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SEA LEVEL VARIATIONS AND THEIR RELATIONS TO THE METEOROLOGICAL FACTORS IN THE ARAB GULF AREA (*) WITH STRESS ON MONTHLY MEANS

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Abstract

The hydrographic and meteorological conditions affecting the sea level in the Arab Gulf region have been reviewed. The monthly mean sea level data along the Saudi Arabian coast, relative to Indian Spring Low Water (ISLW) and the atmospheric pressure of eight years from 1980 to 1987 have been analysed spectrally. This indicated that the annual cycle is the main oscillation in both the sea level and pressure records. The oscillations with frequency less than 0.2 cycle/month were coherent. The Fourier analysis of six years data of monthly means showed that the annual cycle has an amplitude of 10-11 cm. The monthly mean sea level in the last two years was calculated using the harmonic simulation and the statistical models relating to the sea level and atmospheric pressure. The comparison between the calculated values and the observed ones in 1986 and 1987 showed reasonable agreement; the harmonic simulation deviated from the observations by about ± 5 cm. The influence of the factors other than the atmospheric pressure on the sea level of the study area was found to be positive from June to December and negative from January to April or May, with maximum absolute value of about 11 cm, while the statistical models predict only the pressure effect.

(*) The place names referred to in this paper are those assigned by the author and their publication in this journal does not constitute endorsement by the International Hydrographic Organization.

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INTRODUCTION

Much attention has been given by physical oceanographers to sea level variations because of their effects in harbour areas, on navigation and the stability of the shorelines.

Since few sea level studies have been published concerning the Arab Gulf region, this paper will deal with a review of the sea level variations in the scales of hourly values and daily means from previous literature, while the monthly mean values will be analysed in more detail.

AREA DESCRIPTION

The Arab Gulf, west of 51°30′ E is a typical shallow area with a channel having depths greater than 40 meters, biased towards the Iranian side (Fig. 1). The length of this region is about 500 km and the average depth is 31 to 37 m (WILLIAM, 1984).

PREVIOUS STUDIES: An Overview

a) Oceanographic and climatological conditions related to sea level changes

The sea level changes are generally affected by several factors: tidal motion, wind effect, atmospheric pressure and its gradient, the steric effect and the current system, (LISITZIN and PATTULLO, 1961). Tides in the Arabian Gulf have been studied by different authors. DEFANT, 1961, found that considering the length of the whole Arab Gulf up to Hormuz Strait as 850 km, with a mean width of about 250 km and mean depth 50 m, the period of free oscillation lies between 21.7 and 22.6 hours, which is not far from resonance with the tidal diurnal and semi-diurnal oscillations. Using EWANS-ROBERTS criteria for classification of tides, according to the ratio (M2+S2)/(K1+O1), where M2, S2, O1 and K1 are the principal constituents in the gulf, LE PROVOST (1983) found different types of tides (Fig. 2). The tides show diurnal, semi-diurnal as well as mixed oscillations. According to the Admiralty Charts two amphidromic points for each of M2 and S2 are found, one in the northwest and the other in the southwest, with only one amphidromic point in the middle of the gulf for K1. The tidal constants of 60 tidal harmonics at 19 tidal stations along the Qatari coasts were published in 1979 by the State of Qatar. In 1988, SHARAF EL-DIN calculated the harmonic constants at 11 stations along the Saudi Arabian side. The results agreed to some extent with that of EWANS-ROBERTS, 1979. Tidal ranges are large and increase from the middle of the Gulf in Kelvin wave style. They exceed one meter everywhere and reach 3 meters in the north at Shatt al Arab. These large amplitudes cause strong tidal currents which commonly exceed 50 cm/sec. at

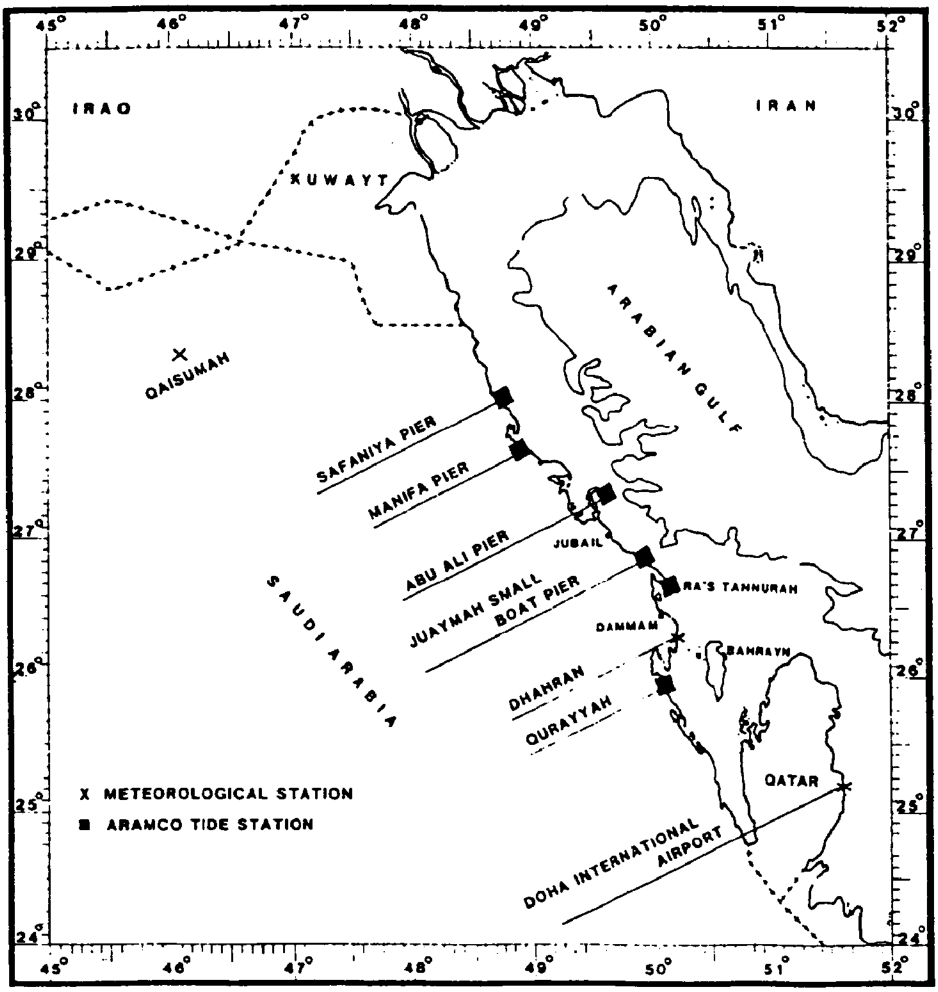

FIG. 1.— Map showing the locations of ARAMCO tide gauges and meteorological station.

maximum ebb and flood (Defence Mapping Agency, 1975). The flow is towards the west and northwest and the ebb is in the opposite direction (WILLIAM, 1984).

The weather conditions in the Arabian Gulf are mainly influenced by extra-tropical weather systems, while the Gulf of Oman is at the northern edge of the tropical weather systems. Thus the Strait of Hormuz region forms the boundary between west to east moving depressions, north of Hormuz, and east to west moving depressions related to tropical systems. The extra-tropical cyclone tracks follow, more or less, the axis of the Arabian Gulf and the Gulf of Oman. Winter Shamal winds, which are strong, occur during November to March, associated with mid-latitude disturbances from west to east with northwest wind speeds less than 20 knots 95% of the time. The summer Shamal winds occur from early June through July, associated with the Arabian and Indian thermal lows (PERONNE, 1981). As a conclusion the dominant winds in the Arabian Gulf all year around blow from northwest with an occasional reversal to blow from southeast in October and January (HASSAN and ELSAMRA, 1985).

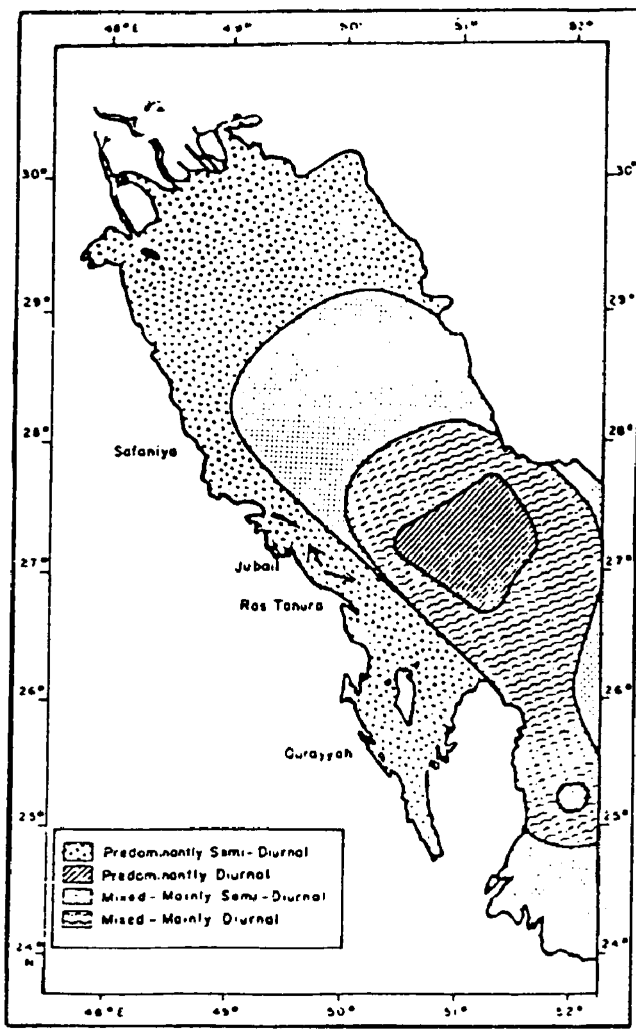

FIG. 2.— Tidal current regime for Arab Gulf.

Evaporation and fresh water inflow affect the sea level. According to PRIVETT, 1959, evaporation in the Gulf has a rate between 0.2 and 0.6 gm/cm^2/day. The maximum evaporation occurs in December, while the minimum occurs in May. However, the measurements by oil companies in the north of the Gulf suggest the opposite (WILLIAM, 1984). On the other hand the fresh water inflow lies between 5 and 100 km^3/year, which represents about 1.3% to 28% of the water loss by evaporation (GRASSHOFF, 1976). However, the fresh water flow could affect the sea level variations in the extreme northern parts of the Gulf during flood periods.

The water balance in the Gulf, which directly affects the sea level elevations, depends on the current system and the exchange between the Arabian Gulf and the Gulf of Oman in addition to evaporation and fresh water discharge. A review of residual currents in the Kuwait Action Plan Area (KAP) was published by HUNTER, 1984. The main sources of information were the observations of ship drift, the salinity distributions and the hydrodynamic models. The evidence is only partially consistent. In general, since the evaporation exceeds precipitation in the Gulf, the dense, more saline water, sinks in the north of the Gulf, flows towards the Gulf of Oman where it passes through the Hormuz Strait which has no silt. These waters are compensated by less saline water flowing in the surface layer into the Arabian Gulf. Due to the Coriolis force, the less saline water is deflected to follow the Iranian side, while the high saline water from north follows the Arabian side. Therefore, at least two opposite flows are expected. This system suggests that the mean density along the northern boundaries is less than the mean density along the Arabian side, hence the steric effect on sea level is expected to be less important along the Arabian side. However, some authors claim that there are two cyclonic eddies in the Arab Gulf.

b) Non-tidal disturbances of sea level in the Arab Gulf

SHARAF EL-DIN, 1988, analysed the hourly readings of the sea level from tidal records at six stations operated by ARAMCO along the Saudi Arabian side, (Fig. 1), in the period from 1980 to 1987. The stations used and their positions, from north to south are given in Table 1. The daily mean atmospheric pressure was also taken at three meteorological stations, which are:

1. Qaisumah (28°20′ N, 46°07′ E)
2. Dhahran International Airport (26°16′ N, 50°10′ E)
3. Doha Airport (25°15′ N, 51°35′ E).

Table 1

ARAMCO Sea Level stations along Saudi Arabian coasts in the Arabian Gulf

Location	N lat.	E long.
Safaniya Pier	28°00′14″	48°46′04″
Manifa	27°35′17″	48°54′30″
Abu Ali Pier	27°18′36″	49°38′48″
Juaymah Small Boat Pier	26°00′52″	49°54′
Ras Tanura	26°38′43″	50°09′58″
Qurayya	25°54′00″	50°05′00″

He also calculated the daily mean sea level as well as the daily mean surge relative to ISLW in the period from 1982 to 1987, using the hourly observations and predictions. Low daily mean values were found during Winter and high values during Spring and Summer. The correlations between these daily means and the atmospheric pressure difference of the daily means between different meteorological stations were not significant. He concluded, therefore, that the pressure itself is the essential factor affecting the daily mean sea level.

The higher values of the monthly mean sea level during the period of the study occured usually in July and August and the lower values from January to March, (Fig. 3). The monthly means of surface atmospheric pressure showed low values in summer and high values in winter; this indicates that the level variations are related to inverted barometer effect in the Gulf.

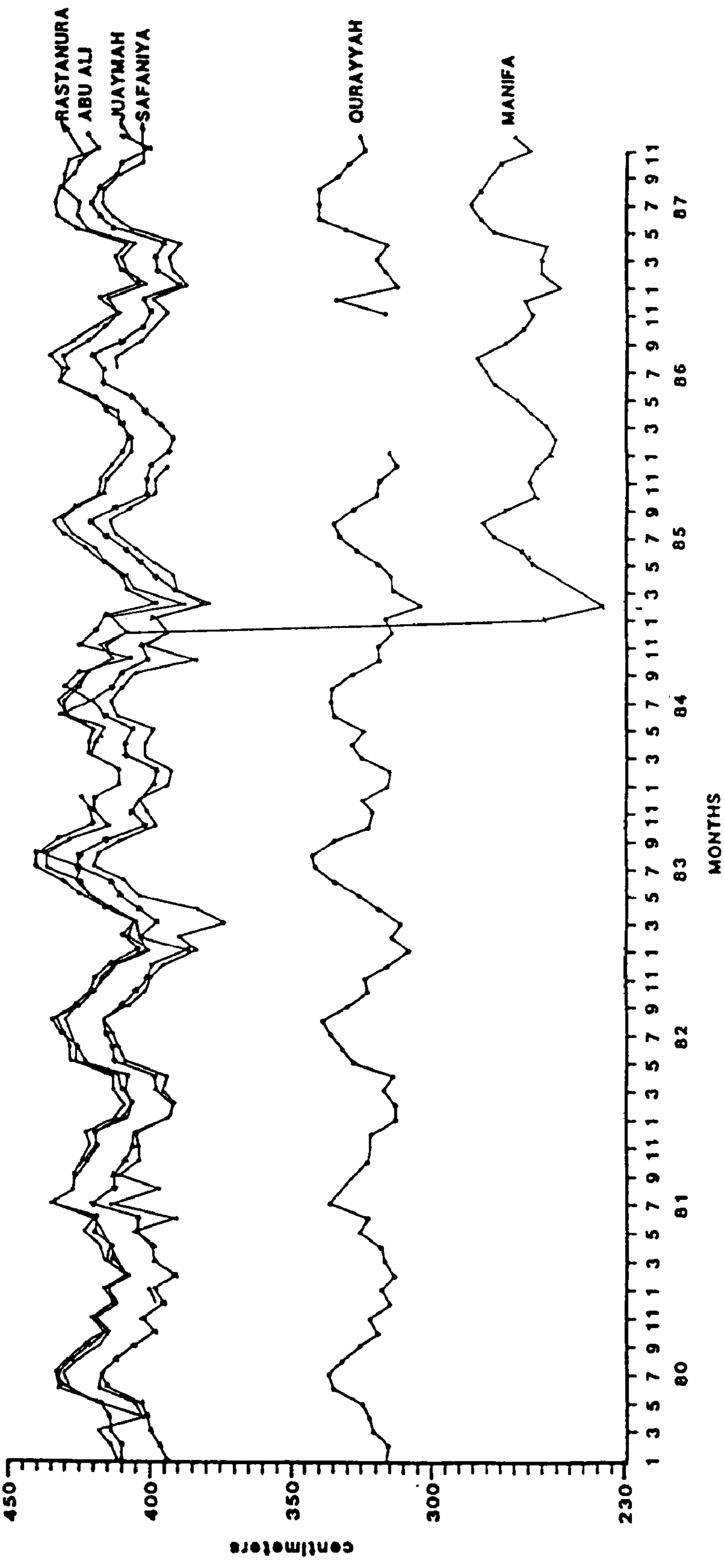

FIG. 3.— Monthly mean sea level at six stations along the Saudi coast of the Arabian Gulf.

SOURCES OF DATA AND METHOD OF ANALYSIS

The data used are those published by SHARAF EL-DIN, 1988, for the period from 1980 to 1987, but Manifa station was excluded since its data of the last two years seems incompatible with the other period. The atmospheric pressures at the three mentioned meteorological stations are also used.

The aim of the work is to study the different oscillations in the monthly mean records of both sea level and pressure at the stations in Table 1 and at the given meteorological stations, and also to find the coherence between the two time series. Therefore, the spectral analysis was done for the different time series in the periods from 1980 to 1985, where continuous records were available.

The simulation of the monthly mean sea level at different stations was attempted using two approaches:

1. Using the harmonic analysis method,
2. Using the multiple regression between sea level and pressure.

The harmonic method is based on the fitting of a part of the time series to a harmonic equation expressed by:

$$S(t) = \sum_{n=1}^{T/2} An\ COS\ ((2\pi nt/T) - Kn) + Ao)$$

where $S(t) =$ the monthly mean sea level at month t relative to the data beginning.
$An =$ the amplitude of the n th harmonic,
$n =$ harmonic number, it is an integer lying between 1 and T/2
$T =$ The length of the record in the units of increment of digitization (here $t = 1$ month)
$t =$ time of prediction,
$Kn =$ phase angle of the n th harmonic relative to the beginning of the analysed time series.

The value of An and Kn are determined by:

$$An = \sqrt{Xn^2 + Yn^2}$$

with $Xn = (2/T) \sum S(t)\ COS(2\pi nt/T)$

$$Yn = (2/T) \sum_{T=0}^{T-1} S(t)\ SIN(2\pi nt/T)$$

$Ao =$ mean value of the time series, and

$Kn = \tan^{-1} (Yn/Xn)$.

The use of T/2 harmonics in the simulation gives exactly the same number of values as the data used in the estimation of the constants. However, assuming that the period of estimation of the constants represents the different important oscillations affecting the time series, the values before and after the period of estimation can be used to validate the equations and check the above hypothesis. A computer program was designed by the author to apply this technique using an XT-IBM compatible PC.

The stepwise multiple regression analysis, using the least square method, to find the best fit equations between sea level and pressure was applied to a part of the data, while the other part of the time series was used for the validation. To do this analysis, the software SPSS-PC was used. Several multiple linear regression models were tried; these models are:

1— S(P12, P13, P23) = Bo + B12 × P12 + B13 × P13 + B23 × P23
2— S(P1, P2, P3) = Co + C1 × P1 + C2 × P2 + C3 × P3
3— S(P1, P2, P3, P12, P13, P23) = Do + D1 × P1 + D2 × P2 + D3 × P3 + D12 × P12 + D13 × P13 + D23 × P23

where P1 = pressure at Qaisuma
P2 = pressure at Dahran Airport
P3 = pressure at Doha Airport
P12 = pressure at Qaisuma — pressure at Dahran
P13 = pressure at Qaisuma — pressure at Doha
P23 = pressure at Dahran — pressure at Doha
B, C and D values are constants.

In both of the above approaches, the data of the six years (1980-1985) were used to build the models while the data of 1986 and 1987 were used for validation.

RESULTS AND DISCUSSION

A — Spectral analysis of sea level and atmospheric pressure

The results of the spectral analysis of the monthly mean sea level in the period from 1980 to 1985, with 72 data points and 18 lags, are shown in Figure 4. It is very clear that the annual cycle with 12-month period is the only oscillation with a significant peak at all tidal stations, at 95% confidence limit. From Figure 5 it is again evident that the annual cycle is the dominant one. The energy distributions in the frequencies lower than 0.2 cycle/month are identical at the three meteorological stations. On the other hand, at the frequencies higher than 0.2 cycle/month, the energy is higher at Qaisuma than at Dhahran and Doha Airports with no significant peaks.

The coherences and the phase angles at the different frequencies, between sea level and atmospheric pressure, are shown in Figure 6. From this figure it can be concluded that the coherences are significant, at all stations, at frequencies less than about 0.14 cycle/month, with the highest correlations at and around the

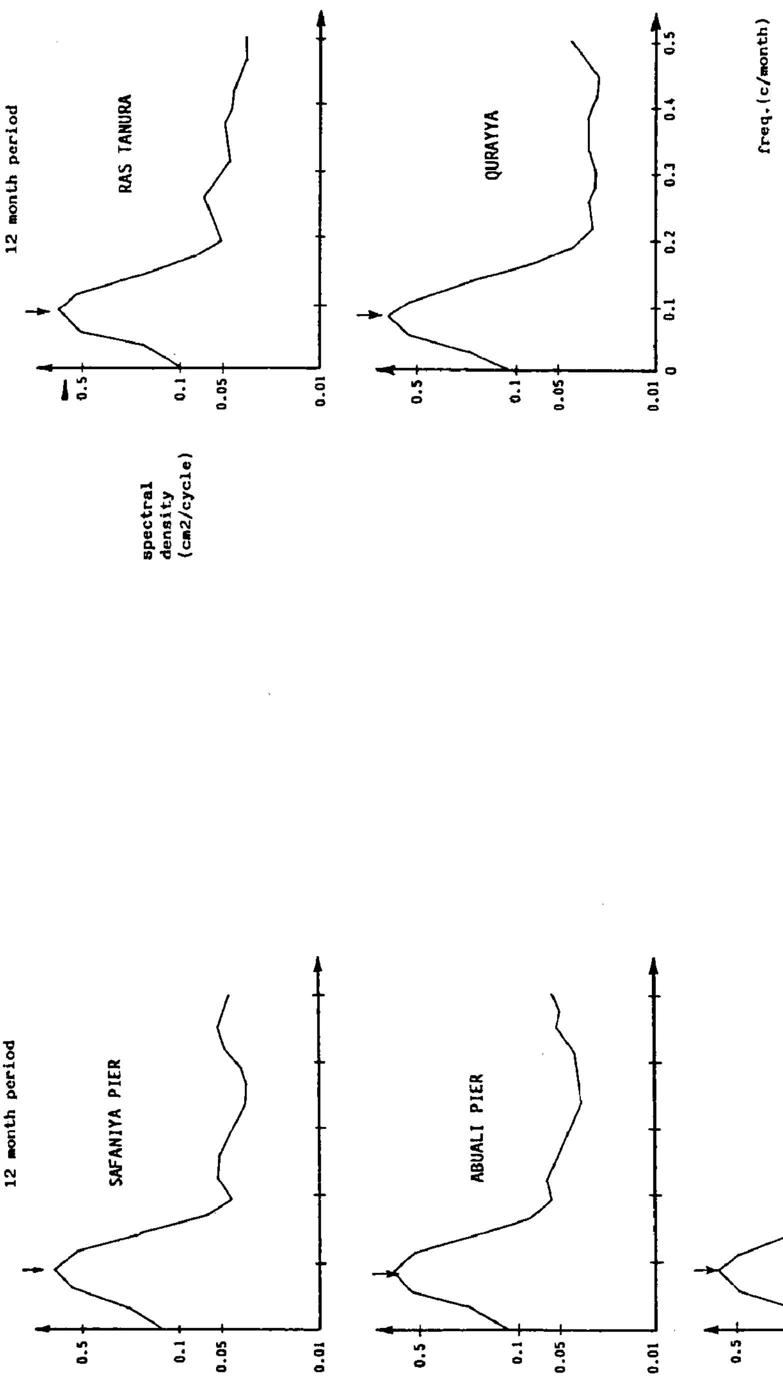

FIG. 4.— Spectral density of monthly mean sea level at 5 stations in the Arab Gulf along Saudi Arabian side from 1980 to 1985, with 18 lags.

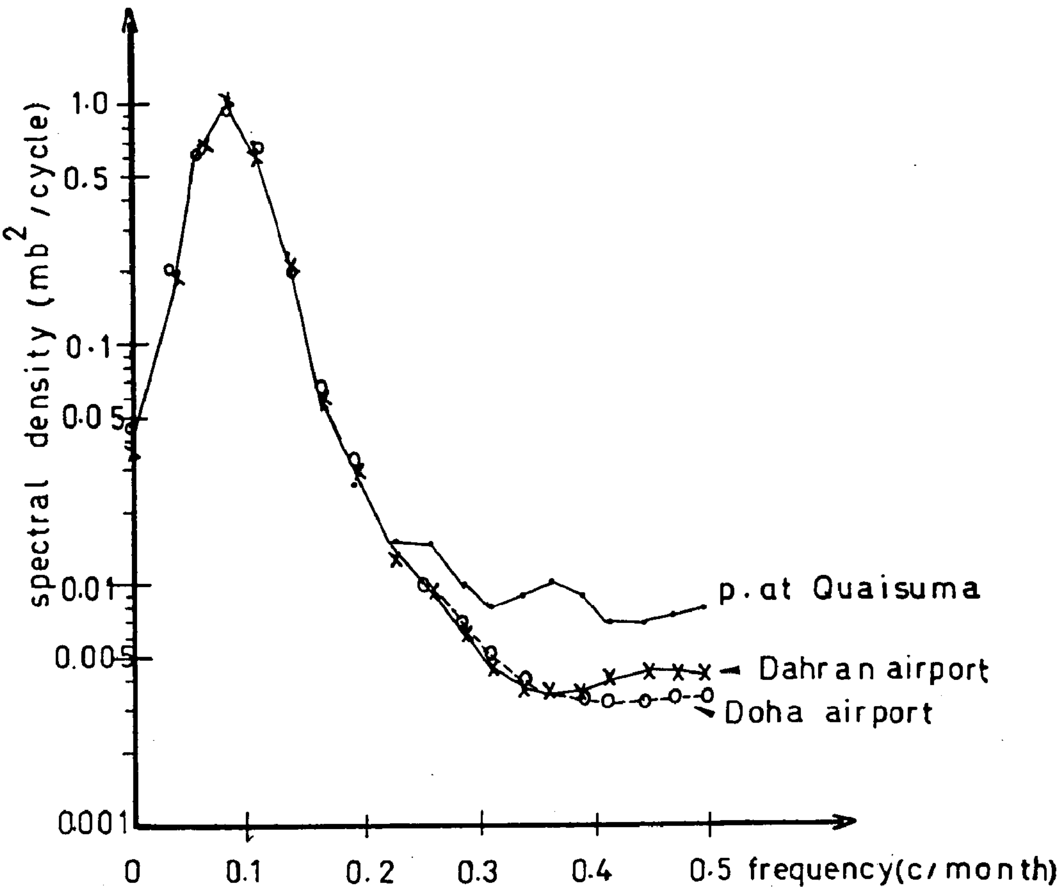

FIG. 5.— Spectral density of atmospheric pressure at three stations in the Arab Gulf, in the period 1980-1985, with 72 points and 18 lags.

annual cycle where most of the energy was contained. This evidence manifests the cause and effect relationships between sea level and pressure. The phase angle in the latter low frequency range is nearly 3 radians.

B — Harmonic analysis of sea level

The harmonic constants, i.e. the amplitudes and the phase angles of 36 oscillations in the 6 years sea level record are represented graphically by Figures 7-a and 7-b, from which it is shown that the oscillation of 12-month period has the maximum amplitude. The values of these amplitudes lies between 10 and 11 cm, with a phase angle, relative to January 1980, of about 1.25π. These results confirm the conclusions from spectral analysis.

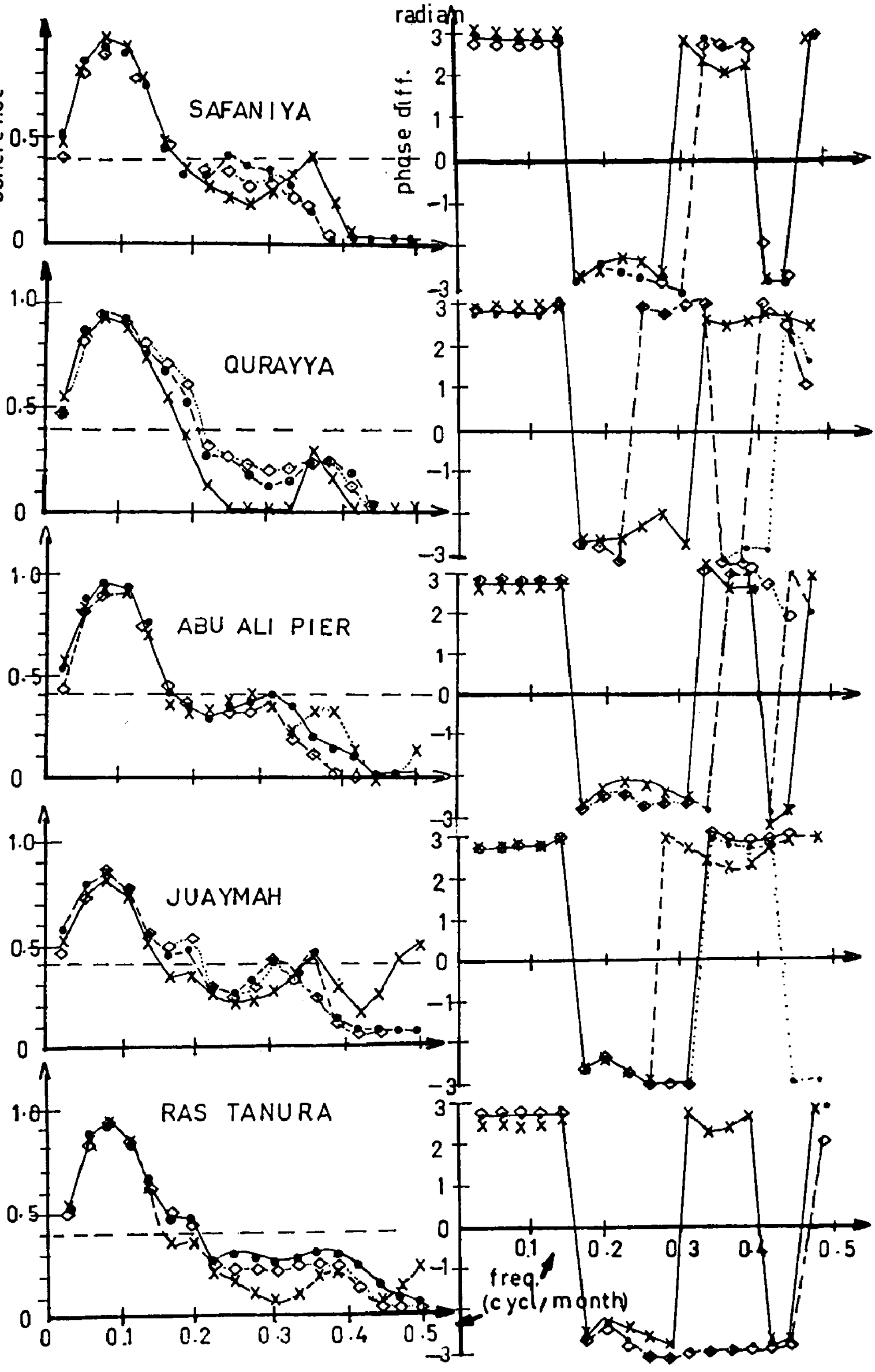

FIG. 6.— Coherences and phase angles at different frequencies, in the Arab Gulf, between monthly mean sea level and atmospheric pressure at Qaisuma(x), Dahran Airport (o) and Doha Airport (<>). Number of points are 72 with 18 lags. Horizontal dashed line represent the lower significant coherence.

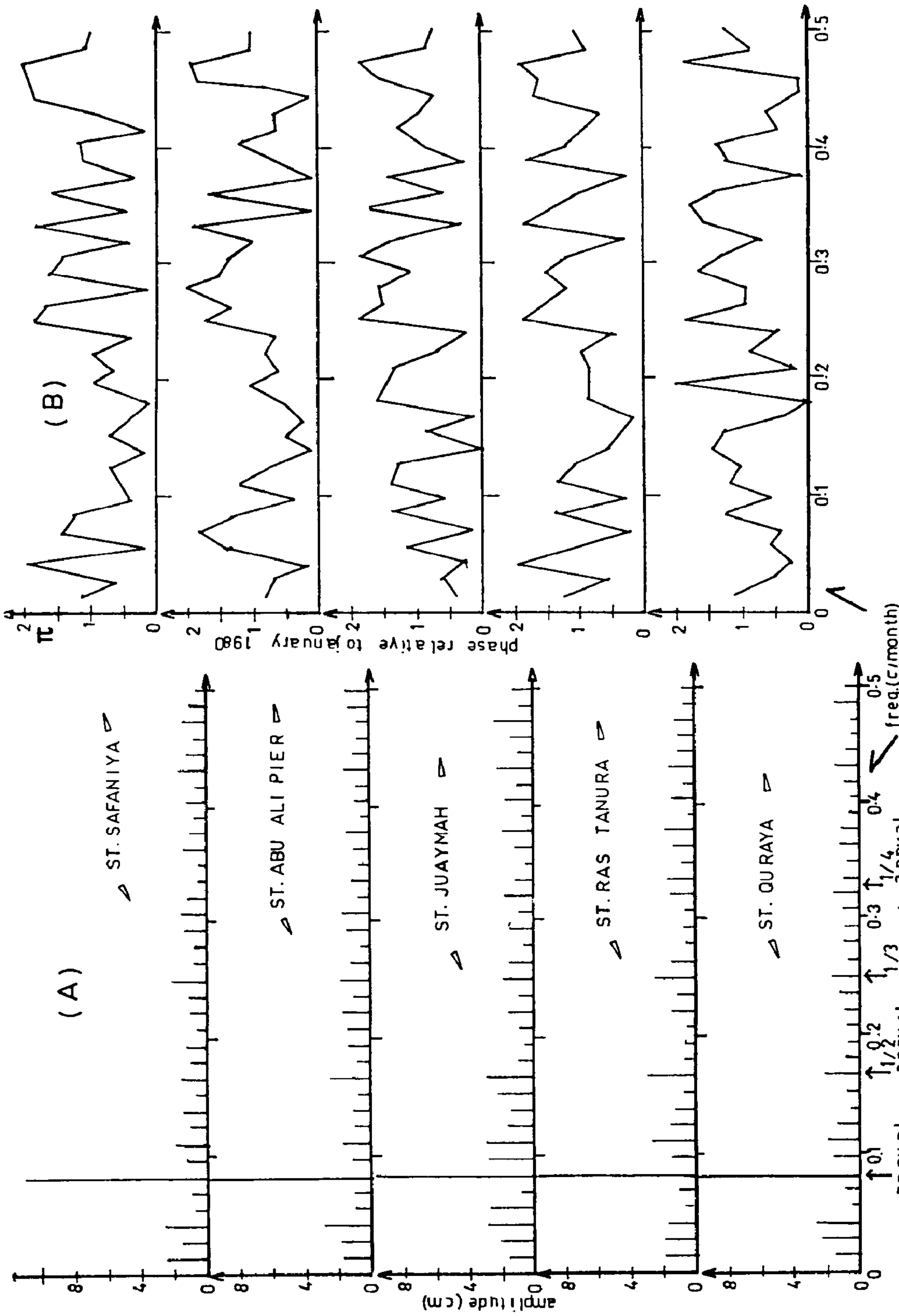

FIG. 7. — The amplitudes and phases relative to January 1980, resulting from Fourier analysis of 72 months (1980-1985) at 5 stations in the Arab Gulf.

C — Monthly mean sea level simulation and its validity

The harmonic simulation of sea level was done using only the harmonics with maximum amplitudes relative to the surrounding oscillations. The detection of these harmonics was done by the computer software, and if the future or past observed time series were read from data file the standard deviation between simulated and observed values could be calculated. These calculations were done at three stations of Safaniya, Abu Ali pier and Ras Tanura, where the observations had no gaps in the time series, during 1986 and 1987. The relations between the simulated and observed values are shown by Figure 8. The solid line passes through the points where observed and calculated values are identical, and the dashed lines show the limits of the standard deviations, which are 4.72, 4.72 and 5.28 cm. at Safaniya, Abu Ali pier and Ras Tanura respectively. From the latter figure, a reasonable agreement is observed between the two plotted values within the standard deviations. However, a few outliers are observed which may be due to extreme meteorological conditions or the neglected harmonics.

Regression analysis method.

The results of the regression analysis are presented in Table 2. The total correlation coefficients are all significant at 95% confidence limit, but the two

Table 2

Results of multiple regression analysis between monthly mean sea level and pressure in the Gulf (PA at Qaisuma, P2 at Dahran, P3 at Doha, P12 = P1-P2, P13 = P1-P3, P23 = P2-P3, No. of points = 72)

Station	Model	Equation	Total corr. coeff.
Safaniya	S(P12,P13,P23)	=404.90+3.94×P12	0.36
Abu Ali Pier		=418.52+4.12×P12	0.38
Juaymah		=400.88+5.01×P12	0.43
Ras Tanura		=419.55+4.97×P12	0.45
Qurayya		=323.18+4.62×P12	0.45
Safaniya	S(P1,P2,P3)	=1444.65-1.03×P2	* 0.82
Abu Ali Pier		=1388.59-0.95×P2	0.76
Juaymah		=1352.93-0.94×P2	* 0.71
Ras Tanura		=1387.74-0.95×P2	0.76
Qurayya		=1341.06-1.01×P2	0.86
Safaniya	S(P1,P2,P3,P12,P13, P23)	=1456.76-1.04×P2	0.83
Abu Ali Pier		=1402.28-0.97×P2	* 0.77
Juaymah		=1367.45-0.96×P2	0.72
Ras Tanura		=1396.40-0.97×P2	* 0.76
Qurayya		=1349.19-1.01×P2	* 0.86

* Equations used in simulation.

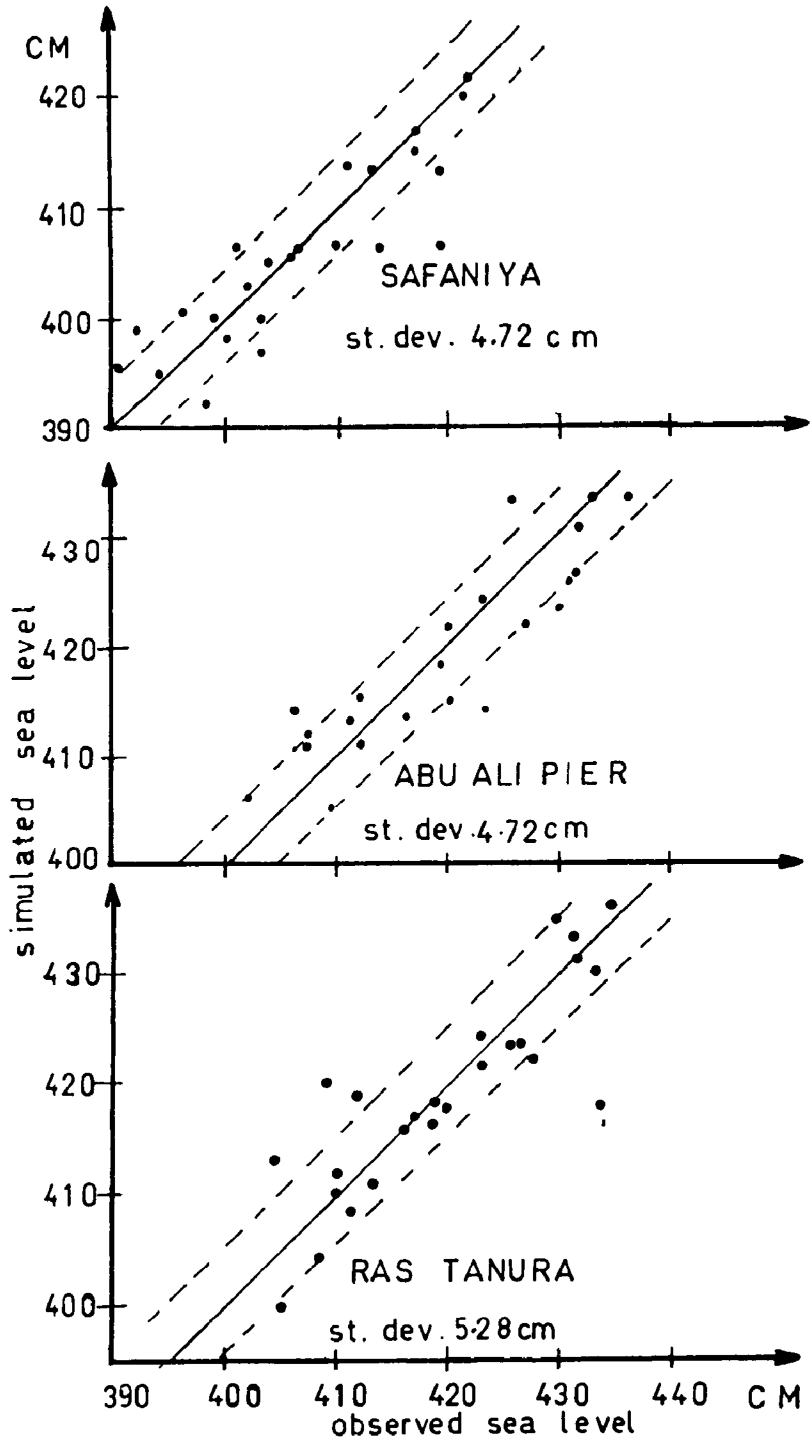

FIG. 8.— Relations between monthly observed mean sea level in 1986-1987, and the values simulated by using harmonic constants with maximum amplitudes calculated from 1980-1985 time series at different stations in the Arab Gulf.

models; S(P1,P2,P3) and S(P1,P2,P3,P12,P13,P23), have much higher values. The step wise method showed that the pressure at Dahran Airport is the most important variable for prediction. It is also significant to observe that the slopes of the straight lines, between the sea level and pressure at Dahran, lie between 0.94 and 1.04, which are very close to the inverted barometer factor.

For the purpose of the simulation, since the correlation coefficients for the last two models are close to each other, models with the smallest standard deviations are used, and are marked by (*), Table 2. The relations between the observed monthly means of sea level and the values calculated from the statistical model are presented in Figure 9. In this figure, again, the solid line passes through identical observed and calculated values, and the dashed lines are the approximate limits of the deviation from the solid line. The scatter diagrams show that:

1 - The solid line passes nearly along the axis of the cloud of points and therefore indicates a reasonable agreement.

2 - The deviations from the observations have the values, from 6.5 to -6.5 cm at Safaniya, from 11 to -11 cm at Abu Ali Pier, from 10 to -10 cm. at Juaymah, from 10 to -5 at Ras Tanura and from 7 to -7 at Quaraya.

The calculated values are actually based only on pressure variations. Therefore, the above mentioned residuals might be related to the other factors affecting the sea level. Inspection of the time series of the differences between observed and calculated values at the different stations in 1986 and 1987 showed that, at the stations of Safaniya, Juaymah, Ras Tanura and Quaraya, the differences were positive from June to December, and negative from January to April or May. At Abu Ali pier, the positive values were found only from September to December. According to the available literature, there are conflicting theories about evaporation variations in the gulf. On the other hand, the steric effect is not estimated in the area. Therefore, the separation of the residuals due to each of the factors other than pressure was not attempted.

CONCLUSIONS

The spectral analysis of the monthly mean sea level at 5 stations along the Saudi Arabian side and the mean monthly surface pressure at Qaisuma, Dahran and Doha Airports, indicated that the annual cycle is the main oscillation among those with periods larger than two months. These results were confirmed by the Fourier analysis of sea level which showed amplitudes between 10 and 11 cm for the latter cycle. The coherence between the sea level and the pressure records were significant at the frequencies lower than 0.2 cycle/month, with maximum coherence at the annual cycle.

The comparison of the simulated monthly mean sea level, with the observations in 1986 and 1987 showed reasonable agreement using both the harmonic and statistical models. Therefore, the monthly mean sea level can be predicted by applying the harmonic constants from past data, within the calculated standard deviation from the most recent observed data. The statistical models indicated

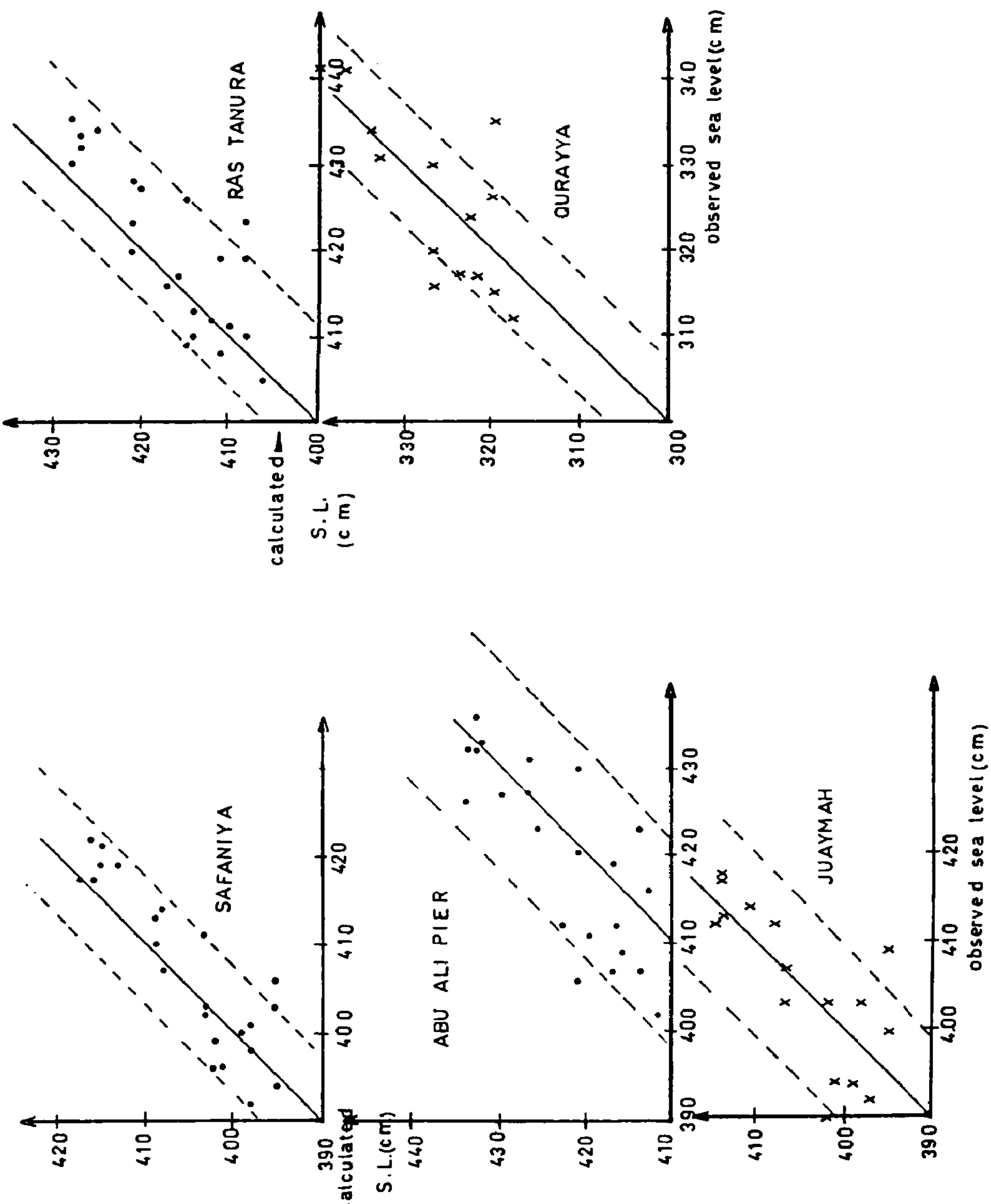

FIG. 9.— Relations between observed monthly mean sea level, in 1986-1987, and the calculated values using statistical equations between sea level and pressure fitted to data of 1980-1985 in the Arab Gulf.

that the inverted barometer effect at Dahran is the most important factor at the considered stations in the Gulf between about 26° and 28° N. The influence of the factors other than pressure on sea level, were found to be positive from June to December, and negative from January to April. The extreme values of the latter influence were (6.5-11) cm and (-5 to -11) cm, which represent about 50% to 100% of the amplitude of the annual cycle.

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