SEASONAL VARIATION IN SEA LEVEL IN THE PACIFIC OCEAN DURING THE INTERNATIONAL GEOPHYSICAL YEAR, 1957-1958[1]

BY

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ABSTRACT

Seasonal variations in sea level derived from IGY measurements are described and compared with those previously published. These measurements confirm the earlier descriptions, which were based on observations from gauges attached mostly to continental coastlines. That is, in low latitudes in each hemisphere, sea level is high at the end of summer. There is a zonal band of high sea level from about the Equator to 40° N in September while in comparable southern latitudes sea level is low. Furthermore, north of 40° N there is a distinct change of phase; sea levels all around the Gulf of Alaska and the Aleutians are highest in December.

The following new information has resulted from the improved distribution of samples. First, sea level variations in the South Pacific are measurably smaller than those in the North Pacific. Second, the seasonal variation is appreciably larger near the continents than in the central oceanic regions of the northern hemisphere; this effect is virtually absent in the southern hemisphere. Finally, the December maxima found earlier in the Gulf of Alaska are now known to be far more widely distributed than previously thought.

In December, sea level is high from Bering Strait south to the central South Pacific and low nearer the coasts from Mexico to Chile and from southern Japan to Australia. Similar contours, but of opposite sign, appear in June.

Introduction. During the recent International Geophysical Year a widespread effort was made to extend and to improve the network of tide gauges over the oceans, with the primary aim of improving our understanding of seasonal variations in the elevation of the sea. The necessity for international co-operation and for at least a full

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year's observations is obvious. Fortunately, workable instruments (tide gauges) were readily available. More significant, though, is the fact that work done just prior to the start of the Year (Lisitzin, 1955; Pattullo, *et al.*, 1955) indicated that the seasonal variation in

sea level is sufficiently coherent over large areas in the ocean so that a grid, even of widely separated locations, could be expected to yield interpretable results. The principal difficulty in previous investigations had been the vast lack of data in midocean; tide gauges, like their human operators, are clustered principally along the coastlines of the more scientifically advanced nations of the world. To remedy this defect, we went to the islands. This paper describes results of these sea level measurements in the Pacific Ocean.

Locations of Observations. The Pacific Ocean contains several thousand islands, but by far the larger number of these are never visited by ships and are only occasionally touched by yachts, fishing boats, or other small craft. Operation of a scientific station in such a spot is difficult logistically, and expensive, and it is usually trying on the morale of the personnel who man it unless resident observers can be found. Therefore, wherever possible, inhabited islands, not impossibly cut off from normal transportation and communication facilities, were selected.

In the North Pacific, the U.S. Coast and Geodetic Survey has established a comprehensive and permanent network of tide gauge stations. There are unfortunate gaps in the grid, principally because there are no suitable islands in the north-central and eastern portions of the North Pacific Ocean. South of the Equator, island control is divided among many nations and here new gauges were installed for the IGY by Chile, France, Australia and New Zealand. At a few points installations were made by the Scripps Institution, for the United States, with the co-operation of the authorities and inhabitants.

Data from all gauges used in this paper are listed in Table I, and station locations are illustrated in Fig. 1.

Instrumentation and Operation of Stations. The difficulties of supply and supervision demanded that the instrument be reliable and simple, relatively easy to install and maintain, and operable by a

TABLE I. STATION LOCATIONS AND MONTHLY

No.	Place	Latitude	Longitude	Operator	Years	Zone
–	Ugolnyi	63° 02′N	179° 25′E	USSR	1945–54	–
C033	Yuzhno Kurilsk	44° 01′N	145° 52′E	UGGI	IGY	–
B070	Attu	52° 50′N	173° 12′E	USCGS	IGY	1
B100	Adak	51° 52′N	176° 39′W	USCGS	IGY	1
B056	Unalaska	53° 53′N	166° 32′W	UGGI	IGY	–
B015	Kodiak	57° 43′N	152° 31′W	USCGS	IGY	1
–	Sitka	57° 03′N	135° 20′W	USCGS	IGY	1
–	Crescent City	41° 45′N	124° 12′W	USCGS	IGY	1
–	San Francisco	37° 48′N	122° 28′W	USCGS	IGY	–
C407	La Jolla	32° 52′N	117° 15′W	USCGS	IGY	–
C240	Ensenada	31° 51′N	116° 38′W	UGGI	IGY	–
C271	La Paz	24° 10′N	110° 21′W	UGGI	IGY	4
C294	Mazatlan	23° 12′N	106° 25′W	UGGI	IGY	4
C295	Socorro I.	18° 44′N	110° 01′W	UGGI	IGY	–
C272	Manzanillo	19° 03′N	104° 20′W	UGGI	IGY	4
C305	Acapulco	16° 50′N	099° 55′W	UGGI	IGY	4
C307	Salina Cruz	16° 10′N	095° 12′W	UGGI	IGY	4
46	Balboa	08° 58′N	79° 34′W	PMRS	1909–46	4
47(1)	Talara	04° 35′S	81° 17′W	PMRS	1942–50	–
47(2)	Matarani	17° 00′S	72° 07′W	PMRS	1941–50	7
47(3)	Valparaiso	33° 01′S	71° 38′W	PMRS	1941–47	7
48	Puerto Montt	41° 29′S	72° 58′W	PMRS	1942–46	–
C937	Juan Fernandez	33° 33′S	78° 47′W	Chile	IGY	7
E712	Easter	27° 09′S	109° 29′W	Chile	IGY	6
C945	Rurutu	22° 27′S	151° 20′W	France	IGY	–
E739	Takaroa	14° 40′S	145° 05′W	France	IGY	–
–	Taiohae	08° 55′S	140° 06′W	France	IGY	6
52	Samoa	14° 17′S	170° 41′W	PMRS	1949–51	–
E467	Christmas	01° 57′N	157° 28′W	USCGS	IGY	3
E585	Fanning	03° 54′N	159° 24′W	SIO/UK	IGY	3
E574	Palmyra	05° 52′N	162° 06′W	SIO	IGY	3
E728	Arorae	02° 37′S	176° 50′E	SIO/UK	IGY	3
E620	Ocean	00° 53′S	169° 35′E	SIO/UK	IGY	3
E569	Kwajalein	08° 44′N	167° 44′E	USCGS	IGY	–
E563	Eniwetok	11° 22′N	162° 21′E	USCGS	IGY	2
E605	Moen	07° 27′N	151° 51′E	USCGS	IGY	–
E606	Koror	07° 20′N	134° 28′E	Japan	1925–33 1936–38	2
E556	Guam	13° 26′N	144° 39′E	USCGS	IGY	2
E534	Wake	19° 17′N	166° 37′E	USCGS	IGY	–
E545	Johnston	16° 45′N	169° 31′W	USCGS	IGY	3

DEVIATIONS FROM MEAN SEA LEVEL (cm)

J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
+ 1	− 1	−10	−12	− 8	−12	− 3	+ 2	+ 5	+11	+17	+12
+ 4	− 3	0	− 7	− 2	+ 2	+ 3	+ 4	+ 5	− 1	− 3	− 2
+ 4	+ 3	+ 2	− 2	0	− 8	− 8	− 2	0	+ 2	+ 6	+ 8
+12	+10	− 2	− 5	0	− 9	− 7	− 6	0	− 2	+ 2	+ 2
−10	− 9	+ 2	− 2	0	+ 2	− 3	− 3	+ 4	+ 1	+ 7	+12
+19	+17	− 9	− 6	−10	−14	− 8	− 2	+ 2	+ 2	+ 6	+ 7
+24	+21	− 8	− 6	−11	−18	−16	− 6	− 5	+ 2	+ 9	+17
+15	+26	+ 2	− 6	−12	− 8	− 8	0	− 4	+ 1	− 4	+ 3
0	+13	+ 3	− 3	− 7	− 5	− 3	− 1	+ 3	+ 2	− 4	+ 1
+ 2	− 3	− 5	− 8	− 9	− 7	+ 1	+ 7	+ 8	+ 7	+ 3	+ 5
− 3	− 6	− 8	− 8	− 7	− 2	+ 2	+ 7	+ 8	+ 9	+ 6	+ 3
− 8	−12	−13	−13	− 5	− 2	+ 8	+13	+16	+11	+ 8	− 1
− 8	−13	−15	−17	− 3	+ 3	+13	+11	+20	+ 1	− 8	− 1
− 7	− 6	− 3	− 1	+ 5	+ 4	0	− 3	+10	+ 5	0	− 4
− 2	−10	−12	−15	− 2	+ 2	+11	+ 8	+11	+ 3	+ 3	+ 2
− 2	− 8	−10	−10	0	+ 3	+11	+ 7	+ 7	− 1	+ 2	0
− 7	− 9	− 9	− 1	+ 4	+10	+10	+ 9	+ 8	− 2	− 3	−10
− 8	−18	−18	−11	+ 2	+ 7	+ 6	+ 5	+ 8	+11	+ 9	+ 6
+ 4	+ 6	+ 4	+ 3	+ 2	+ 2	0	− 3	− 5	− 5	− 5	− 4
+ 4	+ 3	+ 4	+ 2	+ 4	0	− 2	− 4	− 5	− 4	− 2	0
+ 3	+ 2	+ 3	+ 2	0	+ 2	− 1	− 1	− 4	− 5	− 3	+ 1
− 1	− 4	− 2	− 2	+ 2	+ 2	+ 2	+ 2	+ 2	− 4	+ 1	+ 2
+ 1	+ 6	+ 4	+ 6	0	+ 1	+10	− 3	− 6	−11	− 5	− 3
+ 2	+ 3	+ 3	+ 3	+ 2	− 2	0	− 1	− 3	− 3	− 2	+ 3
+ 8	+ 8	+ 1	+ 5	+ 6	+ 3	− 4	− 2	− 6	−10	− 3	− 4
0	+ 7	+ 6	+ 3	+ 2	− 2	0	− 2	− 2	− 5	0	− 1
+ 3	+ 2	+ 3	+ 1	+ 1	− 2	− 1	− 1	− 2	− 2	− 2	+ 2
− 2	+ 2	+ 4	+ 3	+ 3	− 2	− 3	− 4	− 2	− 1	− 1	+ 1
+ 3	0	− 5	− 6	− 4	− 7	− 2	0	0	+ 4	+ 7	+12
0	− 1	− 5	−10	−14	− 8	− 1	+ 5	+ 8	+ 9	+ 6	+16
+ 1	− 6	− 7	− 7	− 8	− 6	+ 1	+ 5	+20	0	+ 9	+ 3
− 4	− 2	+ 1	− 1	− 2	− 2	0	+ 2	+ 5	+ 3	+ 3	− 2
0	− 7	− 7	− 3	− 2	− 2	0	+ 1	+ 2	+ 6	+ 7	+ 6
−15	− 3	+ 4	+ 8	+ 5	+ 2	+ 4	+ 5	+ 3	+ 2	− 5	−11
−13	− 7	− 5	− 5	+ 4	+ 5	+ 7	+ 7	+ 5	+ 1	− 1	− 3
−16	− 8	+ 2	+10	+11	+ 7	+ 2	+ 1	+ 1	− 2	− 6	− 5
−15	−15	− 6	− 1	− 1	+ 4	+ 8	+10	+ 8	+ 9	+ 4	− 4
− 6	− 3	− 4	− 1	− 1	− 4	+10	+11	+ 7	+ 3	− 1	− 7
− 9	− 8	+ 2	+ 6	−12	− 2	+ 2	+13	+ 4	+ 1	+ 5	+ 2
+ 1	− 1	− 7	− 7	− 7	−16	− 4	+ 9	+11	+ 7	+13	+ 1

(cont.)

TABLE I. STATION LOCATIONS AND MONTHLY

No.	*Place*	*Latitude*	*Longitude*	*Operator*	*Years*	*Zone*
C288	Hilo	19° 44′N	155° 03′W	USCGS	IGY	3
C278	Honolulu	21° 18′N	157° 52′W	USCGS	IGY	3
C282	Kahului	20° 45′N	156° 28′W	USCGS	IGY	3
C408	Mokuoloe	21° 26′N	157° 47′W	USCGS	IGY	3
C275	Nawiliwili	21° 58′N	159° 21′W	USCGS	IGY	3
C262	Midway	28° 13′N	177° 22′W	USCGS	IGY	3
–	Hanasaki	43° 17′N	145° 35′E	UGGI	IGY	–
C178	Aburatsubo	35° 09′N	139° 37′E	UGGI	IGY	2
E499	Naze	28° 23′N	129° 30′E	UGGI	IGY	2
62	Takao	22° 37′N	120° 16′E	PMRS	1904–43	2
E552	Manila	14° 35′N	120° 58′E	UGGI	IGY	2
E607	Davao	07° 05′N	125° 38′E	UGGI	IGY	–
58a	Menado	01° 32′N	124° 50′E	PMRS	1927–31	–
55(1)	Port Moresby	09° 26′S	147° 06′E	PMRS	1939–40	5
55(2)	Guadalcanal	09° 25′S	159° 59′E	PMRS	1947–49	5
–	Cairns	16° 55′S	145° 43′E	UGGI	IGY	5
–	Townsville	19° 20′S	146° 50′E	UGGI	IGY	5
–	Gladstone	23° 53′S	151° 12′E	UGGI	IGY	5
–	Coff's Harbour	30° 20′S	153° 00′E	UGGI	IGY	–
–	Camp Cove	33° 53′S	151° 15′E	UGGI	IGY	–
C929	Lord Howe I.	31° 31′S	159° 07′E	UGGI	IGY	–
–	Williamstown	37° 52′S	144° 58′E	UGGI	IGY	–
–	Cape Sorrell	42° 13′S	145° 13′E	UGGI	IGY	–
70	Auckland	36° 51′S	174° 49′E	PMRS	1917–19, 1921–23, 1937, 1941	5
71	Bluff	46° 35′S	168° 22′E	PMRS	1917–22	–

TABLE I.

Number When available, the number designated by Comité Spécial de l'Année Géophysique Internationale has been used to identify the station. Stations for which data have been taken from Pattullo, *et al.* (1955) are given the number assigned to the station group by these workers. Several times an additional number is added in parentheses to distinguish between different members of the same station group. In some cases neither CSAGI nor PMRS numbers apply.

Place Name of city or island at which each tide guage was located.

Operators The operator or source of data are identified as follows:

USSR: data collected by Russian workers; transmitted to Scripps Institution by personal communication.

USCGS: stations operated by United States Coast and Geodetic Survey. Data obtained through World Data Center (A) Oceanography, A & M College of Texas.

PMRS: Data taken directly from Pattullo, *et al.*, 1955.

Chile: IGY stations operated by the National IGY Committee of Chile. Data transmitted to Scripps by the Chilean IGY Committee.

DEVIATIONS FROM MEAN SEA LEVEL (cm) (cont.)

J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
−8	−5	+1	−7	−2	0	−1	+4	+5	+7	+2	+1
−9	−2	−1	−7	−4	−4	+3	+5	+5	+6	+6	+2
−9	−2	−2	−6	−3	−1	+1	+4	+7	+6	+6	+2
−6	−2	+1	−8	−3	−5	+3	+5	+5	+7	+5	+3
−8	−5	−4	−2	−1	−6	+1	+1	+9	+8	+9	+3
+11	+12	−9	−15	−3	−5	−7	+1	+7	+5	+1	−1
+4	−2	+2	−4	−1	−2	+1	+2	+4	−1	−3	0
−8	−6	−6	−11	−2	+6	+6	+1	+8	+6	+5	+1
−14	−17	−20	−16	+3	+7	+17	+16	+18	+9	+3	−6
−13	−11	−7	−4	0	+5	+10	+13	+11	+7	0	−10
−12	−11	−8	−5	−1	+6	+10	+12	+17	+4	−4	−9
−6	−3	−3	+1	+4	+8	+8	+6	+5	+1	−2	−18
+1	−1	+3	+4	+1	0	+1	−3	−5	−2	−1	+2
0	+3	+10	+10	+10	+11	−5	−12	−5	−10	−6	−6
−4	−2	+3	+8	+10	0	−5	−4	−2	−1	0	−3
−4	+4	+10	+21	+4	+5	−7	−6	−9	−6	−8	−4
−4	+9	+13	+26	+5	0	−8	−7	−10	−10	−8	−3
−2	+7	+9	+14	0	+7	−3	−5	−9	−11	−5	−1
−12	−6	+6	+9	+13	+2	+6	−2	+1	−2	−10	−3
−6	+1	+10	+5	+12	+3	+1	−9	−8	−3	−5	−2
−5	−2	+23	+16	+11	−22	−8	−8	−13	−7	+6	+11
−18	−4	+1	+2	+12	+2	+6	−3	−2	+1	+3	−1
−8	−9	−3	−7	+23	+8	+11	−4	−3	−2	−1	−5
+2	0	+3	+2	+4	+5	0	−2	−5	−3	−5	−1
−5	+1	+6	+3	+1	−2	−2	−2	−4	+2	0	+2

EXPLANATIONS

France: IGY stations operated by National IGY Committee of France, in part with equipment and assistance from Scripps Institution. Data obtained directly from French IGY Officers in French Polynesia.

SIO/UK: stations operated by Scripps Institution personnel or island resident in co-operation with National IGY Committee of the United Kingdom.

Japan: stations operated by Japan; data provided by Japanese Hydrographic Department.

UGGI: Monthly means published by Union Géodesique et Geophysique Internationale.

Years Indicates the years during which observations were taken. IGY means 1957 and/or 1958.

Zone Area of ocean in which gauge is located; if gauge is close to a boundary between zones, no number appears in this column. See Fig. 5 and the discussion of this figure in text.

J, F, M etc. Monthly mean sea level minus annual mean sea level at the gauge, in centimeters. This quantity is referred to in the text as the "deviation."

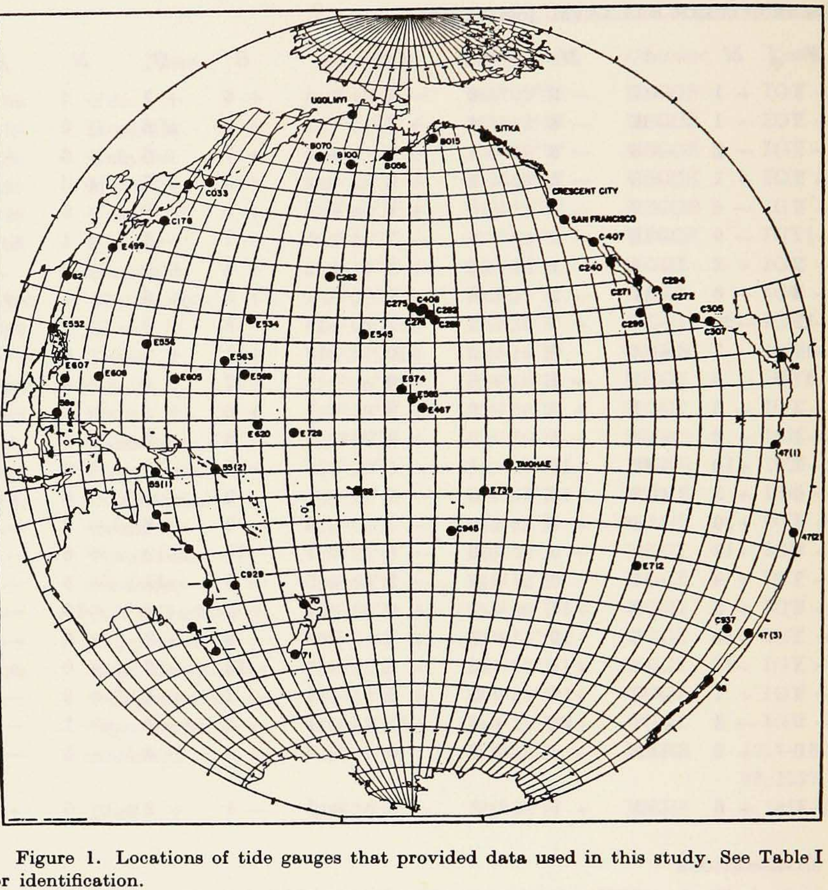


Figure 1. Locations of tide gauges that provided data used in this study. See Table I for identification.

semiskilled observer. Further, the data had to be such that, with reasonable care, they could be referred to a constant datum (reference level) throughout the observational period. Standard tide gauges, such as those used by the Coast Survey (Crouse-Hinds Instrument Co., or D. Ballauf and Co., manufacturers), or water level recorders made by Leupold and Stevens, Inc. filled these requirements, and both were used at various locations.

Operation was provided by local residents whenever possible. When this was not feasible, special technicians were maintained on the islands, at least until residents could be trained. In almost all cases the observers donated all or part of their efforts generously without reimbursement. This and the exceptionally high level of international co-operation achieved were the deciding factors in making the observational program a success. Details of the trials and ingenuity of the operators at each station are impressive and they will be included in a mimeographed data report.[3]

Results. The seasonal deviation of sea level from its annual mean is illustrated in Fig. 2 by four quarterly contour charts. Wherever available, values from the IGY data are used for these charts; most of the values are from this period. Where IGY data have not become available or are lacking, data from earlier years have been used, but these instances are few. The problems raised by this combination of IGY and non-IGY data will be mentioned later.

Let us look first at the chart centered around September (Fig. 2a). Note particularly the unbroken zone of higher-than-average sea level across the entire ocean from Asia to North America and from near the Equator to about 45° N. Zero deviation lines run east-west nearly along the Equator and on a line slightly northwest-southeast at 45° to 55° N. Outside of this band, *i.e.*, north of 50° N and south of the Equator, all deviations are negative. There is a slight indication of another zero deviation line to the south of the sampled region: Puerto Montt, Chile, at 40° S, has a slight positive value, and gauges on New Zealand and southern Australia show only small negative values.

In addition to this principal feature we note that the coastal deviations, at least in the northern hemisphere, are a little larger than those out at sea. We have a band of high sea level from Japan to North America, but the level tilts up as the coastal edges are approached. Note also that the deviations in the southern hemisphere are generally smaller than those in the northern and that the near-shore deviations here are not particularly larger than those offshore.

We can make nearly the same remarks about the chart for March (Fig. 2c) as we did for the September one, except that now the areas that had positive deviations had negative ones, etc. The two pictures are nearly mirror images of each other.

When we turn to the remaining pair of charts we find an immediate difference. Again the deviations are appreciable, but instead of east-west contours the isolines run largely north-south. For example,

[3] Island Observatories, Pacific, available from World Data Center (A), Oceanography, A. and M. College of Texas.

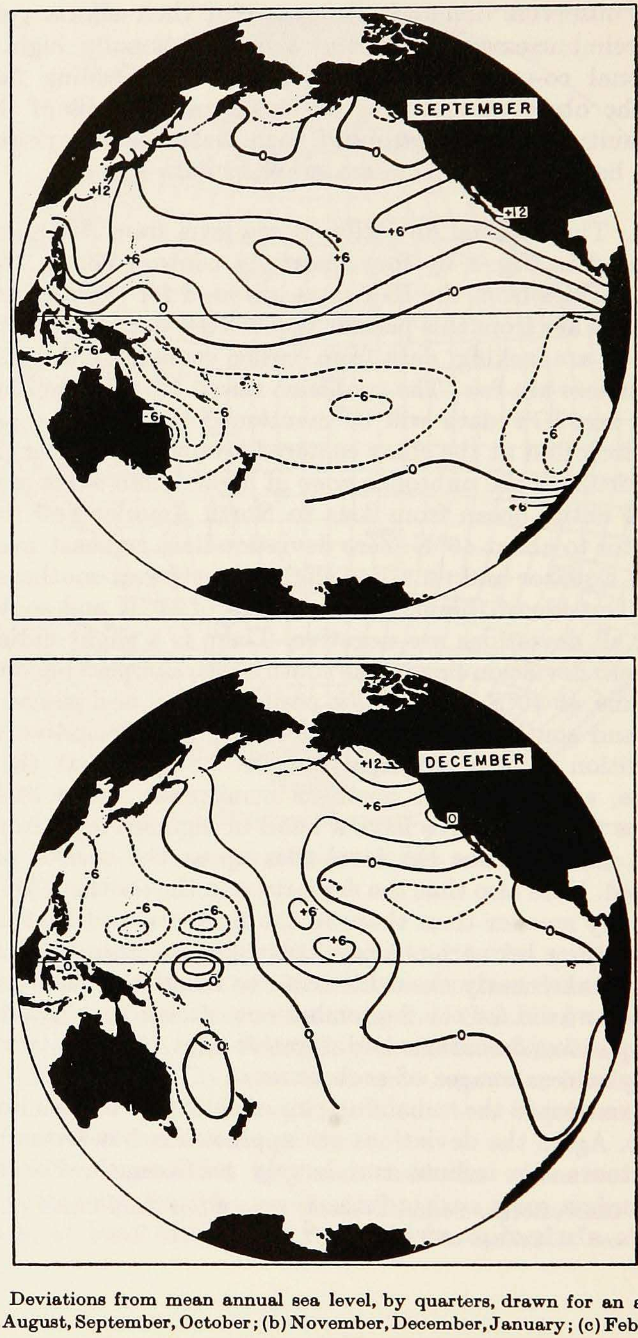
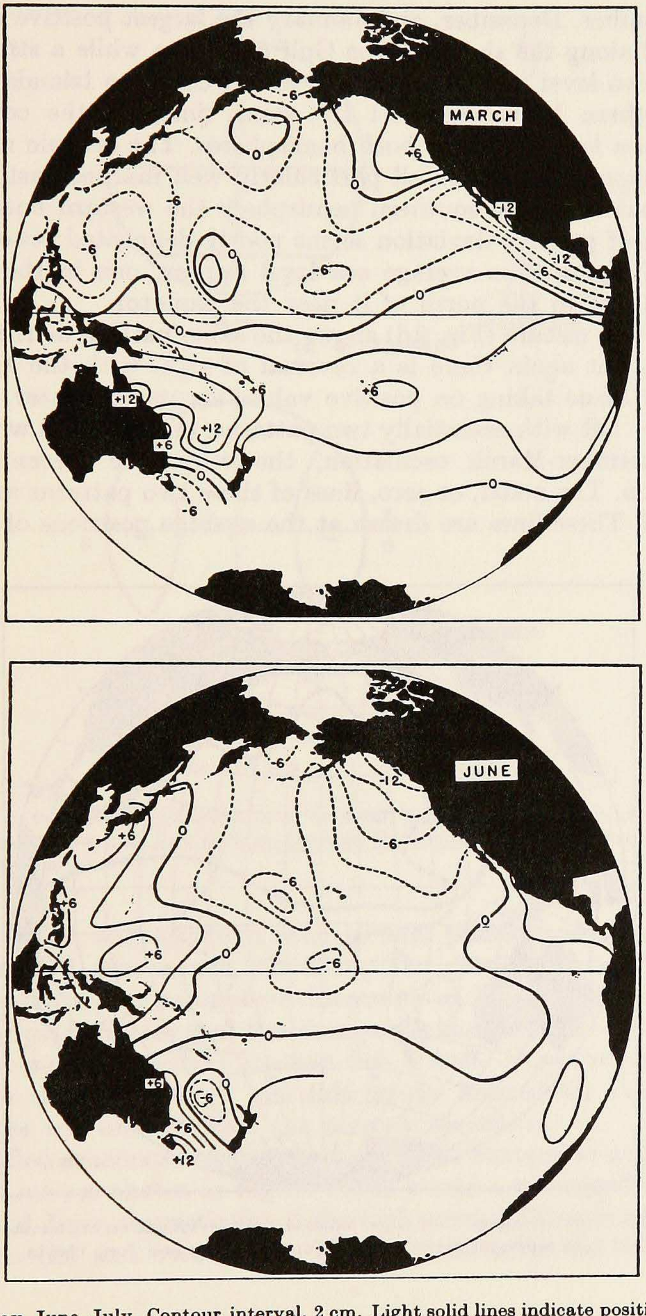


Figure 2. Deviations from mean annual sea level, by quarters, drawn for an average of all values in: (a) August, September, October; (b) November, December, January; (c) February, March,



April; (d) May, June, July. Contour interval, 2 cm. Light solid lines indicate positive deviations (higher than annual mean); dashed lines negative deviations; heavy solid lines zero deviations.

in November, December, and January the largest positive deviation is found along the shores of the Gulf of Alaska while a strong ridge of high sea level sweeps southward across the Line Islands and into the southern hemisphere. At the same time, off the continental coasts, sea level is low in both hemispheres. The oceanic maximum and offshore minima are all particularly well marked just north of the Equator. In the southern hemisphere the western boundary of the area of positive deviation seems poorly delineated; two isolated areas of higher-than-average sea level appear, one in the Tasman Sea and one to the north of it near the Equator.

The June picture (Fig. 2d) shows the same pattern as the December one, but again there is a reversal of sign, with the December negative areas taking on positive values six months later.

We are left with essentially two patterns, one of which we can call the September-March oscillation, the other the December-June oscillation. The nodal, or zero, lines of these two patterns are shown in Fig. 3. These lines are drawn at the average positions of the zero

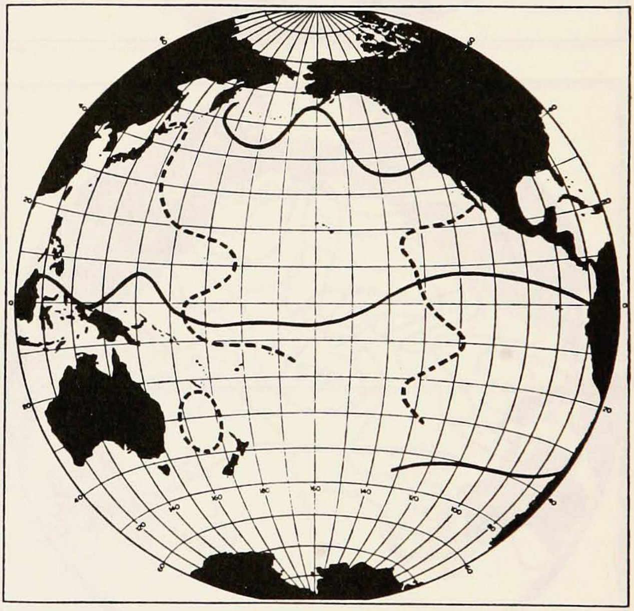


Figure 3. Zero deviations. Solid lines indicate zero deviations on September and March charts; dashed lines represent zero deviations on December and June charts.

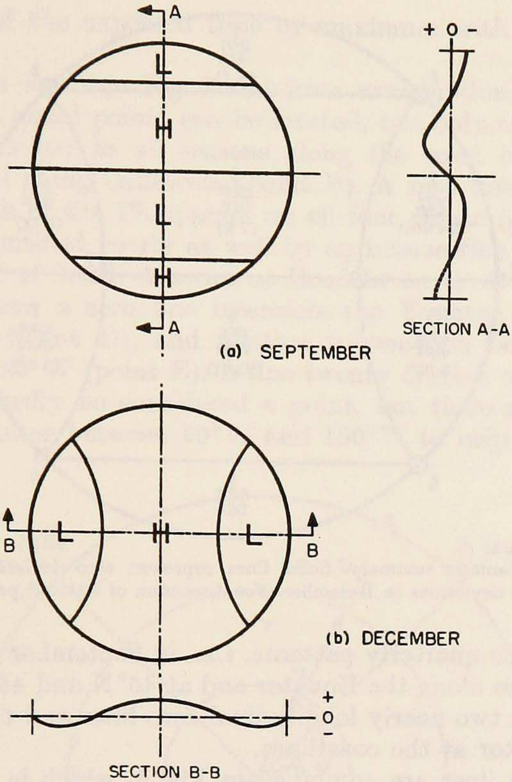


Figure 4. Schematic representation of seasonal variation in sea level. (a) September plan and elevation section looking from the east; (b) December plan and elevation section looking from the south.

lines of Fig. 2, and although their general positions and trends can be considered determined, obviously the details cannot be given much credence. For example, evidence given by Hamon and Stacey (manuscript) indicates that the change of phase between the Australian coast and the central Tasman Sea is real. However, since it is based on data from only one tide gauge located on Lord Howe Island, we will omit it from the present discussion.

Simplified schematic representations of the September and December patterns are shown in Fig. 4. These would serve equally well for March and June, respectively, if the high areas (H) were replaced by low areas (L) and vice versa. They include only the most basic

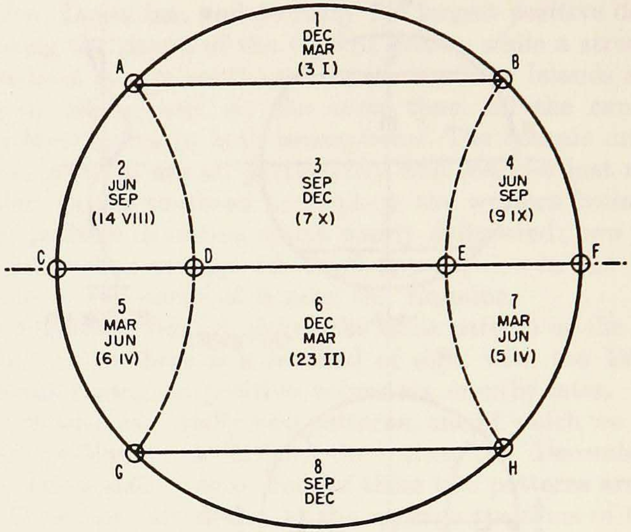


Figure 5. Schematic summary. Solid lines represent zero deviations in September; dashed lines zero deviations in December. For discussion of lettered points, etc., see text.

features of the quarterly patterns, *i.e.*, in September there are east-west zero lines along the Equator and at 45°N and 45°S; in December there are two nearly longitudinal zero lines and two zero points on the Equator at the coastlines.

These zero lines are combined in Fig. 5, which is the schematic representation of Fig. 3. According to this model there are eight nodal points, lettered A to H, where the deviation in sea level is zero during *all four quarters of the year*. Also, since the equinoctial nodal line on the Equator bisects the solstitial nodal lines, the model ocean is divided into eight zones, two each of four possible kinds. Sea level is high in both December and March in zones 1 and 6, high in June and in September in zones 2 and 4, etc. The two quarters of high level are always successive, of course, according to our postulate that where sea level is high in one quarter it is low two quarters later. The quarters of high level are indicated by the names of the months lettered in each zone; the earlier of the two is given on top. We say, for example, December to March, *not* March to December.

We can examine the usefulness of this model as a description of the variations in two ways: (1) verification of the nodal points, and (2) comparison of the expected time of maximum with the observed time.

As one can see from Fig. 3 and from examination of the charts in Fig. 2, the nodal points can be located, but only approximately. Variations are low at all seasons along the coast of Kamchatka (point A) and along California (point B). A zero line lies near the Equator south of the Philippines on all four charts (point C) while point F is identified nearly as well by an intersection of a zero line and the coast of South America at Ecuador on three of the charts. In every season a zero line intersects the Equator just north of Guadalcanal (point D), and another intersection occurs between 140° W and 120° W (point E). A line twenty degress of longitude in extent can hardly be considered a point, but there are no islands near the Equator between 90° W and 150° W to help us locate the

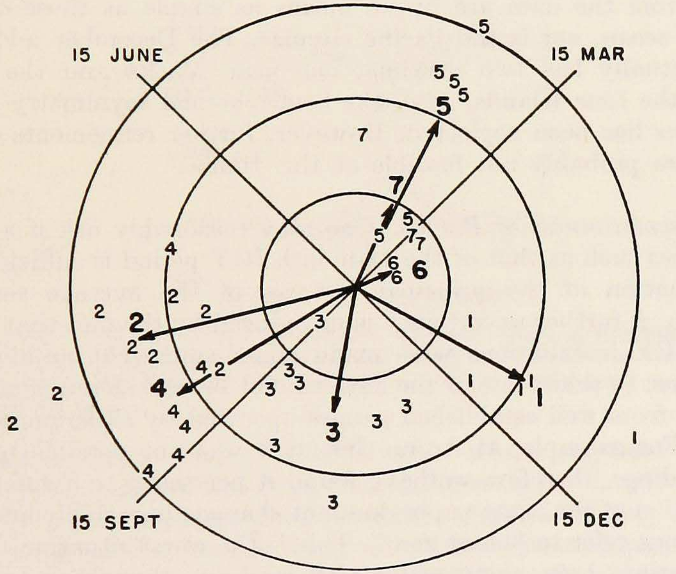


Figure 6. Phase and amplitude of the annual term for all localities within each zone. Date of maximum is given by angular position: 15 March at top right, 15 June at top left, etc. Amplitude is indicated by distance from center; the concentric circles show amplitudes of 5, 10 and 15 cm. Each small number represents one locality within the zone indicated, excepting Hawaii, where all five gauge results were averaged before the harmonic analysis was made. Vectors show mean phase and amplitude for all localities within the zone (vector mean); the zone to which each applies is indicated by the large number placed near the end of the vector.

intersection more accurately. Points G and H can be neither determined nor rejected with the present distribution of data.

Harmonic analyses of the data from each gauge lying within the zones were made, zones being delineated according to Fig. 3. Gauges lying on or near nodal lines were omitted; zone numbers as assigned are given in Table I. The vector mean date of maximum for the annual term for each zone is shown in parentheses in Fig. 5 and plotted as a vector in Fig. 6. From Fig. 5 we see that the time of maximum so computed lies within the expected months in all seven zones where data were available. Fig. 6 illustrates the fact that not only the vector means but the individual station vectors as well agree with the expected times of maxima. We conclude that the schematic model is an adequate if not complete summary of the seasonal sea level variations in the Pacific Ocean during the IGY.

This simple model has certain obvious weaknesses. The nodal lines drawn from the data are by no means as simple as those on our circular ocean, nor is the Pacific circular. The December midocean ridge actually has two maxima, one near Alaska and the other around the Line Islands. Also, the hemispherical asymmetry of the variations has been neglected. However, further refinements of the model are probably not feasible at this time.

Representativeness of Results. One may reasonably ask if a short time-series such as that of the 18-month IGY period is sufficient for determination of the principal features of the average seasonal variation. A further uncertainty is introduced by the fact that many of the IGY installations were made under somewhat unfavorable conditions, so that some of the data cannot be considered as reliable as those from well established gauges operated by experienced personnel. For example, at Arorae Island it was not possible to take staff readings, therefore we have found it necessary to assume that the position of the chart paper does not change appreciably and that all readings refer to "chart zero". This is the worst situation, for all other stations have comparative staff readings, though on occasion parts of the records are missing and other difficulties have occurred.

An estimate of the representativeness of the IGY data may be obtained from the five samples shown in Fig. 7, each representing a different zone among the eight illustrated in Fig. 5. There is by no means exact agreement; month-to-month changes are appreciable and sometimes erratic, and the range of heights observed at each

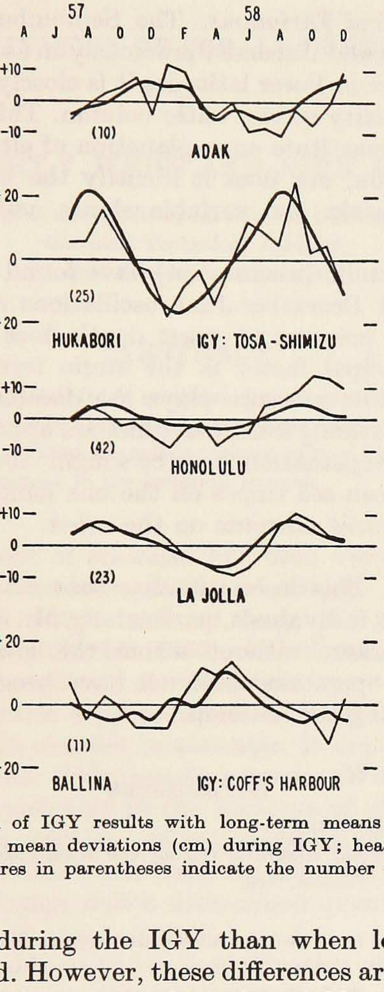


Figure 7. Comparison of IGY results with long-term means at five localities. Light solid lines show monthly mean deviations (cm) during IGY; heavy lines show long-term monthly means. The figures in parentheses indicate the number of years used in finding the long-term mean.

location is larger during the IGY than when long-term monthly means are compared. However, these differences are exactly what one expects when measuring climatological variables for only one year, and we can see that the phase and amplitude relationships among the stations were much the same during the IGY as they were found to be from the long-term means. This implies that combination of and comparison of data from different years is probably permissible, and we can state with some confidence that the patterns shown in Fig. 2 are typical of the average seasonal variations in sea level although neither the details nor the relative slopes indicated should be given any credence.

Causes of Observed Variations. The September-March oscillation has been described and discussed previously in some detail (Pattullo, *et al.*, 1955); at least in lower latitudes it is closely related to seasonal changes in the density of the water column. This close relationship does not in itself constitute an explanation of either the recorded or the steric oscillation, nor does it identify the forces that must be operative to maintain the variable slopes associated with these oscillations.

Lisitzin and Pattullo (manuscript) have found that both the September-March and December-June oscillations are isostatic in the open ocean (total pressure at great depth does not vary). In low latitudes the principal factor is the steric term whereas in high latitudes atmospheric pressure plays the dominant role. However, the large deviations along some coastlines are apparently not isostatic and an additional explanation must be sought; it probably lies in the relationships between sea slopes on the one hand and the effects of winds and nonisostatic currents on the other.

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