts are only identified when analyzing model output including years past 2050.

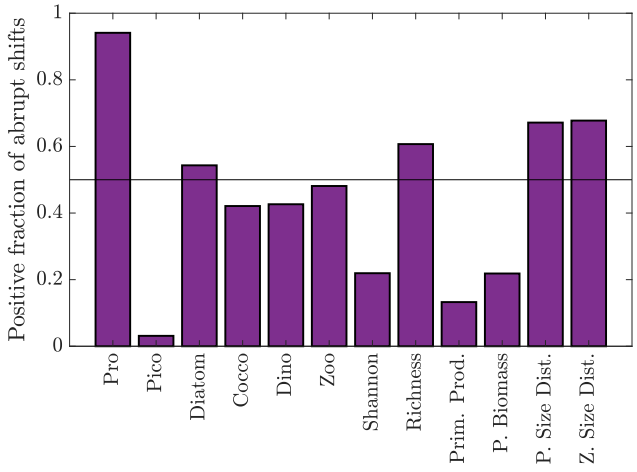

Figure S8: For each ecosystem property, the fraction of 21st-century abrupt shifts identified that are positive, i.e. increases.

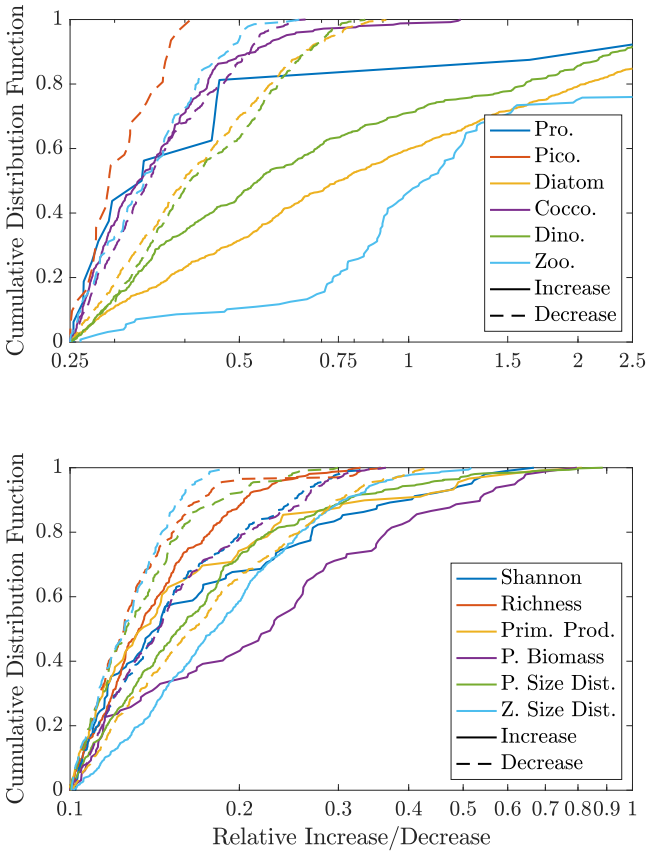

Figure S9: For each ecosystem property, the cumulative distribution of the amplitude of both positive (increasing) and negative (decreasing) abrupt shifts. Negative prokaryotic and positive picoeukaryotic abrupt shifts are not plotted because each is comprised of only a single anomalous grid cell.

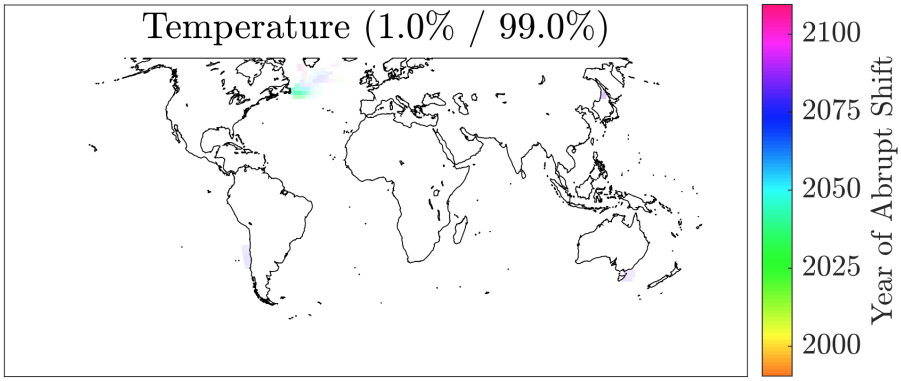

Figure S10: Same as Figures 3a-f for top ocean grid layer temperature.

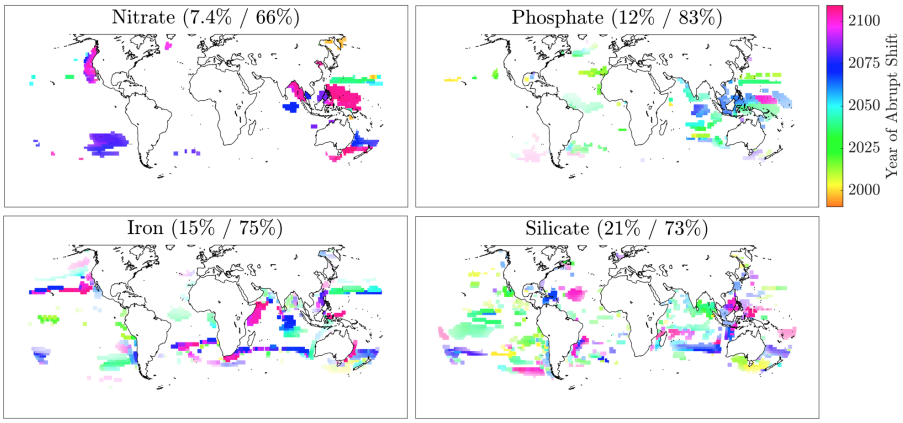

Figure S11: Same as Figures 2a-f for top ocean grid layer nutrient concentrations.

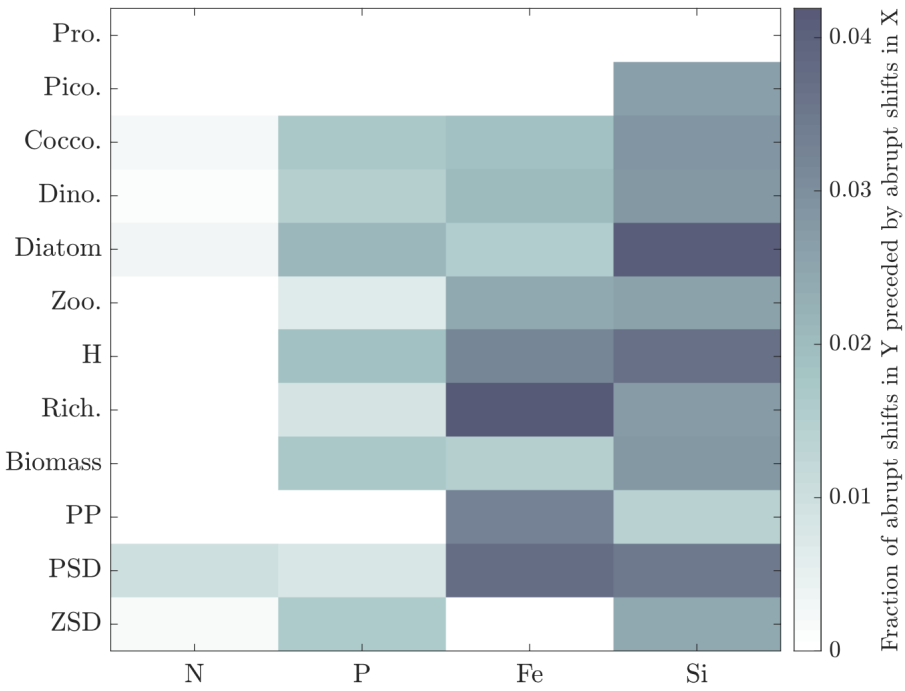

Figure S12: Fraction of abrupt shifts in each ecosystem property preceded (within five years) by an abrupt shift in each nutrient. For instance, in the maximum case, for 4.2% of the locations where an abrupt shift in diatom biomass is detected, an abrupt shift in silicate concentrations is detected 1-5 years beforehand. When using a window of 2 years, these fractions range from 0-0.027; when using a window of 10 years, they range from 0-0.057.

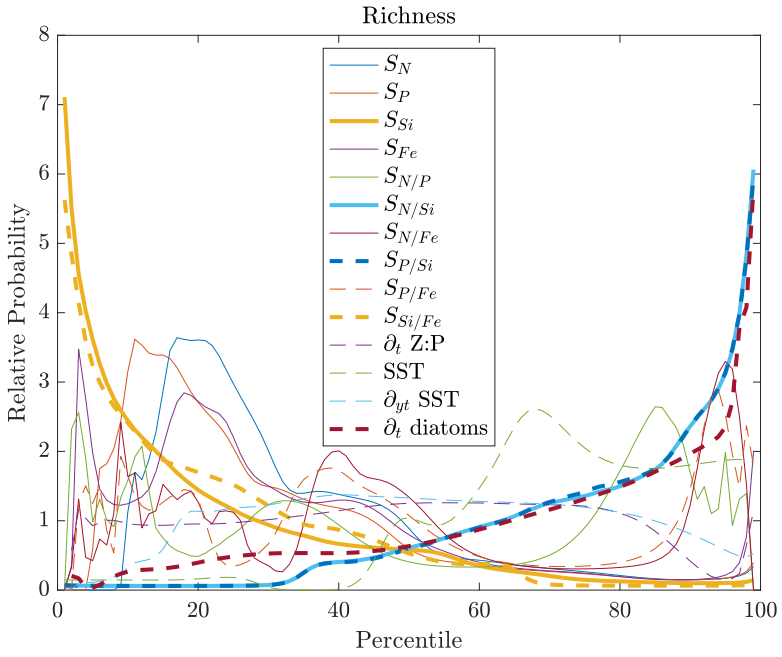

Figure S13: Relative likelihood of an abrupt shift occurring in species richness as a function of different driver variables, and as a function of the relative rate of change of diatom biomass. X-axis refers to the percentiles of the driver variables, so that all drivers can be plotted on a single axis. The only systematic relationship is with silicate supply $S_{Si(/N/P/Fe)}$ and ∂_t diatoms.

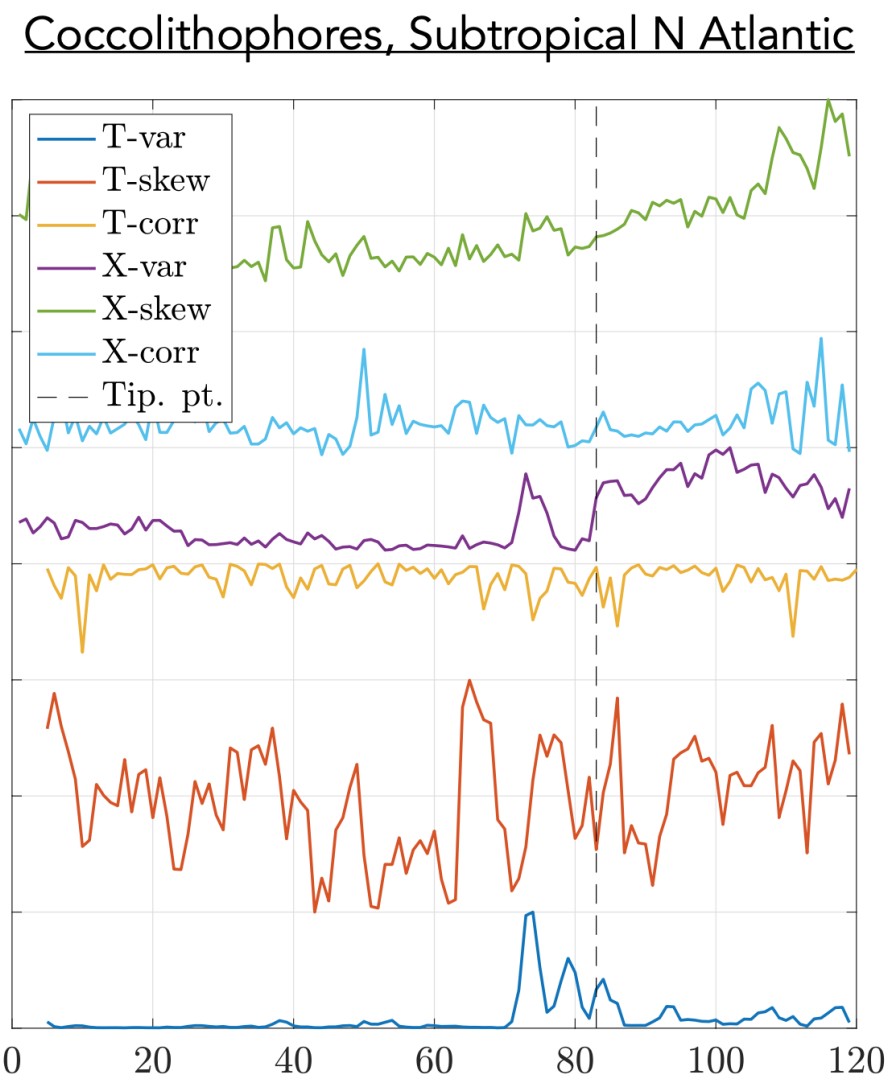

Figure S14: Same as Figure 4 for coccolithophores in the Subtropical North Atlantic. Note the purple and blue variance time series' maxima.

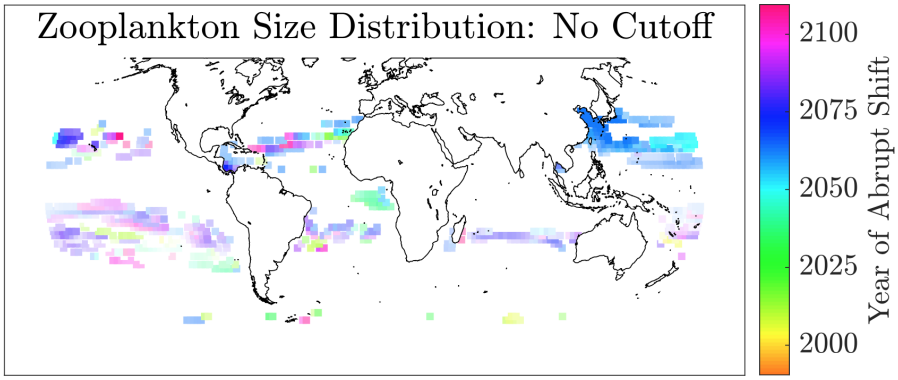

Figure S15: a) Same as Figure 3f. b) Same as Figure 3f without 10% cutoff threshold. Regions with abrupt shifts are slightly expanded but still confined to the subtropics.

Table S1: For each ecosystem property considered here, the fraction of ocean area equatorward of 65° for which abrupt changes are identified (Ext.) is given for both the emissions (E.) scenario simulation and the control (C.) simulation. The third and fourth column give the median amplitude (Amp.) of the abrupt shifts in each case.

Property	E. Ext. (%)	C. Ext. (%)	E. Amp. (%)	C. Amp. (%)
Prokaryotes	0.30	0.015	42	34
Picoeukaryotes	1.2	0.21	82	29
Coccolithophores	12	0.69	27	34
Diazotrophs	40	10	37	81
Diatoms	25	7.5	40	51
Dinoflagellates	20	4.1	31	45
Zooplankton	5.3	1.9	32	47
Shannon Index	8.4	1.6	12	14
Richness	9.2	0.93	12	13
Primary Production	12	4.3	14	16
Phyto. Biomass	7.9	1.6	12	15
Phyto. Size Dist.	12	1.8	11	14
Zoo. Size Dist.	8.8	0.78	14	15

Table S2: For each ecosystem property considered here, whether or not there is a systematic increase in the relative probability of an abrupt change occurring at a given place and time as the supply rate S_{Si} decreases (and as the supply ratios $S_{Si/N}$, $S_{Si/P}$, $S_{Si/Fe}$ decrease, and as the relative change in diatom biomass ∂_t(diatoms) increases), or whether that ecosystem property has a systematic relationship with any other putative driver. See also Figure S13. Prokaryotes and Picoeukaryotes are not considered because their abrupt shifts are too rare to resolve systematic relationships confidently, though $\partial_t Z/P$ is higher than average when and where abrupt shifts in these plankton types occur.

Property	$S_{Si(/N/P/Fe)}$ and ∂_t(diatoms)	another putative driver
Coccolithophores	Yes	No
Diatoms	Yes	No
Dinoflagellates	Yes	No
Zooplankton	No	No
Shannon Index	Yes	No
Richness	Yes	No
Primary Production	Yes	No
Phyto. Biomass	Yes	No
Phyto. Size Dist.	Yes	No
Zoo. Size Dist.	Yes	No

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