周防灘東部沿岸域において1987-2010年に観測された水温の変動解析

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Trend Analysis of Monthly Water Temperature at the Eastern Coast of Suo Nada, 1987-2010

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Abstract: The surface temperature of the Uma-shima Strait of the eastern coast of Suo Nada, Yamaguchi, Japan, was monitored every month from 1987 to 2010 and temporal trends were analyzed using Ordinary Least Squares regression analysis. The annual average temperature increased at a rate of 3.31×10^{-2} ℃/year during this period, with more pronounced monthly patterns in August, October, and November. Similar patterns were observed in the temperature data recorded at air and water monitoring stations located nearby. Analyses of these records using regressions demonstrated that the surface temperature of the water of Uma-shima Strait water is influenced by the properties of the atmosphere and the water mass of the offshore area and that this influence varies from season to season with five distinct phases: an aircorrelated phase (April); an air-correlated and water-altered phase (August–October); a water-correlated and air-altered phase (January–March); a water-correlated phase (May and November); and an uncorrelated phase (June-July and December).

Key words: water temperature, monthly pattern, trend analysis, regression, Suo Nada

Introduction

Climate change has received considerable attention owing to its influence on many aspects of life—in particular, because of its importance in food and energy supply for human subsistence.[1-6] Against the background of the growing concern regarding climate change worldwide, a large body of literature has accumulated on the subject. In Japan, research has been carried out on various environment indices, and parameters such as seawater temperature have been monitored.[7, 8] Water temperature of littoral areas has been recorded to understand the phenology of regional fauna and its effect on fisheries.[9-11] In the western Seto Naikai (Japanese Inland Sea), a number of issues related to the water temperature, migratory patterns of fish, and the occurrence of plankton have been documented.[12-17] It is therefore very important to characterize the distribution of the water temperature at a fine temporal and spatial resolution. Since 1987, sea surface temperature has been recorded at a monitoring station at the center of the Uma-shima Strait (approximately 1 km wide) off the eastern coast of Suo Nada (33° 54′ 24″ N 132° 2′ 29″ E; B in Fig. 1), Yamaguchi, Japan. Temperature has been observed on a monthly basis, and the data for the period 1987–2010 have been analyzed. Regression methods were used to analyze the relationship between the temperature of the water and the temperature of the atmosphere recorded nearby. This analysis has demonstrated how the surface temperature at the monitoring station was influenced by environmental temperature.[18] Namely, this study dedicates to representing some basic views on the oceanography which undertakes analyzing the oceanologic process: hydrodynamics and heat balance between air temperature and water temperature of the coastal area.

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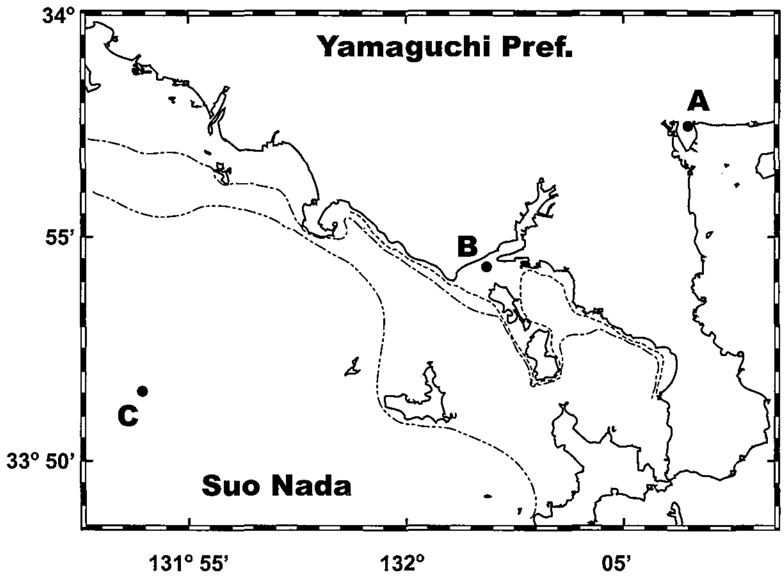

Fig. 1 Location of the monitoring stations within the study area.
A: AMeDAS Yanai observatory (Japan Meteorological Agency: 81481); B: monitoring site in the Uma-shima Strait; C: monitoring station for oceanographic observation (YNS9) administered by the Yamaguchi Prefectural Fisheries Research Center. Broken line: 10-m depth; chain line: 20-m depth; two-dot chain line: 30-m depth.

Materials and Methods

Temperature

Surface temperature was measured using a mercury thermometer[19] on a monthly basis; measurements were made on days with the same lunar phase (i.e., either of the spring tide) throughout the year. Two separate measurements approximately 5 min apart were recorded and then averaged. The research boat "Nagisa" of the Tana Marine Laboratory of the National Fisheries University was used to carry out the sampling in the Uma-shima Strait. The dataset of the surface water temperature is referred to as *USSW*.

Atmospheric temperature data were obtained from the Yanai station (33° 57.5′ N 132° 6′ E) of the Automated Meteorological Data Acquisition System (AMeDAS) network of the Japan Meteorological Agency; this is the observatory closest— approximately 8 km away—to our sampling site (Fig. 1) (http://www.data.jma.go.jp/obd/stats/etrn/index.php). The atmospheric temperature dataset is referred to as *YANA*.

Water temperature data were also obtained at a depth of ~40 m from of a nearby monitoring location YNS9 (33° 51′ 42″ N 131° 53′ 54″ E), a fixed station for oceanographic observation administered by the Yamaguchi Prefectural Fisheries Research Center (YPFRC). With the permission of YPFRC, the logbook was inspected (http://www.pref.yamaguchi.lg.jp/cms/a16500/suisan-s/suo.html) and the records were obtained for four different layers (at depths of 0, 10, 20, and 30 m). This station is located approximately 14 km away from our monitoring site toward the center of Suo Nada (Fig. 1). We considered the station YNS9 because it provides information on the characteristics of multiple water layers in the offshore area. The water temperature at YNS9 corresponding to the depths of 0, 10, 20, and 30 m are referred to as *SY00*, *SY10*, *SY20*, and *SY30*, respectively.

Regression analysis

Ordinary Least Squares (OLS) multivariate regression analysis was carried out to determine relationships between the datasets. Autocorrelation was determined using the Durbin-Watson test and heteroscedasticity was determined using the Breusch-Pagan test with ESS/2 (explained sum of squares)[20-22].

Results

Monthly patterns

The monthly minimum and maximum temperatures and the monthly temperature averaged over the 24-year period (climatological mean)[23] of the *USSW* data are shown in Fig. 2. The climatological seasonal cycle shows a minimum temperature of 8.0 ℃ (February 2006) and a maximum temperature of 30.3 ℃ (August 2001), while the averaged temperature fluctuated between 10.1 ℃ in February and 27.2 ℃ in August. The difference between the monthly minimum and maximum varied between 2.4 ℃ (March) and 6.8 ℃ (August), while the standard deviation (SD) is the smallest in March (0.67 ℃) and the largest in August (1.85 ℃).

Fig 3 shows the relationships between the climatological means of *YANA*, *SY00*, *SY10*, *SY20* and *SY30*, and *USSW*. The climatological means of *YANA* during the period 1987–2010 exceeded those of *USSW* from April to July, varying between 5.3 ℃ in January and 27.1 ℃ in August. The climatological mean of *SY00* fell below those of *USSW* from April to August, varying between 11.0 ℃ in March and 26.3 ℃ in September. The climatological means for *SY10*, *SY20* and *SY30* varied between 10.8 ℃ in March and 25.6 ℃ in September, between 10.8 ℃ in March and 24.9 ℃ in September, and between 10.7 ℃ in March and 23.6 ℃ in October, respectively. All fell below those of *USSW* from April to September.

The climatological seasonal variation in the vertical profile of the water temperature at the YNS9 station is shown in Fig 4. This illustrates that vertical mixing up to a depth of 30 m occurred from November to March with the difference of only 0.3 ℃. A thermocline developed from May to September with a much larger difference of 2.4–4.8 ℃, while the surface temperature rose to 26.3 ℃. Based on these results, the stratified period can be defined as the period from May to September, and the mixing period as that from November to March.

Trend analysis

Trend analysis of the *USSW* data was carried out using both the annual average and monthly temperatures (Table 1). The annually averaged temperature increased during this period by 3.31×10^{-2} ℃ /year (Fig. 5); considerably large increases were observed in August, October, and November (Table 1). For example, the maximum and standard deviation recorded in August introduced a steep trend greater than 0.1 ℃ /year. This indicates that these months have witnessed larger increases in the annually averaged *USSW*, whereas the *USSW* for the months January to July remained constant. This warming trend was also observed in the atmospheric and marine conditions in the nearby areas

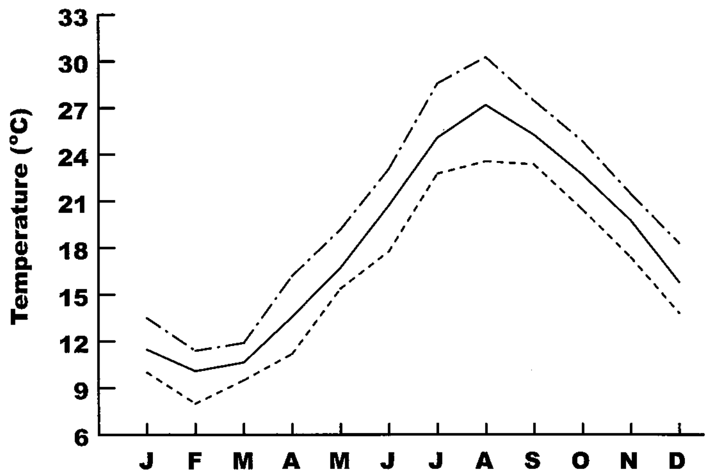

Fig. 2 Climatological monthly mean temperature averaged for 1987–2010 in the Uma-shima Strait (B in Fig.1). Solid line: averaged; broken line: minimum record; chain line: maximum record.

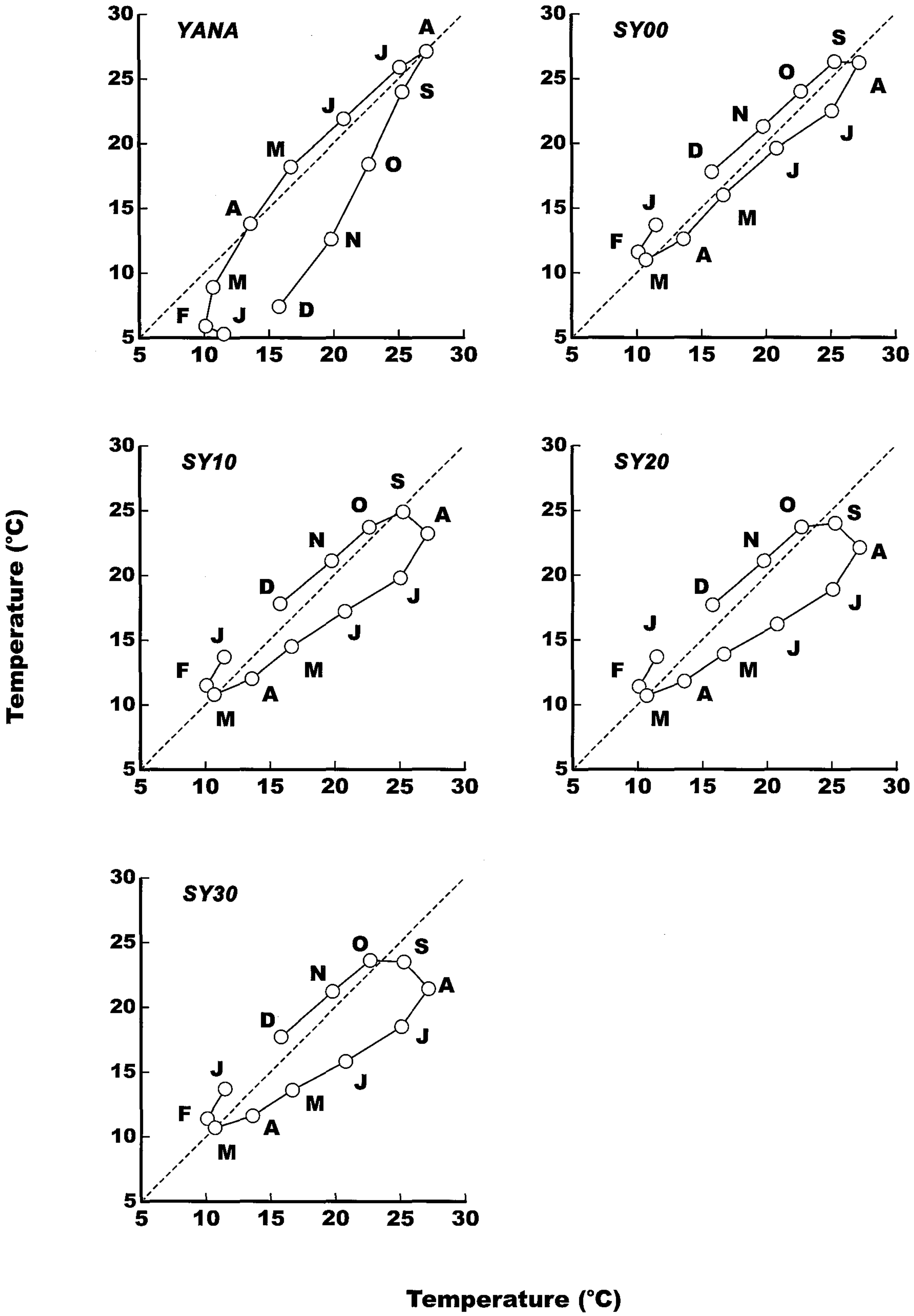

Fig. 3 Relationships between the climatological means of *YANA*, *SY00*, *SY10*, *SY20* and *SY30*, and *USSW*. Broken line: equivalency plot; abscissa: *USSW*.

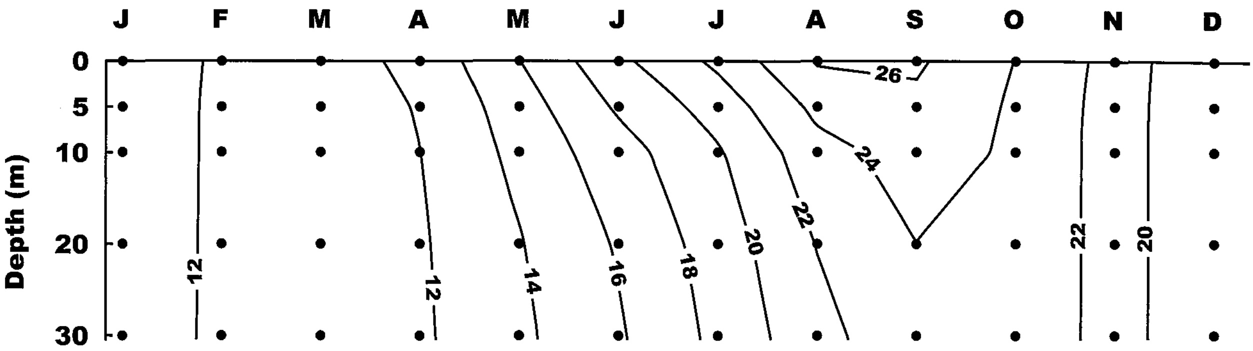

Fig. 4 Climatological seasonal variation of the vertical profile of water temperature (℃) at the YNS9 (C in Fig.1) determined by averaging the data for 1987-2010.
The isoclines are depicted with the data of 0, 5, 10, 20 and 30 m depth.

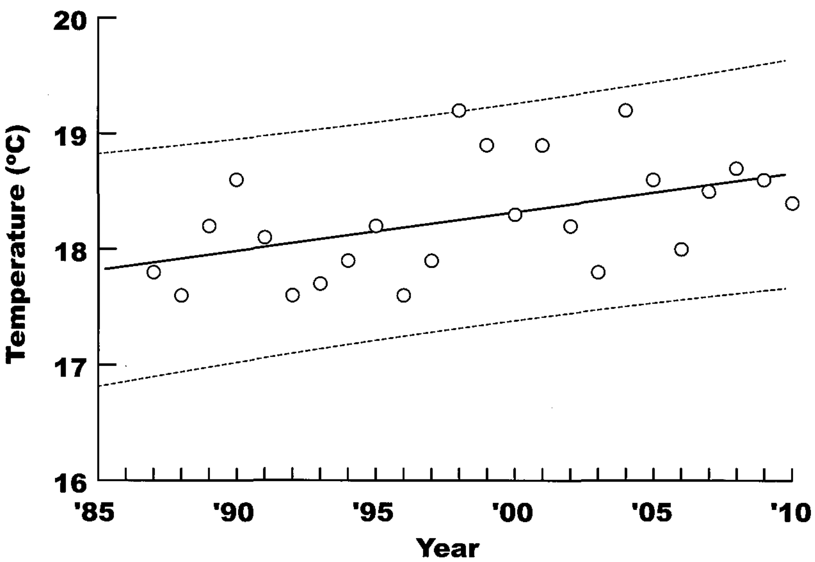

Fig. 5 Annual mean temperature of the Uma-shima Strait (B in Fig.1).
Open circle: temperature; solid line: regression line; broken line: 95% confidence limits of regression.

(Table 1). Specifically, *YANA* in September and October, and *SY00*, *SY10*, and *SY30* in December show substantial increases over time. These results indicate that the cooling process from October to December has been modified in the study area. However, no trends are evident in the annual average temperatures of *YANA*, *SY00*, *SY10*, *SY20*, and *SY30* (Table 1). In addition, there were no correlative shifts from January to July, except for sporadic trends in May and June.

Bivariate regression

The annually averaged *USSW* correlated with the temperature of the atmosphere and the seawater in nearby areas (Table 2). None of the significant correlations are negative. The regression with the atmospheric temperature (*YANA*) per year explains 46.3% of the variability in *USSW*[20]. In addition, *USSW* was found to be influenced by the air temperature from February to April and from August to October. The R^2 values of the latter period are higher than those of the former and showed a tendency to decrease; this implies the effect of air temperature was lesser during this period. The result for the water temperature of YNS9 per year shows that *SY00*, *SY20*, and *SY30* are significantly correlated with *USSW* with coefficients of determination of 0.227-0.458. The monthly analysis shows

Table 1. Statistical values of Durbin-Watson test (DW), Breusch-Pagan test (ESS/2), and regression (trend) on trend analysis.

Division class	*USSW*			*YANA*			*SY00*			*SY10*			*SY20*			*SY30*		
	DW	ESS/2	trend+	DW	ESS/2	trend	DW	ESS/2	trend	DW	ESS/2	trend	DW	ESS/2	trend	DW	ESS/2	trend
per annum	1.806	0.001	3.310*	2.200	0.640	2.395	2.515	2.659	1.942	2.504	0.124	2.919	2.311	0.015	2.104	2.084	0.001>	2.216
January	2.482	1.219	2.243	2.315	0.688	-2.770	2.265	0.738	-0.401	2.323	1.057	-1.295	2.282	0.983	-1.372	2.318	1.034	-1.881
February	2.310	1.413	-0.307	2.377	0.040	3.109	2.226	0.144	-0.247	1.979	0.047	0.840	1.875	0.008	0.484	1.977	0.139	-0.939
March	2.187	0.014	1.800	1.840	0.418	2.535	2.699	0.268	1.063	2.736	0.575	1.791	2.671	0.849	1.273	2.648	1.114	1.001
April	1.856	0.340	1.096	1.672	0.012	1.417	2.125	0.342	-4.761	2.163	0.285	-1.000	2.050	0.082	0.291	2.200	0.116	0.007
May	2.384	0.063	-2.837	1.596	0.392	3.809*	1.858	1.851	-1.400	1.917	0.005	-0.587	1.867	0.177	-0.996	1.856	0.367	-1.987
June	2.253	0.003	-1.652	1.844	0.537	2.648	1.927	1.671	-11.757**	2.198	1.257	-3.226	2.452	0.197	-3.383	2.329	0.096	-1.191
July	2.653	2.251	0.589	2.886*	0.093	0.496	2.158	0.419	-1.317	2.403	0.117	-0.300	2.058	0.059	-0.222	2.353	0.134	-1.191
August	2.117	1.352	10.989*	2.223	1.202	3.857	2.594	1.095	8.365	2.022	0.118	-0.491	2.240	0.206	-2.830	2.371	0.047	-2.856
September	1.948	1.114	5.165	2.215	0.092	7.213*	1.647	0.100	1.430	1.902	0.056	6.170	2.375	1.425	0.474	2.197	0.386	0.135
October	2.693	0.036	8.007**	1.760	0.023	6.039*	2.357	1.183	4.196	2.411	0.333	6.035*	2.368	0.324	5.691*	2.363	1.071	5.330*
November	1.932	0.179	8.761**	2.268	0.001>	0.513	1.700	0.646	4.043	1.814	0.403	5.335*	1.874	0.631	5.317*	1.817	0.882	4.887
December	2.283	0.092	5.874	2.513	1.366	-0.117	2.043	3.805	7.117*	2.052	3.790	7.148*	2.073	3.960*	7.043*	2.015	3.759	6.922*

+:($\times 10^{-2}$) ℃ / year ; *: $p < 5\%$; **: $p < 1\%$.

Table 2. Statistical values of Durbin-Watson test (DW), Breusch-Pagan test (ESS/2), trend, and coefficient of determination (R^2) on bivariate regression for *USSW*.

Division class	*YANA*				*SY00*				*SY10*				*SY20*				*SY30*			
	DW	ESS/2	trend	R^2	DW	ESS/2	trend	R^2	DW	ESS/2	trend	R^2	DW	ESS/2	trend	R^2	DW	ESS/2	trend	R^2
per annum	2.116	0.586	0.706	0.463**	1.624	3.043	0.441	0.227*	1.945	4.061*	0.633	0.470**	1.936	2.342	0.685	0.438**	1.905	1.057	0.652	0.458**
January	2.313	1.670	-0.309	0.051	2.114	0.053	0.583	0.333**	2.019	0.004	0.573	0.319**	2.041	0.057	0.551	0.304**	2.032	0.119	0.550	0.311**
February	2.110	0.152	0.328	0.240*	2.056	0.039	0.690	0.264*	2.126	0.042	0.533	0.174*	2.167	0.035	0.523	0.183*	2.184	0.004	0.560	0.211*
March	1.745	0.117	0.342	0.209*	2.293	0.007	0.491	0.246*	2.321	0.125	0.414	0.148	2.337	0.001>	0.488	0.180*	2.342	0.075	0.552	0.225*
April	2.434	0.027	0.589	0.286**	1.843	0.771	0.341	0.071	1.976	0.781	0.599	0.121	2.014	0.08	0.736	0.151	2.083	1.643	0.829	0.166
May	2.193	0.736	0.376	0.056	2.341	0.240	0.202	0.061	2.340	2.073	0.561	0.216*	2.149	0.888	0.732	0.245*	2.100	0.664	0.603	0.217*
June	2.327	0.397	0.644	0.092	2.243	1.414	0.083	0.008	2.290	1.235	0.224	0.021	2.242	0.219	0.022	0.001>	2.241	0.120	0.040	0.001>
July	2.631*	4.326	0.774	0.222*	2.696*	0.512	0.140	0.162	2.786*	0.725	0.642	0.101	2.759*	0.956	0.521	0.050	2.749*	0.465	0.465	0.039
August	2.116	0.040	1.568	0.516**	1.161*	0.051	0.733	0.656**	1.883	0.099	0.589	0.117	1.720	0.374	-0.183	0.006	1.699	1.067	-0.263	0.013
September	2.525	0.473	0.645	0.351**	1.657	0.052	0.171	0.003	1.299*	1.092	0.583	0.353**	0.994**	0.001>	0.942	0.331**	1.217*	0.057	0.562	0.182*
October	2.410	0.031	0.607	0.334**	2.259	0.454	0.578	0.274**	2.565	0.291	0.482	0.457**	2.588	0.415	0.817	0.438**	2.616	0.142	0.787	0.391**
November	1.220*	0.199	0.241	0.088	1.256*	0.004	0.745	0.415**	1.378*	0.009	0.789	0.504**	1.425	0.085	0.808	0.526**	1.378*	0.117	0.807	0.507**
December	2.004	1.243	-0.143	0.018	2.240	0.666	0.273	0.075	2.246	0.653	0.294	0.090	2.235	0.636	0.285	0.086	2.232	0.742	0.285	0.082

*: $p < 5\%$; **: $p < 1\%$.

that all the regressions were significant during the mixing period (January-February), with the R^2 value of January being higher than that of February, and in the transition period from the stratified to the mixing period (October). Significant correlations between *SY10*, *SY20*, and *SY30*, and *USSW* were observed in May.

Multivariate regression

The bivariate regression analysis identified a number of single explanatory variable with respect to the atmospheric and water temperatures of nearby areas. The presence of multicolinearity was determined prior to multivariate regression analysis. Multicollinearity was estimated by the variation inflation factor (VIF), with significance explained when VIF > 3.0[20].

The matrix of correlation coefficients for *YANA*, *SY00*, *SY10*, *SY20*, and *SY30* are shown in Fig. 6. Multicollinearity appears mostly between *SY00*, *SY10*, *SY20*, and *SY30* (VIF: 1.004–587.0), mostly during the mixing period (Fig. 4). This suggests that care should be

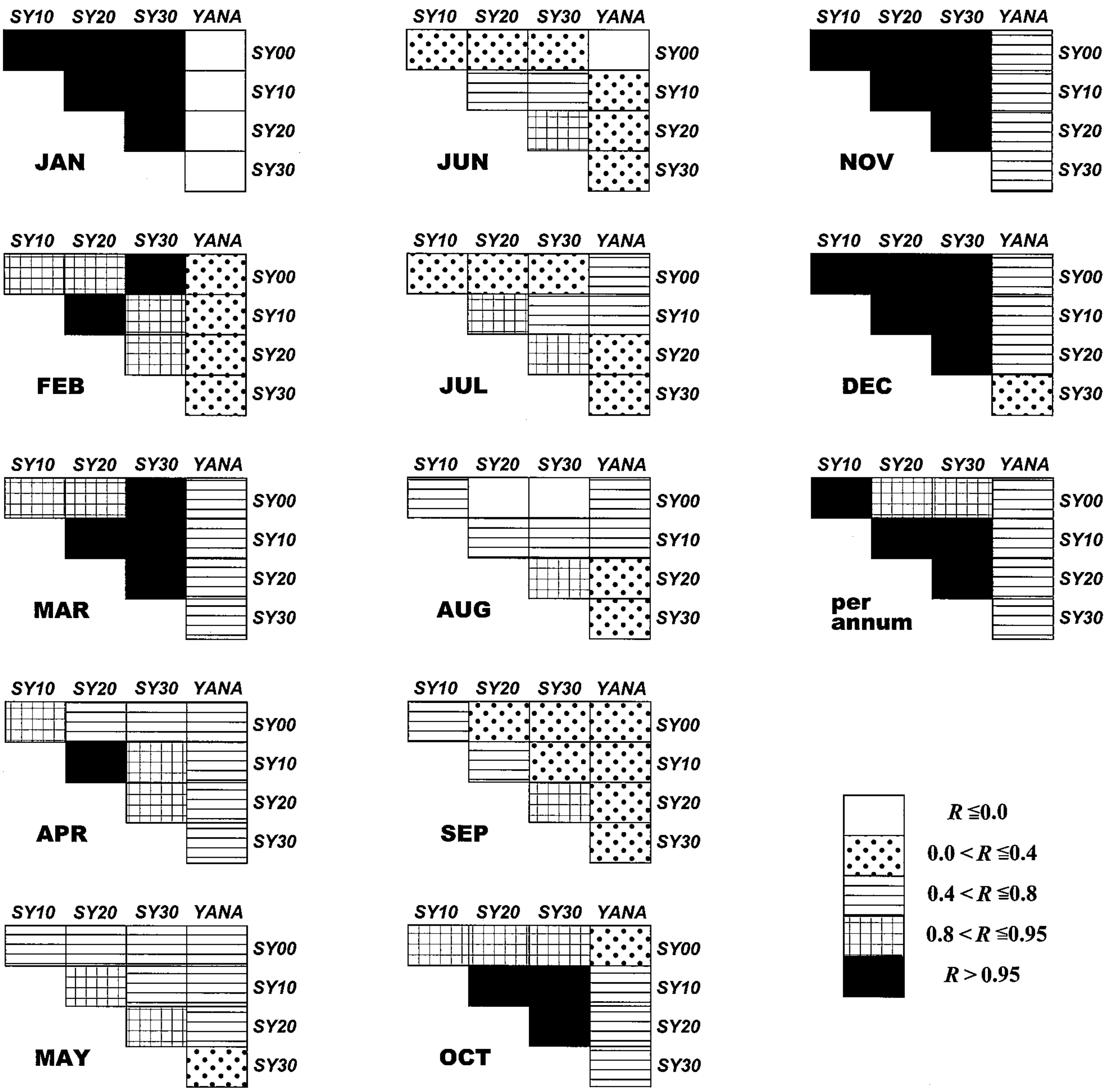

Fig. 6 Matrices of correlation coefficient R among valuables of *YANA*, *SY00*, *SY10*, *SY20*, *SY30* and *USSW*.

taken when creating equations using more than two data sets from the YNS9 station. However, the VIF values for relationships between *YANA* and the temperature data of the YNS9 station were all less than 2.586. Therefore, multivariate regressions were developed using *YANA* as the first independent variable, and either *SY00*, *SY10*, *SY20*, or *SY30* as the second.

Following a total of 52 trials, three significant regressions were found for February as follows:

$$USSW=2.770+0.3104\ YANA+0.4792\ SY10 \quad (1)$$

$$USSW=2.756+0.3137\ YANA+0.4800\ SY20 \quad (2)$$

$$USSW=2.460+0.3078\ YANA+0.5100\ SY30 \quad (3)$$

Table 3 lists statistical values for these regressions. It has been established that *USSW* was influenced by every single independent variable in February (Table 2). Both variables in Eqs. 1-3 are positive and support the argument that both the air and water temperature of nearby areas have a positive influence. A similarity in Eqs.1-3 can be accounted by the vertical mixing in February shown in Fig.4. While the range of air temperature *YANA* is larger than those of water temperature *SY10*, *SY20* and *SY30*, the coefficient for *YANA* is the smaller of the two in each equation. The range of *USSW* is among them. Fig.7 shows the annual changes of *YANA*, *SY10*, *SY20*, *SY30* and *USSW* in February and the estimated values of *USSW* which are calculated by multivariate regressions. The residuals between them in each year are less than 1.0 ℃ except the years 2000 and 2006.

Discussion

The present study has documented an increase in the annual averaged surface water temperature of the Umashima Strait; this observation is consistent with the results of other research conducted in the Suo Nada area[24, 25). Furthermore, the present study has determined the influence of nearby areas on the documented temperature fluctuations at the monitoring site. Both bivariate and multivariate analyses demonstrate that while surface water temperature was subject to vertically homogeneous water mass in the mixing period of YNS9 (January-March), *YANA* operated additionally from February to April with cutting off the effect of water temperature; thereafter, in May, the effect of the cooler water mass of the deeper layer in YNS9 was observed (Table 2). *USSW* exhibits a locally uncorrelated period in June-July, after which *YANA* intensely influenced *USSW* in August-September. Thereafter, the effect of *YANA* reduced in October, and the temperatures recorded at YNS9, especially *SY10* and *SY20*, had significant effects; this was again followed by a period of stability.

In conclusion, the seasonal pattern in the relationship between the air and water temperatures of areas near the surface water temperature at the monitoring site consists of five phases: an air-correlated phase (April); an air-correlated and water-altered phase (August-October); a water-correlated and air-altered phase (January-March); a watercorrelated phase (May and

Table 3. Statistical values of Durbin-Watson test (DW), Breusch-Pagan test (ESS/2), coefficient of determination (R^2), VIF and significance level on two-variable regression for *USSW*.

Regression	DW	ESS/2	R^2	VIF	p for a_1^+ (%)	p for a_2^+ (%)
Eq.1	1.980	1.136	0.3760**	1.009	1.93	4.74
Eq.2	2.018	0.819	0.3900**	1.006	1.70	3.67
Eq.3	2.001	0.398	0.4101**	1.009	1.73	2.49

$^+$: $Y=C+a_1X_1+a_2X_2$; **: p<1%.

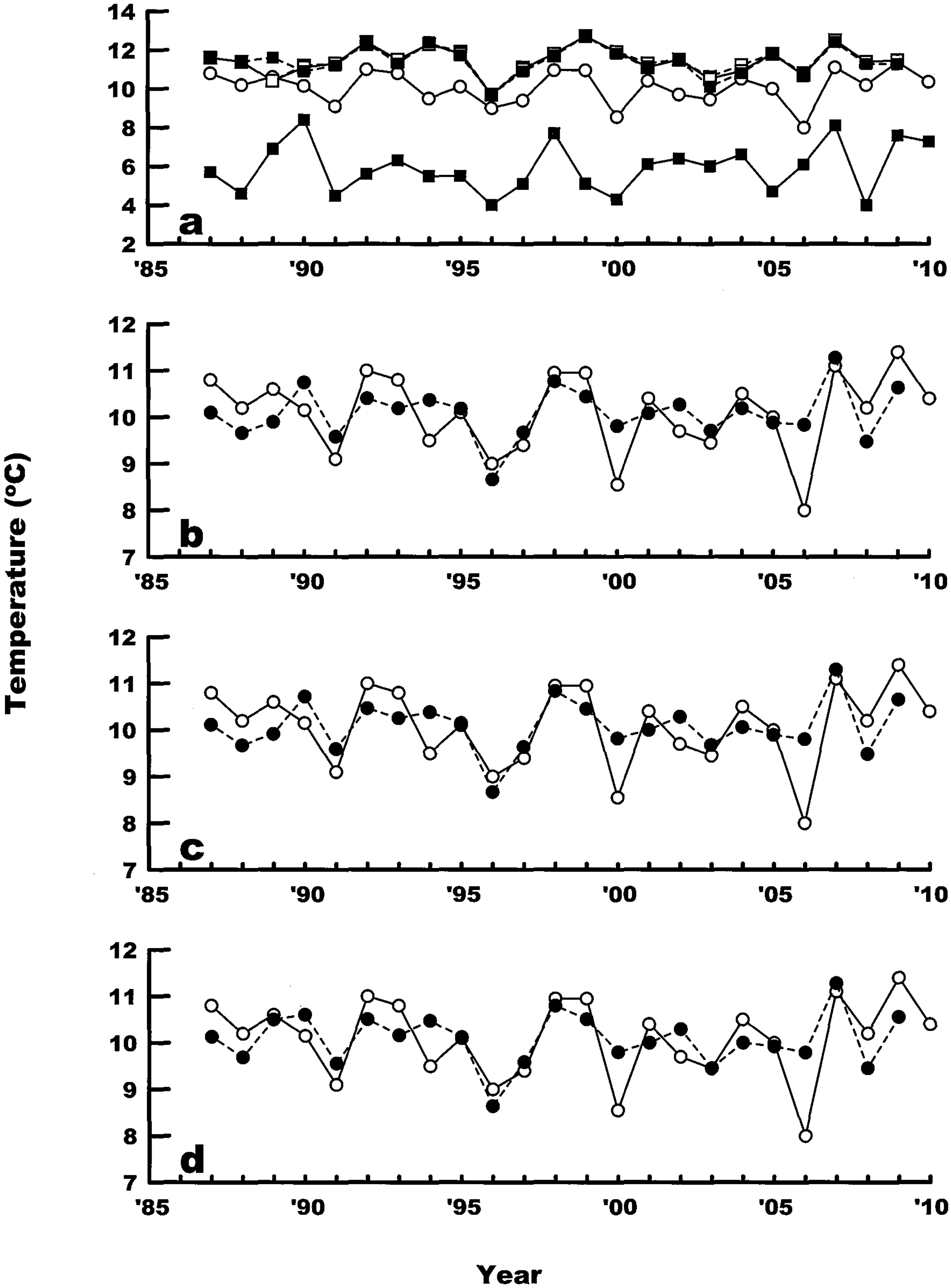

Fig. 7 Annual changes of *YANA*, *SY10*, *SY20*, *SY30* and *USSW* in February and the estimated values of *USSW* which are calculated by multivariate regression.
a: *YANA*, *SY10*, *SY20*, *SY30* and *USSW*; b: *USSW* and the estimates by Eq. 1; c: *USSW* and the estimates by Eq. 2; d: *USSW* and the estimates by Eq. 3. Closed square with solid line: *YANA*; open square with broken line: *SY10*; open square with solid line: *SY20*; closed square with broken line: *SY30*; open circle with solid line: *USSW*; closed circle with broken line: the estimated values by multivariate regression.
The multivariate regressions were applied to the data from 1987 to 2009 on account of the absence of information at YNS9 in February 2010.

November); and an uncorrelated phase (June–July and December). Against our study, however, the documents about the seasonal pattern monitored in the other zones of the Suo Nada area mentioned that the increment in surface temperature appeared in the period of December-April[24] and January-March[25]. This discrepancy may result from the disparity in spatial scale they adopted for analysis, other than the geographic condition.

The regression analyses indicate that the surface water temperature of the Umashima Strait is influenced differently from season to season by the water mass of the offshore area and the atmospheric conditions. In terms of heat transfer, all the areas where data have been collected for the present study can be regarded as a connectable environment[26]. This supports the similarity in the seasonal patterns in the increasing trend of all the datasets (Table 1). In addition, a phase with no clear influence from nearby areas was identified and an abrupt phase change from April (air-correlated) to May (deeper water-correlated).

Underlying the observations made in the present study are hydrodynamic processes such as advection and tides, the influx of fresh water from the coastal region and meteorological process. Understanding these mechanisms is important to properly explaining the observations since some of the relationships remain speculative. Characterizing the physical structure of the system will make it possible to describe the ethological and/or ecological characteristics of aquatic vegetation and animals in the area. Reductions in the productivity of the fishery as well as the frequency of biological disturbance such as red tide and deterioration of nursery conditions[27-29] make it imperative to better understand the effects of changes in surface water temperatures on the habitats of the area.

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周防灘東部沿岸域において1987-2010 年に観測された水温の変動解析

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1987-2010年に周防灘東部沿岸域の馬島水道において表面水温を毎月観測し、その経年変化の特徴を解析したところ、年間平均水温はこの間に3.31×10^{-2}℃/年の割合で上昇していることがわかった。また、８月および10・11月の水温が8.01×10^{-2} -1.10×10^{-1}℃/年の上昇率をしめした。本水域の近辺域で測定された気温や沖合域で観測された水温について月別に解析したところ、同様の傾向がみられた。回帰分析法をもちいてこれらの温度間の関係を調べたところ、馬島水道の水温はこれらの気温・水温の影響を受けて変動しているようであり、両者の間には月によって異なるいくつかの相関パターンのあることがわかった。