

Supporting Information for

Warming Amplifies the Frequency of Harmful Algal Blooms with Eutrophication in Chinese Coastal Waters

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Methodology details and national standards for Marine Environmental monitoring in China.

Because of the importance of fisheries and aquaculture resources for China and the impacts of HABs on these resources, China has allocated significant efforts to monitoring these events. These efforts were initiated in 1933, but became systematic following the establishment of China's SOA in 1964. Since then the same methods have been used by national, provincial, regional and country-level monitoring stations affiliated with SOA. Laboratory calibrations and technician-training programs were carried out regularly in the context of SOA monitoring system. For instance, exercises including water, sediment and biological samples with 8 parameters and 16 concentrations were deployed 7 times between 1984 and 1989. The HABs monitoring follows technical specifications for plankton bloom monitoring described in the National Standard of China "Specification of Marine Monitoring (GB 17378-2007)", including the specification of ecological survey for offshore pollution and biological monitoring as Chapter 7, which is slightly modified from the earlier version (GB 17378-1998), itself revised from the professional standard entitled "Specification of Marine Environmental Monitoring (HY003.9-91)" in 1991, which summarized practical experience and research outcomes obtained by more than 50 SOA's branches involving more than 2000 staff over the previous 20 years from the 1970's. SOA also released the "Technical Specification for Red Tide Monitoring" (HY-T 069-2003, and its current version HY-T 069-2005) that provided additional details for the monitoring procedure, which followed the principle technical specification described in the national standard "Specification of Marine Monitoring (GB 17378-1998)". This program defines a harmful algal bloom as "the out-of-control growth of toxic or non-toxic algae that cause water discoloration, or cause toxic effects or physical damage to the habitats of other organisms even when the concentration of algae is not high enough to change the water color" (SOA technical standard HY-T 069-2005). This definition is consistent with that of NOAA in the US, which states "Under the right conditions, algae may grow out of control - and a few of these "blooms" produce toxins that can kill fish, mammals and birds, and may cause human illness or even death in extreme cases. Other algae are nontoxic, but eat up all of the oxygen in the water as they decay, clog the gills of fish and invertebrates, or smother corals and submerged aquatic vegetation. Still others discolor water, form huge, smelly piles on beaches or contaminate drinking water. Collectively, these events are called harmful algal blooms, or HABs (<https://www.noaa.gov/what-is-harmful-algal-bloom>). Hence, we use the term harmful algal blooms (HABs) to refer to the blooms reported by the program. The size-dependent thresholds of cell density were set in the standard procedure, which is $> 10^7$, $> 10^6$, $> 2 \times 10^5$, $> 10^5$ and $> 3 \times 10^3$ cells dm^{-3} for algae with cell lengths of < 10 , 10~29, 30~99, 100~299 and 300~1000 μm , respectively. We assessed that the monitoring efforts became systematic in 1970, when the methods adopted for HAB reporting continue to be essentially the same as those used at present (current version: HY/T 069-2005).

All monitoring tasks included sample collection to determine phytoplankton species density and documentation of the color of the water. The occurrence of a bloom was determined where cell density exceeded size-dependent thresholds set in the standard procedure (HY/T 069-2005), which then triggered tracking monitoring to determine the area affected and the duration of the bloom. The blooms tracked included blooms dominated by cyanobacteria, diatoms and dinoflagellates etc. and

while they do include red tides, they are best defined as “harmful algal blooms” (HABs). It was common for two or more algal species to co-exist in a bloom, and for species composition to change during long-lasting blooms. All causative species were recorded by SOA as long as their cell concentrations exceeded the thresholds set by the technical specification. A single HAB event was defined as that caused by one or multiple species from development to extinction phase. If in the process, the HAB disappeared (i.e. water color recovered and/or the cell density decreased below the threshold concentrations) but re-occurred in the same area or an adjacent one in the following days involving the same species, it was considered to correspond to the same HAB event; if other species caused the HAB in the following days, this was recorded as a different HAB event. For HAB events that occurred simultaneously in two or more adjacent areas, these events were documented as separate HAB events if caused by different species. If the event was caused by the same species and occurred in a harbor or small enclosed waterbody, it was recorded as a single event; if occurring in larger bays or coastal waters where the blooms observed were isolated by natural geographical barriers and open waters, it was recorded as two or more events, otherwise it was recorded as a single event. HAB events occurring successively were recorded as two or more event. The observers recorded water quality (transparency, salinity, pH, dissolved oxygen, inorganic nitrogen, phosphorus and silicate concentrations, and chemical oxygen demand) measures along with the chlorophyll-a concentration and the cell density of the causative species when blooms were detected, and interviewed fishermen to acquire data on the occurrence of such events as fish kills. Nutrient concentration was, however, not reported in the sources reporting the blooms (Table S1). Taxonomic identifications of the species confirming the blooms were documented even for the earliest records in 1970s, and were often accompanied by photographs in the reports.

The reports used (Table S1) also include HABs detected from expanded monitoring programs deployed by regional governments in coastal waters supporting significant mariculture, which aimed at providing an early warning of HAB occurrence. These higher-frequency efforts targeting important mariculture areas were adopted by SOA from 2002 onwards.

Sampling for the coastal seawater quality monitoring of SOA was performed 4 times per year, in February, May, August and October, respectively. The yearly averages for each coastal administrative area were calculated from monitoring data of 1394 national water quality control stations (1232 underway monitoring stations and 162 monitoring stations near SOA’s ocean stations). For each station, the nitrite, nitrate and ammonia concentrations were measured following the procedures described in the National Standard of China “Specification of Marine Monitoring” (current version GB 17378-2007), and added up to represent dissolved inorganic nitrogen, used in our study. The offshore seawater quality monitoring of MEP was performed 3 times per year, in March to May, July and August, and October, respectively. MEP sampled a total of 417 national control stations, where nutrient concentrations were analyzed following the methods described in the national standard of seawater quality (GB3097-1997) and the specification for environmental monitoring in offshore areas (HJ442-2008). Specifically, the detection method of nitrite, nitrate and ammonia concentrations in HJ442-2008 directly employed those described in GB 17378.

Table S1. Data sources for the database of coastal HABs for China.

Title	Data Source	Location
Bulletin of Marine Disasters of China (1989-2015)	State Oceanic Administration of China	China
Bulletin of Marine Environmental Quality of China (2000-2009)	State Oceanic Administration of China	China
Bulletin of Marine Environmental Status of China (2010-2015)	State Oceanic Administration of China	China
Bulletin of Environmental Status of China (1989-2015)	Ministry of Environmental Protection of China	China
Bulletin of Marine Environment of North China Sea (2010-2015)	North China Sea Branch of State Oceanic Administration	North China Sea
Bulletin of Marine Disasters of North China Sea (2012-2015)	North China Sea Branch of State Oceanic Administration	North China Sea
Bulletin of Marine Environmental Quality of East China Sea	East China Sea Branch of State Oceanic Administration	East China Sea
Bulletin of Marine Environment of East China Sea (2010-2015)	East China Sea Branch of State Oceanic Administration	East China Sea
Bulletin of Marine Environmental Quality of South China Sea (2009, 2012-2015)	South China Sea Branch of State Oceanic Administration	South China Sea
Bulletin of Marine Environmental Quality of Liaoning Province (2001-2003, 2007-2009, 2012-2015)	Department of Ocean and Fisheries of Liaoning Province	Liaoning
Bulletin of Marine Environmental Quality of Dalian (2003-2009)	Dalian City Oceanic and Fishery Administration	Dalian
Bulletin of Marine Environment of Dalian (2010)	Dalian City Oceanic and Fishery Administration	Dalian
Bulletin of Marine Environmental Status of Dalian (2011-2015)	Dalian City Oceanic and Fishery Administration	Dalian
Bulletin of Marine Environmental Quality of Hebei Province (2003-2009)	Hebei Provincial Department of Land and Resources (Oceanic Administration)	Hebei
Bulletin of Marine Environmental Status of Hebei Province (2010-2015)	Hebei Provincial Department of Land and Resources (Oceanic Administration)	Hebei
Bulletin of Marine Environmental Quality of Shandong Province (2001-2009)	Shandong Provincial Oceanic and Fishery Department	Shandong
Bulletin of Marine Environment of Shandong Province (2010-2015)	Shandong Provincial Oceanic and Fishery Department	Shandong
Bulletin of Marine Environmental Quality of Jiangsu Province (2003-2015)	Administration of Ocean and Fisheries of Jiangsu Province	Jiangsu
Bulletin of Marine Environmental Quality of Shanghai (2003)	Shanghai Municipal Oceanic Bureau	Shanghai
Bulletin of Marine Environmental Status of	Shanghai Municipal Oceanic Bureau	Shanghai

Shanghai (2004)		
Bulletin of Marine Environmental Quality of Shanghai (2005)	Shanghai Municipal Oceanic Bureau	Shanghai
Bulletin of Marine Environmental Quality of Shanghai (2012-2015)	Shanghai Municipal Oceanic Bureau	Shanghai
Bulletin of Marine Environmental Quality of Zhejiang Province (2001-2002)	Zhejiang Province Ocean and Fisheries Bureau	Zhejiang
Bulletin of Marine Environment of Zhejiang Province (2003-2015)	Zhejiang Province Ocean and Fisheries Bureau	Zhejiang
Bulletin of Marine Environmental Quality of Fujian Province (2003-2008)	Fujian Provincial Department of Ocean and Fisheries	Fujian
Bulletin of Marine Environmental Status of Fujian Province (2009-2015)	Fujian Provincial Department of Ocean and Fisheries	Fujian
Bulletin of Marine Environmental Quality of Guangdong Province (2001-2010)	Administration of Ocean and Fisheries of Guangdong Province	Guangdong
Bulletin of Marine Environmental Status of Guangdong Province (2011-2015)	Administration of Ocean and Fisheries of Guangdong Province	Guangdong
Bulletin of Marine Environmental Quality of Guangxi Province (2003-2004, 2007-2009, 2011-2015)	the Oceanic Administration of Guangxi	Guangxi
Bulletin of Marine Environmental Status of Hainan Province (2002, 2004-2015)	Department of Ocean and Fisheries of Hainan Province	Hainan
Investigation and evaluation of red tide disaster in China	China Ocean Press, 2012 (Liang Yubo et al.)	China
Occurrence regularity of red tide disaster in typical sea areas of China	China Ocean Press, 2010 (Zhao Dongzhi et al.)	China

Table S2. The database of coastal HABs for China from 1933 to 2015 (CCHAB dataset).

(In total, the clean CCHAB dataset contains 1952 assessments of coastal algal blooms in China from 1933 to 2015. See the file named “Table S4”).

Table S3. The annual mean SST data for the eleven Chinese coastal regions from the Met Office Marine Data Bank from 1970 to 2015.

Year	Liaoning	Tianjin	Hebei	Shandong	Jiangsu	Shanghai	Zhejiang	Fujian	Guangdong	Guangxi	Hainan
1970	12.70	12.85	12.89	14.27	15.10	17.66	18.40	20.68	25.14	24.95	26.11
1971	12.51	12.81	12.85	14.75	15.51	17.65	18.47	20.76	24.96	24.61	25.49
1972	13.07	12.67	12.95	14.64	15.30	18.00	18.46	20.87	24.97	24.39	25.52
1973	13.28	14.04	14.11	15.31	16.22	18.72	19.24	21.26	25.56	25.31	26.41
1974	12.72	13.30	13.59	15.39	16.15	19.30	19.38	21.01	25.08	25.26	26.08
1975	13.49	14.01	14.25	15.72	16.83	19.01	19.48	21.43	25.54	25.95	26.75
1976	12.50	12.74	12.80	14.77	15.36	18.40	18.83	20.72	24.88	25.22	26.12
1977	10.18	9.93	10.03	12.50	13.25	17.77	18.53	21.41	25.05	25.01	26.11
1978	13.00	13.75	13.82	15.78	16.39	18.80	19.28	21.64	25.16	25.37	26.26
1979	13.12	12.67	12.94	15.02	15.73	19.23	19.69	21.83	25.31	25.42	26.38
1980	11.99	11.94	11.91	13.52	14.67	18.33	18.89	21.33	25.34	25.49	26.28
1981	10.79	10.86	10.91	12.61	13.82	17.62	18.46	21.64	25.27	25.50	26.27
1982	12.54	12.64	12.68	14.57	15.46	18.79	19.08	21.18	25.16	25.14	25.81
1983	13.21	12.81	13.30	15.49	16.13	19.12	19.81	22.55	24.87	24.93	25.87
1984	12.66	12.72	12.84	15.08	15.68	18.49	19.33	21.91	24.78	24.82	25.43
1985	12.32	12.39	12.54	15.09	15.83	18.43	19.23	22.18	25.07	24.92	25.76
1986	12.90	12.94	12.91	15.26	15.88	19.82	19.95	22.31	24.99	24.91	25.32
1987	12.46	12.32	12.59	14.96	15.85	19.35	19.73	22.32	25.86	25.71	26.45
1988	12.94	13.05	13.14	14.98	15.63	19.41	19.98	22.34	25.33	24.98	26.03
1989	13.14	13.37	13.59	15.52	16.20	19.06	19.71	22.36	24.80	24.84	25.41
1990	13.36	13.35	13.58	15.66	16.48	19.91	20.37	22.40	25.36	25.24	25.95
1991	13.16	13.04	13.24	15.36	16.10	19.02	19.76	22.29	25.23	25.42	25.99
1992	12.82	12.72	13.14	15.21	15.70	18.01	19.08	22.22	24.79	24.94	25.64
1993	12.71	12.60	12.82	15.02	15.57	18.27	19.12	22.42	25.23	25.26	26.16
1994	13.13	13.16	13.31	15.45	16.03	17.76	19.18	22.45	25.57	25.20	25.89
1995	12.98	13.17	13.37	15.19	15.81	17.80	18.92	22.17	25.39	25.03	25.79

1996	12.42	12.35	12.59	15.08	15.66	17.87	19.14	22.07	25.36	24.82	25.60
1997	13.23	13.57	13.78	15.97	16.59	18.59	19.64	22.45	25.66	25.11	25.95
1998	14.15	14.03	14.44	16.12	16.75	19.77	20.66	23.33	26.10	25.18	26.36
1999	13.69	13.84	14.09	15.99	16.67	19.29	20.19	22.89	25.67	25.14	25.96
2000	13.41	13.47	13.72	15.74	16.45	19.24	20.17	22.99	25.41	24.99	25.82
2001	13.65	13.52	13.70	15.65	16.49	19.88	20.61	23.31	25.97	25.38	26.27
2002	13.36	13.21	13.33	15.16	16.08	19.13	20.04	23.08	26.01	25.44	26.22
2003	12.99	12.90	12.97	14.99	15.83	19.03	19.90	22.79	25.96	25.49	26.31
2004	12.98	13.17	13.37	15.52	16.31	18.88	19.83	22.60	25.43	25.27	25.97
2005	13.22	13.01	13.17	15.22	16.10	19.24	19.94	22.39	25.41	25.26	25.85
2006	13.21	13.23	13.36	15.47	16.28	19.09	19.90	22.67	25.80	25.34	26.22
2007	12.84	12.70	12.94	15.21	15.95	18.64	19.84	22.77	25.70	25.36	26.24
2008	13.19	13.45	13.54	15.57	16.27	19.10	19.86	22.58	25.46	25.14	25.92
2009	13.00	12.63	12.97	15.26	16.04	19.11	19.83	22.56	25.48	25.12	26.04
2010	12.71	12.42	12.70	15.10	15.91	18.05	19.23	22.81	25.86	25.57	26.58
2011	12.50	12.60	12.87	15.14	15.86	18.00	19.05	22.34	25.07	25.04	25.79
2012	12.94	12.93	13.18	15.34	16.03	18.90	19.63	22.63	25.54	25.32	26.33
2013	13.00	12.92	13.19	15.45	16.11	18.66	19.66	22.65	25.22	25.12	26.03
2014	13.36	13.34	13.61	15.66	16.36	18.58	19.58	22.74	25.73	25.21	26.09
2015	13.46	13.30	13.59	15.54	16.31	19.12	19.92	22.89	25.79	25.55	26.33

* The original data derived from the Met Office Marine Data Bank are monthly average sea-surface temperature from 1970 to 2015, for the following representative location for each of the Chinese coastal area: Liangning (122°07' E, 40°29' N), Tianjin (118°52' E, 39°06' N), Hebei (119°50' E, 37°58' N), Shandong (121°06' E, 36°12' N), Jiangsu (119°55' E, 35°09' N), Shanghai (121°23' E, 31°28' N), Zhejiang (121°53' E, 30°28' N), Fujian (119°50' E, 26°14' N), Guangdong (113°44' E, 22°34' N), Guangxi (109°01' E, 21°34' N) and Hainan (110°36' E, 19°56' N); and the yearly average sea-surface temperature were calculated as arithmetic mean of 12 monthly average sea-surface temperatures for each area.

Table S4. (1) Linear regressions of sea-surface temperature versus years for the eleven Chinese coastal regions, showing the warming rate of sea-surface temperature.

Province	Warming rate ($^{\circ}\text{C decade}^{-1}$)	a	R ²	F	p	Sig.
Liaoning	0.17 ± 0.07	-21.23	0.12	6.11	0.0174	**
Tianjin	0.10 ± 0.08	-7.81	0.04	1.68	0.2017	NA
Hebei	0.13 ± 0.08	-13.61	0.06	2.62	0.1129	NA
Shandong	0.22 ± 0.07	-29.58	0.18	9.35	0.0038	***
Jiangsu	0.21 ± 0.07	-25.44	0.17	9.23	0.0040	***
Shanghai	0.11 ± 0.07	-2.77	0.05	2.40	0.1287	NA
Zhejiang	0.23 ± 0.05	-25.75	0.29	18.24	0.0001	***
Fujian	0.44 ± 0.04	-64.64	0.69	99.27	< 0.0001	***
Guangdong	0.14 ± 0.03	-3.29	0.30	18.72	< 0.0001	***
Guangxi	0.05 ± 0.03	16.18	0.05	2.10	0.1545	NA
Hainan	0.03 ± 0.04	20.44	0.01	0.62	0.4339	NA
Average	0.17 ± 0.03					

*** the difference is significant at the 0.01 level;

** the difference is significant at the 0.05 level;

* the difference is significant at the 0.1 level;

NA not available.

(2) Results of the Mann-Kendall test for the trends of sea-surface temperature over years in the eleven Chinese coastal regions.

	Sen's slope	LCL ^a	HCL ^b	intercept	Tau	z	p
Liaoning	0.011	0.001	0.021	-8.7	0.226	2.207	0.03
Tianjin	0.007	-0.007	0.018	0.0	0.092	0.890	0.37
Hebei	0.009	-0.004	0.020	-4.9	0.152	1.478	0.14
Shandong	0.014	0.005	0.025	-13.5	0.298	2.908	0.00
Jiangsu	0.016	0.006	0.025	-16.7	0.287	2.803	0.01
Shanghai	0.008	-0.005	0.023	2.5	0.131	1.278	0.20
Zhejiang	0.021	0.008	0.033	-21.5	0.329	3.210	0.00
Fujian	0.042	0.031	0.053	-62.1	0.652	6.383	0.00
Guangdong	0.015	0.008	0.020	-4.0	0.396	3.874	0.00
Guangxi	0.005	-0.002	0.012	15.2	0.148	1.440	0.15
Hainan	0.003	-0.005	0.011	19.4	0.073	0.710	0.48
Average ^c	0.014 ± 0.010						

a&b represents the lower and higher confidence limit, respectively;

c showed the warming rate of $0.14 \pm 0.10 \text{ }^{\circ}\text{C decade}^{-1}$.

Table S5. Linear regressions of the natural logarithm of harmful algal blooms frequency, $\ln F(\text{HAB})$, versus sea-surface temperature for the eleven Chinese coastal regions, showing the rate of increase in HAB frequency with warming.

Province	Increasing rate ($^{\circ}\text{C}^{-1}$)	a	R^2	F	p	Sig.
Liaoning	0.32 ± 0.19	-2.94	0.06	2.75	0.1044	NA
Tianjin	0.12 ± 0.13	-1.10	0.02	0.36	0.3568	NA
Hebei	0.27 ± 0.18	-2.75	0.05	2.25	0.1407	NA
Shandong	0.52 ± 0.17	-7.01	0.17	8.78	0.0049	***
Jiangsu	0.23 ± 0.14	-3.25	0.06	2.75	0.1044	NA
Shanghai	0.55 ± 0.18	-9.53	0.17	9.06	0.0043	***
Zhejiang	1.43 ± 0.33	-26.08	0.29	18.33	<0.0001	***
Fujian	1.07 ± 0.21	-22.47	0.37	25.49	<0.0001	***
Guangdong	1.43 ± 0.43	-34.77	0.20	11.02	0.0018	***
Guangxi	0.12 ± 0.15	-2.87	0.01	0.65	0.4244	NA
Hainan	0.04 ± 0.24	-0.65	0.00	0.02	0.8808	NA
Average	0.55 ± 0.16					

*** the difference is significant at the 0.01 level;

** the difference is significant at the 0.05 level;

* the difference is significant at the 0.1 level;

NA not available.

Table S6. Result of two-sample Kolmogorov-Smirnov test between the distribution of HABs frequency along the year for the four decades: 1976-1985, 1986-1995, 1996-2005 and 2006-2015.

Decade 1	Decade 2	D value	p value	Sig.
2006-2015	1996-2005	0.092	0.003	***
2006-2015	1986-1995	0.159	0.000	***
2006-2015	1976-1985	0.261	0.003	***
1996-2005	1986-1995	0.179	0.000	***
1996-2005	1976-1985	0.268	0.002	***
1986-1995	1976-1985	0.140	0.326	NA

*** the difference is significant at the 0.01 level.

NA not available.

Table S7. Result of two-sample Kolmogorov-Smirnov test between the distribution of HABs frequency along the year for the five latitude bands: 38° -43°N, 33° - 38°N, 28° - 33°N, 23° - 28°N, and 18°- 23°N.

Region 1	Region 2	D value	p value	Sig.
18°-23°N	23°-28°N	0.355	0.000	***
18°-23°N	28°-33°N	0.383	0.000	***
18°-23°N	33°-38°N	0.317	0.000	***
18°-23°N	38°-43°N	0.457	0.000	***
23°-28°N	28°-33°N	0.128	0.000	***
23°-28°N	33°-38°N	0.387	0.000	***
23°-28°N	38°-43°N	0.464	0.000	***
28°-33°N	33°-38°N	0.308	0.000	***
28°-33°N	38°-43°N	0.373	0.000	***
33°-38°N	38°-43°N	0.170	0.009	***

*** the difference is significant at the 0.01 level.

Table S8. Results of the Kendall Trend Test on the changes in the average (\pm SE) normalized frequency of harmful algal blooms (HAB z score) and sea surface temperature (SST z score) across China from 1970 to 2015.

	Sen's slope	LCL ^a	HCL ^b	intercept	Tau	z	p
HAB z score	0.039	0.031	0.048	-78.4	0.625	6.121	0.00
SST z score	0.026	0.011	0.040	-50.8	0.349	3.409	0.00

a&b represents the lower and higher confidence limit, respectively.

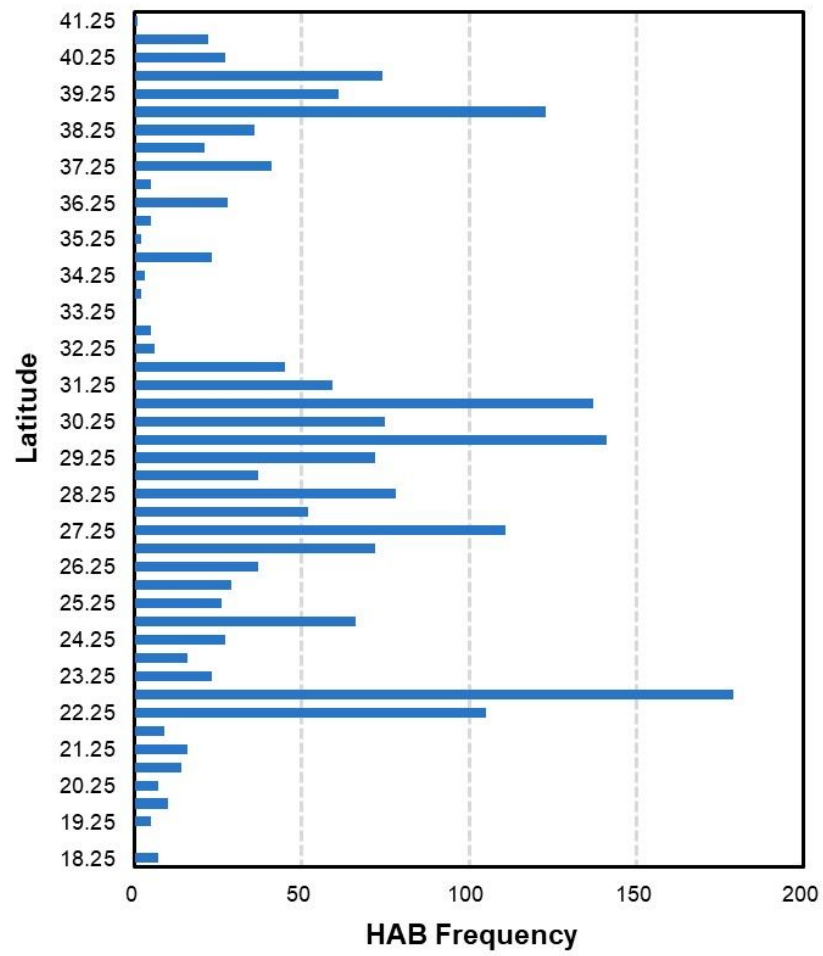


Figure S1. Numbers of harmful algal bloom events recorded in Chinese coastal area from 1933 to 2015, categorized on an interval of 0.5 degree from 41.25° N to 18.25° N.

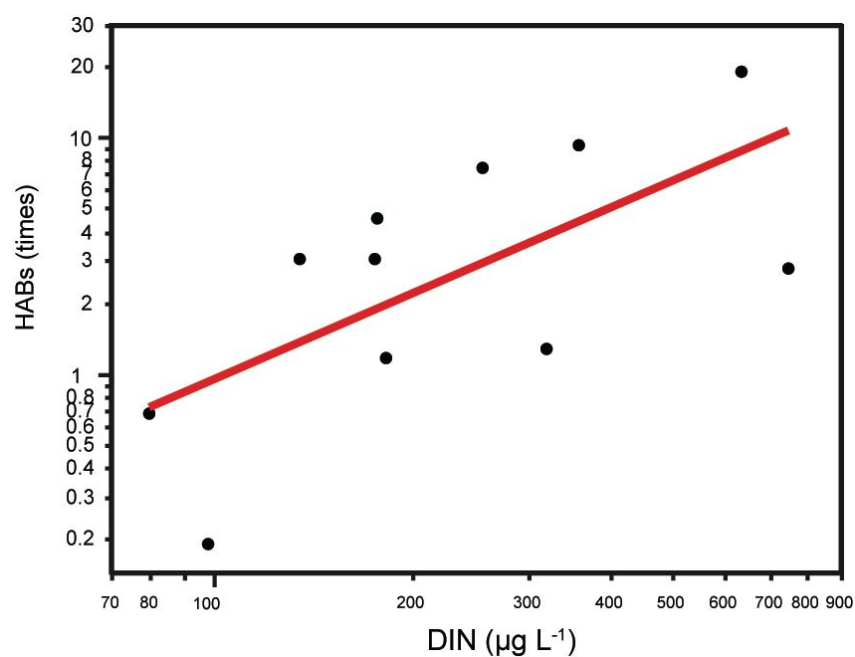


Figure S2. The relationship between the frequency of coastal harmful algal blooms and the concentration of Dissolved Inorganic Nitrogen (DIN) in China. For each province or municipality, the DIN concentration is a mean value of the yearly average DIN concentrations from 1979 to 2015. Note the logarithmic axis. The solid red line shows the fitted equation $\text{Log } F(\text{HAB}) = -5.61 + 1.21 \cdot \text{Log } \text{DIN}$ ($R^2 = 0.43$, $P < 0.05$).

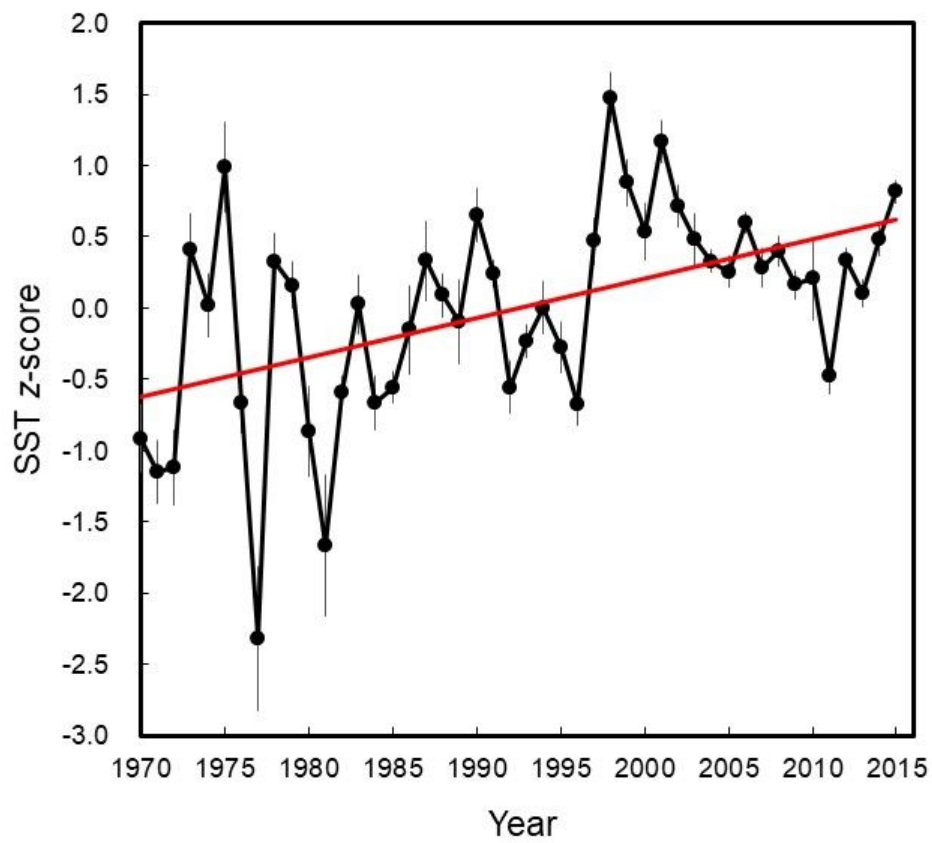


Fig. S3. The annual average normalized (z-scores) average seawater surface temperature across coastal China from 1970 to 2015. The solid red line shows the fitted equation standardized SST = $-55.2 + 0.027 \text{ Year}$ ($R^2 = 0.26$, $P = 0.0003$).

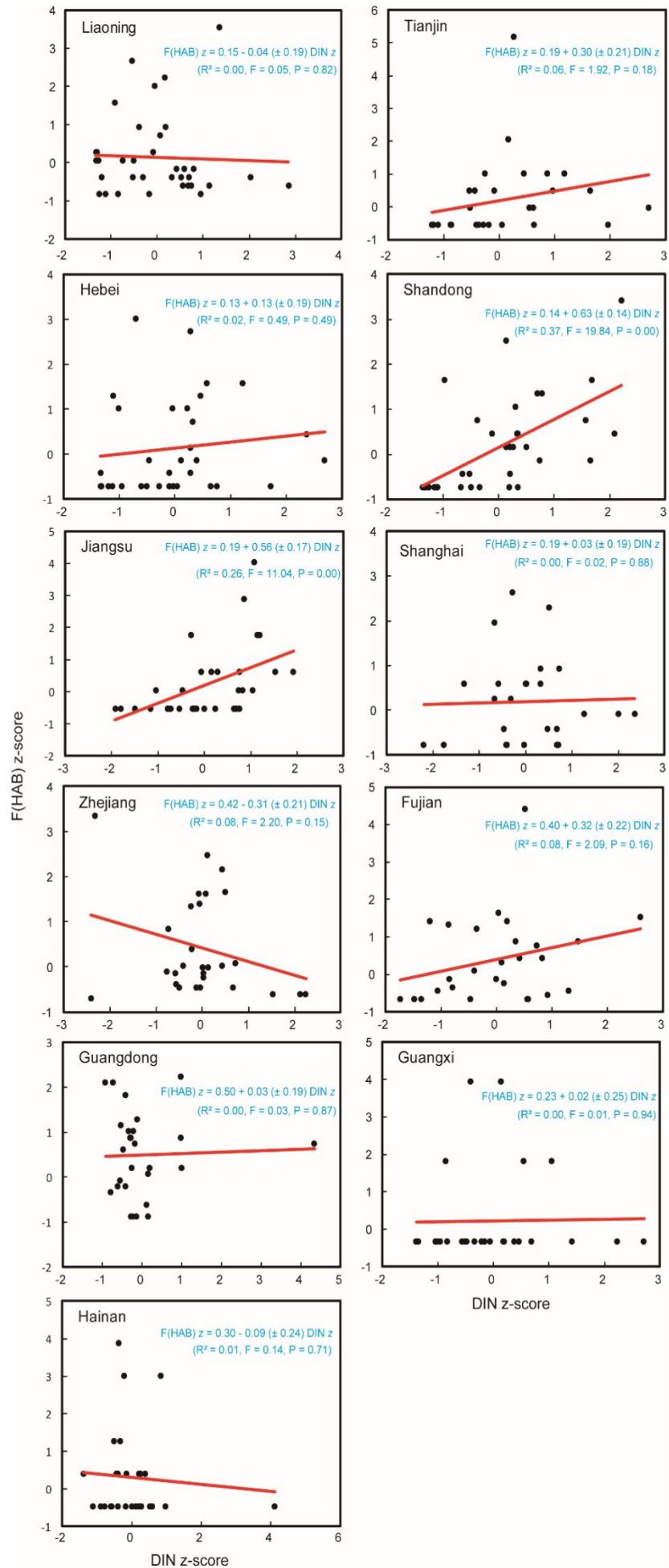


Figure S4. The relationship between the normalized (z-scores) frequency of coastal harmful algal blooms and the normalized (z-scores) concentration of Dissolved Inorganic Nitrogen (DIN) in 11 coastal provinces and municipalities of China.

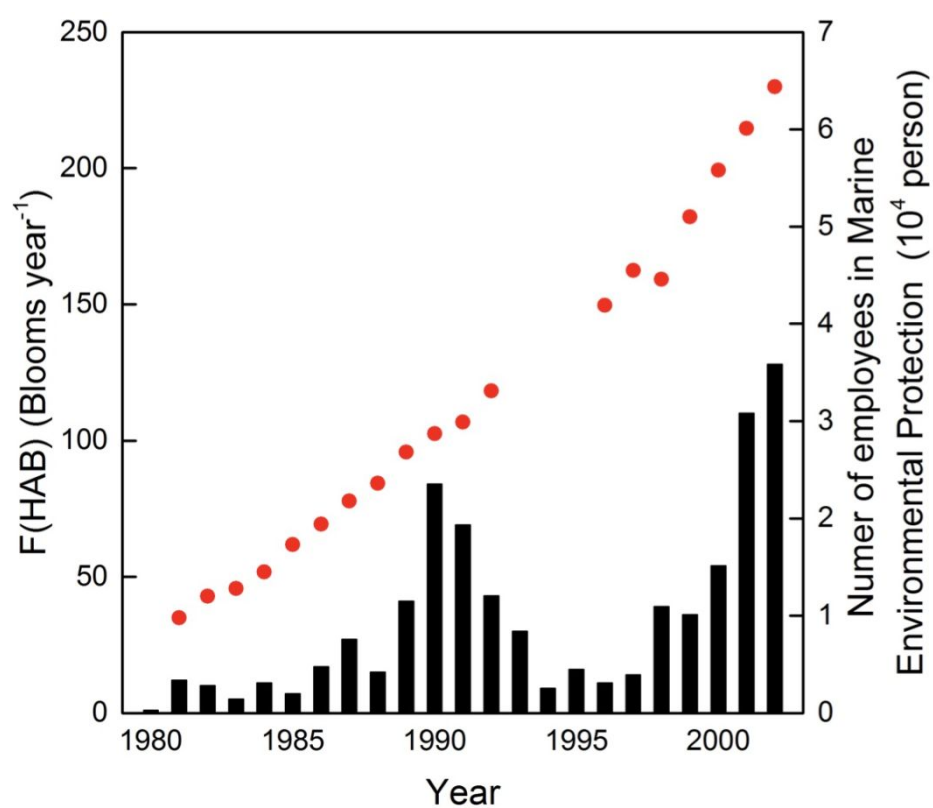


Figure S5. Number of persons engaged in marine environmental protection in China (red dots) showing the marine environment monitoring efforts, and the observed coastal harmful algal blooms in China (blue bars) from 1980 to 2002.