The following supplement accompanies the article

Long-term change in the distribution of Japanese sardine in the Sea of Japan during population fluctuations

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Supplementary data

Table S1. Approximate significance and ΔAIC of each explanatory variable of the best model for the presence and absence of sardine. *ID* indicates the fishing method: 1 is purse seine fisheries and 2 is gill net surveys.

Smooth terms	edf	Ref.df	χ^2	p-value	ΔAIC
$year_{ID=1}$	9.00	9.00	106.98	<0.001	337
$year_{ID=2}$	8.19	8.61	195.50	<0.001	
(*lon*, *lat*)	20.88	24.35	159.17	<0.001	85
SST	8.89	8.99	139.50	<0.001	39
$(lon, lat)_{year=1970}$	3.39	4.28	8.32	<0.1	427
$(lon, lat)_{year=1971}$	7.03	7.96	10.74	0.20	
$(lon, lat)_{year=1972}$	7.66	8.78	23.61	<0.01	
$(lon, lat)_{year=1973}$	9.69	11.24	38.92	<0.001	
$(lon, lat)_{year=1974}$	2.00	2.00	0.77	0.68	
$(lon, lat)_{year=1975}$	8.64	11.42	15.38	0.19	
$(lon, lat)_{year=1976}$	28.03	28.75	43.34	<0.1	
$(lon, lat)_{year=1977}$	28.81	28.97	22.75	0.79	
$(lon, lat)_{year=1978}$	2.00	2.00	0.95	0.62	
$(lon, lat)_{year=1979}$	3.89	5.12	4.23	0.54	
$(lon, lat)_{year=1980}$	2.00	2.01	0.96	0.62	
$(lon, lat)_{year=1981}$	11.48	14.89	21.27	0.12	
$(lon, lat)_{year=1982}$	8.85	11.69	17.72	0.11	
$(lon, lat)_{year=1983}$	11.21	14.43	29.91	<0.01	
$(lon, lat)_{year=1984}$	15.02	18.83	30.77	<0.05	
$(lon, lat)_{year=1985}$	2.01	2.01	0.66	0.72	
$(lon, lat)_{year=1986}$	18.74	22.34	32.46	<0.1	
$(lon, lat)_{year=1987}$	9.29	12.24	20.24	<0.1	
$(lon, lat)_{year=1988}$	12.86	16.30	37.81	<0.01	
$(lon, lat)_{year=1989}$	15.01	18.51	32.23	<0.05	
$(lon, lat)_{year=1990}$	2.00	2.00	0.83	0.66	
$(lon, lat)_{year=1991}$	13.69	16.87	20.20	0.26	
$(lon, lat)_{year=1992}$	3.38	4.32	2.34	0.72	
$(lon, lat)_{year=1993}$	16.14	17.94	18.52	0.42	
$(lon, lat)_{year=1994}$	3.88	4.94	6.76	0.26	
$(lon, lat)_{year=1995}$	14.85	16.92	33.35	<0.01	
$(lon, lat)_{year=1996}$	2.29	2.52	0.49	0.83	

Smooth terms	edf	Ref.df	χ^2	p-value	ΔAIC
$(lon, lat)_{year=1997}$	5.37	6.68	14.39	<0.05	
$(lon, lat)_{year=1998}$	5.10	6.33	15.39	<0.05	
$(lon, lat)_{year=1999}$	2.90	3.51	2.48	0.68	
$SST_{year=1970}$	3.46	3.83	2.25	0.65	118
$SST_{year=1971}$	2.44	2.93	8.13	<0.1	
$SST_{year=1972}$	1.86	2.26	1.94	0.61	
$SST_{year=1973}$	1.00	1.00	0.09	0.77	
$SST_{year=1974}$	3.00	3.64	7.04	0.14	
$SST_{year=1975}$	1.27	1.48	0.30	0.82	
$SST_{year=1976}$	1.00	1.00	0.09	0.77	
$SST_{year=1977}$	8.97	9.00	14.14	0.12	
$SST_{year=1978}$	3.57	4.45	3.81	0.46	
$SST_{year=1979}$	1.47	1.77	0.51	0.67	
$SST_{year=1980}$	1.00	1.00	0.08	0.77	
$SST_{year=1981}$	1.00	1.00	0.08	0.78	
$SST_{year=1982}$	1.00	1.00	0.08	0.77	
$SST_{year=1983}$	5.90	6.88	17.21	<0.05	
$SST_{year=1984}$	3.31	4.14	2.90	0.58	
$SST_{year=1985}$	3.41	4.25	5.41	0.26	
$SST_{year=1986}$	1.56	1.93	1.15	0.58	
$SST_{year=1987}$	5.27	6.28	8.27	0.24	
$SST_{year=1988}$	1.00	1.00	0.08	0.77	
$SST_{year=1989}$	3.54	4.39	4.44	0.40	
$SST_{year=1990}$	1.00	1.00	0.09	0.77	
$SST_{year=1991}$	2.03	2.58	2.24	0.39	
$SST_{year=1992}$	4.29	5.17	7.90	0.18	
$SST_{year=1993}$	1.00	1.00	0.07	0.79	
$SST_{year=1994}$	1.00	1.00	0.08	0.78	
$SST_{year=1995}$	1.00	1.00	0.08	0.78	
$SST_{year=1996}$	2.38	2.97	1.71	0.65	
$SST_{year=1997}$	1.00	1.00	0.08	0.78	
$SST_{year=1998}$	1.22	1.39	0.22	0.84	
$SST_{year=1999}$	4.23	5.04	4.88	0.42	

Table S2. Top five generalized additive models selected using Akaike's Information Criterion (AIC) for the presence and absence of sardine by both gill net surveys (*ID* = 1) and purse seine fisheries (*ID* = 2) between 1970 and 1999 (n = 7419), assuming a binomial distribution for the binary data (presence = 1 and absence = 0). s $(x)_{year}$ indicates the spline function of a variable *x* calculated for each categorical variable *year*.

Formula	UBRE	% Total Deviance	AIC
1. $s(year)_{ID}$ + $s(lon, lat)$ + $s(lon, lat)_{year}$ + $s(SST)$ + $s(SST)_{year}$	-0.26	54.1	5517.3
2. $s(year)_{ID}$ + $s(lon, lat)$ + $s(lon, lat)_{year}$ + $s(SST)_{year}$ + ID	-0.25	53.9	5540.0
3. $s(year)_{ID}$ + $s(lon, lat)$ + $s(lon, lat)_{year}$ + $s(SST)_{year}$	-0.25	54.0	5556.6
4. $s(year)_{ID}$ + $s(lon, lat)_{year}$ + $s(SST)$ + $s(SST)_{year}$ +	-0.24	54.8	5602.8
5. $s(year)_{ID}$ + $s(lon, lat)_{year}$ + $s(SST)$ + $s(SST)_{year}$ + ID	-0.25	54.7	5610.2

Figure S1. Decadal mean (a and c) and standard deviation (b and d) maps of observed presence probability per decade per grid point at a resolution of 0.5° in longitude and latitude. (a) and (b) are for purse seine fisheries. (c) and (d) are for gill net surveys. Presence probability was annually calculated by the ratio of the number of operations that caught sardine to the total number of operations at each grid.

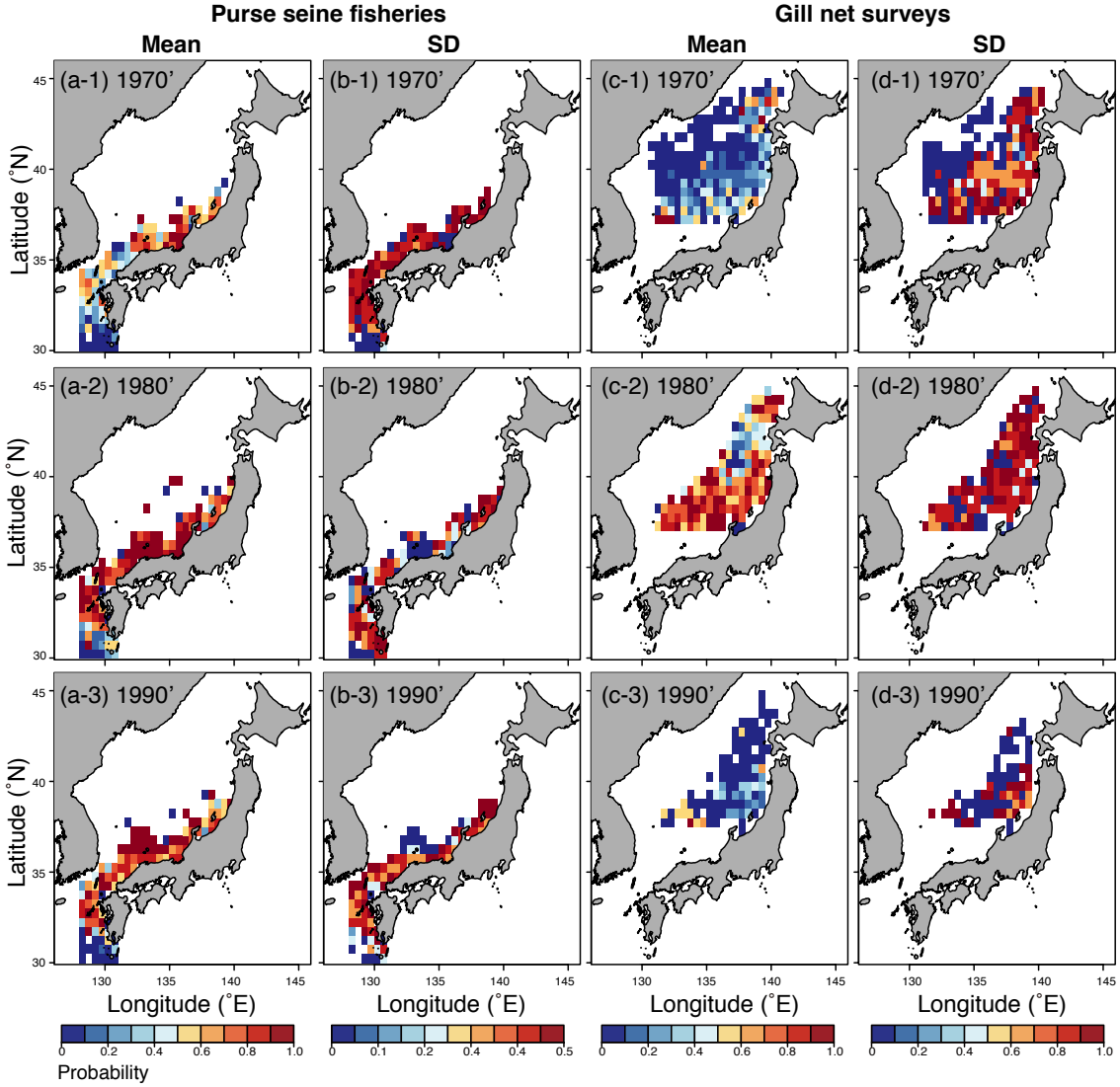

Table S3. Approximate significance and ΔAIC of each explanatory variable of the best model for the weight of sardine catch per fishing operation (CPUE: tons) by purse seine fisheries.

Smooth terms	edf	Ref.df	F	p-value	ΔAIC
year	9.00	9.00	54.74	<0.001	
(*lon*, *lat*)	24.60	27.22	21.38	<0.001	106
SST	4.15	5.15	9.71	<0.001	23
$(lon, lat)_{year=1970}$	1.54	1.80	0.09	0.91	640
$(lon, lat)_{year=1971}$	3.60	4.46	1.65	0.30	
$(lon, lat)_{year=1972}$	8.84	9.95	6.41	<0.001	
$(lon, lat)_{year=1973}$	14.57	15.79	5.09	<0.001	
$(lon, lat)_{year=1974}$	2.00	2.00	0.39	0.68	
$(lon, lat)_{year=1975}$	2.33	2.62	0.48	0.75	
$(lon, lat)_{year=1976}$	9.76	12.29	1.85	<0.05	
$(lon, lat)_{year=1977}$	7.84	10.00	2.35	<0.01	
$(lon, lat)_{year=1978}$	20.68	23.47	4.98	<0.001	
$(lon, lat)_{year=1979}$	8.65	11.48	1.19	0.28	
$(lon, lat)_{year=1980}$	15.70	19.28	2.81	<0.001	
$(lon, lat)_{year=1981}$	22.75	25.67	2.28	<0.001	
$(lon, lat)_{year=1982}$	2.00	2.00	0.36	0.69	
$(lon, lat)_{year=1983}$	11.40	14.73	1.51	<0.1	
$(lon, lat)_{year=1984}$	2.00	2.00	0.40	0.67	
$(lon, lat)_{year=1985}$	9.21	12.17	1.42	0.14	
$(lon, lat)_{year=1986}$	2.00	2.00	0.45	0.64	
$(lon, lat)_{year=1987}$	7.86	10.45	1.30	0.22	
$(lon, lat)_{year=1988}$	9.81	12.76	1.35	0.20	
$(lon, lat)_{year=1989}$	2.00	2.00	0.46	0.63	
$(lon, lat)_{year=1990}$	20.81	24.24	4.14	<0.001	
$(lon, lat)_{year=1991}$	2.00	2.00	0.43	0.65	
$(lon, lat)_{year=1992}$	2.00	2.00	0.32	0.73	
$(lon, lat)_{year=1993}$	14.60	17.01	5.31	<0.001	
$(lon, lat)_{year=1994}$	10.89	14.10	2.77	<0.001	
$(lon, lat)_{year=1995}$	10.91	14.05	7.53	<0.001	
$(lon, lat)_{year=1996}$	24.33	25.97	5.69	<0.001	
$(lon, lat)_{year=1997}$	20.32	22.33	7.92	<0.001	
$(lon, lat)_{year=1998}$	2.00	2.00	0.61	0.54	
$(lon, lat)_{year=1999}$	5.60	7.39	2.61	<0.01	
$SST_{year=1970}$	0.00	0.00	0.01	1.00	301
$SST_{year=1971}$	1.68	1.96	1.06	0.30	
$SST_{year=1972}$	1.00	1.00	2.56	0.11	
$SST_{year=1973}$	5.78	6.21	2.30	<0.05	
$SST_{year=1974}$	6.05	6.42	5.43	<0.001	
$SST_{year=1975}$	5.03	5.50	5.50	<0.001	
$SST_{year=1976}$	2.47	3.05	2.89	<0.05	
$SST_{year=1977}$	2.09	2.63	1.71	0.18	
$SST_{year=1978}$	1.00	1.00	0.47	0.49	
$SST_{year=1979}$	2.95	3.68	2.83	<0.05	
$SST_{year=1980}$	3.15	3.85	7.31	<0.001	
$SST_{year=1981}$	2.07	2.61	1.94	0.18	
$SST_{year=1982}$	1.35	1.62	0.82	0.55	
$SST_{year=1983}$	1.00	1.00	0.37	0.54	
$SST_{year=1984}$	1.00	1.00	0.38	0.54	

$SST_{year=1985}$	2.74	3.42	4.48	<0.01
$SST_{year=1986}$	1.51	1.86	0.69	0.57
$SST_{year=1987}$	1.00	1.00	0.34	0.56
$SST_{year=1988}$	1.33	1.58	0.20	0.65
$SST_{year=1989}$	1.00	1.00	0.50	0.48
$SST_{year=1990}$	8.81	8.97	5.27	<0.001
$SST_{year=1991}$	1.00	1.00	0.46	0.50
$SST_{year=1992}$	4.77	5.66	7.26	<0.001
$SST_{year=1993}$	2.07	2.58	1.54	0.13
$SST_{year=1994}$	2.20	2.77	2.57	<0.05
$SST_{year=1995}$	2.64	3.31	0.88	0.40
$SST_{year=1996}$	2.05	2.58	0.72	0.36
$SST_{year=1997}$	1.99	2.47	1.00	0.44
$SST_{year=1998}$	8.92	8.99	10.70	<0.001
$SST_{year=1999}$	7.20	7.61	5.03	<0.001

Table S4. Top five generalized additive models selected using Akaike's Information Criterion (AIC) for the weight of sardine catch per fishing operation (CPUE: tons) by purse seine fisheries between 1970 and 1999 (n = 2670), assuming a Gamma distribution with log link function.

Formula	GCV	% Total Deviance	AIC
1. s(*year*) + s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*) + s(*SST*)$_{year}$	1.96	69.5	15147.6
2. s(*year*) + s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*)$_{year}$	1.96	69.4	15170.3
3. s(*year*) + s(*lon*, *lat*)$_{year}$ + s(*SST*) + s(*SST*)$_{year}$	2.05	69.3	15253.7
4. s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*) + s(*SST*)$_{yea}$	2.12	67.2	15398.8
5. s(*year*) + s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*)	2.10	64.6	15449.0

Table S5. Approximate significance and ΔAIC of each explanatory variable of the best model for the number of sardine catch per net (CPUE) by gill net surveys.

Smooth terms	edf	Ref.df	F	p-value	ΔAIC
year	7.86	8.39	14.40	<0.001	80
(*lon*, *lat*)	22.86	26.38	4.10	<0.001	40
SST	3.44	4.27	5.57	<0.001	8
$(lon, lat)_{year=1975}$	6.87	8.40	1.23	0.28	185
$(lon, lat)_{year=1976}$	10.70	13.71	2.34	<0.01	
$(lon, lat)_{year=1977}$	4.15	5.34	1.27	0.25	
$(lon, lat)_{year=1978}$	3.20	4.14	1.29	0.27	
$(lon, lat)_{year=1979}$	2.00	2.00	1.79	0.17	
$(lon, lat)_{year=1980}$	2.00	2.00	0.76	0.47	
$(lon, lat)_{year=1981}$	23.85	26.83	2.48	<0.001	
$(lon, lat)_{year=1982}$	15.61	20.04	1.95	<0.01	
$(lon, lat)_{year=1983}$	2.00	2.00	1.59	0.21	
$(lon, lat)_{year=1984}$	2.00	2.00	2.31	<0.1	
$(lon, lat)_{year=1985}$	15.21	18.91	2.24	<0.01	
$(lon, lat)_{year=1986}$	4.75	6.38	1.27	0.29	
$(lon, lat)_{year=1987}$	11.75	15.25	0.98	0.46	
$(lon, lat)_{year=1988}$	2.00	2.00	2.81	<0.1	
$(lon, lat)_{year=1989}$	10.23	13.45	2.34	<0.01	
$(lon, lat)_{year=1990}$	0.00	0.00	0.00	1.00	
$(lon, lat)_{year=1991}$	2.00	2.00	0.13	0.88	
$(lon, lat)_{year=1992}$	2.00	2.00	0.34	0.71	
$SST_{year=1975}$	2.99	3.35	0.58	0.60	15
$SST_{year=1976}$	1.00	1.00	0.02	0.89	
$SST_{year=1977}$	1.00	1.00	0.00	0.97	
$SST_{year=1978}$	1.00	1.00	0.01	0.91	
$SST_{year=1979}$	1.00	1.00	0.02	0.90	
$SST_{year=1980}$	1.00	1.00	0.06	0.82	
$SST_{year=1981}$	1.00	1.00	0.03	0.87	
$SST_{year=1982}$	1.00	1.00	0.00	0.99	
$SST_{year=1983}$	1.00	1.00	0.03	0.88	
$SST_{year=1984}$	1.00	1.00	0.40	0.53	
$SST_{year=1985}$	2.22	2.71	1.91	0.20	
$SST_{year=1986}$	1.00	1.00	0.01	0.94	
$SST_{year=1987}$	1.00	1.00	0.08	0.78	
$SST_{year=1988}$	1.37	1.64	0.60	0.63	
$SST_{year=1989}$	1.00	1.00	0.17	0.68	
$SST_{year=1990}$	0.00	0.00	0.00	1.00	
$SST_{year=1991}$	1.00	1.00	0.54	0.46	
$SST_{year=1992}$	2.27	2.72	0.38	0.70	

Table S6. Top five generalized additive models selected using Akaike's Information Criterion for the number of sardine catch per net (CPUE) by gill net surveys between 1975 and 1992 (n = 935), assuming a Gamma distribution with log link function.

Formula	GCV	% Total Deviance	AIC
1. s(*year*) + s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*) + s(*SST*)$_{year}$	1.94	52.3	910.0
2. s(*year*) + s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*)$_{year}$	1.96	52.0	918.0
3. s(*year*) + s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*)$_{year}$	1.97	51.6	925.0
4. s(*year*) + s(*lon*, *lat*)$_{year}$ + s(*SST*) + s(*SST*)$_{year}$	1.98	48.9	950.2
5. s(*lon*, *lat*) + s(*lon*, *lat*)$_{year}$ + s(*SST*) + s(*SST*)$_{year}$	2.06	47.6	990.3

Figure S2. Mean catch per unit effort (CPUE) for (a) purse seine fisheries (tons/operation) and (b) gill net surveys (number/net panel). Filled circles and bold lines indicate the observed data. Open circles indicate CPUEs predicted by the best models. Dashed lines indicate 95% confidence limits.

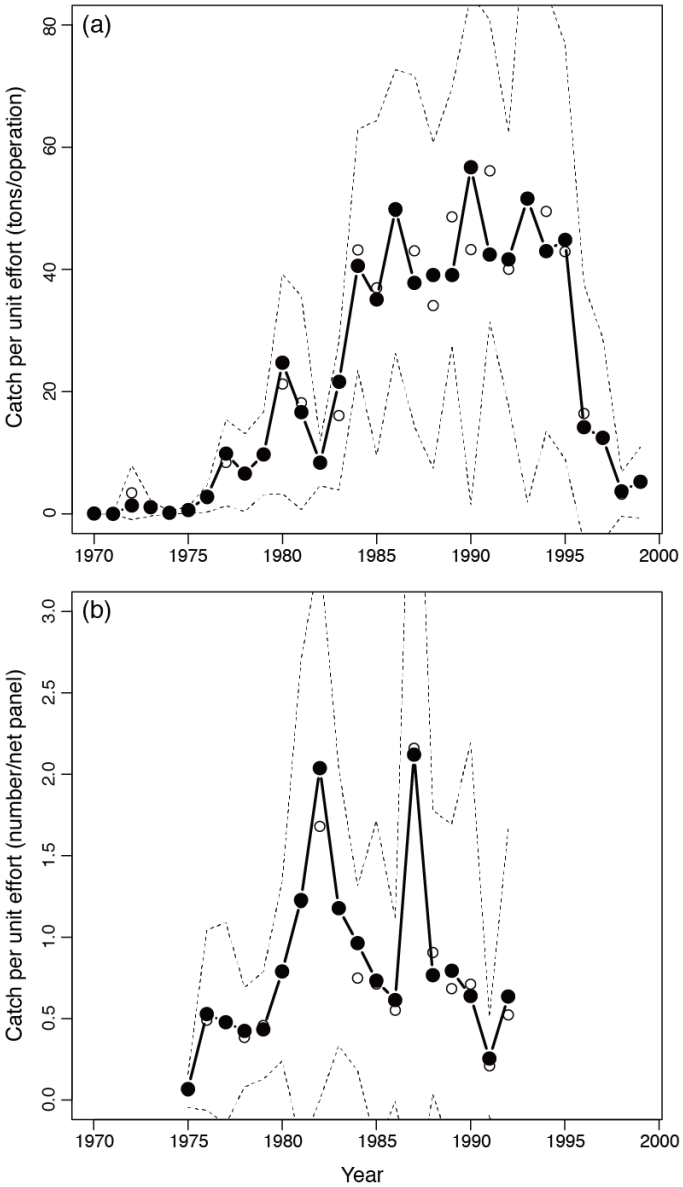

Figure S3. Cross correlation coefficient for the trajectory of distribution area and that of stock biomass.

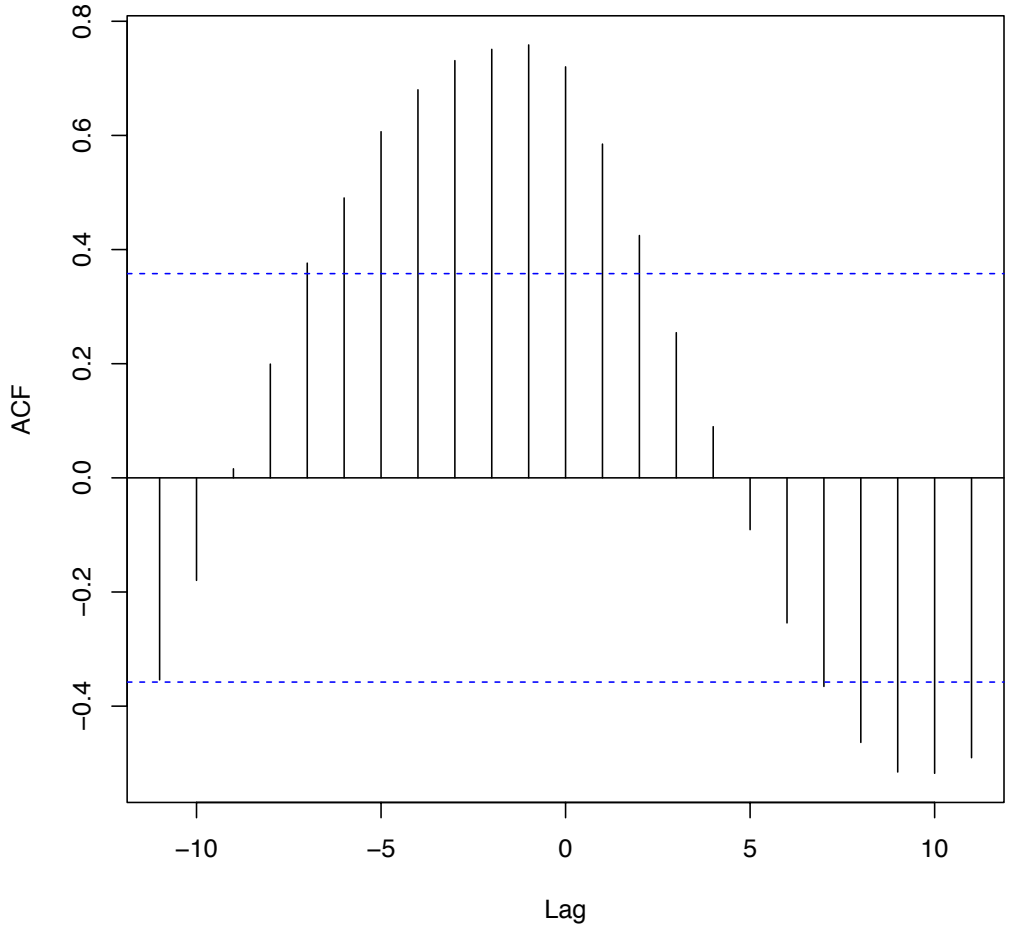
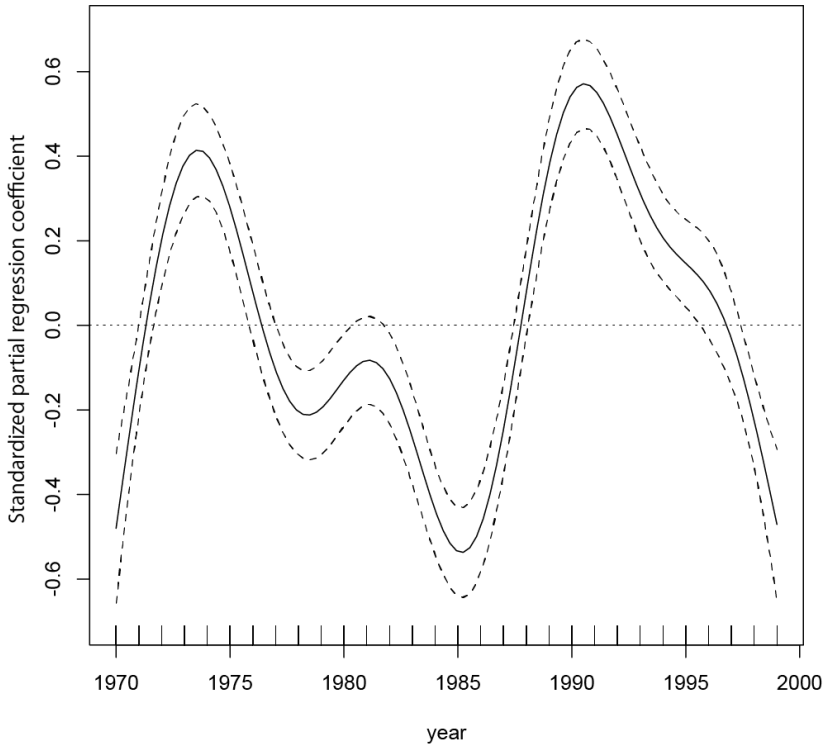
Figure S4. Annual trends of sea surface temperature (SST) during March and May in the whole area of the Sea of Japan (30.5° N to 49.5° N and 128.5° E to 141.5° E). Data were published by the Meteorological Agency. A generalized additive model with a Gaussian error distribution was developed as follows: SST ~ s(year) + s(longitude, latitude).