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Sea-level Variations at Iceland and Bermuda[1]

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ABSTRACT

Data from tide gauges at Iceland and Bermuda combined with data on atmospheric pressure at both stations plus hydrographic serial observations at Bermuda are utilized to analyze sea-level variations in both regions. Residual sea-level anomalies (raw sea-level anomaly minus barometric and steric effects) are computed and discussed for Bermuda. The analysis, which indicates a periodicity of four months, is regarded as very tentative. The Bermuda and Iceland results tend to confirm previous conclusions, derived from studies of the Pacific Ocean, that sea-level variations are controlled to a very large extent in low latitudes by steric effects and in high latitudes by barometric effects. These results are explained in turn on the basis of contrasts between both the annual zonal temperature regime in the oceans and the annual pressure variations in the atmosphere.

1. *Introduction.* Considerable interest was generated in the annual variation of sea level when Pattullo et al. (1955) reported their comprehensive investigation of the global pattern of annual sea-level variation. Later, more detailed work in this field, such as that by Pattullo (1960) and Lisitzin and Pattullo (1961), was concentrated on only the Pacific Ocean. Until the IGY, few similar detailed studies were carried on in the Atlantic owing to the nature and distribution of islands in that ocean. The purpose of this report is the presentation

1. Lamont Geological Observatory (Columbia University), Contribution No. 705.

and analysis of detailed sea-level, hydrographic, and barometric observations taken at Iceland and Bermuda. The tide-gauge stations were established by the Lamont Geological Observatory as part of the IGY Island Observatories program.

2. *The Annual Sea-level Cycle.* Because the results of this investigation are to be compared to the more extensive results for the Pacific Ocean, noted above, we wish first to review and critically analyze the earlier work. Pattullo et al. noted that the sea level in each hemisphere is high during the respective autumn, and low during the spring; they also concluded that most of the deviation from mean sea level results from density changes in the ocean. Lisitzin and Pattullo showed the importance also of the atmospheric pressure effect, which is in fact more prominent in high latitudes than in low latitudes; furthermore, they demonstrated that the influence of water density is greater in the subtropics and lower middle latitudes than in the more northern latitudes. Recently, Saur (1962) analyzed statistically the variability in sea level at six stations in the eastern North Pacific Ocean and compared his results with the variability in atmospheric pressure in that area. He has shown that seasonal variability in sea level increases markedly with increasing latitude, correlating well with similar variations in atmospheric pressure.

Pattullo recognized that much of the deviation from mean sea level is a function of isostatic effects resulting from oceanic pressure and density (or volumetric) changes. Such effects maintain a constant pressure on the bottom. Nonisostatic effects that involve a pressure change on the ocean bottom require an uncompensated mass transport of water.

Any complete investigation of the annual cycle in sea level must attempt the separation of the isostatic from the nonisostatic terms. To accomplish this, observations of sea level (taken from standard tide-gauge records) must be supplemented with observations of atmospheric pressure and with serial observations of water temperature and salinity, the latter from fairly deep water.

In order to compare the effects of variations in both atmospheric pressure and seawater density on sea level in the Atlantic with those in the Pacific, we selected for analysis the data from Iceland and Bermuda. Although both hydrographic serial observations and air pressure observations are available for Bermuda, only air pressure data are available for Iceland. However, the earlier work in the Pacific suggests that, for Iceland and the high latitudes of the North Atlantic Ocean in general, water temperature and salinity are much less important than atmospheric pressure.

3. *Sea-level Variations at Iceland.* The Iceland gauge, located in Grindavik Harbor on the southern coast, was operated from October 1957 to July 1962. The three-month moving means of the monthly deviation from mean sea level are shown in Fig. 1, together with atmospheric pressure over the

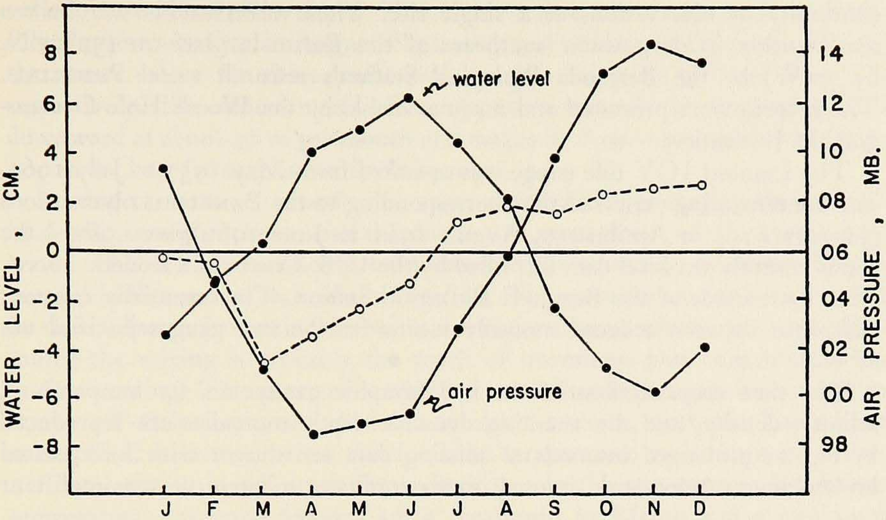


Figure 1. Mean sea-level and air-pressure deviations together with residual sea level (dashed lines) at Grindavik on the southern coast of Iceland.

same time interval. The inverse (nearly one-to-one) relationship is quite striking. Because air pressure was obtained at three different stations (none at Grindavik) and because air pressure gradients are often very steep over Iceland, we have estimated a possible error of about 1 mb in the pressure values, and therefore an error of 1 cm of water in the analysis.

The curve for residual sea level indicates a slight maximum in the fall and a minimum in the spring. This residual deviation is in phase with the annual water-temperature cycle and is probably a result of the small temperature changes affecting water density. However, it may also represent the effect of water-mass transfer between continents and oceans. Van Hylckama (1956) calculated that the spring-minus-fall water storage on the continents is 0.75×10^{19} g. This value corresponds to a sea-level change of about one to two cm.

The results for the high latitudes in the Atlantic Ocean compare well with the earlier results for the high latitudes in the Pacific Ocean. For the most part the high-latitude pressure effect is a consequence of the relatively intense annual variation in air pressure associated with the Icelandic and Aleutian low-pressure systems. In lower latitudes, other factors predominate over the pressure effect, the annual variation of which is much smaller.

4. *Sea-level Variations at Bermuda.* Possibly the most complete data available for sea-level and steric analysis are those taken at Bermuda. The 173 hydrographic serial observations available to us, taken from January 1954 through the first half of 1962, represent an unusual collection in view of the

continuity of observations at a single site. These observations were taken semimonthly in deep water southeast of the Bermuda platform (32°15′N, 64°30′W) by the Bermuda Biological Station's research vessel PANULIRIS. The records were processed and made available by the Woods Hole Oceanographic Institution.

The Lamont IGY tide gauge was operated from May 1957 to July 1961. For the remaining period of time corresponding to the PANULIRIS observations (January 1954 to April 1957, August 1961 to June 1962), we utilized the mean monthly sea-level data furnished by the U. S. Coast and Geodetic Survey from the records of the Bermuda Biological Station. The essentially constant difference between reduced monthly means for the two gauges justified use of these data.

The time cross sections of the hydrographic parameters for temperature, salinity, density, and the resulting dynamic depth anomalies are reproduced in Fig. 2; prolonged intervals of missing data are shown with interpolated broken lines. A log scale is used on the ordinate to preserve the important

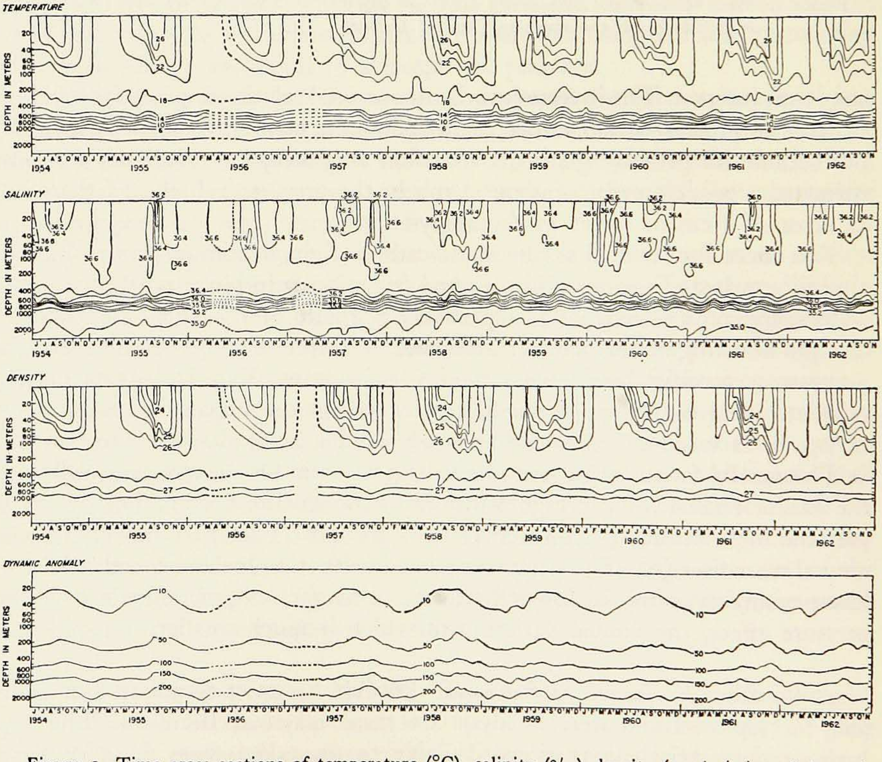


Figure 2. Time cross sections of temperature (°C), salinity (‰), density (10^{-4} g/cc), and dynamic depth anomaly (in cm) for Bermuda.

variations in the shallow layer. The water-temperature cross section clearly shows surface maxima in August–September and minima in February–March, the mean values for these peaks and troughs being 27.33° and 19.33°C, respectively. The annual maximum temperature wave in the ocean progresses downward at about 40 m per month and makes its deepest penetration to about 200 m in late January or early February.

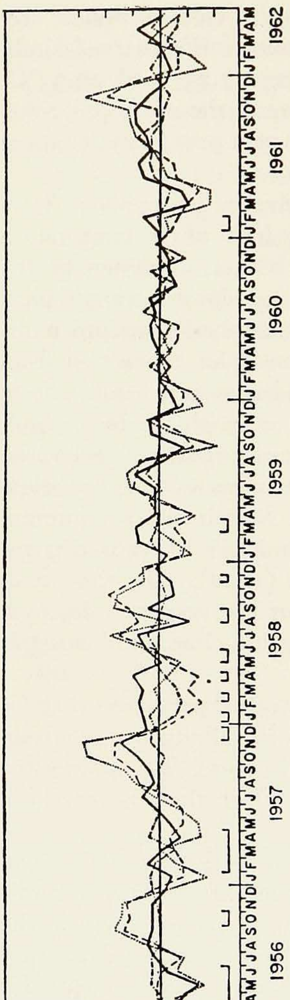
During the warmer months, an upper thermocline, averaging about 80 m in depth, slowly thickens with the downward propagation of the temperature wave. This is rather abruptly terminated in early winter, as shown by the vertical isotherms and lack of stratification. The strong winter mixing implied in these observations coincides with the regional atmospheric pressure minimum; the mixing is probably the result of storminess plus convection from surface cooling. The permanent stable thermocline begins just below 200 m at the 18°-C isotherm and descends to about 1000 m, with the lower limit at the 6°-C isotherm; below this level the temperature variation is even less.

The variation in salinity is shown in Fig. 2 in the cross section just below temperature. Its gross features are a maximum in March and a minimum in September. These local data agree well with Böhnicke's METEOR data for the Atlantic Ocean, as plotted by Sverdrup et al. (1942). The time cross section shows that salinity is well mixed throughout the year to a depth of about 300 to 400 m, below which there is a strong halocline terminating at about 1000 m.

The time cross section for density is nearly identical in pattern to that for temperature. The effects of salinity and variations in salinity are relatively weak, controlling only the details of the density structure. The pycnocline begins at about 400 m and ends at 1000 m, below which there is very little change in density with depth.

Using the data described in the first three cross sections, the National Oceanographic Data Analysis Center computed for us the resulting dynamic depth anomalies to a depth of 2000 m. The contoured values shown in the last time cross section of Fig. 2 represent deviations from standard pressure depths due to volume expansion; the ordinate is standard pressure depth for an ocean at 0°C and 35‰, with the approximate relationship that pressure in decibars is equivalent to depth in meters. The contoured values thus give corrections in centimeters for conversion of standard depths to true depths. The correction is invariably positive.

Because the time variations in the basic parameters are insignificant below 2000 m, the fundamental isostatic variations in sea level are produced in the upper 2000 m. To test this, we calculated the correlation coefficient between the dynamic depth anomaly at 2000 m and the anomaly at 1500 m, using 130 pairs of data. The result, 0.996, indicates that little change is produced by density variations between 1500 and 2000 m. It is reasonable to assume, then, that practically no effect comes from below that depth. Note that we



are concerned here with only the monthly variations in dynamic anomaly at a given depth and not with the absolute values. The steric sea-level variations are thus the changes caused by changes in dynamic depth anomaly.

To determine the steric anomaly or level, we simply determined the correction to be applied to the 2000-m standard depth for each month. This was accomplished by extracting the monthly means of dynamic-depth anomaly at 2000 m from the time cross section.

Finally, in order to determine any residual sea-level cycles related to water-mass transport, the isostatic terms involving steric and barometric effects (available on a continuous basis for Bermuda) were combined with the data for mean monthly deviations of raw sea level (raw sea-level anomaly). These data are given in Table 1 and plotted in Fig. 3; the solid line in Fig. 3 represents the monthly residual sea-level anomaly for the interval studied; the brackets show all intervals of missing data.

The experimental error in the determination of the residual sea-level anomaly is variable because it depends on both a constant and a variable source of error. Temperature measurements used in the steric-level determinations are considered accurate to $\pm 0.01\,^{\circ}C$, corresponding to ± 1 cm in level determinations. The variable source of error comes from the irregular time spacing of the serial observations, which achieved the desired semimonthly frequency during only 46 out of 96 months, with a range of from 0 to 4 observations per month during the other 50 months. We estimate that the resulting error from the necessary interpolation varies from less than 1 cm to as much as 5 cm. A possible but unevaluated source of error lies in the interpolation of densities to standard depths from the true

Figure 3. Time series of raw sea-level anomaly, barometric correction, steric anomaly, and residual sea level at Bermuda.

TABLE I. Data Used in the Determination of Residual Sea-Level Anomaly. All Values are in Centimeters.

1954	Raw Sea-level Anomaly	Steric Anomaly	Barometric Effect	Residual Sea-level Anomaly
Jun.	−11.58	−6.26	−2.30	−7.62
Jul.	−7.92	−1.26	2.73	−3.93
Aug.	−6.09	1.24	1.15	−6.18
Sept.	−4.87	6.24	.68	−10.43
Oct.	−6.40	9.24	.65	−14.99
Nov.	13.72	8.24	.30	5.78
Dec.	−4.88	−4.76	.47	.35
1955				
Jan.	−7.31	−11.76	−.85	3.60
Feb.	−2.74	2.24	3.64	−1.34
Mar.	1.83	3.24	.83	−.58
Apr.	−5.49	−4.76	−1.36	−2.09
May	−4.88	−2.76	.19	−1.93
Jun.	.61	4.24	−.86	−4.49
Jul.	−2.74	1.24	1.45	−2.53
Aug.	10.36	6.74	−.52	3.10
Sept.	18.90	24.24	.55	−4.79
Oct.	24.69	21.24	−5.41	−1.96
Nov.	11.58	12.24	−1.33	−1.99
Dec.	−3.35	4.24	−.85	−8.44
1956				
Jan.	−.91	−.76	−7.68	−7.83
Feb.	−10.66	−12.76	2.01	4.11
Mar.	−12.50	−7.76	.54	−4.20
Apr.	−5.49	1.24	−1.05	−7.78
May	−16.15	1.24	3.11	−14.28
Jun.	−6.10	−.76	2.74	−2.60
Jul.	−8.84	−7.76	3.03	1.95
Aug.	6.40	1.24	−.91	4.25
Sept.	16.46	13.24	−.31	2.91
Oct.	14.02	11.24	−.03	2.75
Nov.	13.72	12.24	.87	2.35
Dec.	−2.13	3.24	3.34	−2.03
1957				
Jan.	−17.37	−8.76	3.65	−4.96
Feb.	−6.40	−8.76	1.77	4.13
Mar.	−.48	−5.76	−5.61	−.33
Apr.	−15.24	−3.76	3.83	−7.65
May	−14.63	−8.76	1.53	−4.34
Jun.	−8.33	−8.76	−.07	.36
Jul.	1.83	−3.76	.53	6.12
Aug.	8.23	7.24	.33	1.32
Sept.	12.80	9.24	−.37	3.19
Oct.	26.21	16.24	−2.37	7.60
Nov.	27.43	16.24	2.63	13.82
Dec.	.61	−.76	2.63	4.00

(Cont.)

TABLE I (Continued)

	Raw Sea-level Anomaly	Steric Anomaly	Barometric Effect	Residual Sea-level Anomaly
1958				
Jan.	3.35	−8.76	−6.17	5.94
Feb.	−.30	−15.76	−8.07	7.39
Mar.	1.83	−10.76	−6.77	5.82
Apr.	−3.35	−14.76	−2.37	9.04
May	−7.62	−4.76	1.23	−1.63
Jun.	4.57	1.24	.73	4.06
Jul.	17.98	14.24	3.63	7.37
Aug.	−4.26	7.24	.63	−10.87
Sept.	16.15	11.24	−1.17	3.74
Oct.	15.24	18.24	−2.80	−5.80
Nov.	5.49	9.24	−.87	−4.62
Dec.	5.79	4.24	−.67	.88
1959				
Jan.	−11.89	−8.76	−.27	−3.40
Feb.	−5.18	−9.76	2.93	7.51
Mar.	1.52	−5.76	1.03	8.31
Apr.	−12.50	−13.76	.23	1.49
May	−.61	1.24	3.13	1.28
Jun.	10.67	9.24	−.27	1.16
Jul.	11.89	8.24	4.83	8.48
Aug.	5.18	7.24	.43	−1.63
Sept.	−21.95	−12.76	−.27	−9.46
Oct.	−5.18	−8.76	−.97	2.61
Nov.	4.27	1.24	.53	3.56
Dec.	−16.15	−8.76	.13	−7.26
1960				
Jan.	−11.89	−8.76	−1.07	−4.20
Feb.	−.61	−3.76	−3.27	−.12
Mar.	.91	3.24	−1.67	−4.00
Apr.	−3.96	−2.76	1.03	−.17
May	−1.52	−6.76	−2.87	2.37
Jun.	−4.26	−6.76	1.23	3.73
Jul.	5.49	6.24	2.03	1.28
Aug.	−.91	−1.76	2.63	3.48
Sept.	−6.10	−1.76	−1.17	−5.51
Oct.	3.05	2.24	−4.05	−3.24
Nov.	−9.45	−5.26	1.03	−3.16
Dec.	1.22	.76	−.67	−.21
1961				
Jan.	−3.05	−3.76	−.17	.54
Feb.	−1.83	−6.26	1.13	5.56
Mar.	−18.29	−9.76	−2.07	−10.60
Apr.	−18.29	−13.76	−3.57	−8.10
May	−2.44	−5.76	2.63	5.95
Jun.	−.91	−4.76	4.13	7.98
Jul.	2.74	2.24	2.63	3.13
Aug.	9.14	8.04	3.63	4.73

(Cont.)

TABLE I (Continued)

	Raw Sea-level Anomaly	Steric Anomaly	Barometric Effect	Residual Sea-level Anomaly
Sept.	10.97	1.24	−.93	8.80
Oct.	11.89	1.24	−1.51	9.14
Nov.	27.13	19.74	−3.20	4.19
Dec.	8.53	11.24	.66	−2.05
1962				
Jan.	−16.76	−8.76	3.99	−4.01
Feb.	−11.28	−8.76	.60	−1.92
Mar.	4.27	−2.76	−6.05	.98
Apr.	−.61	−5.76	3.51	8.66
May	−7.32	−7.76	−1.07	−.63

depth of observation. We have considered that the cumulative experimental error may vary from less than 1 cm to about 6 cm of water, but that the probable average error is not more than 3 cm.

The residual sea-level anomaly exceeds the expected maximum error (6 cm) in 20 of the 96 intervals. In nine of these cases, all or part of the month in question involved an interval of no data. The results exceed the average evaluated error in 65 of the 96 intervals.

At first glance the distribution of these anomalies in the time series suggests white noise due to various unevaluated sources of error and random sea-level

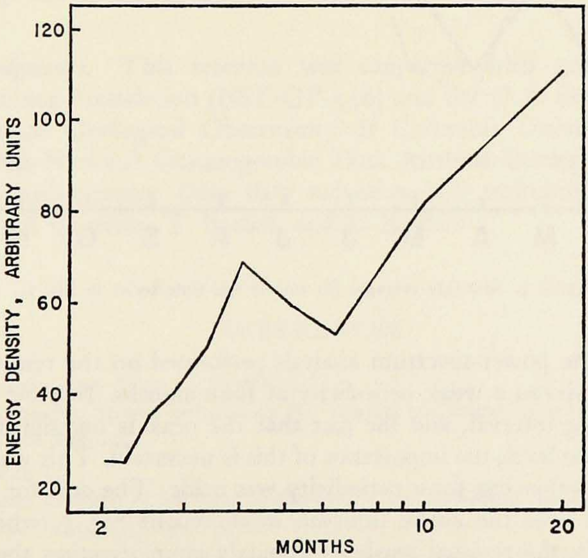


Figure 4. Power spectrum of residual sea-level anomaly.

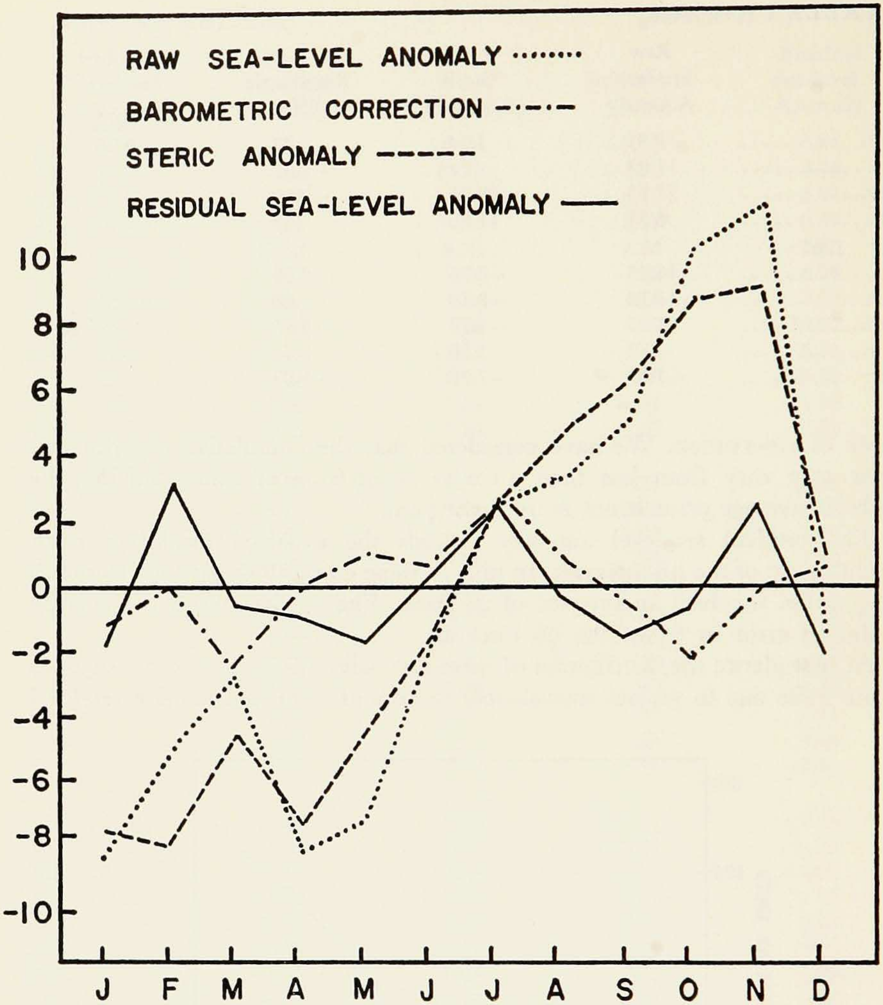


Figure 5. Monthly averages (in cm) of the time series in Fig. 3.

changes, but the power-spectrum analysis performed on the residual sea-level series (Fig. 4) shows a weak periodicity at four months. In view of the one-month sampling interval, and the fact that the peak is not significant at the 95% confidence level, the importance of this is uncertain. This was suggestive, however, so another test for a periodicity was made. The data for each month were averaged over the entire interval, as shown in Fig. 5, which indicates a periodicity in the residual sea-level anomaly approximating that shown by the power-spectrum analysis.

None of our results indicates an annual periodicity and we have no explanation for any possible 4-to-5-month cycle. Until a series of observations for a much longer period of time is available, it is doubtful if such a periodicity can be demonstrated with confidence.

In Fig. 3 it is evident, but in Fig. 5 much clearer, that most of the raw sea level is a consequence of the steric effect, with the barometric correction being relatively small. This is emphasized further in a comparison of the variability of raw sea level with that of residual sea-level anomaly as expressed by the standard deviation. The standard deviation of the former is 10.6 and that of the latter only 5.9.

5. *Comparison Between High and Low Latitude Stations.* Detailed study of two stations in high and low latitudes of the Atlantic Ocean tends to confirm previous results for the Pacific Ocean: (i) in low latitudes, the annual sea-level cycle is mostly a function of density changes in the upper layers of the ocean; (ii) in high latitudes, the annual variation is primarily dependent upon relatively large changes in atmospheric pressure.

The difference between the steric effects at high and low latitudes is very likely a function of the annual vertical temperature range in the oceans. For example, the surface waters near Bermuda have an annual range of about 8°C (19° to 27°C), whereas the surface-water variations in the Icelandic and Aleutian areas are about 2° and 4°C, respectively (U. S. Dept. of Commerce, 1959, 1961). At the lowest water layer affecting sea level, the temperature and its range are much the same in both zones.

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