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Annual and Interannual Fluctuations of Coastal Water Temperatures in the Tsushima Current and the Kuroshio Regions

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We studied the annual and interannual fluctuations of sea surface temperature (SST) for 30 years (1941~1970) at 9 coastal stations in the Tsushima Current and the Kuroshio regions by means of harmonic analysis, correlation analysis, and spectral analysis. The fluctuations of annual mean and amplitude are 0.3 to 0.7°C, and those of annual phase are 3 to 4 days. The SST anomalies are about 1°C, and they are relatively large in summer and winter than in spring and fall. The SST anomalies in the Tsushima Current and the Kuroshio regions are related with each other. The predominant periods of SST anomalies differ slightly from station to station. The quasi-biennial (26 months) and pole tide (14 months) oscillations are found in the spectra of SST anomalies.

Introduction

The fluctuations of sea surface temperature (SST) are closely related with the fisheries and the climatic variability (Kang, 1984). The annual variations of SST in the Pacific Ocean were reported by many authors including Koizumi (1962), Wyrtki (1965), Robinson (1976), and Gorshkov (1976). The annual variations of SST in the neighbouring seas of Korea were studied by Kang and Jin (1984) based on the monthly normals of SST reported by the Fisheries Research and Development Agency (1979). Kang (1985a) studied the annual variations of SST in the Japan Sea by using the data reported by Maizuru Marine Observatory (1972).

The interannual fluctuations of SST in the East China Sea were studied by Koizumi (1964), Moriyasu (1967, 1968), and Sawara (1974), and those in Korea Strait were studied by Nan-niti and Fujiki (1967) and Kang and Lee (1984), The interannual fluctuations of SST in the downstream of the Tsushima Current region and their relation with those in the Kuroshio region are not well posed yet.

In this paper we present the annual and interannual fluctuations of SST in the Tsushima Current and the Kuroshio regions. Our analysis is based on the 10-day SST data of 30 years (1941~1970) at 9 coastal stations reported by Japan Meteorological Agency (1976). The specific questions we tried to answer are the followings: How much persistent is the annual variation of SST? In other words, how much stable are the annual mean, amplitude, and phase of SST, and how large are the SST anomalies? Are there any seasonal dependency of SST anomalies? How large are the space scales of SST anomalies? Are the fluctuations of SST in the Tsushima Current and the Kuroshio regions related with each other? What are the predominant periods of SST fluctuations other than the annual cycle?

Data and Method of Analysis

Our analysis is based on the 10-day (decad) SST data for 30 years (1941～1970) at 9 coastal stations in the Tsushima Current and the Kuroshio regions (Japan Meteorological Agency, 1976). The stations are shown in Fig. 1.

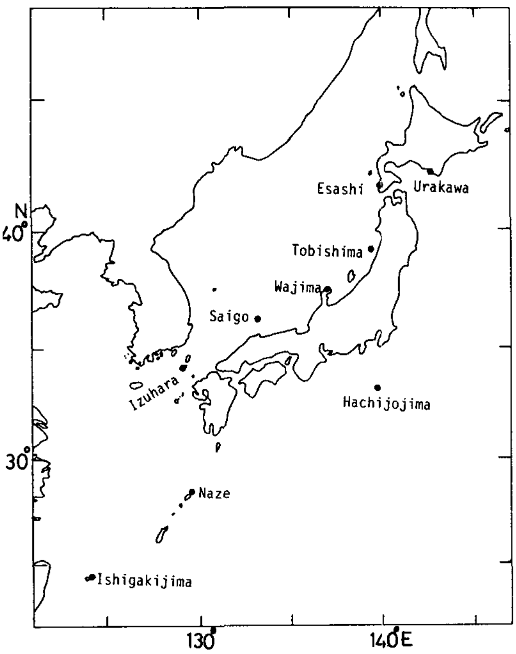

Fig. 1. Locations of coastal stations.

The seasonal variations of SST is studied by means of harmonic analysis. The SST's of each year at each station are fitted to a function

$$T(t)=T_0+T_1\cos(\omega t-\phi_1)+T_2\cos(2\omega t-\phi_2),$$

where T_0 is the the annual mean, ω the annual angular frequency, t the time from the beginning of the year, T_1 and T_2 the annual and semi-annual amplitudes, respectively, and ϕ_1 and ϕ_2 the annual and semi-annual phases, repectively. The 5 harmonic constants (T_0, T_1, T_2, ϕ_1 and ϕ_2) are determined by the least squares fit. The harmonic constants at each station differ from year to year, and their variabilities are measured by their standard deviations.

Monthly (or 10-day) normals of SST in this paper are defined by the mean SST of the same calendar month (or decad) averaged over 30 years. The time series of SST anomalies are generated by removing the normals. The seasonal dependency of SST anomalies is studied by computing the root-mean-square (RMS) amplitude of 10-day SST anomalies of each calendar months for 30 years.

In order to study the space scales of SST anomalies, we computed the cross-correlations coefficients between monthly SST anomalies of each pair among 9 stations. Also, in order to study the advection of SST anomalies, we computed cross-correlation functions (with time lag and leads) between each pair of 10-day SST anomalies.

The predominant periods of SST anomalies are studied by means of spectral analysis. The smoothed spectra of SST anomalies of 360 months at each station are computed by the Fourier transform of auto-covariance function with Bartlet (triangular) lag window with length of 100 months (Jenkins and Watts, 1968). The composite spectrum is computed by averaging the spectra at 9 stations.

Results

Seasonal variation:

The harmonic constants and their standard deviations of seasonal variation of SST at 9 stations are shown in Table 1 and Fig. 2. Fig. 2 shows that the annual mean of SST decreases with the downstream distance of the Tsushima Current and the Kuroshio. The annual amplitude, on the other hand, increases with the downstream distances. The annual phase in the Kuroshio region delays with the downstream, and that along the Tsushima Current in the Japan Sea fluctuates around 230°. The semi-annual amplitudes of SST in the regions considered are between 0.4 and 1.3°C (Table 1).

The standard deviations of the annual mean and amplitude are between 0.3 and 0.7°C. The standard deviations of annual phase are 3 to 4 days. This means that the annual march of SST at each station repeats basically the same pattern every year. This statement holds true even though

Table 1. Harmonic constants and their standard deviation for seasonal variation of SST at coastal stations of the Tsushima Current and the Kurosio region for 30 years (1941～1970)

Station	T_0(°C)	T_1(°C)	ϕ_1(°)	T_2(°C)	ϕ_2(°)
Urakawa	8.9±0.4	9.0±0.5	234±4	1.1±0.4	125±20
Esashi	12.9±0.7	8.7±0.7	227±3	1.3±0.3	111±16
Tobishima	15.6±0.6	8.3±0.6	234±4	1.1±0.3	89±23
Wajima	16.6±0.5	8.7±0.5	226±3	0.7±0.3	76±25
Saigo	17.7±0.5	7.7±0.5	229±3	0.6±0.3	105±70
Izuhara	18.9±0.5	6.1±0.6	237±4	0.8±0.3	112±10
Hachijojima	21.8±0.5	4.9±0.6	233±4	0.6±0.3	149±72
Naze	23.3±0.4	4.5±0.4	225±3	0.5±0.2	119±68
Ishigakigima	24.8±0.3	4.5±0.4	211±4	0.4±0.2	207±82

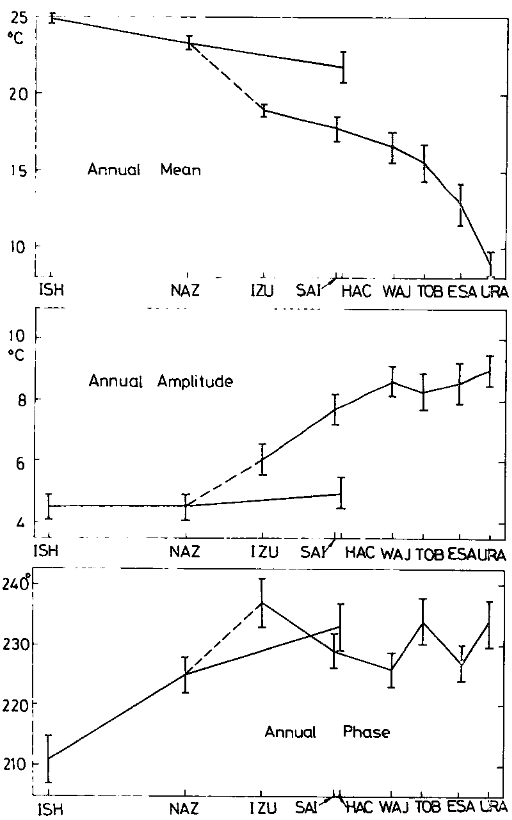

Fig. 2. Annual mean, amplitude and phase of SST for 30 years (1941-1970) and their standard deviations at 9 coastal stations in the Tsushima Current and the Kuroshio regions.

the standard deviations of semi-annual phse reaches up to 80° (Table 1), because the semi-annual amplitude is typically less than 10% of the anuual amplitude.

The year-to-year fluctuation of annual mean, annual amplitde and annual phase for 30 years (1941～1970) at 9 station are shown in Fig. 3, 4 and 5, respectively. Figs. 3, 4 and 5 suggest that the interannual fluctuations of harmonic constants between nearby stations are very coherent but those between remote stations are quite different.

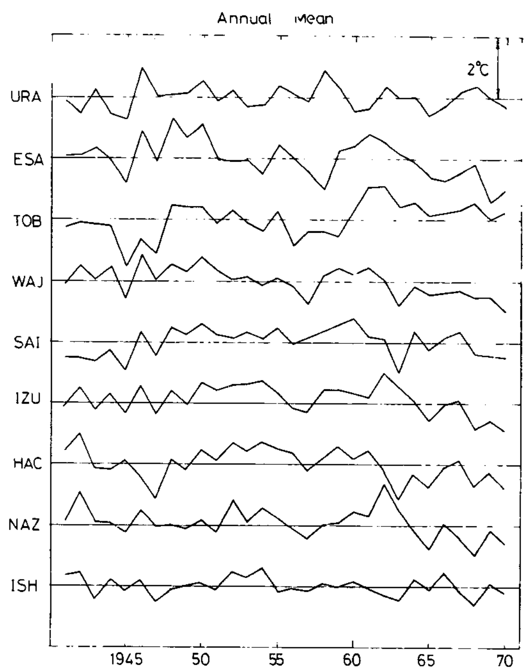

Fig. 3. Interannual fluctuations of annual means of SST for 30 years (1941～1979) at 9 coastal stations.

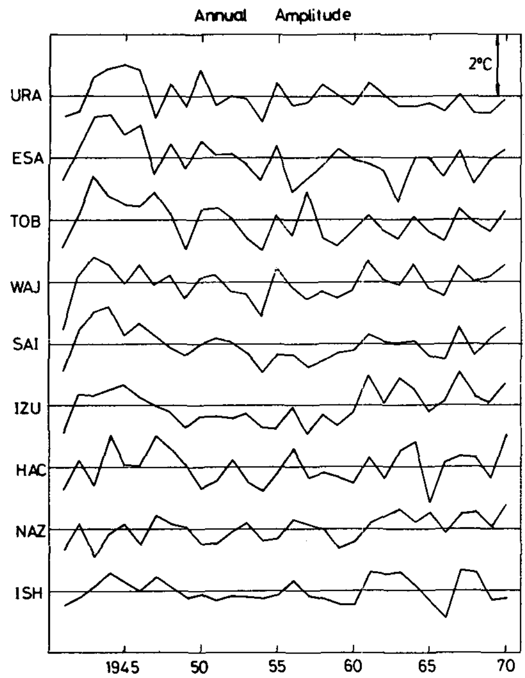

Fig. 4. Interannual fluctuations of annual amplitude of SST for 30 years (1941~1970) at 9 coastal stations.

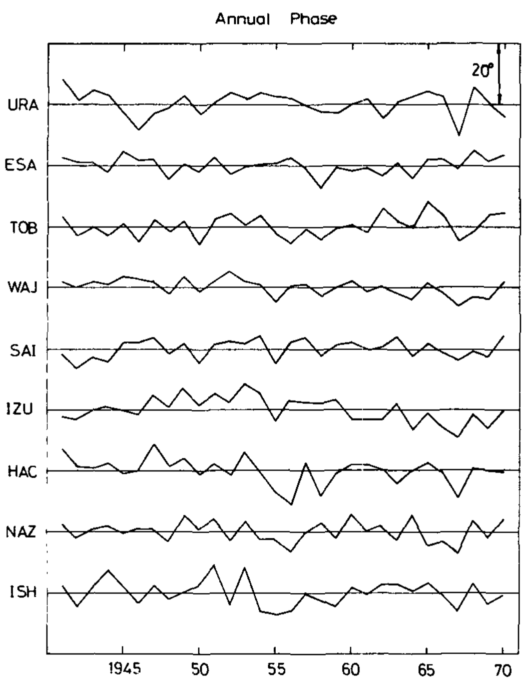

Fig. 5. Interannual fluctuations of annual phase for 30 years (1941~1970) at 9 coastal stations.

SST anomalies:

The seasonal dependency of SST anomalies is investigated by computing the RMS amplitude of 10-day SST anomalies of the same calendar months for 30 years at each station. The monthly distributions of RMS amplitude at each station are shown in Table 2, and their average over 9 stations is shown in Fig. 6. Table 2 and Fig. 6 show that the SST anomalies in summer and winter are larger than those in spring and fall. The RMS amplitudes

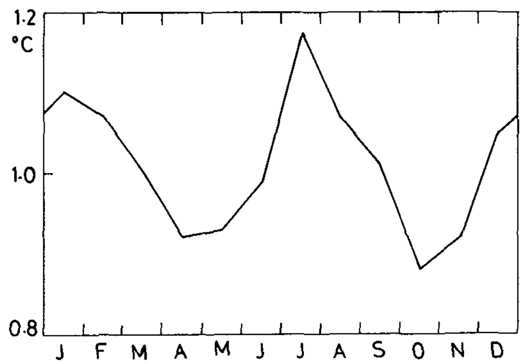

Fig. 6. Monthly distribution of RMS amplitude of SST anomalies for 30 years averaged over 9 stations.

of SST anomalies averaged over 9 stations are 1.1 to 1.2°C in winter and summer and about 0.9°C in spring and fall.

The space scales of SST anomalies can be inferred from the cross-correlation coefficients of SST anomalies with zero time lag. Table 3 shows the cross-correlation coefficients of monthly SST anomalies for 30 years between each each pair among 9 coastal stations. The cross-correlation coefficieont of SST anomalies between nearby stations (the tri-diagonal band in Table 3) are beween 0.34 and 0.63. The cross-correlation coefficients generally decrease decrease with the distance between the sttations. For example, the cross-correlation coefficients between Ishigakijima and Naze is 0.57 and that between Ishigakijima and Esashi is close to zero (−0.02). In other words, the SST anomalies between nearby stations are coherent while those at a large distance have no correlation. It is

Table 2. RMS amplitude (°C) of SST anomalies for 30 years (1941~1970) at coastal stations of the Tsushima Current and the Kuroshio regions

Station	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Urakawa	1.1	0.8	0.8	1.0	1.0	1.3	1.4	1.5	1.2	1.1	1.3	1.4
Esashi	1.2	1.2	1.0	0.9	1.1	1.2	1.4	1.5	1.0	1.1	1.1	1.3
Tobishima	1.3	1.2	0.9	1.0	1.0	1.0	1.5	1.0	0.9	1.0	1.1	1.2
Wajima	0.9	0.9	0.8	0.9	0.9	1.0	1.3	1.1	1.0	0.8	0.8	0.8
Saigo	1.0	0.9	1.0	0.8	0.8	0.9	1.2	1.0	0.9	0.8	0.8	1.1
Izuhara	1.1	1.1	0.9	0.7	0.7	0.8	1.1	1.1	0.8	0.8	0.8	0.9
Hachijojima	1.3	1.3	1.5	1.2	1.2	1.1	1.2	1.0	1.2	0.8	0.8	1.1
Naze	0.9	1.1	1.1	0.9	0.8	1.0	0.9	0.8	0.8	0.8	0.8	0.8
Ishigakigima	1.2	1.3	1.1	0.9	0.8	0.7	0.6	0.6	1.2	0.8	0.9	0.9
Average	1.1	1.1	1.0	0.9	0.9	1.0	1.2	1.1	1.0	0.9	0.9	1.1

Table 3. Cross-correlation coefficients of SST anomalies for 30 years(1941~1970) between each pair among 9 coastal stations in the Tsushima Current and the Kuroshio regions

St.	URA	ESA	TOB	WAJ	SAI	IZU	HAC	NAZ	ISH
URA	1.0	0.41	0.28	0.32	0.25	0.17	0.09	−0.01	0.03
ESA	0.41	1.00	0.38	0.53	0.43	0.21	0.15	0.05	−0.02
TOB	0.28	0.38	1.00	0.34	0.41	0.09	0.17	0.03	0.13
WAZ	0.32	0.53	0.34	1.00	0.63	0.63	0.41	0.35	0.27
SAI	0.25	0.43	0.41	0.63	1.00	0.62	0.31	0.15	0.24
IZU	0.17	0.21	0.09	0.63	0.62	1.00	0.48	0.39	0.41
HAC	0.09	0.15	0.17	0.41	0.31	0.48	1.00	0.42	0.35
NAZ	−0.01	0.05	0.03	0.35	0.15	0.39	0.42	1.00	0.57
ISH	0.03	−0.02	0.13	0.27	0.24	0.41	0.35	0.57	1.00

to be noted that the SST anomalies at Hachijojima are highly correlated with those at Izuhara (0.48), Saigo (0.31) and Wajima (0.41). This indicates that the SST anomalies in the Tsushima Current region are correlated with those in the downstream of the Kuroshio region.

In order to study whether there is a lead or lag relation between SST anomalies at two stations, we computed cross-correlation function using 10-day SST anomaly series. Fig. 7 shows the cross-correlation function between the SST anomalies at Izuhara and those at other stations. The maximum of the cross-correlation function occurs at time lag zero or within 10 days.

Predominant periods:

The predominant periods of SST anomalies are studied by computing the power spectra of SST anomaly series for 30 years at each station. Since the monthly normals of SST are already removed, the spectra of SST anomalies are free of annual oscillation and its higher harmonics. The predominant low-frequency periods (longer than 10 months) at each station identified by spectral peaks are shown in Table 4. Fig. 8 shows the power spectra of SST anomalies at three stations (Esashi, Saigo and Izuhara). The composite spectrum is constructed by averaging the spectra at 9 stations. The most predominant spectal peak at all stations except one station is found at periods longer than 10 years. Spectral peaks about quasi-biennial oscillation (26 months) and pole-tide (14 monthes) are found at 7 and 5 stations, respectively, among 9 stations. Other spectral peaks are found at periods 33 to 55, 16 to 18, and 10.6 to 12.2 months.

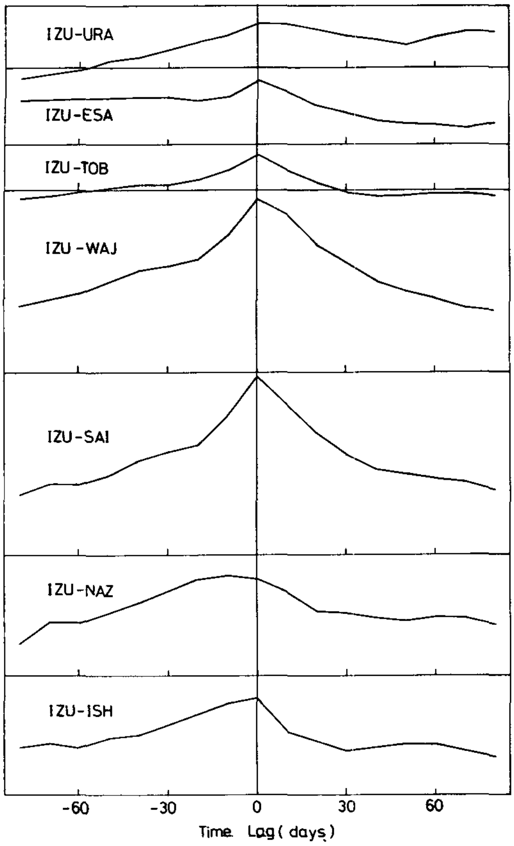

Fig. 7. Cross-correlation function between the SST anomalies at Izuhara and those at other stations.

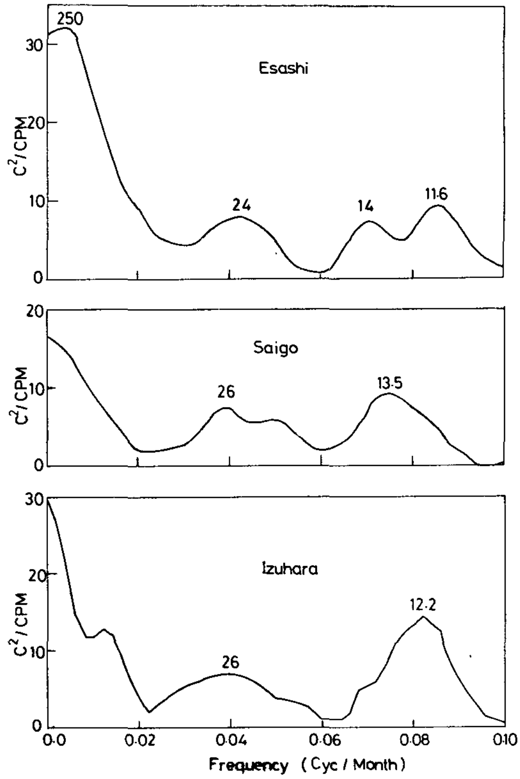

Fig. 8. Spectra of SST anomalies for 30 years at Esashi, Saigo, and Izuhara. Numbers at the spectral peaks are predominant periods.

Table 4. Predominant periods (spectral peaks) of SST anomalies for 30 years (1941~1970) at coastal stations of the Tsushima Current and the Kuroshio regions. 'Inf' means an infinite

Station	Predominant periods (months)					
Urakawa		38		17		10.9
Esashi	250		24		14	11.6
Tobishima	250	36	24	16		11.4
Wajima	Inf		25		15	
Saigo	Inf		26		13.5	
Izuhara	Inf		26			12.2
Hachijojima	Inf	33		17	13	
Naze	Inf		24			12.2
Ishigakigima	125	54	27	18	14.5	10.6
Composite	Inf		26		14.4	12.0

Discussion and Conclusions

In this paper we presented the annual and inter-annual fluctuations of SST in the Tsushima Current and the Kuroshio region by means of time series analysis of coastal SST for 30 years (1941~1970) at 9 stations.

At each station the annual variation of SST repeats basically the same pattern every year. The standard deviations of the flucuations in annual mean and amplitude of SST are less than 1°C, and those of annual phase are less than 4 days. The annual mean of SST decreases with the downstream distance of the Kuroshio and the Tsushima Current whereas the annual phase increases with the downstream distance. As was demonstrated by Kang (1985b), the annual mean and annual amplitude of the SST in the Tsushima Current and the Kuroshio regions are determined not only by the local heat transfers across the sea surface but also by the heat advections associated with the ocean currents and the Asian monsoon.

The cross-correlation coefficients, shown in Table 3, yields the followings. (a) The cross-correlations coefficient of SST anomalies generally decreases with the distances betwen stations. (b) The SST anomalies in the Tsushima Current region are correlated with those in the upstream of the Kuroshio. The cross-correlation coefficient between Izuhara and Naze is 0.39 and that between Izuhara and Ishigakijima is 0.41. (c) The SST anomalies in the downstream of the Kuroshio are correlated with those in the upstream of the Kuroshio. This can be inferred from the fact that the SST anomalies at Hachijojima are correlated with those at Naze (0.42) and Ishigakijima (0.35). (d) The SST anomalies in the Tsushima Current region are correlated with those in the downstream of the Kuroshio. This can be inferred from the fact that the SST anomalies at Hachijojima are correlated with those at Izuhara (0,48), Saigo (0.31) and Wajima (0.41). Although the Tsushima Current and the downstream of the Kuroshio are not directly connected by the flow pattern, their SST anomalies are correlated because both of them are originated from the same upstream of the Kuroshio. (e) The SST anomalies in the northern part of the Japan Sea have almost no correlation with those in the upstream of the Tsushima Current or the Kuroshio regions. The correlation coefficient between Tobishima and Naze is only 0.03 and that between Tobishima and Izuhara is only 0.09.

Spectral analysis of SST anomalies shows that secular variability with periods longer than 10 years are most predominant at almost all stations. Other long period fluctuations of interest are the quasi-biennial oscillation with a period of 26 months and the pole-tide oscillation with a period of 14 months. Incidentally, the air temperatures in Korea also show fluctuations with quasi-biennial and pole-tide fluctuatures (Kang and Rho, 1985). The pole-tide or Chandler wobble with a period of 14 months is reported to occur in the fluctuations of mean sea level (Sarukhanyan, 1969; Lisitzin, 1974; Thomson, 1980) and also in the fluctuations of ocean current (Maximov et al, 1972). The quasi-biennial oscillation is known to be excited in the zonal wind primarily by vertically propagating equatorial Kelvin wave and the mixed Rossby-gravity wave in the atomosphere (Holton, 1975). It is interesting that the quasi-biennial oscillations, which are excited by the atmospheric motion, also appear in the fluctuations of SST.

Our presentation in this paper is limited to the time series analysis of SST fluctuations in the Tsushima Current and the Kuroshio regions. We are planning to study the relationship between the SST and atmospheric variabilities such as the air temperature, the precipitation, etc.

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쓰시마 해류와 쿠로시오 해역 연안 수온의 연변화 및 연별변동

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(1985년 7월 15일 수리)

쓰시마해류와 쿠로시오 해역의 9개 연안 정점의 30년간 (1941~1970) 순별 표면수온 자료에 대한 분석 (조화분석, 상관분석 및 스펙트럼 분석)을 통하여 동 해역 표면수온의 연변화와 연별변동을 구명하였다. 계절적 수온변화의 연평균과 연진폭은 해마다 차이가 있으며, 변동의 편차는 0.3 내지 0.7°C 정도이고, 연위상의 편차는 3 내지 4일 정도이다. 누년 평균적인 계절변화를 제거한 이상수온(temperature anomalies)은 약 1°C 정도이며, 봄과 가을보다는 여름과 겨울에 이상수온의 변화가 심하다. 쓰시마 해역의 이상수온 쿠로시오 해역의 이상수온과 상관관계를 가지고 있다. 이상수온의 스펙트럼 분석에 의하면 주기 26개월의 준격년 진동(quasi-biennial oscillation)과 주기 14개월의 극조(pole tide) 주기에 따른 수온 변동이 나타난다