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VARIATIONS OF SEA LEVEL AND SEA SURFACE TEMPERATURE ASSOCIATED WITH WIND–INDUCED UPWELLING IN THE SOUTHEAST COAST OF KOREA IN SUMMER

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夏季 韓國 南東海岸에서 湧昇과 관련된 바람, 海水面 및 表層水温의 變化

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Abstract: Extensive wind, sea level and sea surface temperature (SST) data collected along the east coast of Korea in 1973~1979 were used to describe the variations of sea level and SST associated with wind forcing during summer. Alongshore components of wind were dominant but the offshore components were of little significance in the southeast coast in summer. The variations in SST and sea level adjusted barometrically agreed with the upwelling-downwelling processes and showed a rapid response to wind. Appearance of cold water to the surface in the upwelling region concurred well with the periods of positive y-component wind when the tangential line at Ulgi was taken as the y-axis. In general, SST at Ulgi and Gampo as well as the adjusted sea level at Pohang, Ulsan and Busan decreased significantly when strong winds favorable for upwelling persisted for more than three days whereas they increased during the relaxation or unfavorable periods. The period of an upwelling event, on the average, was about 10 days and the mean speed of alongshore wind was 4.0 m/sec.

要約: 해수면과 연안표층수온의 기록으로 부터 바람에 의한 용승효과를 확인하기 위해서 1973년 부터 1979년 까지의 자료들이 이용되었다. 하계에 남동해안에 평행한 바람이 우세하며 울기—감포 근해에서 용승을 일으키는 것으로 나타났는데 강한 남서풍이 3일 이상 지속될때 해수면과 표층수온이 감소하는 용승효과가 현저하게 나타났다. 평균적으로 한번의 용승은 약 10일 동안 지속되었고 그 동안에 해안에 평행한 성분의 평균풍속은 약 4.0m/sec였다.

INTRODUCTION

Along the southeast coast of Korea, cold water mass appears frequently during summer so that the surface water temperatures in this region are usually lower than those elsewhere. There have been some difficulties to define precisely this phenomenon as an upwelling because the geographical scale in which the cold water appears is small and the upwelling-favorable winds are not so predominant compared with those in the northwest Africa or the Oregon coast.

Kim and Kim (1983) concluded that this cold water mass was not upwelled from the Japan Sea Proper Water but was an extension of the North Korean Cold Water characterized by low salinity and high dissolved oxygen content. However, several conditions favorable for upwelling have been reported. The Tsushima Current fluctuates seasonally and is strongest in late summer (Lee and Jung, 1977). The intensification of current causes a shoaling of the isotherms towards the coast to maintain the geostrophic balance and this process will contribute to the coastal upwelling significantly (Philander, 1979). An (1974) and Seung (1974) investigated the hydrographic fields of the eastern sea of Korea in relation to the cold water mass and suggested that the southerly geostrophic winds were responsible for upwelling to some extent. Lee (1978) emphasized the significance of the cyclonic circulation of the strong Tsushima Current near Ulsan in enhancing the upwelling.

Although the coastal upwelling is commonly attributed to the wind, the importance of wind as a driving force for the upwelling along the east coast of Korea has not been explored sufficiently yet. Therefore, employing the extensive wind data measured at the weather stations near the coast, the upwelling-downwelling responses of the adjusted sea level and SST associated with wind forcing are shown in detail.

TREATMENT OF DATA

Wind, mean sea level and SST data from 1973 to 1979 were analyzed to examine the wind-induced upwelling along the southeast coast. Hourly wind records were obtained from the Government Computer Center's meteorological data file. Daily mean sea level data of the tidal stations at Pohang (1976~1979), Ulsan and Busan were excerpted from the Technical Report of the Hydrographic Office. Daily SST data measured at major lighthouses were used in describing the water temperature variations. Locations of tidal, meteorological and SST stations are shown in Fig.1.

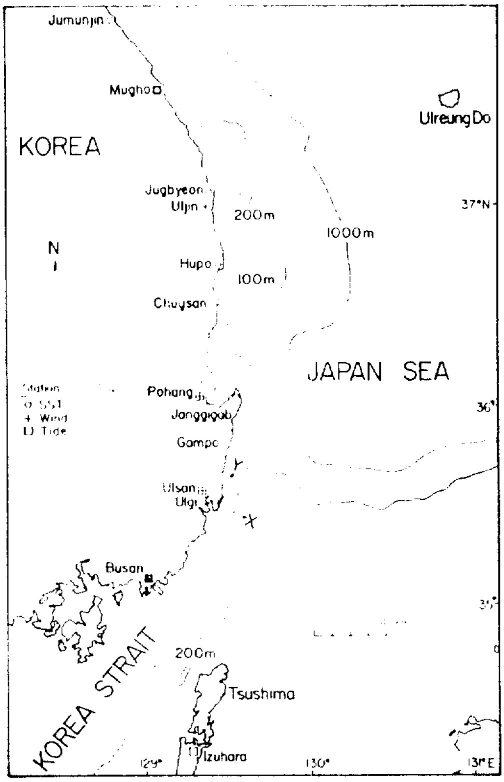

Fig. 1. Location map showing the bathymetry, tidal stations (square), SST stations (circle) and meteorological stations (cross).

In order to separate the alongshore and the offshore components of wind over the southeast coast, tangential line at Ulgi was taken as the y-axis (Fig.1). As a result, positive y-axis of this local coordinate is directed 22.5° east of north. The daily vector-averaged components of wind were computed from the hourly data to be compatible with the obtainable daily data of mean sea level and SST, and comparisons between the time series of those data were made.

Table 1. Heights of meteorological stations from mean sea level.

station	H	Ha
Pohang	49.5	13.6
Ulsan	5.6	10.8
Busan	69.2	17.8

H; Height of observation field above mean sea level (m).

Ha; Height of Robinson anemometer above the ground (m).

Ve simply used the wind velocity instead of vind stress because it was difficult to determine he drag coefficient for stress computation due to he greater height of anemometer from mean sea evel than the standard one, 10 m (Table 1).

The direct static effect on sea level was renoved through the inverse barometric adjustment f −1.0 cm/mb using the daily mean atmospheric pressure at the nearest weather stations. The difference between this barometrically adjusted level and the average value over 112 days from 1 June to 20 September was finally used as the adjusted sea level. In order to examine the influence of atmospheric pressure change on sea level variations, the paths of cyclones were referred from the Monthly Weather Report by the Central Meteorological Office.

RESULTS

1. General wind conditions

Because of the monsoon effect, southerly wind generally prevails during summer in Korea. Local wind depends on this seasonal wind pattern and the topography. Frequency distributions of wind sorted from the hourly data during summer are presented by the wind roses at three stations near the coast in order to know the general wind conditions (Fig. 2).

Considering the geography around the southeast coast (Fig. 1), it is natural that the N-NE wind is strongest at Pohang, and the SW or NE wind parallel to the coast is dominant at Busan as shown in Fig. 2. In fact, the SSW wind is

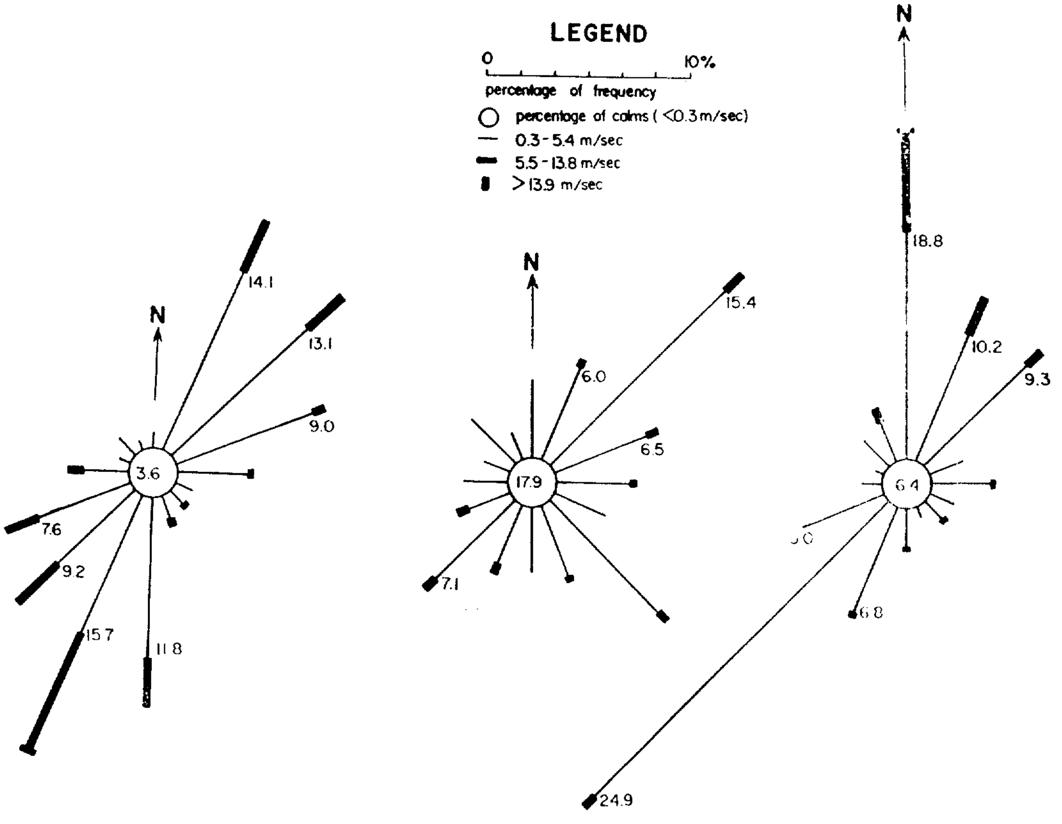

Fig. 2. Wind roses at the meteorological stations during summer (1973~1979).

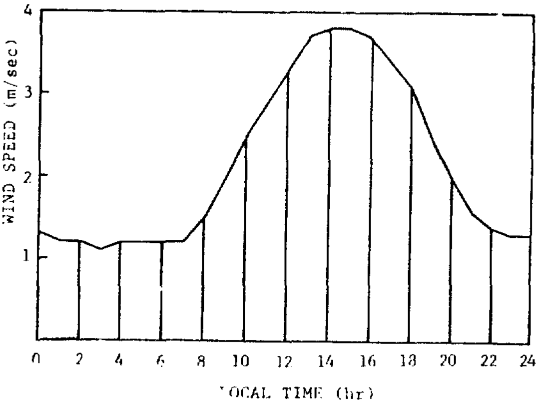

Fig. 3. Daily variation of average wind speed at Ulsan during summer.

strongest and amounts to 15.7 % in frequency at Busan. At Pohang, SW wind occurs most frequently although the southerly winds may be hindered by the surrounding topography. Wind rose at Ulsan, on the other hand, shows that the winds are mostly weak (percentage of calms is about 18 %) and the principal direction is not outstanding. This is certainly due to the inland topographic effect because the weather station is far from the coast. In addition, there is a quite regular diurnal variation in wind speed that is very weak at night (Fig.3). Thus wind data at Ulsan are not adequate for interpreting the wind-induced processes of upwelling although the weather station is nearest to the upwelling region. In summary, it can be concluded that the wind data at Busan are most suitable to be related with the upwelling-downwelling processes.

2. Variations in 10-day mean SST along the east coast

Using the 10-day average values, gross features of SST variation with latitude and time are shown in Fig. 4. SST variations at Jumunjin-Mugho, Janggigab and Busan seem to follow the typical seasonal cycle having maximum values in August. High and low temperatures are distinguished by the laterally hatched and the

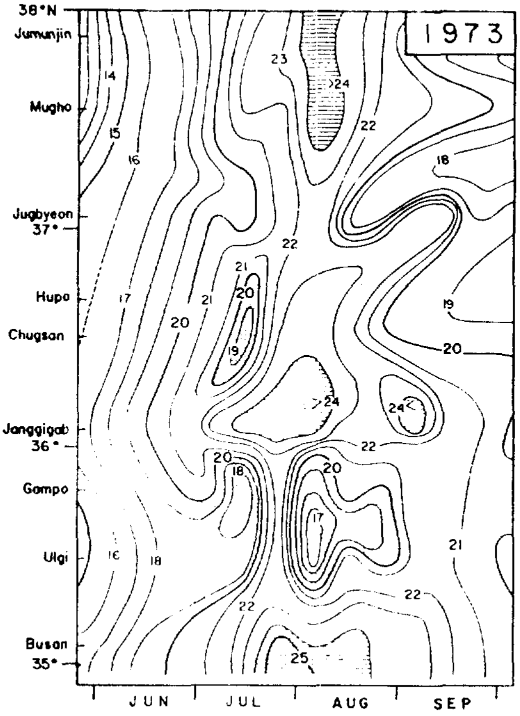

Fig. 4-a. Variations of 10-day mean SST along the east coast in summer 1973.

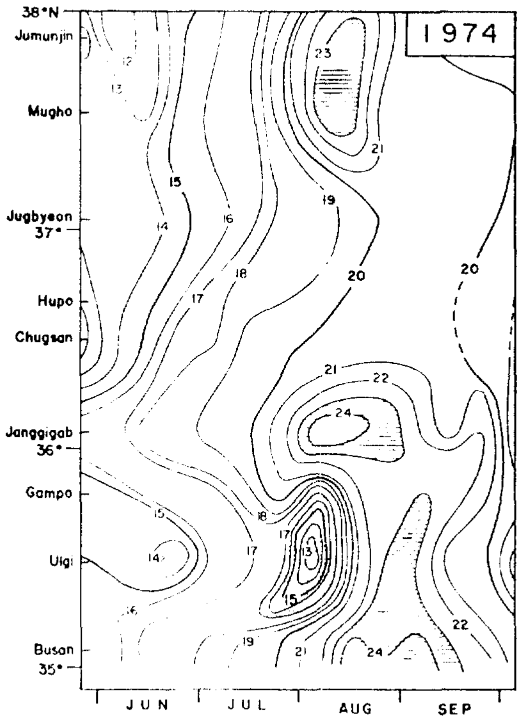

Fig. 4-b. Variations of 10-day mean SST along the east coast in summer 1974.

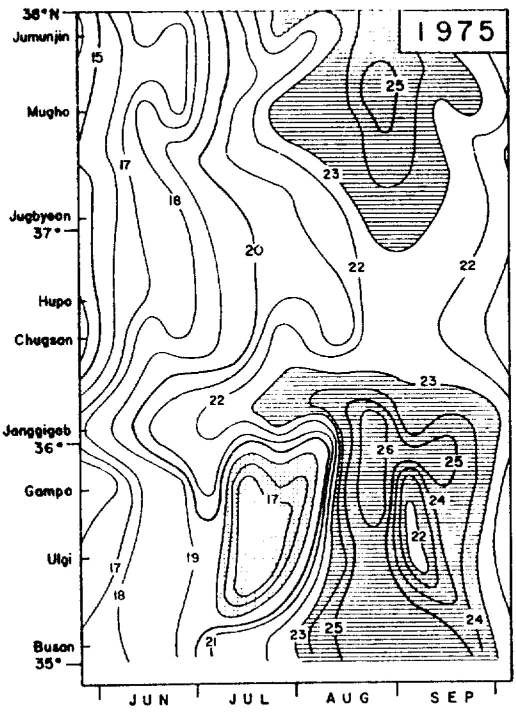

Fig. 4-c. Variations of 10-day mean SST along the east coast in summer 1975.

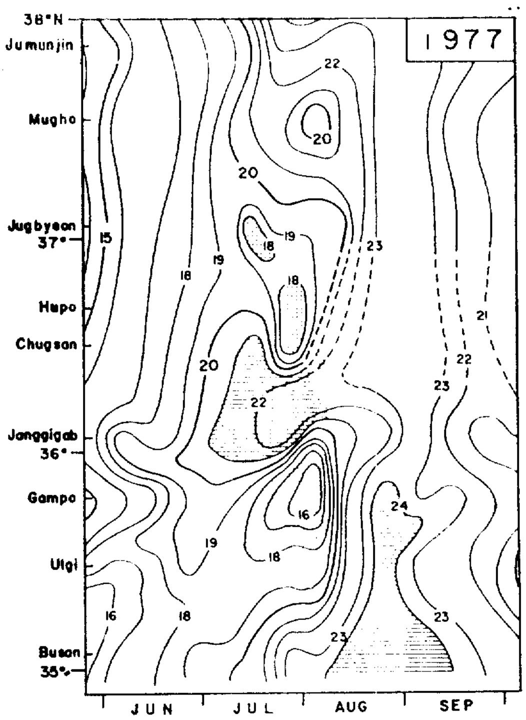

Fig. 4-e. Variations of 10-day mean SST along the east coast in summer 1977.

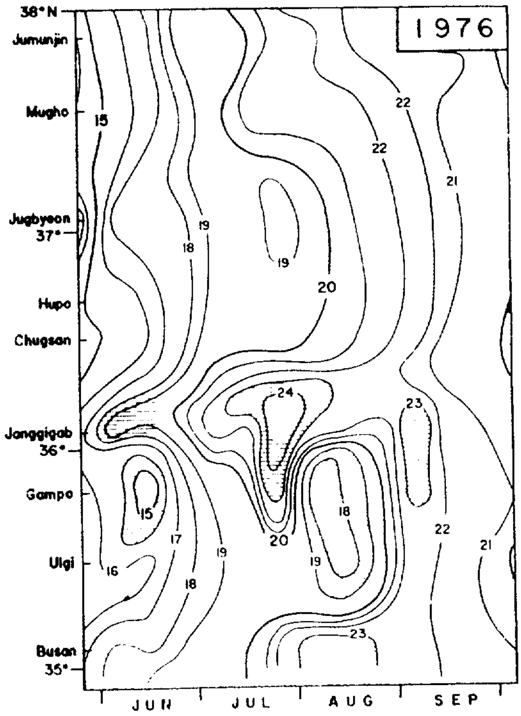

Fig. 4-d. Variations of 10-day mean SST along the east coast in summer 1976.

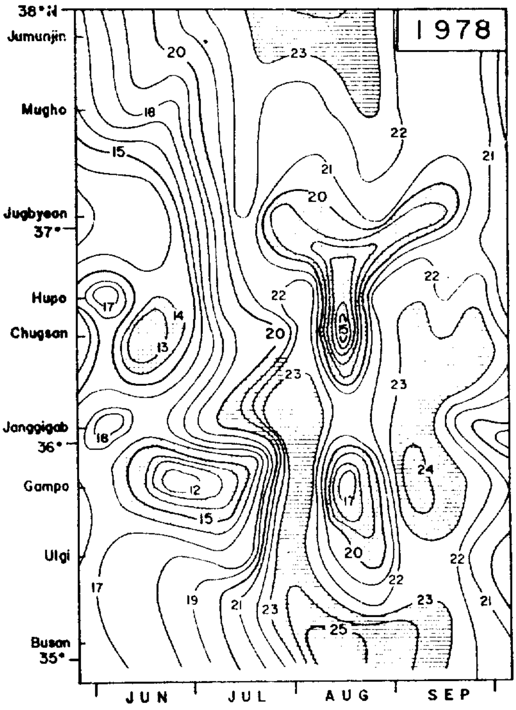

Fig. 4-f. Variations of 10-day mean SST along the east coast in summer 1978.

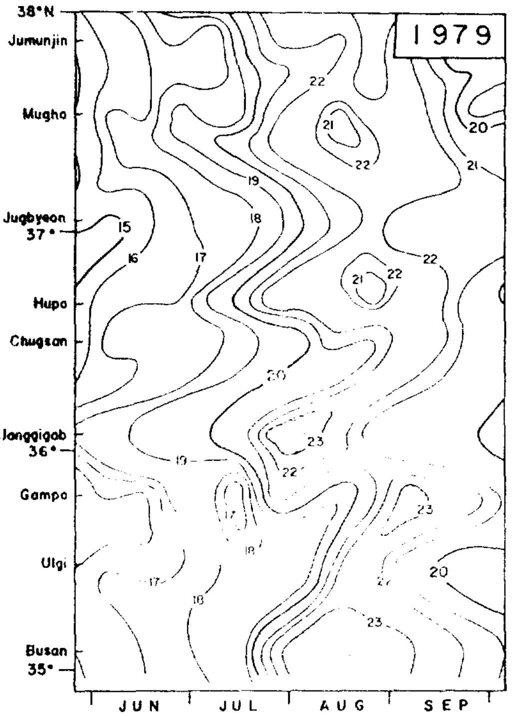

Fig. 4-g. Variations of 10-day mean SST along the east coast in summer 1979.

dotted areas respectively. There are two upwelling regions along the east coast; around the Gampo-Ulgi coast cold water appears every summer while SST at Jugbyeon-Chugsan was considerably low in 1973, 1977 and 1978. It is also noted that SST is very high at Janggigab during the upwelling periods in spite of the short distance from the two upwelling regions.

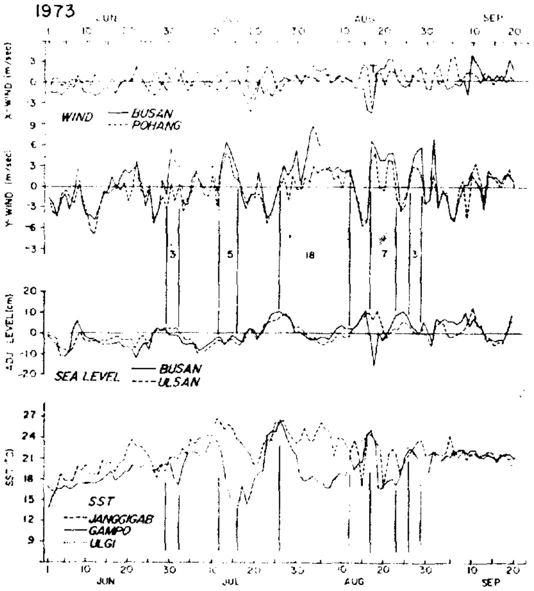

Fig. 5-a. Daily values of wind components, adjusted sea level and SST in summer 1973.

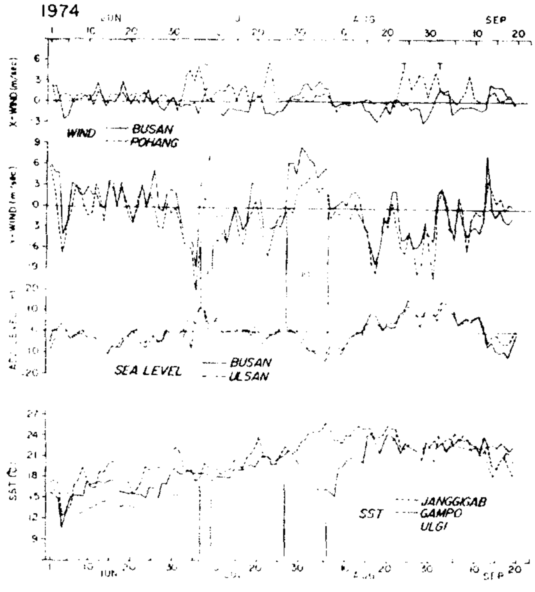

Fig. 5-b. Daily values of wind components, adjusted sea level and SST in summer 1974.

3. Variations of sea level and SST in association with wind

Significant correlations between current, sea level and wind variations during the coastal upwelling have been reported off the Oregon coast (Smith, 1974). Upwelling-downwelling responses of sea level and water temperatures at various depths in relation to the wind variations have been investigated in the Florida Current region (Brooks and Mooers, 1977). The evolution of hydrographic fields caused by wind was also studied (Barton, et al., 1976; Halpern, 1976).

The upwellng-downwelling processes can be studied through the analysis of the continuous series of current and hydrographic data accompanied by the simultaneous wind observation. However, current and hydrographic data adequate for such a study are quite scarce in the

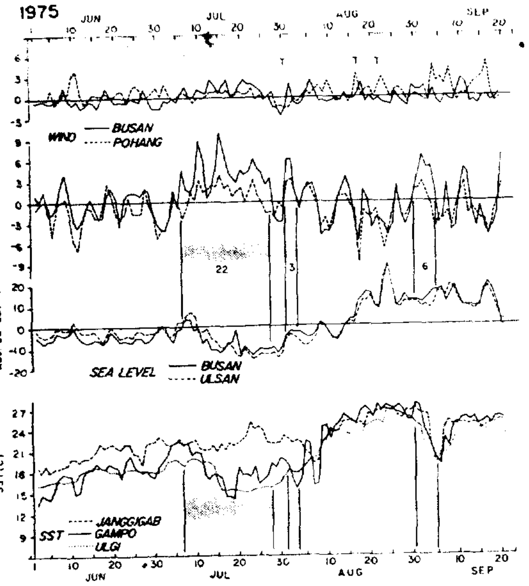

Fig. 5-c. Daily values of wind components, adjusted sea level and SST in summer 1975.

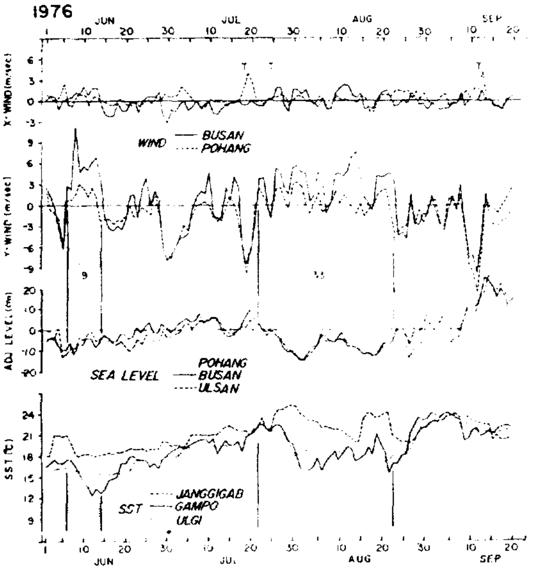

Fig. 5-d. Daily values of wind components, adjusted sea level and SST in summer 1976.

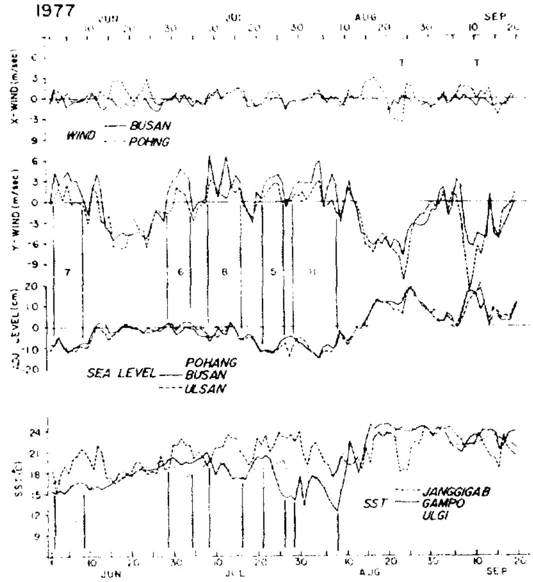

Fig. 5-e. Daily values of wind components, adjusted sea level and SST in summer 1977.

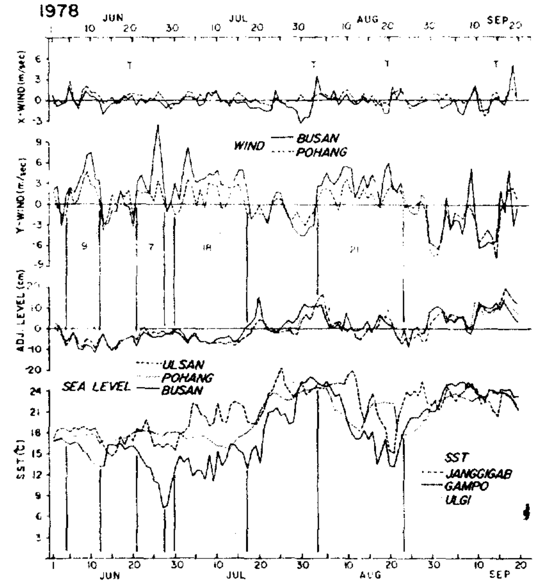

Fig. 5-f. Daily values of wind components, adjusted sea level and SST in summer 1978.

study area. Instead of them, fortunately, the daily data of SST and mean sea level are useful. In order to find out the upwelling responses of sea level and SST to the wind, comparisons between the time series of those data are made as shown in Fig. 5. Stippled bars on the uppermost line mark the periods of cyclones with pressure lower than 1000 mb and 'T' denotes the typhoon. For the cases in which the upwelling process due to the wind appeared significantly, in sea level or SST records the duration of favorable wind was indicated by the length

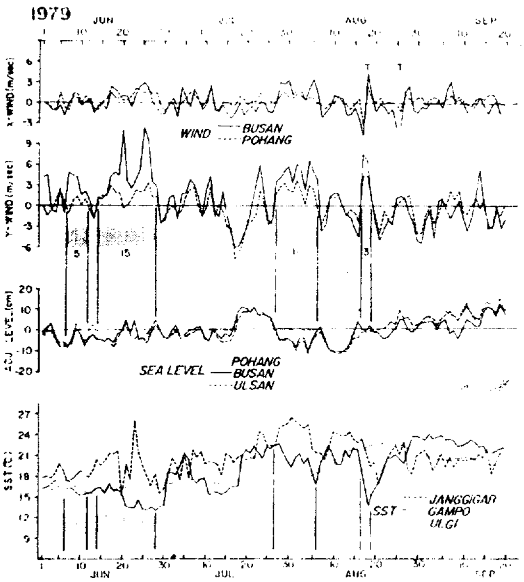

Fig. 5-g. Daily values of wind components, adujsted sea level and SST in summer 1979.

of stippled bar and the number of days.

The offshore (x-component) wind is of little importance. The alongshore (y-component) winds at both stations of Pohang and Busan fluctuate in similar fashion but the positive values (southerly winds) are greater at Busan whereas the northerly winds are stronger at Pohang probably due to the topographic effects. The inverse correlations of the alongshore wind *vs.* sea level and the alongshore wind *vs.* SST are visually apparent.

Sea surface temperature *vs.* wind

On the whole, SST's at Gampo and Ulgi, which are mostly lower than that at Janggigab, show the rapid upwelling response during the favorable winds. With the onset of strong favorable wind, SST decreases immediately, but it increases during a relaxation or an unfavorable period. Concerning the magnitude of SST change, there is a considerable difference between the intensities of upwelling at Gampo and those at Ulgi. For example, the upwelling effect was stronger at Ulgi in 1974, while it was more prominent at Gampo in 1977 and 1978. From 7 to 18 July in 1979, exceptionally, SST at Gampo decreased although the winds were variable, and it increased in later stage with the growing of northerly wind. Except for the few extraordinary cases, the alongshore wind seems to be a decisive factor for upwelling-downwelling process of SST.

As pointed out previously, SST at Janggigab is higher than elsewhere or increases during the major upwelling events such as the first and the third events in 1974, the first event in 1975 etc. Of special interest is the discrepancy from the normal response of coastal upwelling at Janggigab.

The duration of upwelling-favorable wind, the mean wind speed, and the magnitude of changes in sea level and SST are summarized in Table 2. There had been 15 major events with durations longer than a week and 10 minor events. On the average, during an event, favorable winds with mean y-component speed of 4.0 m/sec persisted for about 10 days. Upwelling effect appears more prominent at Gampo than at Ulgi; average magnitude of SST decrease is 4.9°C at Gampo and 2.9°C at Ulgi. For the major downwelling cases, a summary of the events is made in Table 3. The asterisks stand for some occasions in which the change of SST or sea level is hard to be estimated.

Sea level *vs.* wind

Sea level fluctuations also show the upwelling response during most of the events indicated in Fig. 5 as in the case of SST; with sustained strong winds favorable for upwelling, sea level decreases or maintains a depressed state. More careful inspection of the figures reveals frequent occurrence of the downwelling response of sea level to the northerly wind (Table 3). The extreme peaks during the down

Table 2. Summary of upwelling events

Year	Period	D	W	ΔH	ΔT_g	ΔT_u
1973	6/30~7/2	3	4.1	−0.2	−3.2	−1.9
	7/12~16	5	4.2	−2.7	−9.5	−3.7
	7/26~8/12	18	3.4	−14.9	−9.8	−10.0
	8/17~23	7	4.5	−13.4	−8.0	−5.1
	8/27~29	3	5.0	−3.0	−3.7	−5.0
1974	7/7~9	3	5.2	−8.1	−0.2	−1.1
	7/28~8/6	10	6.2	−13.0	−6.5	−6.7
1975	7/6~27	22	4.3	−22.7	−8.0	−4.9
	7/31~8/2	3	4.5	****	−3.3	−0.5
	8/30~9/4	6	3.9	−3.4	−8.0	−5.4
1976	6/6~14	9	5.4	+10.9	−5.1	−0.8
	7/22~8/23	33	3.2	−17.0	−6.9	−4.9
1977	6/2~8	7	3.3	−6.8	+1.6	−1.5
	6/29~7/4	6	3.4	****	−0.7	−2.5
	7/9~16	8	3.7	+7.0	−2.4	−2.5
	7/22~26	5	3.3	+2.5	−5.9	+1.3
	7/29~8/8	11	2.9	−9.6	−5.2	−2.5
1978	6/4~12	9	3.8	−7.6	−3.5	−1.0
	6/21~27	7	5.0	****	−8.2	−0.7
	6/30~7/17	18	3.9	−6.9	−3.7	−2.6
	8/3~23	21	3.5	−24.0	−12.2	−6.9
1979	6/7~11	5	3.5	****	−0.9	−1.7
	6/14~28	15	4.7	****	−0.8	−1.9
	7/27~8/6	11	4.6	−21.7	−5.7	−0.5
	8/17~19	3	4.9	+0.8	−8.3	+0.3
Mean		9.9	4.0	−7.7	−4.9	−2.9

D; Duration of upwelling-favorable winds (days)
W; Average speed of y-component wind at Busan (m/sec)
ΔH; Change in daily mean sea level at Ulsan during an upwelling event (cm)
$\Delta T_g, \Delta T_u$; Change in SST during an upwelling event at Gampo and Ulgi respectively (°C)

welling periods are occasionally related to the typhoon especially in late summer. For example, during the periods of 9 to 13 September 1976 and 14 August to 18 Septemper 1977, the northerly winds were very strong so that the adjusted sea level reached a maximum value just when the typhoon passed the adjacent regions. The high inverse correlation between wind and sea level is similar, in principle, to the result of Smith (1974).

However, there are some fluctuations in sea level which do not follow the upwelling process; during the last event in 1975, the first event in 1976 and the third and the fourth event in 1977, sea level rose considerably. Moreover, the patterns and amplitudes of sea level variation are nearly the same at all the stations. In other words, although sea level generally fluctuates according to the upwelling-downwelling process, this phenomenon is not restricted in the upwelling region (Ulsan) but takes place in the non-upwelling regions.

Table 3. Summary of downwelling events

Year	Period	D	W	ΔH	ΔT_g	ΔT_u
1973	718~24	7	1.9	+11.9	+7.8	+7.0
	8/14~16	3	4.2	+6.6	+4.9	+1.5
1974	7/2~6	5	4.7	+12.9	****	+2.2
	8/15~9/1	17	3.7	+13.5	+4.5	+4.2
1976	6/29~7/5	7	5.9	+6.4	+2.0	+1.7
	7/18~21	4	5.9	+3.0	+2.9	+0.9
	9/9~13	5	6.4	+11.4	+1.7	****
1977	6/14~25	12	4.5	+7.6	+2.8	+2.4
	8/14~30	17	4.9	+24.1	+7.1	+3.0
	9/8~18	11	4.2	+12.3	+1.6	+1.4
1978	7/28~8/2	6	3.7	+12.8	+5.8	+1.3
	8/30~9/15	17	3.4	+17.7	+4.1	+2.0
1979	7/16~19	4	5.0	+13.7	+6.1	+3.8
Mean		8.9	4.3	+11.8	+3.9	+2.4

DISCUSSION AND CONCLUSIONS

As seen in Fig. 5, the variations in SST and sea level showed the rapid upwelling-downwelling responses to the wind forcing. According to Halpern (1976), off the Oregon coast, the time scale for surfacing of the interface was about 22 hours and the time scale of the maximum offshore transport corresponding to the interval between the onset of the favorable wind and the arrival of the coldest water at the surface was 1-3 days. These time scales off the Gampo-Ulgi coast would be less than those off Oregon, because the hydrographic field off the wide southeastern shelf of Korea with gentle slope and shallow depth of bottom would be more susceptible to the wind forcing. The average period of about 10 days and the mean alongshore speed of wind of 4.0 m/sec for one upwelling event are comparable with those off Oregon having speeds 0-8 m/sec and periods of 3-7 days (Huyer, 1976).

The high water temperatures at Janggigab even during the upwelling events are not likely to be explained by the differential heating or other heat transfer processes because of the short distance from the two upwelling regions of Jugbyeon-Chugsan Gampo-Ulgi. The SST increase at Janggigab might be due to the approach of the East Korean warm Current towards that coast. Westward deflection of this warm current would occur in order to conserve the potential vorticity as the bottom depth increases abruptly as in Fig. 1 (Lee and Chung, 1981) although the strong baroclinicity may reduce this topographic effect to some extent. It is particularly notable that the SST can increase at Janggigab even during the intense upwelling such as the second event in 1974, the first event in 1975, the third event in 1979 and so on (Fig. 5). This seems to suggest that the warm current intensified by the strong favorable wind may be deflected westward more efficiently than the weak current despite the influence of offshore Ekman transport. Then the East Korean Warm Current flowing northeastward would have a cyclnic curvature around the Gampo-Ulgi coast, which can be confirmed easily in the horizontal temperature distribution (Lee, 1978; KORDI, 1982).

Extreme values of the adjusted sea level are frequently coupled with typhoons and, at the same time, SST reaches the maximum especially in late summer. Besides the wind-induced downwelling process, the thermosteric effect due to the temperature increase would also be significant. Considering the case of the west Florida shelf where the maximum amplitude in sea level fluctuations may be about 60 cm in response to 1 dyn/cm^2 alongshore stress (Marmorino, 1982), the range of about 40 cm in August to September of 1976 and 1977 seems reasonable. The same tendency of sea level fluctuations at three stations could be attributed to the fact that the wind patterns at Pohang and Busan are similar to each other. However, it is difficult to explain that the SST at Busan or Pohang does not reveal the upwelling-downwelling response whereas the sea level there does. If the fluctuations of adjusted sea level were attributed to the upwelling-downwelling process, their amplitudes would be larger in the upwelling region than at Busan or Pohang. The fact that the sea levels at three stations vary in the same way implies the possible influence of other driving mechanisms, for example, the subinertial waves generated by the alongshore wind stress.

Some statistical analyses of these data have been tried. The cross-correlation coefficients between the series of sea level, SST and those of y-component wind were about 0.7 with lags of 1-2 days to the wind. The number of data in each series and the time interval would not be sufficient for the cross spectrum or coherence analysis with fine resolution. But it is believed that the wind variations with subinertial periods would evoke the corresponding response of sea level and SST. The results of further analysis will be presented in later work.

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