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EFFECTS OF ATMOSPHERIC PRESSURE AND WIND STRESS ON DAILY MEAN SEA LEVEL IN THE BAY OF BISCAY. ANALYSIS OF CONTINENTAL SHELF WAVES

Heung-Jae Lie
Korea Ocean Research and Development Institute, KIST

ABSTRACT

The barometric factor is estimated at five stations in the Bay of Biscay from the linear regression between daily mean sea level and atmospheric pressure. The results show that the adjusted sea level change is important in amplitude in spite of the barometric response of the sea level to the atmospheric pressure. The cross-correlations between adjusted sea levels and the two components of wind stress suggest that the adjusted sea level is highly related to the longshore wind stress. The observed phase and the time lag between adjusted sea levels at adjacent stations are consistent with the hypothesis of the northward travelling continental shelf waves.

I. INTRODUCTION

If the tidal forces ceased to operate, the waters would have a surface known as the mean sea level. In theory, the mean sea level should respond as an inverse barometer to the atmospheric pressure change(-1.01 cm/mb.). However, the sea level does not always show the barometric response to low-frequency atmospheric pressure changes in the shallow water. Hamon (1962, 1966) observed that the response of the sea level was not barometric or isostatic on the Australian coast and that there existed time lags between the sea levels adjusted to atmospheric pressures at different stations. Such abnormal response and time lags were also shown on the Oregon coast by Mooers and Smith (1968) and on the North Carolina by Mysak and Hamon (1969).

Robinson (1964) first proposed generation of shelf waves by moving atmospheric pressure to explain the observed anomalous sea levels and time lags off the Australian coast. The continental shelf wave theory of Robinson was extended to the influence of wind stress on the sea level by Gill and Schumann (1974). Crépon (1976) gave an explanation to abnormal response of the sea level based on a process of geostrophic adjustment. The existence of shelf waves has been observed by the phase and the time lags between the adjusted sea levels and by the direct current measurements (Cutchin and Smith, 1973; Brooks and Mooers, 1977).

This paper attempts statistical analysis of the sea level changes recorded at tidal stations in the Bay of Biscay. Atmospheric pressure and wind stress (east and north components) are examined with respect to their effects on the sea level changes. It will be also shown that adjusted sea level changes are related to longshore wind stress much more than to onshore wind stress and that time lags between adjusted sea levels at different stations are explained by barotropic shelf wave theory.

II. DATA AND COMPUTATIONS

Figure 1 shows the locations of tidal and weather stations and the bathymetric features (500 and 2000m) in the Bay of Biscay.

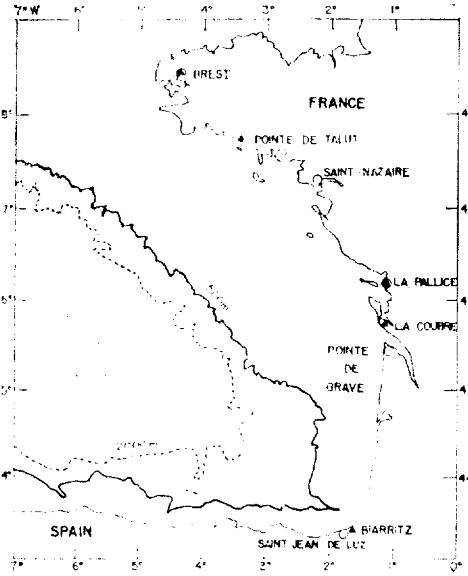

Fig. 1. Locations of tidal stations (○) and weather stations (▲).

The sea level, pressure and wind observed simultaneously were chosen for analysis. The hourly tide heights were filtered using the Demerliac filter (Demerliac, 1974) to compute the daily mean sea level, centred on 1300 UT. The Demerliac filter eliminates almost completely the sea level due to tidal effects, but its defect resides in the fact that 71 consecutive hourly observations should be used for the calculation of daily mean sea level. The daily mean atmospheric pressure and wind stress were obtained by averaging 6-hourly observation as follows:

$$\bar{X}(12h) = \frac{1}{4}\left\{\frac{1}{2}X(0h) + X(6h) + X(12h) + X(18h) + \frac{1}{2}X(24h)\right\}$$

where $\bar{X}$ is the daily mean value centred on 1200 UT and X the instantaneous value. Spectrum of this mean filter corresponds to:

$$F(\sigma) = \sin(24\pi\sigma)/4\sin(6\pi\sigma).$$

There is no great difference between the two filters for the mean values in the period range greater than 3 days.

There were some missing values in the mean sea level series and the meteorological series. The missing instantaneous wind or pressure observations were filled in by averaging two adjacent observations. The missing daily mean sea levels were interpolated according to the hydrostatic hypothesis; i.e., a 1 mb increase in atmospheric pressure decreases sea level by 1 cm.

Data lengths of 100 and 180 days were chosen for the purpose of analysis. Data sets of 180 day-period represent summer period, extending from April 17 to October 13, or winter period from October 16 to April 16 of the following year.

III. EFFECTS OF ATMOSPHERIC PRESSURE ON MEAN SEA LEVEL

The daily mean sea levels and the negative atmospheric pressures at Brest, Saint Nazaire and La Pointe de Grave are shown in Figure 2. A few preliminary points can be drawn from a visual inspection; (a) the maximum amplitude of the daily mean sea level is of the order of 30 cm while the pressure anomalies seldom exceed 20cm, (b) there exists a significant difference in amplitude (of the order of 10 cm) between sea level and pressure changes, which represents non-isostatic behaviour of mean sea level, (c) the mean sea level and the negative pressure changes are in phase.

The influence of atmospheric pressure on mean sea level can be estimated by using barometric factor which is defined as the response of the sea level per unit change in atmospheric pressure.

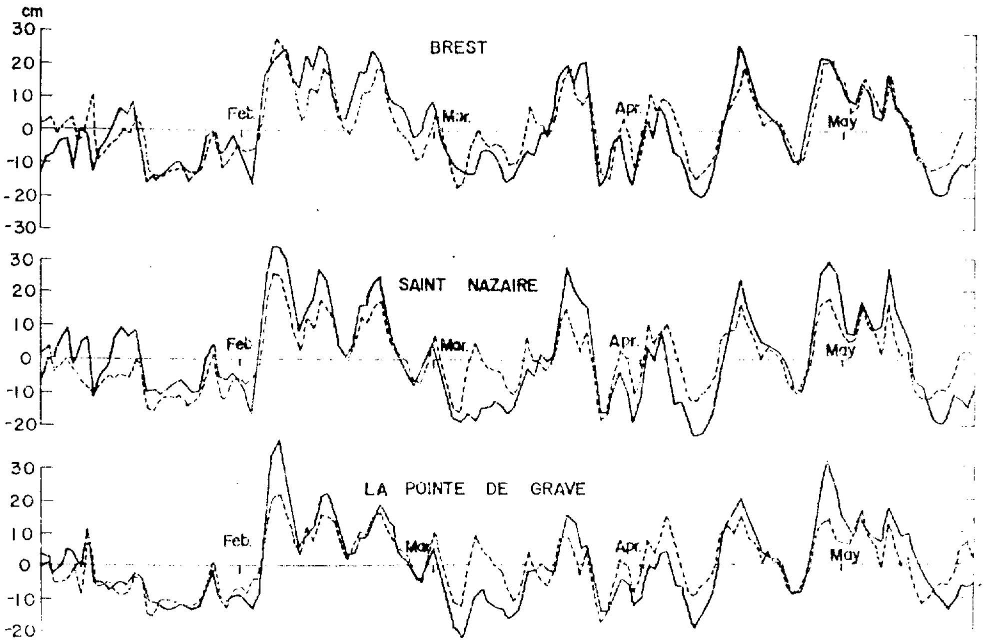

Fig. 2. Daily mean sea level changes(continuous curves) and negative atmospheric pressure changes(discontinuous curves) in 1968.

Table 1. Barometric factor from the linear regression (cm/mb)

stations / length	BREST	SAINT NAZAIRE	LA PALLICE	LA POINTE DE GRAVE	SAINT JEAN DE LUZ
Jan. 2∼ June 29 1968 (180 days)	−1.09	−1.23		−1.10	
Apr. 17∼ Oct. 13 1969 (summer)	−1.10				−0.97
Oct. 16∼ Apr. 13 1970 (winter)	−1.17				−1.04
Apr. 17∼ Oct. 13 1970 (summer)	−1.00	−1.11	−1.09		−0.98
Oct. 16 1970∼ Apr. 13 1971 (winter)	−1.03				−1.14
Apr. 17∼ Oct. 13 1971 (summer)	−0.84				−1.12
Oct. 16 1971∼ Apr. 13 1972 (winter)	−0.98		−1.18		
Apr. 1 1969∼ May 5 1970 (400 days)	−1.18				−1.03
Oct. 1 1970∼ Nov. 4 1971 (400 days)	−0.97				−1.13

The barometric factor can be estimated from a linear regression by the following expression:

$$\hat{Z}(t)=bY(t),$$

where $\hat{Z}(t)$ is a linear prediction of the sea level $Z(t)$ from atmospheric pressure $Y(t)$ and b is a constant to be determined. The constant b, called barometric factor, can be determined according to Bendat and Piersol (1966):

$$b=R_{yz}(0)/R_{yy}(0)$$

where $R_{yy}(0)$ is the autocorrelation function $R_{yy}(\tau)$ of pressure series $\{Y(t)\}$ at time lag equal to zero ($\tau=0$) and $R_{yz}(0)$ the cross-correlation $R_{yz}(\tau)$ between $\{Y(t)\}$ and $\{Z(t)\}$ at $\tau=0$.

Table 1 gives the barometric factor b which is nearly isostatic at all stations in the Bay of Biscay. It suggests that the influence of atmospheric pressure on the sea level change is almost isostatic and there is no obvious dependence of the barometric factor on season.

IV. CORRELATION BETWEEN ADJUSTED SEA LEVELS AND WIND STRESS

The residual variable $\Delta Z(t)$ of the mean sea level is defined from the linear prediction by the expression:

$$\Delta Z(t)=Z(t)-\hat{Z}(t)\ =Z(t)-bY(t).$$

This new sea level $\Delta Z(t)$ is called the adjusted sea level and it can be considered as a part of $Z(t)$ which is not directly influenced by $Y(t)$.

According to Gill and Shumann (1974), the abnormal behaviour of sea level is most likely to be due to the effect of wind stress, especially to the longshore wind stress. Attempts are made to study the effect of wind stress on the sea level by the cross-correlation function. The wind stress components $T_{x,t}$ toward east and $T_{y,t}$ toward north were computed as follows:

$$T_{x,t}=2.5\times10^{-3}\rho_a\ v_x\sqrt{v_x^2+v_y^2}$$

$$T_{y,t}=2.5\times10^{-3}\rho_a\ v_y\sqrt{v_x^2+v_y^2}$$

where ρ_a is the air density (10^{-3} g/cm^3), v_x and v_y are components of the wind speed v toward east and north, respectively.

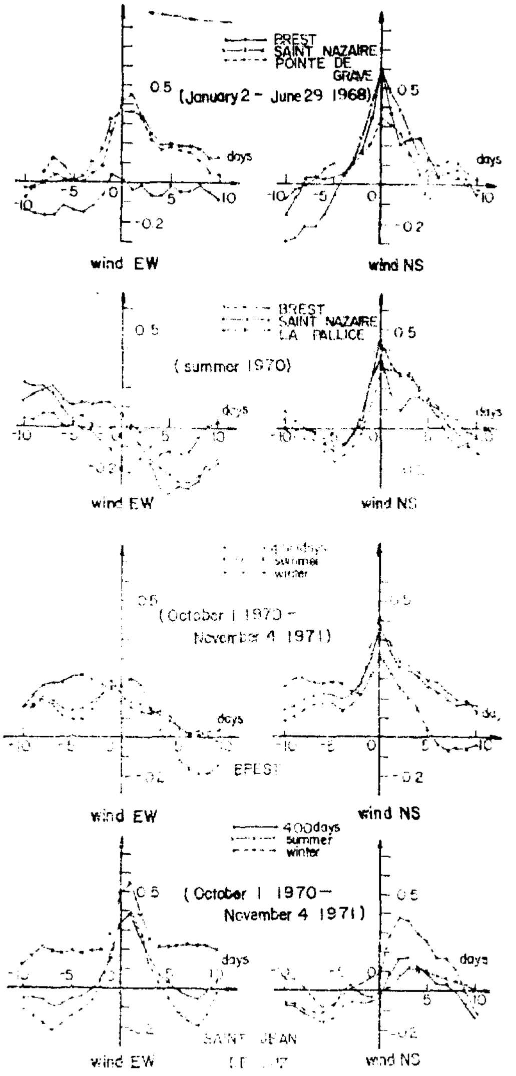

Fig. 3. Cross-correlations between adjusted sea and wind stress. Positive time lag means that the adjusted sea level lags the wind stress.

Figure 3 represents the cross-correlation coefficients between each component of the wind stress and the adjusted sea level (left figures for the eastward wind stress, right figures for the northward wind stress). It is shown from the cross-correlation that there is a significant correlation between the northward wind stress and the adjusted sea level at Brest, Saint Nazaire and La Pallice where the coastline is nearly parallel to the direction of south-north. At La Pointe de Grave where the coastline is interrupted by the Gironde River, the cross-correlation between the eastward wind stress and the adjusted sea level is also important. At the station Saint Jean de Luz, the eastward wind stress seems to be related to the adjusted sea level change and the cross-correlation functions show the maximum value at a positive time lag, which means that wind stress leads the adjusted sea level.

In summary, the results suggest that the correlation between the adjusted sea level and the wind stress seems to be dependent on the geographic situation of the station in question; in other words, there exists a statistically significant relation between the longshore wind stress and the adjusted sea level change. The positive sign of the cross-correlation functions near $\tau=0$ means that the longshore wind stress tends to raise the sea level.

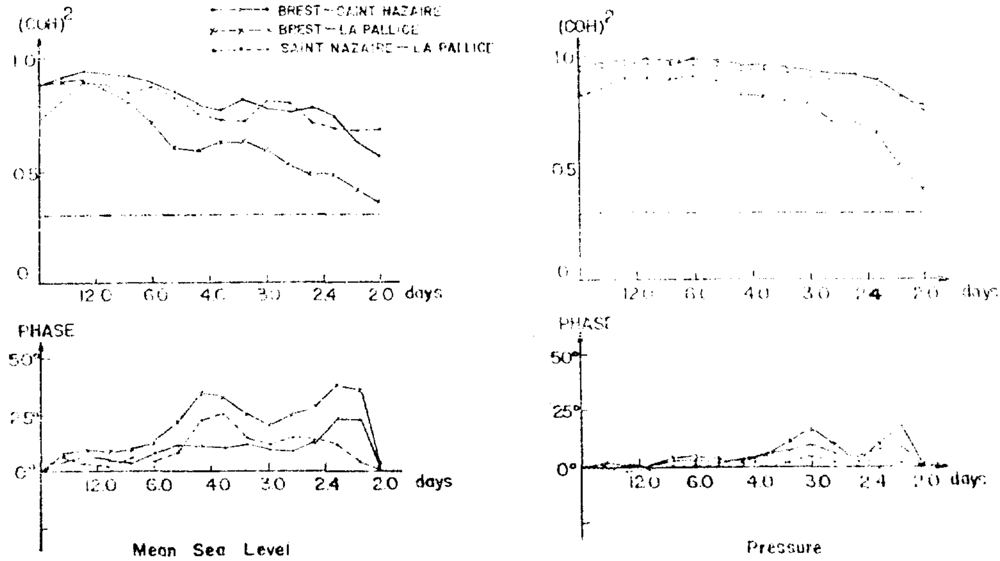

Fig. 4. Coherences and phases between mean sea levels and between pressures at adjacent stations for the period from January 2 to June 29 1968. Dashed line indicates 95% confidence limit for coherence. Positive phase means that the northern station leads the southern station.

V. CORRELATION BETWEEN ADJUSTED SEA LEVELS AT ADJACENT STATIONS AND ANALYSIS OF CONTINENTAL SHELF WAVES

Figure 4 shows the coherence and the phase between mean sea levels and between atmospheric pressures observed at adjacent stations. The mean sea levels and the atmospheric pressures at the northern stations always lead those at the southern stations. The phase between mean sea levels is larger than that between pressures, but the coherences are very high in spite of the great distance between any two stations.

The question arises if similar results are shown between adjusted sea levels at different stations.

The adjusted sea level changes are presented in Figure 5. It shows that (a) the adjusted

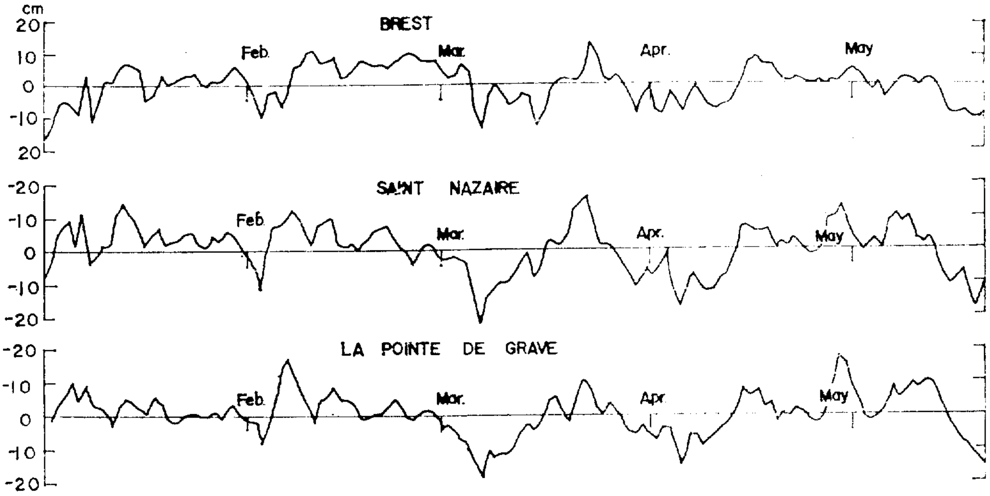

Fig. 5. Adjusted sea level changes in 1968.

sea level at the southern station leads the sea level at the northern station, (b) time lags between adjusted sea levels seem to depend on the distance between stations (it is nearly equal to zero between Brest and Saint Nazaire and almost one day between Brest and La Pointe de Grave), (c) all adjusted sea level changes are very similar in spite of the distance of some hundred kilometers.

The cross-correlation functions between adjusted sea levels at adjacent stations are plotted for time lags to ±10 days in Figure 6. The time lag corresponding to the maximum correlation coefficients represents a weighted mean of the phases at different frequencies. The cross-correlograms show that the correlation coefficient is maximum near $\tau=0$ between Brest and Saint Nazaire, while the maximum values are shown approximately at $\tau=1$ day between Brest and La Pointe de Grave and between Brest and Saint Jean de Luz.

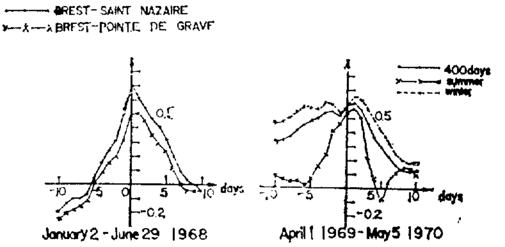

Fig. 6. Cross-correlations between adjusted sea levels at different stations. Positive time lag means that the northern station lags the southern station.

Time lags can be also determined in detail from the phase difference between the adjusted sea levels by the expression: $\tau(f)=\theta(f)/2\pi f$, where $\theta(f)$ is the phase shift expressed in degrees at frequency f. It is shown from Figure 7 that the time lag becomes greater and greater when the distance between stations in consideration is more important and that the phase difference increases linearly with frequency in the period range 4.0 to 12.0 days. The time lags and the phases between adjusted sea levels imply the existence of waves, essentially non-dispersive, travelling toward the north.

According to the shelf wave theory, waves trapped over continental margin would propagate in one direction only with the coast on their right in the Northern Hemisphere, like classical Kelvin waves, so in the Bay of Biscay shelf waves should propagate from south to north. The propagation direction of shelf waves agrees with the observed direction from the correlograms and phase differences between adjusted sea levels at adjacent stations.

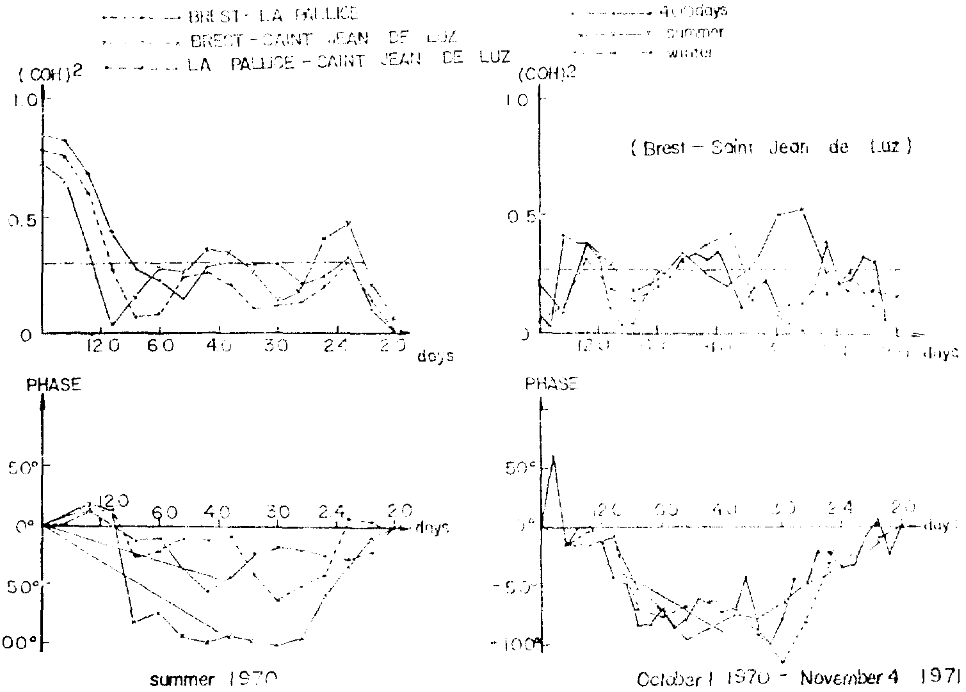

Fig. 7. Coherences and phases between the adjusted sea levels. Dashed line indicates 95% confidence limit for coherence. The negative phase means that the northern station lags the southern station. Straight lines present the phase as a linear function of frequency.

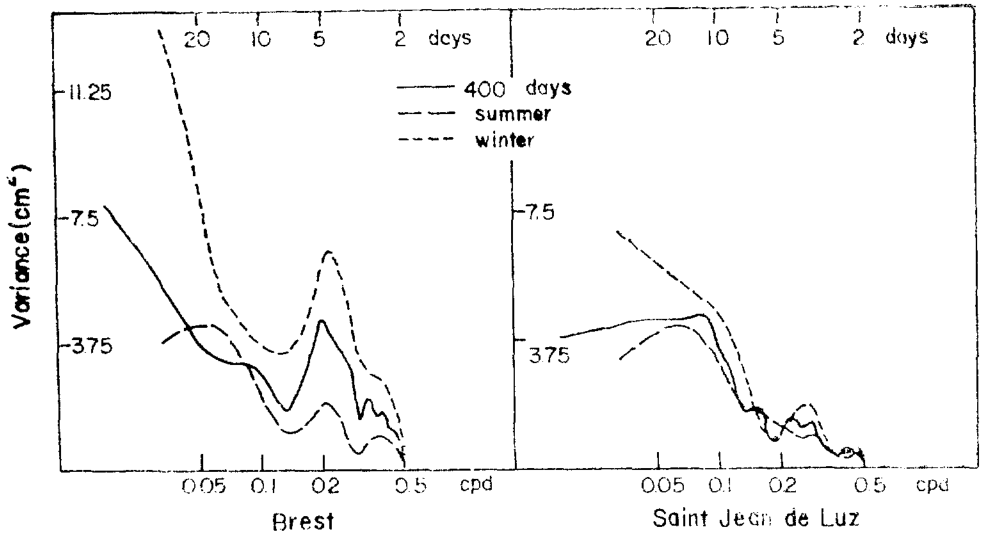

Fig. 8. Spectrums of adjusted sea levels at Brest and Saint Jean de Luz for the period from April 1 1969 to May 5 1970.

The observed phase velocity c at any given frequency f can be obtained from the phase shift by the expression:

$$c=L/\tau(f)=2\pi fL/\theta(f),$$

where L is the distance between stations. The phase speed observed from Figure 7 is approximately 800 km/day between Breast and Saint Jean de Luz, 1000 km/day between Brest and

La Pallice at the frequency of 0.2 cpd. The maximum corrleation coefficient between the adjusted sea levels at Brest and Saint Jean de Luz is higher in winter than in summer, so the coefficient seems to depend on season (see Fig. 6).

The theoretical phase speed of the first-mode shelf wave is 1100 km/day for a frequency of 0.2 cpd. The discrepancy between the observed and theoretical phase speeds may be due to some limits assumed in the theory; shelf topography in the Bay of Biscay expressed in a exponential form and the mean shelf width of the order of 300km, etc.

VI. CONCLUSIONS

The mean sea level change in the Bay of Biscay cannot be explained completely by the hydrostatic hypothesis since the adjusted sea level change is important in amplitude, although the influence of atmospheric pressure on the sea level is shown to be barometric.

The wind stress may be related to the elevation of the sea level. Piling-up of water against the coast, due to onshore wind stress, is not sufficient to explain the adjusted sea level change, but according to the cross-correlation funtion between wind stress and adjusted sea levels, the sea level is shown to be significantly related to longshore wind stress. The positive maximum of the cross-correlation coefficient at $\tau=0$ represents that the sea level increases during the wind blowing from south to north and vice versa.

The spectrums of adjusted sea levels show the important spectral energy density in winter with the net and dominant peaks for the stations Brest and Saint Jean de Luz(Figure 8), and the adjusted sea level changes are highly related to the wind stress(Fig. 3). Therefore, the observed seasonal variation in the cross-correlation between the adjusted sea levels might be due to the seasonally varying wind stress which is generally strong in winter. However, it is difficult to explain clearly how the cross-correlation coefficients between the adjusted sea levels are higher in winter than in summer.

From the observations, it is found that non-dispersive waves propagate from south to north. This wave motion, in a limited band of period between 4 and 12 days, is consistent with the predicted values for a first-mode shelf wave. According to shelf wave theory(Lie, 1977), the contributions of the second and the third modes to the elevation of the sea level are only 32% and 8% of that of the first-mode, when the longshore wind stress is given in the form of sinusoidal progressive wave in time and in space. The phase velocities of the other low mode shelf waves do not appear in the observations because of their small contribution to the elevation of the sea level.

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