Table S1. All stochastic cusp model outcomes. Statistical results of all cusp analyses. z_t: state variable; α: asymmetry parameter; β: bifurcation parameter; AIC: Akaike information criterion; SSB: spawning stock biomass; R: recruitment; F: fishing mortality. % within bifurcation area is only shown for cusp models. The number of parameters were 4, 5, and 6 for all linear, logistic and cusp models, respectively.

z_t	α	β	Model	AIC	Cobb's pseudo-R^2	% within bifurcation area
SSB	F	Recruitment	Linear Logist Cusp	1350.29 1346.54 121.54	0.36 0.43 0.50	36.36
SSB	F	PC2 biotic and abiotic	Linear Logist Cusp	1371.17 1366.35 143.03	0.06 0.17 0.54	50.91
SSB	F	NAO	Linear Logist Cusp	1367.10 1365.46 144.76	0.13 0.19 0.56	45.45
SSB	F	SBT	Linear Logist Cusp	1364.50 1365.67 138.46	0.17 0.18 0.35	36.36
SSB	F	Large copepods	Linear Logist Cusp	1359.96 1361.59 132.90	0.24 0.29 0.40	52.72
SSB	F	Diatoms	Linear Logist Cusp	1355.03 1349.46 137.19	0.30 0.39 0.33	/
SSB	F	Dinoflagellates	Linear Logist Cusp	1363.21 1347.11 136.258	0.19 0.42 0.41	/
SSB	F	Small copepods	Linear Logist Cusp	1359.98 1339.76 136.10	0.23 0.49 0.23	/
SSB	F	Phytoplankton	Linear Logist Cusp	1344.62 1319.37 124.28	0.42 0.65 0.39	/
SSB	F	Inflow	Linear Logist Cusp	1347.25 13344.65 133.94	0.39 0.44 0.39	/
SSB	F	PC1 biotic and abiotic	Linear Logist Cusp	1328.14 1310.78 110.21	0.57 0.70 0.55	/
SSB	F	PC1+PC2 biotic and abiotic	Linear Logist Cusp	1325.82 1312.28 108.53	0.60 0.70 0.58	/
R	SSB	PC1 + PC2 biotic and abiotic	Linear Logist Cusp	1552.08 1547.09 98.47	0.43 0.50 0.58	83.33
R	SSB	Small copepods	Linear Logist Cusp	1560.96 1550.31 166.80	0.31 0.45 0.49	50.00

z_t	α	β	Model	AIC	Cobb's pseudo-R^2	% within bifurcation area
R	SSB	SBT	Linear Logist Cusp	1561.32 1549.556 119.334	0.30 0.46 0.26	/
R	SSB	Diatoms	Linear Logist Cusp	1561.90 1549.33 119.35	0.29 0.48 0.24	/
R	SSB	Dinoflagellates	Linear Logist Cusp	1565.29 1547.89 123.78	0.25 0.47 0.25	/
R	SSB	Large copepods	Linear Logist Cusp	1560.24 1547.14 120.95	0.31 0.48 0.25	/
R	SSB	Phytoplankton	Linear Logist Cusp	1550.94 1537.39 108.64	0.42 0.57 0.41	/
R	SSB	Inflow	Linear Logist Cusp	1565.13 1551.58 126.17	0.25 0.44 0.19	/
R	SSB	NAO	Linear Logist Cusp	1565.25 1549.45 128.01	0.25 0.46 0.16	/
R	SSB	PC1 biotic and abiotic	Linear Logist Cusp	1550.27 1545.92 99.68	0.42 0.48 0.47	/
R	SSB	PC2 biotic and abiotic	Linear Logist Cusp	1565.51 1545.74 125.35	0.24 0.48 0.26	/

To gain a deeper understanding into the different effects of biotic and abiotic variables, we performed distinct PCAs (Figures S1 & S2). The PCAs show contrasting principle components (PCs). The PC1 of the biotic variables is continuously decreasing (Figure S1), with small copepods and phytoplankton being the main biotic variables contributing to PC1(Figure S1a). PC2 is mainly determined by dinoflagellates and large copepods, and increasing until 1987, followed by a steady decrease until 2017 (Figure S1b). As for the overall PCA analyses, three periods could be identified for the biotic variables as well (Figures S1c,d). The first cluster (1963–1986) determines a high SSB and recruitment, and strong appearances of dinoflagellates and large and small copepods. In contrast, the third cluster (1997–2017) demonstrates a low SSB and recruitment, and high abundances of diatoms and phytoplankton, being the biotic opponents to PC1.

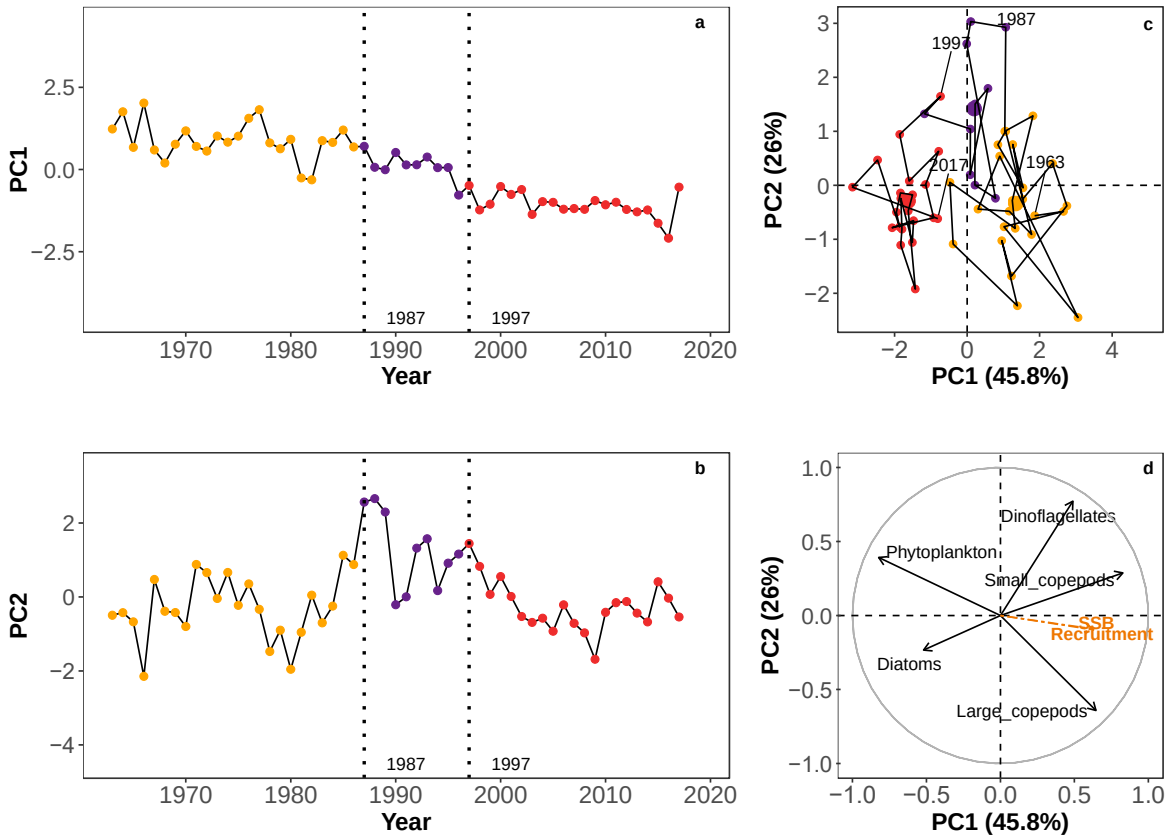

Figure S1. Biotic North Sea ecosystem dynamics. Results of Principal Component Analysis. (a) PC1 trajectory over time, (b) PC2 trajectory over time, (c) PCA individuals, (d) PCA variables (spawning stock biomass (SSB), Phytoplankton (Phytoplankton Color Index). SSB and recruitment are supplementary quantitative variables (orange); vertical lines in (a) and (b) indicate transitions between clusters identified by constrained clustering analyses in (c); cluster 1 in yellow (1963–1986), cluster 2 in purple (1987–1996), cluster 3 in red (1997–2017); icons represent main variables contributing to PC.

We found a similar strong distinction within abiotic variables (Figure S2). PC1 is steadily increasing and represents climatic variables with strong contributions by the NAO, wind and inflow. The warming variable SBT contrarily strongly contributes to PC2, which is continuously increasing too. Here, we also identified three clusters using constrained clustering (Figure S2c). The low reproductive stock (SSB and recruitment) characterizes the first cluster (1963–1987) solely (Figure S2c,d). The second (1988–2000) and third clusters (1989–2017) highlight the distinction between variables characterizing atmospheric dynamics and thermal conditions, as well as the upcoming relevance of abiotic variables for the cod stock. The second period experienced a high NAO, strong winds, currents and North Sea inflow, whereas the recent period demonstrates increased warming.

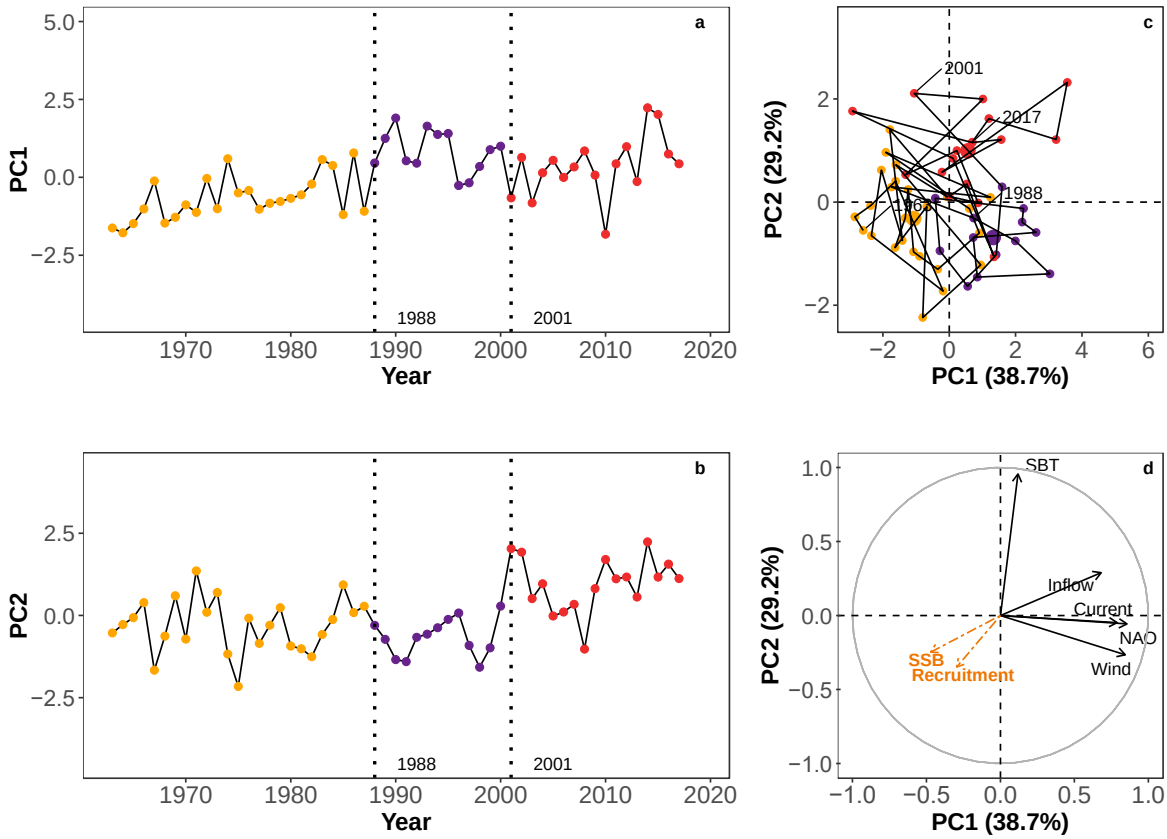

Figure S2. Abiotic North Sea ecosystem dynamics. Results of Principal Component Analysis. (a) PC1 trajectory over time, (b) PC2 trajectory over time, (c) PCA individuals, (d) PCA variables (SSB: spawning stock biomass; SBT: sea bottom temperature; NAO: North Atlantic oscillation). SSB and recruitment are supplementary quantitative variables (orange); vertical lines in (a) and (b) indicate transitions between clusters identified by constrained clustering analyses in (c); cluster 1 in yellow (1963–1987), cluster 2 in purple (1988–2000), cluster 3 in red (2001–2017); icons represent main variables contributing to PC.