Supporting information for "Coastal eutrophication drives acidification, oxygen loss and ecosystem change in a major oceanic upwelling system"

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Figure S10 Evolution of the tolerance depth of giant kelp *Macrocystis pyrifera* in San Pedro and Ventura shelves (as shown in yellow in the domain panel, top left.). Top right panel shows a climatology of the tolerance depth of *Macrocystis pyrifera* in CTRL run Vs ANTH run. Bottom left panel illustrates a climatology (1997-1999) of the relative change in the tolerance depth of *Macrocystis pyrifera* shown in the top right panel. The bottom right panel is the absolute change of the tolerance depth of *Macrocystis pyrifera*. These analysis are showing the possible change caused by the eutrophication.

Figure S11 Climatology of the mixed layer depth in the south (San Diego area), center (Los Angeles coast) and north (Santa Barbara coast) of the SCB.

Terrestrial and Atmospheric Loads	
	Total Nitrogen loads (kg N d^{-1})
Atmospheric deposition	8,589
Rivers	17,975
Coastal outfalls, 4 large POTWs	148,170
Coastal outfalls, other small POTWs	21,445
Total	196,179

Table S1. Multi-year average loads of total nitrogen from different anthropogenically-enhanced sources in the Southern California Bight averaged between

Surface total phytoplankton biomass (mg C m^{-3}) (March-May)								
	CTRL	ANTH	Mean Change	% Change	CTRL (El Niño)	ANTH (El Niño)	Mean Change (El Niño)	% Change (El Niño)
All Coast [0-15 km]	8.75	11.77	3.01	+79	3.85	6.99	3.14	+129
Santa Barbara	15.51	15.66	0.14	+7.8	6.12	8.14	2.02	+56
Ventura	9.64	11.82	2.18	+44	4.13	6.59	2.45	+84
Santa Monica	8.70	13.22	4.51	+87	4.00	8.74	4.74	+162
Los Angeles	7.02	14.09	7.06	+192	3.31	9.51	6.19	+278
San Pedro	5.66	17.72	12.05	+367	2.81	12.61	9.80	+495
Orange County	4.45	6.66	2.20	+59	2.40	4.49	2.08	+97
San Diego North	4.80	7.22	2.41	+68	2.58	4.05	1.47	+62
San Diego South	6.25	9.59	3.33	+76	2.79	5.36	2.56	+125
MPA1: Campus Point Santa Barbara	15.16	15.51	0.34	+13	5.34	8.02	2.68	+71
MPA2: Point Dume Santa Monica	8.37	11.25	2.87	+63	3.79	6.51	2.72	+102
MPA3: Point Vicente and Abalone Cove	5.65	11.60	5.95	+130	2.97	8.65	5.68	+210
MPA4: Laguna Beach and Dana Point	4.93	7.63	2.70	+74	2.52	5.61	3.08	+135
MPA5: South La Jolla	6.21	8.84	2.63	+57	2.95	4.41	1.45	+63
MPA6: Cabrillo	8.06	11.44	3.37	+57	3.30	5.55	2.24	+96

Table S2. Surface chlorophyll *a* concentration for the months of February to July, averaged by regions shown in Figure S2. The first column shows results from the CTRL simulation, the second column from the ANTH simulation, the third column the absolute difference (ANTH- CTRL), and the fourth column the relative difference expressed as percent (100*[ANTH-CTRL]/CTRL).

Total Primary Production (mmol C m^{-2} d^{-1}) (February-July, 0-40 m depth)				
	CTRL	ANTH	Abs Change	% Change
All Coast [0-15 km]	88.51	108.80	20.29	+23
Santa Barbara	129.19	140.89	11.69	+9
Ventura	92.79	110.08	17.29	+18
Santa Monica	85.63	121.89	36.25	+42
Los Angeles	76.05	114.65	38.59	+50
San Pedro	63.55	114.46	50.91	+80
Orange County	64.91	79.72	14.80	+22
San Diego North	73.54	86.42	12.88	+17
San Diego South	68.85	85.47	16.62	+24
MPA1: Campus Point Santa Barbara	117.90	132.94	15.03	+12
MPA2: Point Dume Santa Monica	87.78	109.37	21.59	+24
MPA3: Point Vicente and Abalone Cove	82.05	119.81	37.76	+46
MPA4: Laguna Beach and Dana Point	77.94	103.39	25.45	+32
MPA5: South La Jolla	73.75	86.69	12.94	+17
MPA6: Cabrillo	56.07	70.17	14.10	+25

Table S3. Same as Table S2 for the total primary production rate in the upper ocean (0-40 m depth).

Particulate carbon export (mmol C m^{-2} d^{-1}) (May-August, at 40 m depth)				
	CTRL	ANTH	Abs Change	% Change
All Coast [0-15 km]	-16.29	-20.35	-4.06	+24
Santa Barbara	-22.67	-25.02	-2.34	+10
Ventura	-16.48	-19.77	-3.28	+19
Santa Monica	-15.92	-23.43	-7.50	+47
Los Angeles	-14.18	-22.42	-8.23	+58
San Pedro	-11.64	-23.07	-11.42	+98
Orange County	-12.74	-15.18	-2.44	+19
San Diego North	-14.42	-16.63	-2.21	+15
San Diego South	-13.91	-17.63	-3.72	+26
MPA1: Campus Point Santa Barbara	-21.38	-23.85	-2.47	+11
MPA2: Point Dume Santa Monica	-16.17	-20.66	-4.49	+27
MPA3: Point Vicente and Abalone Cove	-14.72	-20.75	-6.03	+40
MPA4: Laguna Beach and Dana Point	-15.40	-20.18	-4.77	+30
MPA5: South La Jolla	-13.89	-17.46	-3.56	+25
MPA6: Cabrillo	-10.64	-13.93	-3.29	+30

Table S4. Same as Table S2 except for particulate carbon export at 40 m depth and during the May-August (stratified) period.

Respiration at depth (mmol O m^{-2} d^{-1}) (May-August, 40-80 m depth)				
	CTRL	ANTH	Abs Change	% Change
All Coast [0-15 km]	-6.40	-9.26	-2.86	+44
Santa Barbara	-11.85	-14.24	-2.38	+20
Ventura	-5.51	-8.24	-2.73	+49
Santa Monica	-7.93	-16.83	-8.90	+112
Los Angeles	-5.01	-10.59	-5.58	+111
San Pedro	-2.94	-6.00	-3.06	+104
Orange County	-3.06	-4.17	-1.10	+36
San Diego North	-5.86	-7.31	-1.45	+24
San Diego South	-4.09	-6.28	-2.19	+53
MPA1: Campus Point Santa Barbara	-11.12	-14.10	-2.98	+26
MPA2: Point Dume Santa Monica	-5.07	-9.73	-4.66	+91
MPA3: Point Vicente and Abalone Cove	-6.20	-13.28	-7.08	+114
MPA4: Laguna Beach and Dana Point	-6.82	-10.70	-3.88	+56
MPA5: South La Jolla	-9.66	-14.36	-4.70	+48
MPA6: Cabrillo	-1.21	-1.61	-0.40	+32

Table S5. Same as Table S4 for respiration rate at subsurface (40-80 m depth).

Oxygen (mmol O m^{-3}) (May-August, 40 m depth)						
	CTRL	ANTH	Mean Change	Maximum change	Mean change (El Niño)	Max change (El Niño)
All Coast [0-15 km]	223	222	-1	-50	-8	-55
Santa Barbara	199	197	-2	-59	-10	-49
Ventura	229	228	-2	-42	-7	-46
Santa Monica	230	222	-8	-51	-13	-56
Los Angeles	232	228	-4	-47	-10	-55
San Pedro	232	231	-1	-42	-8	-53
Orange County	238	237	-1	-49	-6	-58
San Diego North	229	228	-1	-42	-6	-60
San Diego South	224	220	-4	-43	-11	-71
MPA1: Campus Point Santa Barbara	207	205	-2	-60	-8	-43
MPA2: Point Dume Santa Monica	231	229	-2	-40	-8	-49
MPA3: Point Vicente and Abalone Cove	231	229	-2	-42	-8	-51
MPA4: Laguna Beach and Dana Point	233	229	-4	-41	-8	-51
MPA5: South La Jolla	219	213	-6	-49	-10	-67
MPA6: Cabrillo	209	202	-7	-52	-14	-65

Table S6. Oxygen averaged by regions of Figure S2 for the months of May to August. The first column shows average values from the CTRL simulation, the second column average values from the ANTH simulation, the third column the mean change (ANTH-CTRL), and the fourth column the maximum change, here defined as the 95th percentile of the frequency distribution of the change for each regions. The fifth column is the average change in May to August of El Niño year 1997-1998.

CO_2 air-sea flux (mmol C m^{-2} d^{-1}) (May-August)				
	CTRL	ANTH	Abs Change	% Change
All Coast [0-15 km]	1.21	1.76	0.54	+31
Santa Barbara	1.40	1.84	0.44	+23
Ventura	1.33	1.98	0.65	+32
Santa Monica	0.97	1.75	0.77	+44
Los Angeles	0.79	1.94	1.14	+58
San Pedro	0.64	2.10	1.46	+69
Orange County	0.70	0.93	0.22	+24
San Diego North	0.68	0.96	0.28	+29
San Diego South	0.71	0.92	0.21	+22

Table S7. Same as Table S4 for CO_2 air-sea flux

Ω_{Ar} (May-August, 40 m depth)						
	CTRL	ANTH	Mean Change	Maximum change	Mean change (El Niño)	Max change (El Niño)
All Coast [0-15 km]	1.66	1.64	-0.016	-0.47	-0.11	-0.63
Santa Barbara	1.42	1.41	-0.011	-0.53	-0.11	-0.59
Ventura	1.71	1.70	-0.006	-0.41	-0.10	-0.53
Santa Monica	1.74	1.66	-0.08	-0.49	-0.15	-0.63
Los Angeles	1.74	1.70	-0.04	-0.46	-0.12	-0.61
San Pedro	1.73	1.72	-0.01	-0.41	-0.10	-0.60
Orange County	1.79	1.79	-0.006	-0.48	-0.09	-0.69
San Diego North	1.70	1.70	-0.001	-0.42	-0.10	-0.71
San Diego South	1.66	1.62	-0.038	-0.42	-0.14	-0.77
MPA1: Campus Point Santa Barbara	1.50	1.48	-0.017	-0.58	-0.10	-0.56
MPA2: Point Dume Santa Monica	1.73	1.72	-0.017	-0.39	-0.11	-0.56
MPA3: Point Vicente and Abalone Cove	1.72	1.70	-0.02	-0.41	-0.11	-0.56
MPA4: Laguna Beach and Dana Point	1.74	-0.03	-0.08	-0.41	-0.11	-0.58
MPA5: South La Jolla	1.60	1.55	-0.05	-0.46	-0.12	-0.76
MPA6: Cabrillo	1.52	1.46	-0.05	-0.10	-0.16	-0.79

Table S8. Same as Table S6 for Ω_{Ar}.

pH (May-August, 40 m depth)						
	CTRL	ANTH	Mean Change	Maximum change	Mean change (El Niño)	Max change (El Niño)
All Coast [0-15 km]	7.97	7.97	-0.0043	-0.09	-0.012	-0.10
Santa Barbara	7.92	7.92	-0.002	-0.10	-0.014	-0.08
Ventura	7.99	7.98	-0.003	-0.08	-0.01	-0.08
Santa Monica	7.99	7.97	-0.017	-0.10	-0.02	-0.10
Los Angeles	7.99	7.98	-0.01	-0.09	-0.014	-0.10
San Pedro	7.99	7.99	-0.004	-0.08	-0.01	-0.09
Orange County	8.02	8.00	-0.003	-0.09	-0.008	-0.10
San Diego North	7.99	7.99	0.00	-0.08	-0.01	-0.10
San Diego South	7.98	7.97	-0.007	-0.08	-0.0173	-0.12
MPA1: Campus Point Santa Barbara	7.94	7.94	-0.0031	-0.09	-0.01	-0.07
MPA2: Point Dume Santa Monica	7.99	7.98	-0.0059	-0.08	-0.01	-0.09
MPA3: Point Vicente and Abalone Cove	7.99	7.98	-0.0059	-0.08	-0.01	-0.09
MPA4: Laguna Beach and Dana Point	7.99	7.99	-0.0098	-0.08	-0.01	-0.09
MPA5: South La Jolla	7.97	7.96	-0.02	-0.10	-0.01	-0.12
MPA6: Cabrillo	7.95	7.94	-0.02	-0.097	-0.02	-0.11

Table S9. Same as Table S6 for pH (Sea water scale).

N_2O air-sea efflux (mmol N m^{-2} d^{-1})

	CTRL	ANTH	Abs Change	% Change
All Coast [0-15 km]	3.10	3.34	0.24	+8
Santa Barbara	5	5.35	0.35	+7
Ventura	3.14	3.37	0.22	+7
Santa Monica	2.27	2.56	0.29	+13
Los Angeles	1.95	2.19	0.24	+12
San Pedro	1.68	1.87	0.2	+12
Orange County	1.24	1.35	0.1	+8
San Diego North	1.25	1.38	0.12	+10
San Diego South	1.59	1.8	0.20	+13

Table S10. Same as Table S4 for N_2O air-sea out-flux.

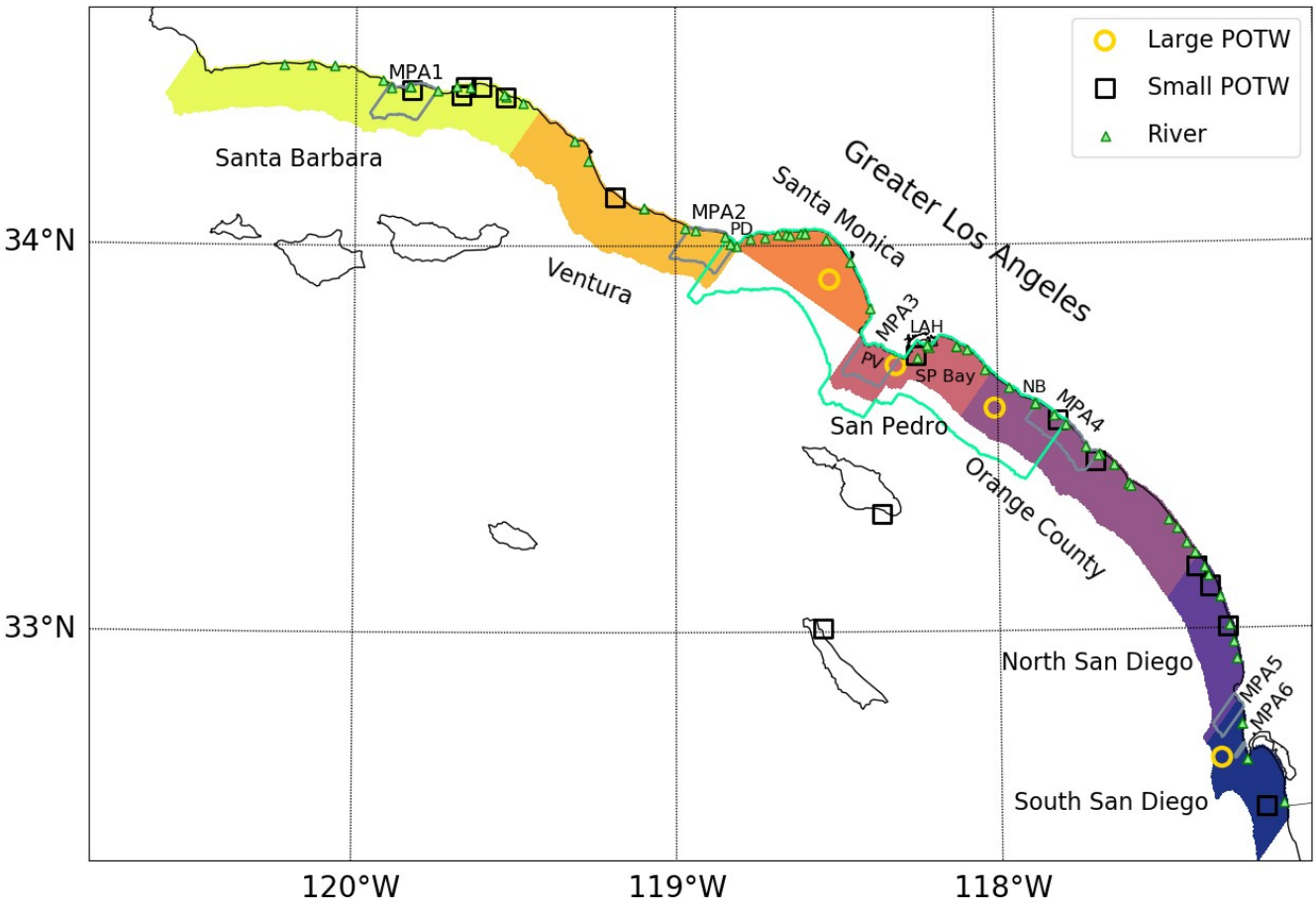

Fig. S1. Areas of the distinct regions and coast (0-15 km) used for analyses (Tables S2 to S10). Yellow circles are the locations of the four large POTW outfalls. Black squares are the locations of small POTW outfalls. Small green triangles are the locations of river mouth discharge. Green outline represents the Greater Los Angeles region. Grey boxes indicate marine protected areas (MPAs) cited in section "Effects on fisheries and vulnerable habitats". For reference, names of locations are shown on the maps as follow: PD = Point Dume, LAH = Los Angeles Harbor, SP Bay = San Pedro Bay, NB = Newport Beach.

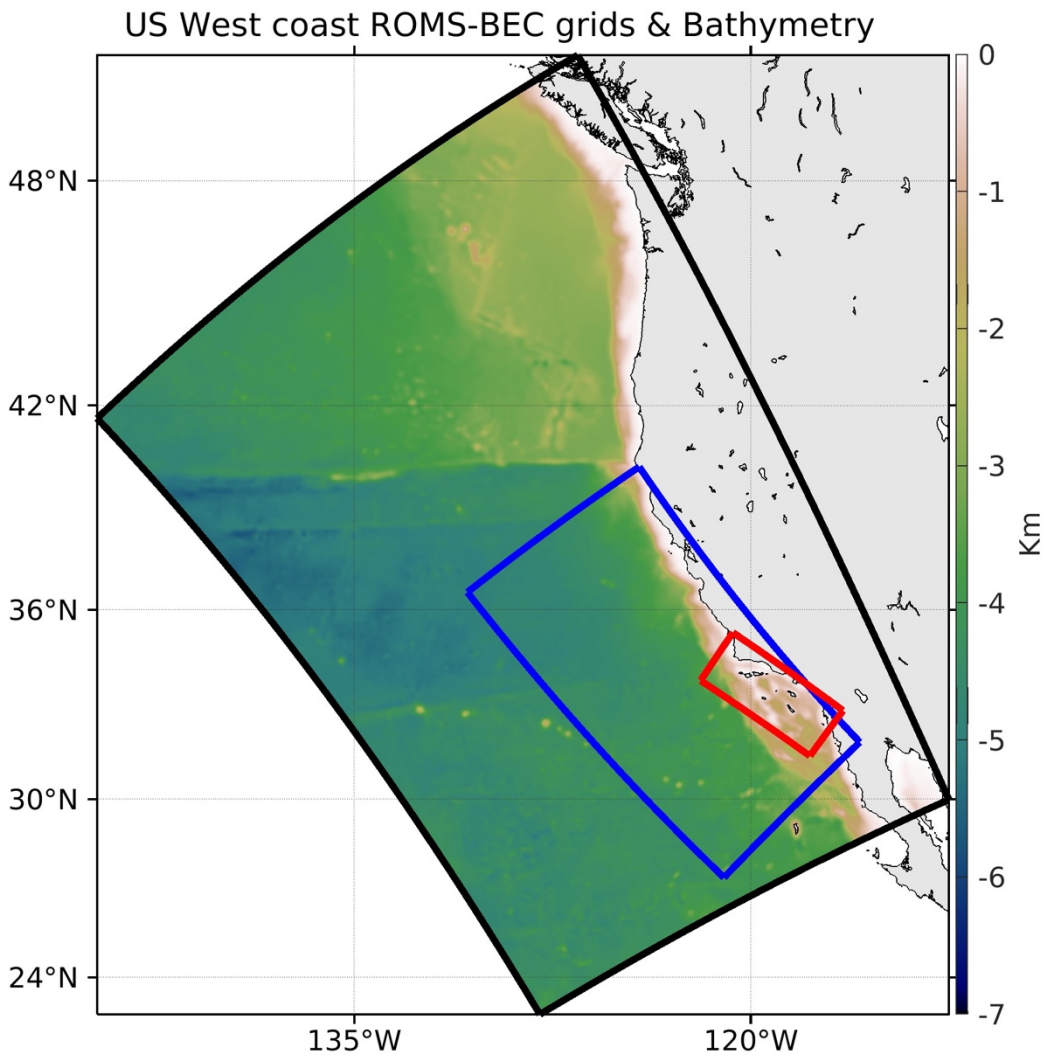

Fig. S2. ROMS-BEC model one-way nests to downscale to the configuration used in this study. The U.S. West Coast domain run at a horizontal resolution of 4 km is shown by the black box, the Southern California Current domain run at 1 km is shown by the blue box, and the SCB domain run at 0.3 km is shown by the red box. Colors show topography from the 4 km simulation. Adapted from (26).

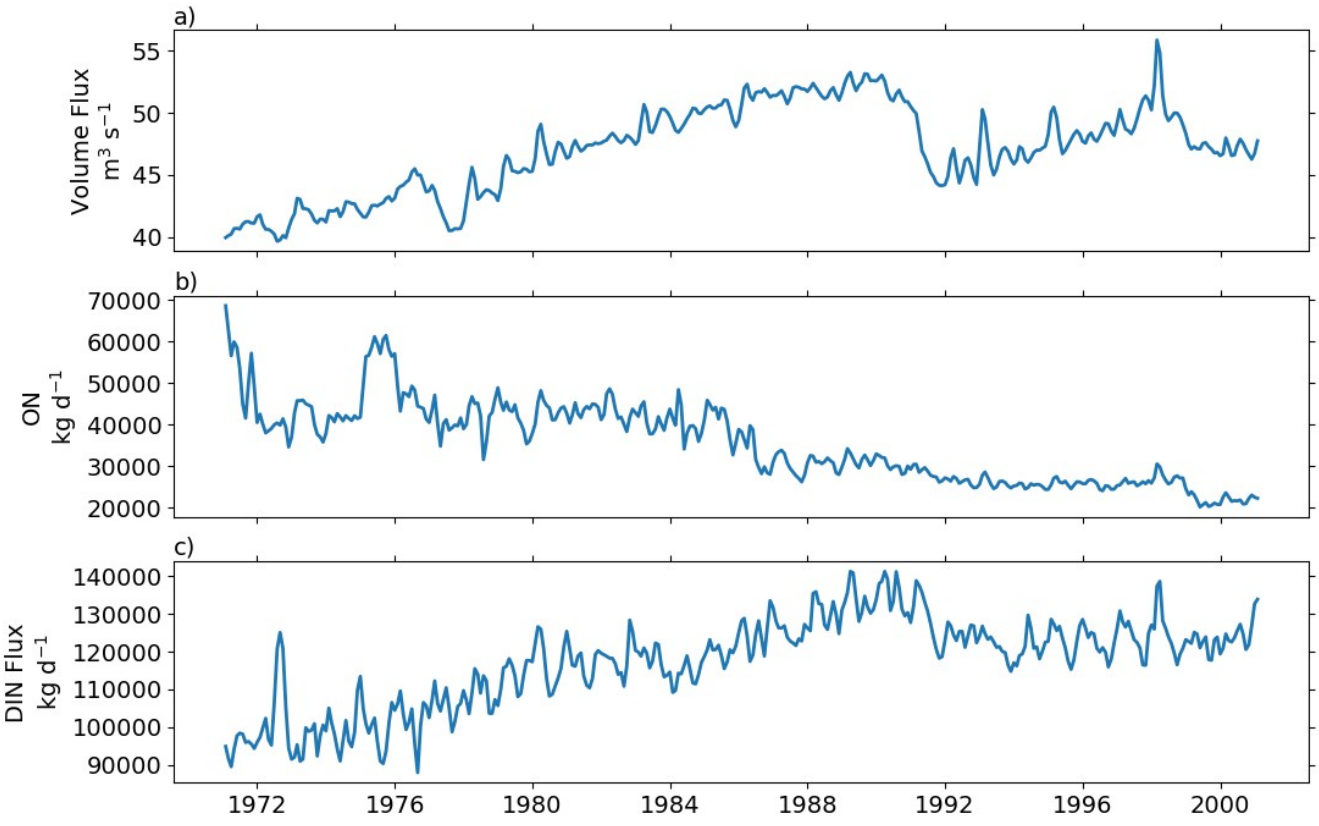

Fig. S3. Time series of all large POTW summed a) volume flux, b) organic N flux and c) dissolved inorganic N flux for 1971-2000.

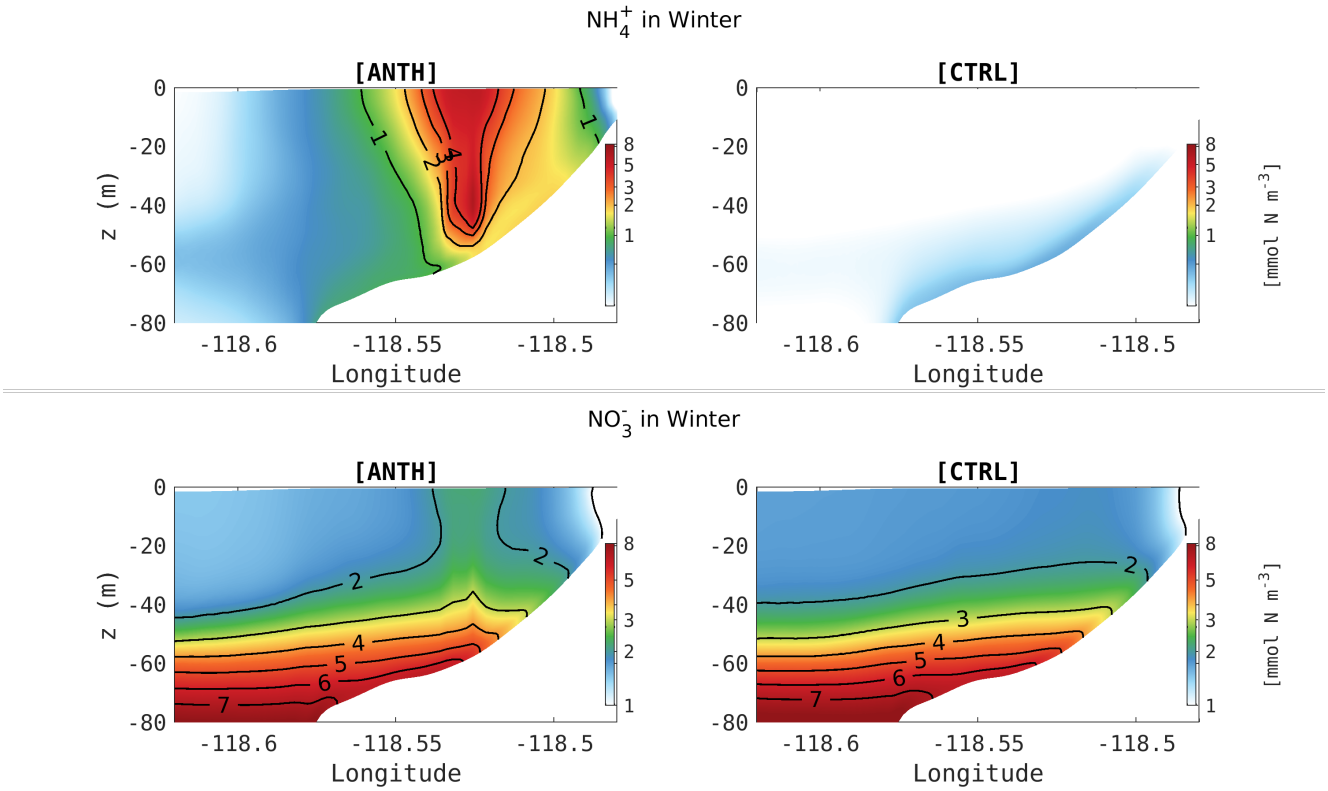

Fig. S4. Comparison of ANTH vs CTRL runs expressing concentrations of ammonium and nitrate along a cross-section in Santa Monica bay. The concentration is an average during winters. The left panels are the anthropogenic runs (ANTH), the right panels are control run (CTRL). The top panels ammonium concentrations, and the bottom are the nitrate concentrations. These panels express the transport of nitrate and ammonium to the upper layer by the buoyant plume.

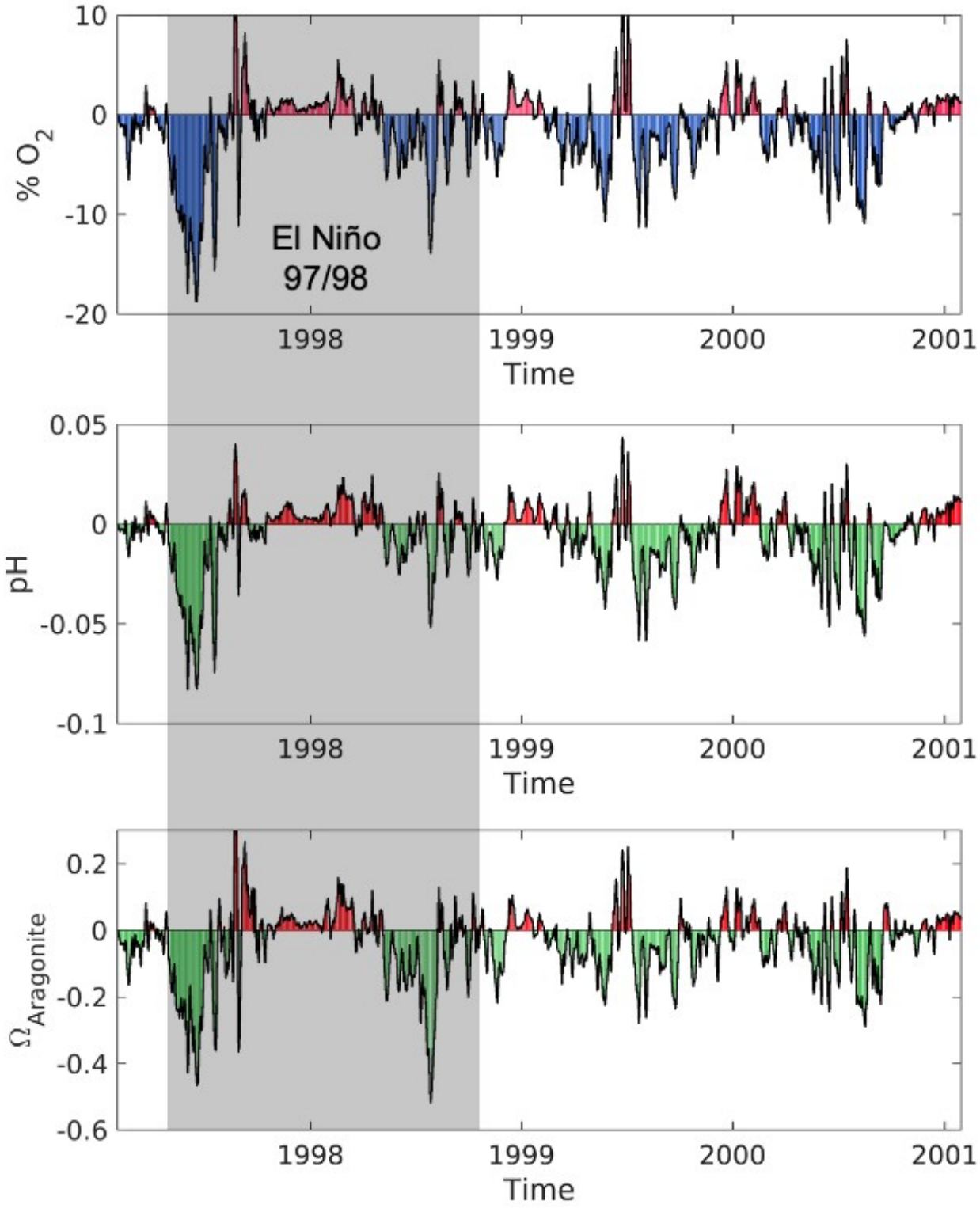

Fig. S5. Time series of the percent difference (ANTH - CTRL / CTRL) in Santa Monica Bay at 40 m depth between Feb 1997 and Jan 2001. The shaded region shows the El Niño time period. Upper: oxygen, middle: pH, lower: omega aragonite. Note the depletion of subsurface oxygen caused by the increased respiration of exported organic matter developed by eutrophication.

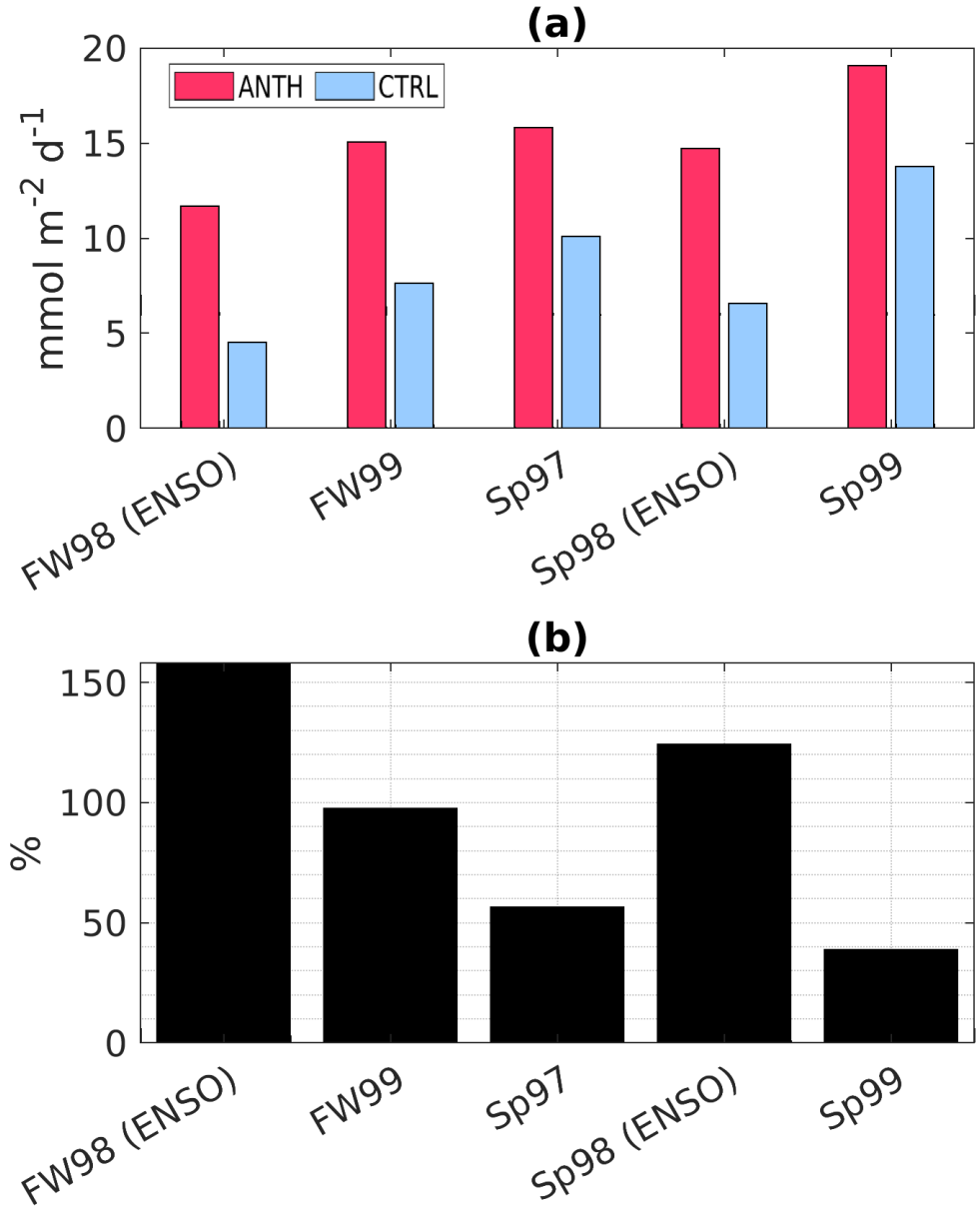

Fig. S6. (a) Seasonal vertically-integrated primary production showing the strong effect of El Niño 98. S is spring [March to June], W is fall to winter period [October to February]. (b) is the fraction of primary production between ANTH/CTRL. Winter and spring of 1998 are the seasons with the greatest change by anthropogenic (+100%). ENSO season presents a strong stratification and weak nutrients supply by upwelling, the main delivery of inorganic nutrients is then provided by anthropogenic sources.

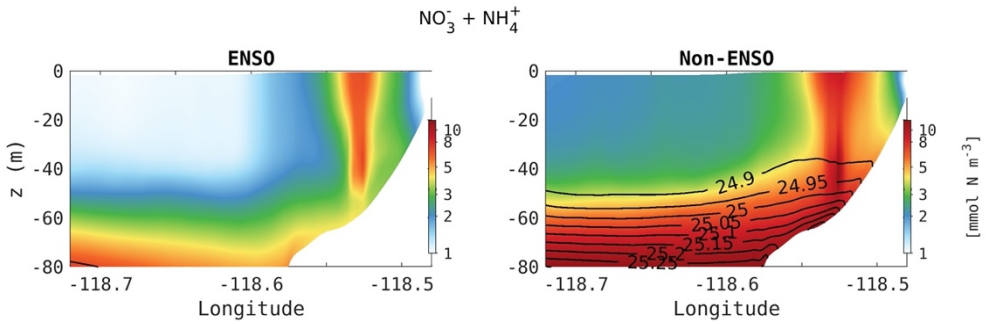

Fig. S7. Comparison of nitrate in winter during El Niño (ENSO in 1998) and a non-ENSO year (1999) in January and February in Santa Monica Bay. The isolines are the water density lines. The cross sections illustrate that the pycnocline is much deeper during ENSO, therefore, the only source of nutrients in the upper layer of Santa Monica Bay during ENSO comes from POTW submarine pipes. While during 1999, the source if inorganic nitrogen combines from deep ocean and POTW.

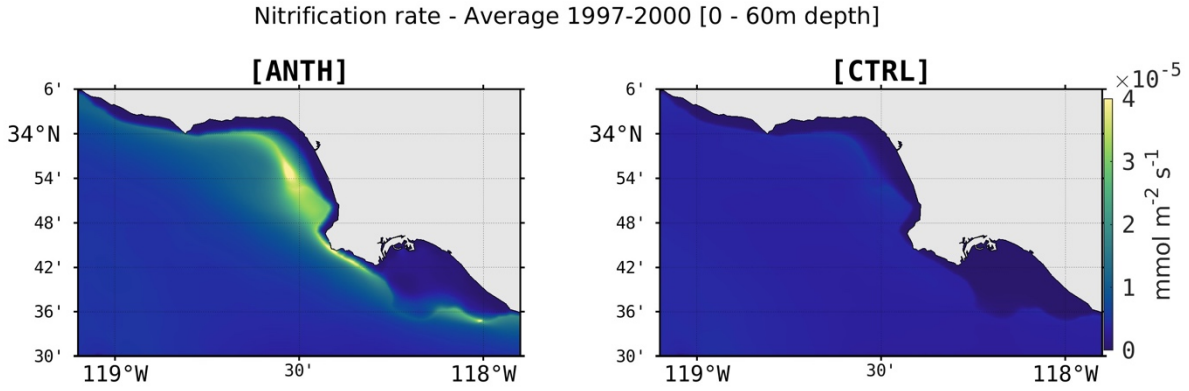

Fig. S8. Multi-year (1997-1999) averages of integrated nitrification in Los Angeles region. It shows the intensified nitrification rate at the locations of the submarine pipes.

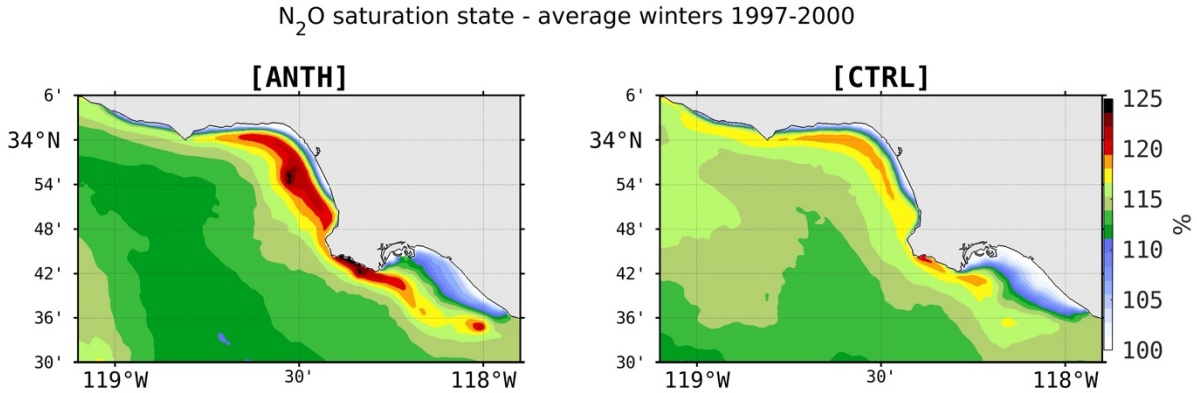

Fig. S9. Surface N_2O saturation state averaged over three winters [1997-1999]. It shows local increase of surface N_2O saturation state in the location of the intensified NH_4 plume. The excess in N_2O saturation state in ANTH run results from the intensification of the nitrification rates as shown in S8.

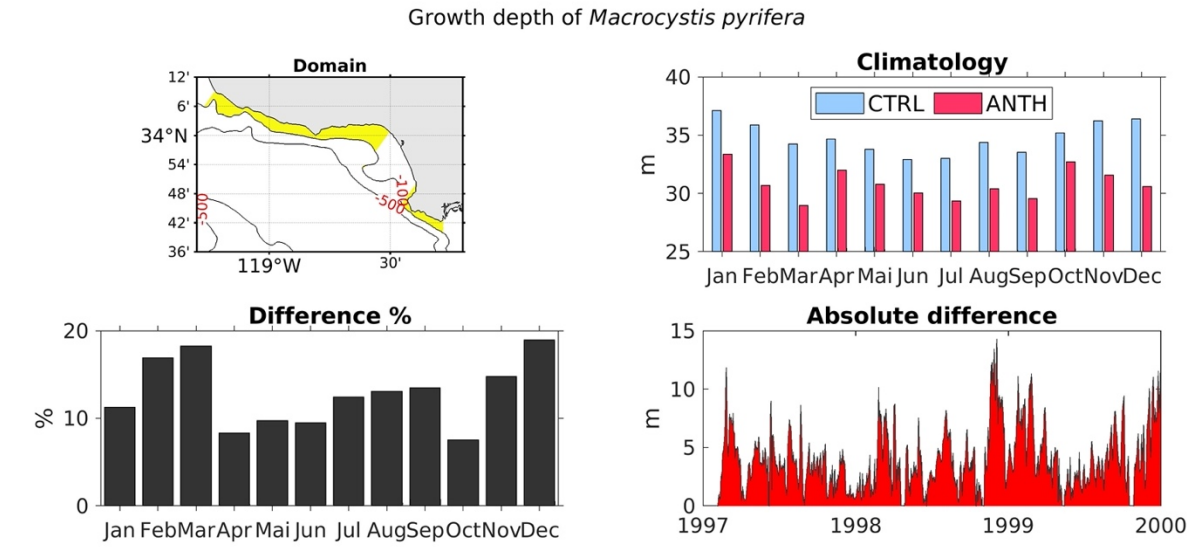

Fig. S10. Evolution of the tolerance depth of giant kelp *Macrocystis pyrifera* in San Pedro and Ventura shelves (as shown in yellow in the domain panel, top left.). Top right panel shows a climatology of the tolerance depth of *Macrocystis pyrifera* in CTRL run Vs ANTH run. Bottom left panel illustrates a climatology (1997-1999) of the relative change in the tolerance depth of *Macrocystis pyrifera* shown in the top right panel. The bottom right panel is the absolute change of the tolerance depth of *Macrocystis pyrifera*. These analysis are showing the possible change caused by the eutrophication.

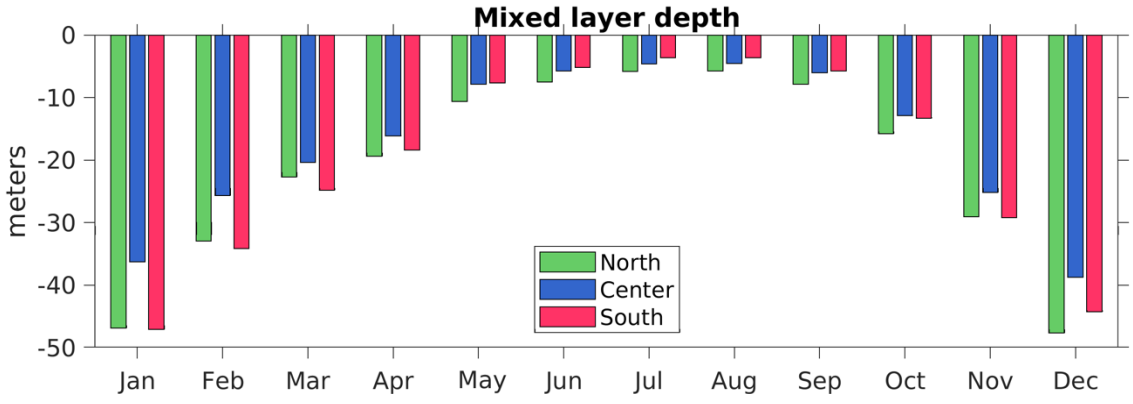

Fig. S11. Climatology of the mixed layer depth in the south (San Diego area), center (Los Angeles coast) and north (Santa Barbara coast) of the SCB.