THE CONTEMPORARY KNOWLEDGE OF THE CAUSES OF THE SEASONAL CYCLE OF SEA LEVEL IN THE OCEANS

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INTRODUCTION

A preliminary effort (10) (*) to solve the problem of the seasonal oscillation of sea level in the oceans on the basis of tidal records collected during the International Geophysical Year, showed that air pressure is in addition to the density of the sea water (13) the principal general factor influencing this variation in the central parts of the Pacific. Considering the significance of the change in air pressure for the fluctuation in sea level in general and the marked seasonal variation in the distribution of atmospheric pressure over the oceans, this result is by no means surprising. In higher latitudes of the northern hemisphere, where changes in air pressure are pronounced, this factor is especially predominant. In lower latitudes with a marked seasonal oscillation of the specific volume of the sea water and slight fluctuations in air pressure the density is, on the contrary, the decisive factor. Nevertheless the effect of both factors must be taken into account everywhere. Conditions are, in other words, *isostatic*. This means that at any depth at which the seasonal variation in the density of sea water practically disappears a pressure gauge would record no noteworthy annual change. It seems, moreover, appropriate to emphasize that the two main causes for the seasonal cycle in sea level in the open parts of the oceans are *static*. In order to avoid misconception this statement needs, however, additional explanation.

In an ocean with no currents the water density would be the result of the effect of radiation, evaporation and precipitation. In actual cases advective heat and salinity transport and the effect of the Coriolis force upon currents, influencing the slope of the sea surface and the stratification of the water, cannot be left out of consideration. A considerable difficulty in this connection is the fact that the share of the different factors cannot be separated when working with sets of isolated observations which render the total effect of all the factors influencing the distribution of temperature and salinity. However, in a study of the seasonal variation in sea level it is of undoubted significance to distinguish between factors the influence of which extends more or less unchanged over relatively large areas, and e.g.

(*) Numbers between brackets refer to the bibliography at the end of the article.

currents which in any particular case produce an effect characteristic for a certain, and sometimes quite restricted region only. Currents as well as winds are thus, unlike density, not only the *dynamic* but also *local* factors influencing the annual cycle of sea level in the oceans and seas. An example may suffice to illustrate this assertion. The amount of radiation can differ but little on both sides of the Gulf Stream, when considering the same latitude. The dynamic effect of the current and its seasonal variation are, on the contrary, fairly different in the two cases. It is therefore not permissible, for instance, to use the density data measured on the east side of the current for an interpretation of sea level variation on the Atlantic coast of Florida without adding the necessary corrections. It must also be borne in mind that extensive studies on the seasonal variation in sea level have shown that the oceans, on the basis of the main characteristics of this variation, may be divided into a few latitudinal zones (7,13). Such a grouping is, of course, possible only in case the effect of currents is left out of consideration.

In the following the additional local causes which may influence the seasonal variation in sea level are studied more closely. This problem is doubtless more complex than the general part of the work, as every tidal station, or at least every group of tidal stations, must be considered separately. An exact knowledge of the local conditions is, of course, necessary in all these cases. For instance, the water discharge by rivers as well as wind-produced piling-up of the surface of the sea may be significant. A sufficiently detailed description of the location of the tidal gauges is, however, as a rule not available. In spite of this an effort is made to explain the character of the seasonal cycle of sea level for some selected tidal stations representing a number of different regions. Areas characterized by a marked monsoon were left out of consideration, as there can be no doubt as to the main cause of the seasonal variation in sea level.

THE SOUTHEASTERN COAST OF THE UNITED STATES

The seasonal cycles of sea level along the southeastern coast of the United States, covering the region between Florida and Cape Hatteras, have been subjected to extensive study, mainly in connection with the seasonal variation in the water transport of the Gulf Stream System. In this respect it may suffice to refer to the results obtained by MONTGOMERY (12), ISELIN (6) and FUGLISTER (4). The relationship between the two factors is fairly pronounced : a decreasing sea level along the coast is, in general, connected with an increase in velocity of the current, and vice versa. It is in other words a dynamic consequence of the Coriolis force. However, the study of FUGLISTER, based on a considerable number of observations of the speed of the surface current, showed that there exists a marked discrepancy between this factor and the sea level. On the whole, the recorded sea level seems to be higher than the speed of the current would suggest during the months from June to October, while conditions are reversed during the remaining part of the year. This indicates that changes in water density, caused by radiation and probably by evaporation and precipitation, must be taken into account. This implies, on the other hand, that the main general cause influencing the seasonal cycle in sea level for the zone concerned is valid, but that an additional factor, the change in speed of the current, must be considered.

Before considering the numerical results of such a proceeding, attention must be paid to one additional phenomenon. The seasonal variation in sea level along the southeastern coast of the United States shows a fairly marked semiannual cycle. In fact, the amplitude of the semiannual cycle in this region is one of the most pronounced in such coastal areas for which data are available (8). There are two possibilities for interpreting this oscillation : either we may consider it as an astronomic tide or we may try to explain it on the basis of the variation in the current system. ISELIN (6) showed that the semiannual variation could be a consequence of the volume of the Gulf Stream due to the influence of the seasonal fluctuation in wind. On the one hand, it must be taken into account that the winds are stronger in winter than in summer. The corresponding changes in the velocity of the main clockwise current result along the American coast in a minimum in sea level in winter and a maximum in summer. On the other hand, the fact must be borne in mind that as the winds increase in strength they also move southwards. The consequence is that a larger part of the water constituting the Gulf Stream must pass the Caribbean and the Straits of Florida. This causes an increase of bottom friction and a decrease of the volume of the Gulf Stream in spite of the strong winds. As the migration of the winds and their changes in speed are not quite simultaneous the whole phenomenon may result in a double rhythm.

ISELIN's interpretation of the semiannual cycle of sea level gives an interesting basis for continued research. It is, however, so far difficult to compute the influence of the two factors separately. It seemed in our special case to be more appropriate not to make any distinction, but to interpret the whole semiannual cycle simply as an astronomic tide.

Table 1 shows the relative influence of the different factors upon the seasonal variation in sea level in Miami. The first line in the table gives the averages in sea level during the years 1931-46, the second line the mean monthly air pressure. *Diff I* corresponds to the sea level corrected for the effect of air pressure. The next line represents the part of sea level variations caused by changes in density of the water, and the line *Diff II* the deviation between *Diff I* and the latter value. All the above data are given in (13).

In this connection it must be pointed out that in spite of the use of these data the definition given in the quoted paper is not adopted in the following. The *steric* level was there defined as nearly equal in magnitude to the dynamic height, which means that no distinction was made between the static change in density and the dynamic influence of the currents. The inevitable result of this definition is that sea-level records made on some of the islands are not strictly comparable to the *steric* data.

In order to agree with the dynamic heights the latter must be based on data measured in relatively deep spots of the oceans, usually far from the coast of continents and islands, as only in this way the *layer of no-*

motion, as defined by Defant, can be reached more or less satisfactorily. For instance, the *steric* sea level reproduced in Table 1 is measured comparatively far from the eastern border of the Gulf Stream where the dynamic influence of the current is probably negligible. A slight effect of Coriolis force which, of course, is opposite to the effect recorded by the tide gauge in Miami is, however, by no means excluded.

The sixth line gives the semiannual tide (8) and *Diff III* is the residue after its elimination.

The line marked *Current* reproduces the dynamic effet of this factor upon the sea level on the basis of data computed by FUGLISTER (4) for the Florida Current, using a considerable number of observations. As only the relative changes in speed are significant here, the deviations from the annual mean were first determined for every month. Thereafter the least-squares method was used for computing the factor by which the speed data must be multiplied in order to render the best agreement with the residue numbers given in line *Diff. III*. This factor was 0.77. The close connection between the residue and the effect of the current is emphasized by the fact that the corresponding data are, without exception, opposite in sign. The final result after the elimination of the current effect is given in line *Diff. IV*.

The last two columns in Table 1 show that the range of the seasonal cycle in sea level and the mean deviation are reduced to less than 40 per cent of the average value, when the influence of these four factors is eliminated. This result is satisfactory, especially as it shows, with the exception of the effect of air pressure, a distinct subsequent decrease of the range and the average deviation. It is therefore an interesting problem to trace the causes of the final residues, reproduced by *Diff. IV*.

Firstly we must, without doubt, consider the possibility of a more or less marked inexactitude concerning all data used in Table 1. It must be borne in mind that the recorded sea level, the mean air pressure, the data for water density, the harmonic constants computed for Ssa and the current data do not refer to the same place and the same period. The variability of all these data may be considerable, even if average values are used. In addition, the current data are based on surface measurements only, and thus not strictly representative of the deeper layers.

With respect to the density of the water it must, moreover, be emphasized that a considerable difference certainly exists between the condition in the deep open sea and along the shallow coasts. A part of the deviations may therefore be due to this fact. We have, however, so far no data to compute this deviation quantitatively. It must also be borne in mind that the density data used may be, to some less degree, influenced by the dynamic effect of the Coriolis force.

Secondly, possible additional factors must be taken into account. The influence of the wind may be significant. This problem has so far not been studied more closely for Miami. Here, for instance, reference may be made to the papers of MILLER (11) and DE VEAUX (3), in which the relationship between wind and changes in sea level is studied for Atlantic City (New Jersey) and Charleston (North Carolina) respectively. The results show in both cases that the piling-up effect of the wind upon the sea level is fairly

TABLE 1.

The influence of different factors (cm) upon the sea-level cycle in Miami

	J	F	M	A	M	J	J	A	S	O	N	D	Range	Mean deviat.
Sea level	—5.4	—6.3	—8.5	—4.1	—1.3	—3.4	—5.4	—0.9	8.6	16.5	10.5	—0.3	25.0	7.7
Air pressure	2.6	2.6	0.2	—0.8	—0.8	—3.5	—2.0	—1.3	—1.4	—0.8	2.4	3.1	6.1	
Diff. I	—2.8	—3.7	—8.3	—4.9	—2.1	—6.9	—7.4	—2.2	7.2	15.7	12.9	2.8	24.0	7.9
Water density	—5.3	—6.5	—8.8	—9.3	—5.0	0.4	4.5	8.4	10.0	8.5	3.5	0.6	19.3	
Diff. II	2.5	2.8	0.5	4.4	2.9	—7.3	—11.9	—10.6	—2.8	7.2	9.4	2.2	21.3	6.8
Ssa	—5.6	—4.6	1.0	5.6	4.6	—1.0	—5.6	—4.6	1.0	5.6	4.6	—1.0	11.2	
Diff. III	8.1	7.4	—0.5	—1.2	—1.7	—6.3	—6.3	—6.0	—3.8	1.6	4.8	3.2	14.4	5.1
Current	—2.9	—1.1	1.4	2.1	2.1	4.0	5.1	4.9	1.1	—5.1	—7.7	—4.0	12.8	
Diff. IV	5.2	6.3	0.9	0.9	0.4	—1.2	—1.2	—1.1	—2.7	—3.5	—2.9	—0.8	9.8	3.1

distinct. This allows us to assume that a part of the residue in *Diff. IV* may be the consequence of the wind-produced piling-up of the water.

One more feature must be considered : the water circulation over the continental shelf. According to a study of BUMPUS (2) this circulation is a transient phenomenon along the coast south of Cape Hatteras and its seasonal variation is so far not known. The main characteristic of this circulation is, however, that the currents are in general northerly, but turn southerly when the run-off is sufficiently pronounced to counteract the predominant thermal distribution, or the frictional drag of the south winds, or the Florida Current. As the water discharge by rivers is, as a rule, most marked in winter, the probability of a southerly current is high during this season and this change in the circulation may through its dynamic consequences be responsible for at least a part of the positive residue in *Diff. IV*.

The above proves that besides the two mean general factors, air pressure and density of sea water, there are several additional causes influencing the seasonal oscillation in sea level at Miami.

THE NORTHERN PARTS OF THE ATLANTIC

In order to give a conception of the relative significance of the two main factors influencing the annual cycle of sea level in the subtropical zone of the Atlantic, on the one hand, the subpolar region, on the other hand, figure 1 was drawn. The upper part of this figure represents conditions at Reykjavik, Iceland; the lower part is characteristic of a group of stations on the North American coast with an average latitude of 40° N (the stations used are Hampton Roads, Baltimore, Atlantic City, Fort Hamilton, New York, and Newport). The thin solid curves reproduce the recorded average sea-level data, the dashed curves result after the elimination of the influence of atmospheric pressure from the data. The thick solid curves represent the residue when the effect of the variation in density of the water is also eliminated. All the mean data used were computed by PATTULLO et al (13). The difference between the two groups of curves is conspicuous. For Reykjavik the elimination of air pressure means much more than the subsequent elimination of density, but the final residue shows a similar general feature as the original curve. For latitude 40° N the result is quite different. The effect of air pressure upon the variation in sea level is not very pronounced, whereas, as could be expected, the elimination of the density totally changes the shape of the recorded curve. In this case the possibility cannot be excluded that the residue, at least to some degree, is due to the existence of a semiannual cycle.

The two thick solid curves in the figure reveal, however, another characteristic which must be considered. When the water is high in Reykjavik, it is, on the whole, low around the 40th parallel, and vice versa. There is, of course, a marked difference in amplitude, but this fact is by no means surprising, as the subtropical region covers a considerably larger area than the subpolar zone. An exchange of water between the two regions seems therefore to be quite possible.

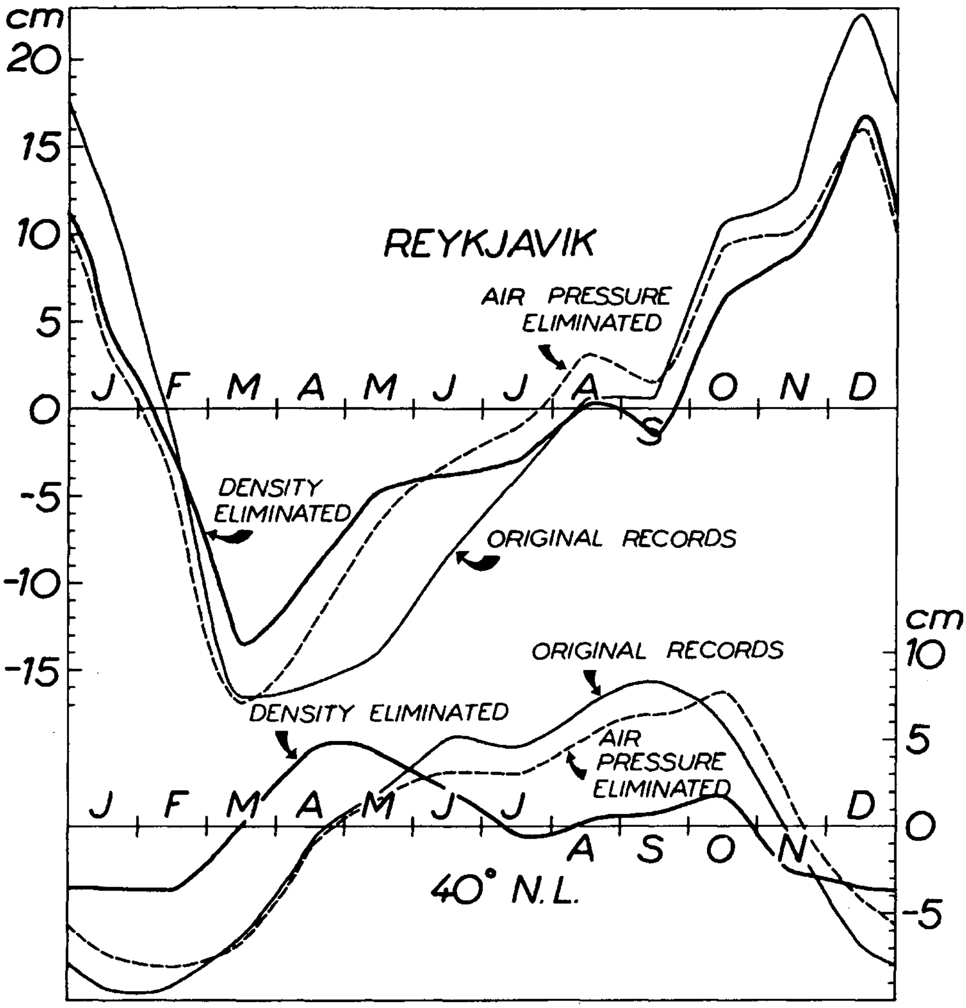

Fig. 1.

To check the validity of this result the averages were computed for a greater number of tidal stations in the northern subpolar area of the Atlantic and the adjacent subtropical region. The effect of air pressure and water density was again eliminated from the recorded means. The resulting monthly averages are reproduced in the upper part of figure 2, where the thin solid curve stands for the subpolar and the thin dashed curve for the subtropical region. The reversed tendency of the two curves is distinct. Although tide-gauge stations with a comparatively pronounced semiannual cycle of sea-level oscillation were omitted when computing the averages, a double rhythm may be noted on the two curves. The elimination of the semiannual cycle gave data which are represented by the thick solid and dashed curves. These curves emphasize still more the opposite tendency of the sea-level cycle in the two zones (9).

It is hardly probable that a phenomenon characterized by such a considerable regularity could be ascribed to a more or less occasional uncertainty concerning the used data. Therefore, it is undoubtedly an interesting problem to trace the cause of the water interchange. Unfortunately, an adequate number of observations to solve the question is not available. The share of the Gulf Stream system, especially of the fluctuation of its water transport can, however, not be left out of consideration. The current data given in Table 1 and corresponding data computed by FUGLISTER (4) for other parts of the Gulf Stream indicate that for the western part of the central " eddy " of the current system the maximum velocity is reached during the summer months, the minimum velocity late in the fall. According to ISELIN's assumption the clockwise current system in the North Atlantic surrounds a core of relatively motionless water, the Sargasso Sea. Gradual variation in the water transport of the mainly circular pattern (the more detailed and complex features of the current system are left out of consideration in this connection) can be expected to change its diameter causing a fluctuation in the discharge of warm surface water towards the coast of northwestern Europe. Increasing currents during summer entail a contraction of the eddy and thus lessen or even interrupt the flow towards the northeast. A period of weakening currents in late

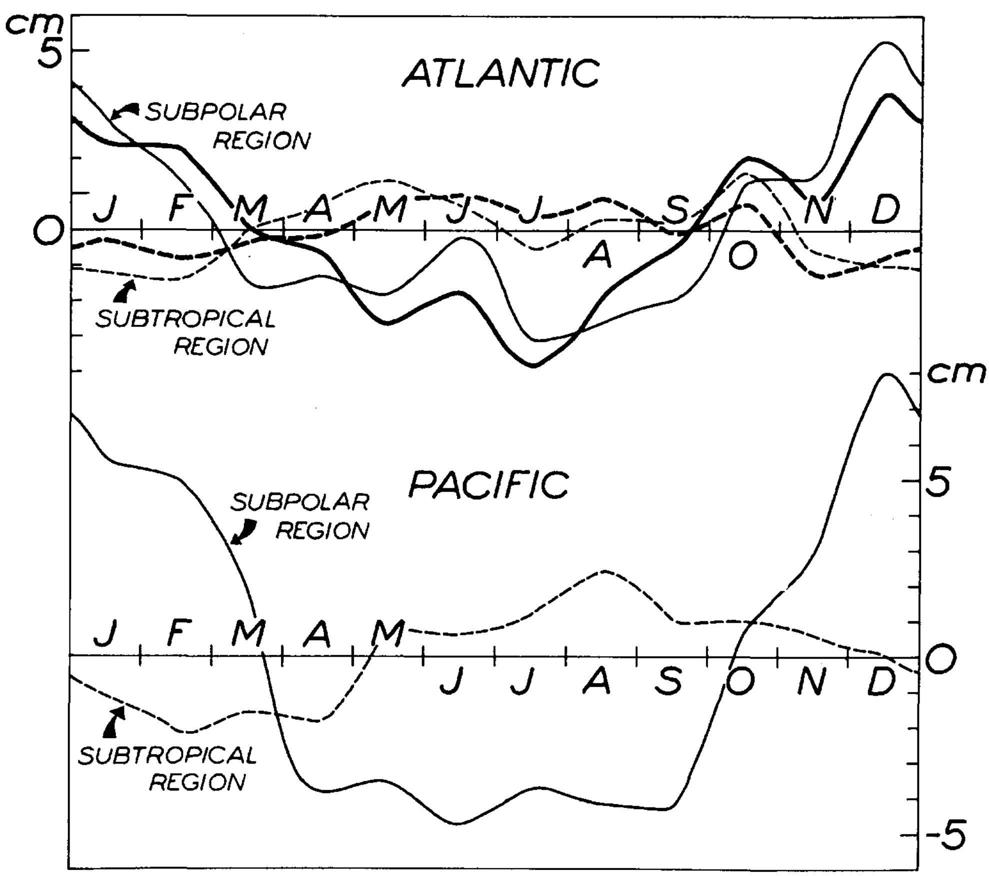

Fig. 2.

autumn increases the water supply in the area of the northeastern North Atlantic (6). In this way fairly small variations in the transport of the Gulf Stream may influence conditions at a considerable distance and be the cause of the positive sea-level residue in the subpolar region during the winter season and the negative residue during the summer months, and vice versa farther southwards.

COASTAL AREAS AND ISLANDS IN THE PACIFIC OCEAN

The two cases considered above show the complexity of the whole phenomenon and the difficulties every student of the problem has to struggle with in order to explain the particular feature of the sea-level residue. In the Pacific these difficulties seem to be still greater. The lower part of figure 2 shows the monthly sea-level averages for a number of tidal stations in the two northern zones of the Pacific. The border between the zones runs along the 40th parallel. The effect of air pressure and water density has been eliminated from the sea-level data. Contrary to the conditions in the Atlantic, it is not possible to trace a double rhythm in this figure, but the reversed tendency of the curves is also distinct in this figure.

Here it must be pointed out that an explanation similar to that given for the northern Atlantic is by no means the only acceptable one. All the tidal stations on which the results for the subpolar region are based are situated along the coast or on the islands bordering the Gulf of Alaska. As a consequence of the considerable seasonal differences in the general air circulation in this area, the counterclockwise current characteristic of the Gulf of Alaska is stronger in winter than in summer. A part of the very pronounced positive residue for the subpolar region in the Pacific ocean is probably due to the Coriolis effect of the changes in velocity of the current. More detailed data are, however, necessary to reach definite conclusions. A possible seasonal occurence of wind-produced piling-up of the water is also a factor that must be studied more closely.

Sea-level records collected from the islands of the Pacific Ocean show very distinctly that the seasonal oscillation in sea level is influenced by additional causes not only along the coast. However, meteorological and hydrographic data being sparser from the central parts of the oceans than from the coastal areas, an interpretation of the results is even more cumbersome. An example may be sufficient to prove this. We have at our disposal the tidal records for three islands in the central Pacific, Midway (28°13′ N, 177°22′ W), Johnston (16°45′ N, 169°31′ W) and Wake (19°17′ N, 166°37′ E), situated at a distance of about 1 500 to 2 500 km from each other. There are, on the average, no really significant deviations in average air pressure at these stations. The difference in water density cannot be expected to be very pronounced in the separate cases. Nevertheless the monthly averages in sea level at these islands, reproduced in figure 3 for the five years 1954-1958, for which years the observations are complete, show considerable deviations (1). It is true that there is a certain resemblance between the curves for Midway and Johnston, the general trend being as

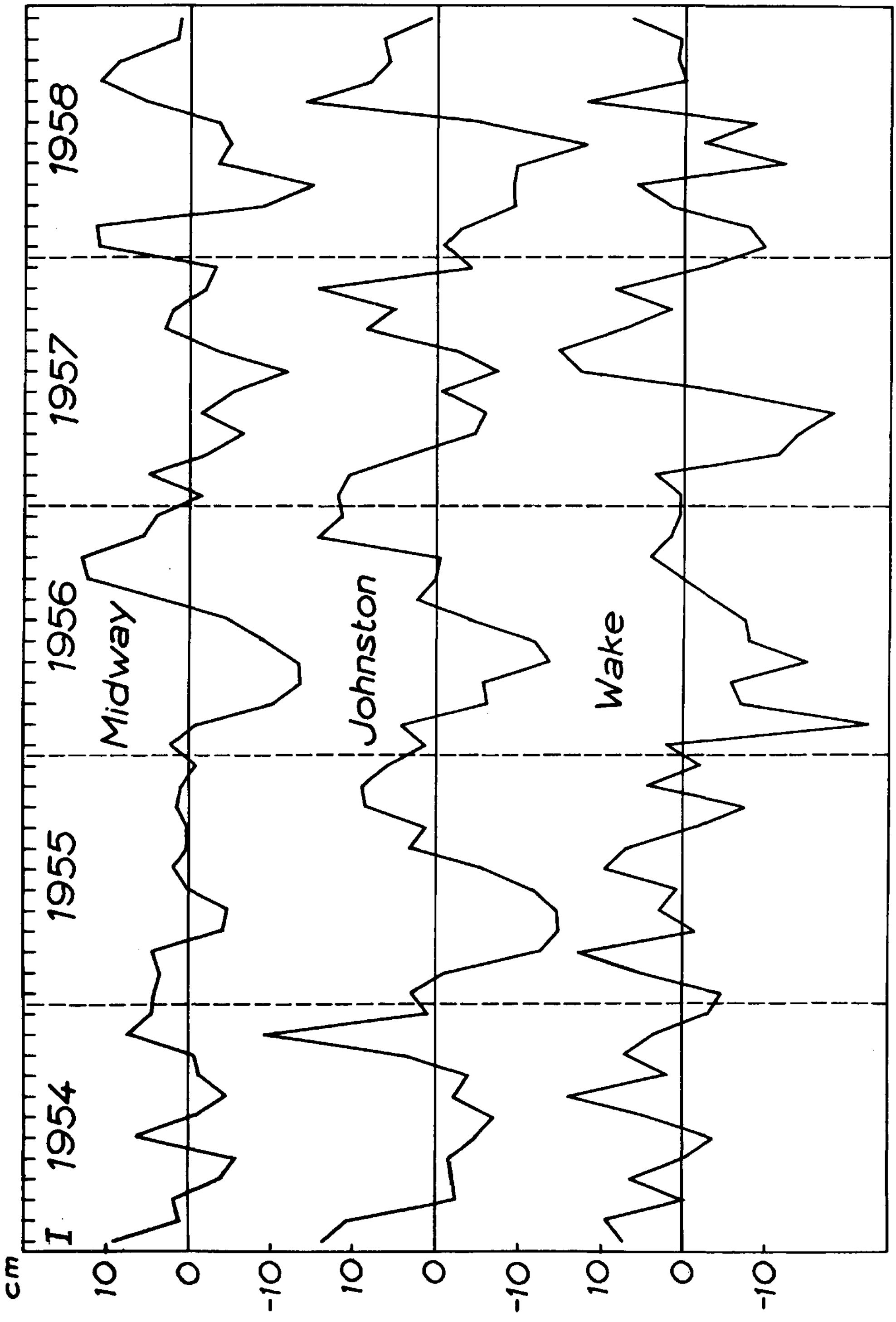

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Fig. 3.

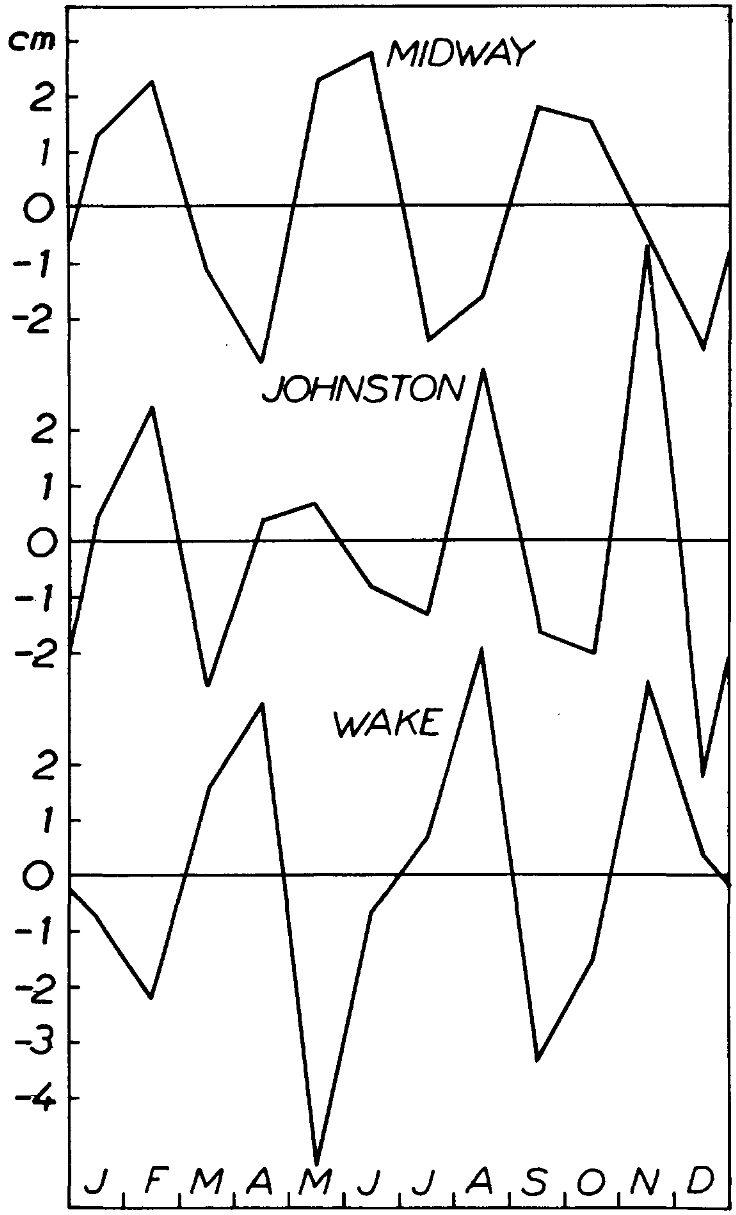

Fig. 4.

a rule similar, although the values differ considerably. Comparing the curves for Midway and Wake, we note at the beginning and the end of the period intervals where the changes for the corresponding months are, practically without exception, opposite, while in the middle of the period a certain conformity may be traced in the general course of the curves. As it is hardly conceivable that these pronounced differences may be ascribed to an inexactitude of the recorded data, they reveal very distinctly the complexity of the phenomenon. It is at present not possible to give an interpretation of the causes of the deviations. They seem to be too marked to be due to the effect of local changes in the velocity of the currents and their dynamic consequences. The piling-up effect of the wind is not excluded, but a study of this problem requires an exact knowledge of the location of the tide gauge and its surroundings, which is not available.

A first step in order to solve the problem is a study of the monthly average for the 5-year period. These data show, in spite of a number of irregularities, the main structure of the seasonal oscillation in sea level. As it was of significance to separate the features that were typical of the different stations from those of a more general character, the harmonic constants for the annual and semiannual cycles were computed, and the value corresponding to every month eliminated from the averages. The harmonic constants are :

	Annual cycle		Semiannual cycle	
For Midway	5.1 cm	234°	1.9 cm	281°
For Johnston	8.6 cm	240°	1.2 cm	296°
For Wake	3.8 cm	193°	2.4 cm	298°

Although the amplitudes show considerable deviations, the angles prove that the general factors influencing the annual cycle are more or less similar. The residues, which result from elimination of the annual and the semi-annual cycles from the mean data are reproduced in figure 4. The characteristic of the residue for Midway and Wake is that of a fairly regular course with three maxima and three minima which are generally opposite for the two stations. The residue for Johnston is somewhat less regular in shape and has four maxima and four minima. The most interesting detail is, however, the fact that the maxima and minima for Johnston coincide at the beginning of the year with those for Midway, while at the end of the year there is a marked similarity between Johnston and Wake. This indicates that conditions are relatively complicated in the considered region. Interesting also is the fact that GROVES (5), in studying the day to day variation in sea level, noted that the correlation between Midway and Johnston is better than between any other pair of islands studied by him, though there are many pairs geographically much closer together. The features of the Midway record seem to appear a day or two later on the Johnston record. GROVES could not give any explanation for this correlation. His results were based on records covering the time from the beginning of November 1952 to the end of January 1953. The correlation seems to be most marked for December and January, thus coinciding with the time when the conformity between Midway and Johnston starts according to Figure 4.

REFERENCES

(1) ASSOCIATION D'OCÉANOGRAPHIE PHYSIQUE DE L'U.G.G.I. Monthly and Annual Mean Heights of Sea-Level for the Period of the International Geophysical Year (1957 to 1958) and unpublished data for earlier years. *Publ. Scient.*, No. 20, 1959.

(2) BUMPUS Dean F. : The Circulation over the Continental Shelf South of Cape Hatteras. *Transactions Amer. Geoph. Un.*, Vol. 36, No. 4, 1955.

(3) De Veaux Eugene J. : Meteorological Trend and the Apparent Rise in Sea Level along the South Carolina Coast. *Monthly Weather Review,* Vol. 83, No. 10, 1955.

(4) Fuglister Frederick C. : Annual Variations in Current Speeds in the Gulf Stream System. *Sears Found. Journal of Marine Research,* Vol. 10, No. 1, 1951.

(5) Groves Gordon W. : Day to Day Variation of Sea Level. *Meteorological Monographs,* Vol. 2, No. 2, 1957.

(6) Iselin C.O.D. : Preliminary Report on Long Period Variations in the Transport of the Gulf Stream System. *Papers on Phys. Oceanogr. and Meteorol.,* Vol. VIII, No. 1, 1940.

(7) Lisitzin Eugenie : Les variations annuelles du niveau des océans. *Bull. d'Information du COEC,* VII, 6, 1955.

(8) Lisitzin Eugenie : Les variations semi-annuelles du niveau de la mer dans les océans. *Bull. d'Information du COEC,* VIII, 8, 1956.

(9) Lisitzin Eugenie : Contribution to the Knowledge of the Annual Cycle of Sea Level. *International Oceanographic Congress (Preprints),* pp. 767-768, 1959.

(10) Lisitzin Eugenie and Pattullo June G. : The Principal Factors Influencing the Seasonal Oscillation in Sea Level (In preparation).

(11) Miller Arthur R. : The Effect of Steady Winds on Sea Level at Atlantic City. *Interaction of Sea and Atmosphere,* pp. 24-31, 1956.

(12) Montgomery R.B. : Fluctuations in Monthly Sea Level on Eastern U.S. Coast as related to Dynamics of Western North Atlantic Ocean. *Sears Found. Journal of Marine Research,* Vol. 1, No. 3, 1938.

(13) Pattullo June, Munk Walter, Revelle Roger and Strong Elisabeth : The Seasonal Oscillation in Sea Level. *Sears Found. Journal of Marine Research,* Vol. 14, No. 1, 1955.