On the Geostrophic Flow at the Surface of the Pacific Ocean with Respect to the 1,000-decibar Surface

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(Manuscript received December 2, 1960, revised version July 18, 1961)

Abstract

The geopotential anomaly at the surface of the Pacific Ocean with respect to the 1,000-decibar surface is computed. Horizontal variations in geopotential at greater depth are shown to be smaller and are neglected. The geostrophic flow at the sea surface with respect to the 1,000-decibar surface is shown to agree in general with the averages of currents estimated from the set and drift of vessels and tabulated in various atlases. The major gyres of the ocean are clearly shown and one new feature, a South Equatorial Countercurrent, is revealed in the western Pacific.

Since there is meridional flow in the ocean, the flow is not entirely geostrophic and the contours of geopotential anomaly may lie at some angle to the streamlines. This is most evident where the contours intersect the coast and cross the equator. A qualitative consideration of wind stress indicates that where wind and current are in the same direction geopotential anomaly will rise along a streamline and where they are opposed geopotential anomaly will decrease along a streamline. This effect can at least qualitatively account for the rise of geopotential anomaly to the west in the region of the trades and toward the east in the northern hemisphere westerlies.

Introduction

For several decades oceanographers have been making some use of the geostrophic relation to estimate flow in the ocean. Although a few systematic attempts have been made to compare the geostrophic flow with other current measurements, they have generally been confined to small areas and short periods. WÜST's (1924) comparison of geostrophic flow in 1914 in the Florida Straits with direct measurements in the period 1885 through 1889 is the classic example in the literature. It deals with a very fast flow in a narrow, shallow passage with a sharply sloping reference surface. Although the agreement is excellent, it does not follow that a useful reference surface can always be chosen or that relative velocities in the slower moving deeper ocean will always be so accurate.

Of the various charts and studies of the geostrophic current in the Pacific, the only chart covering the greater part of the area was that prepared from the CARNEGIE data (FLEMING AND OTHERS, 1945), but the data were too sparse to permit a detailed study of the circulation. Other large areas were studied by UDA (1955), MAO AND YOSHIDA (1955), DOE (1955) and DODIMEAD (1958).

In this paper it seemed worthwhile to compare the geostrophic flow of a substantial part of the ocean with the long-term averages of set and drift of vessels. The results are encouraging, and they imply that in certain areas where other data are lacking (Bering Sea, central South Pacific) the geostrophic currents can be accepted with some confidence. In particular, the indication of a geostrophic

South Equatorial Countercurrent in the western Pacific is of interest. Since the rest of the equatorial current system is found in the geostrophic system, this may be accepted as a real current.

1. The geostrophic approximation

Although the variation of the geopotential difference between two pressure surfaces may be interpreted in various ways, such as the slope of the sea surface under wind stress or a simple comparison of the average sea level and density of different areas and oceans, its most common interpretation is in terms of the geostrophic current.

If certain terms are neglected, the equations of motion may be written

$$\alpha \partial p / \partial x = fv + \alpha \partial \tau_x / \partial z \qquad (1a)$$

$$\alpha \partial p / \partial y = -fu + \alpha \partial \tau_y / \partial z \qquad (1b)$$

$$\alpha \partial p / \partial z = -g \qquad (1c)$$

where x, y, and z are directed toward the east, the north, and upward, u and v are the velocity components toward east and north, α is specific volume, f is the Coriolis parameter $2\,\omega \sin \phi$ (ω the earth's angular velocity, ϕ the latitude), p the pressure, and τ_x and τ_y are the vertical shearing stresses.

The geostrophic approximation neglects the friction terms in equations (1a) and (1b). The anomaly of the geopotential difference between the 1,000-decibar surface and the sea surface is determined from (1c) and shown in Figure 1. The gradient of the anomaly is then used to estimate the geostrophic flow for comparison with various atlases (Section IV). It is well to point out that although the neglected terms are usually small compared with those retained and (as will be seen) the geostrophic current may be at any place approximately equal to the actual current, the neglect imposes certain important limitations which lead to more or less obvious contradictions.

2. The data

The data used in Figure 1 are listed in the appendix. Among these were the three co-operative expeditions NORPAC (June—October 1955), EQUAPAC (July—November 1956) and EASTROPIC (September—December 1955), each of which attempted to obtain an approximately isochronal sampling of the hydrography of the upper 1,000 meters over large areas of the Pacific.

Most of the northern observations were made in northern summer and the southern observations in southern summer, but there probably remain some artificial features on the chart which are the result of seasonal and nonseasonal variations of the hydrographic regime.

3. The reference surface

The 1,000-decibar surface was chosen as a reference because most of the NORPAC, EQUAPAC and EASTROPIC measurements did not reach much deeper, and these were the most suitable materials for an isochronal treatment. Since all of the results are to be referred to the 1,000-decibar surface, it is necessary to describe at least approximately its variation with respect to some deeper surface. From the CARNEGIE, DANA, DISCOVERY, TRANSPAC, SNELLIUS, NORPAC, VITYAZ 25 and 26, OB 3, DOWNWIND, MUKLUK, and CHINOOK materials a chart of the geopotential differences between the 1,000- and 2,000-decibar surface was prepared. Its details will not be discussed here other than to say that it had a systematic variation somewhat similar to the shallower chart, but that the range of variation was much less. North of 50° S the total range is about 0.22 dynamic meters, and over the whole Pacific the range is about 0.50. The range of the geopotential difference in the upper thousand decibars north of 50° S is 1.40, or six times as great, and over the whole Pacific is 2.00, or four times as great. With these limitations in mind the anomaly of geopotential difference between the sea surface and the 1,000-decibar surface will be discussed as if it represented north of 50° S the actual shape of the sea surface.

4. The surface currents

A. *Direction*

The conventional descriptions of surface currents are derived from measurements of set and drift of ships compiled into atlases and from versions of these that have been smoothed and elaborated by various authors, in particular Schott (1935).

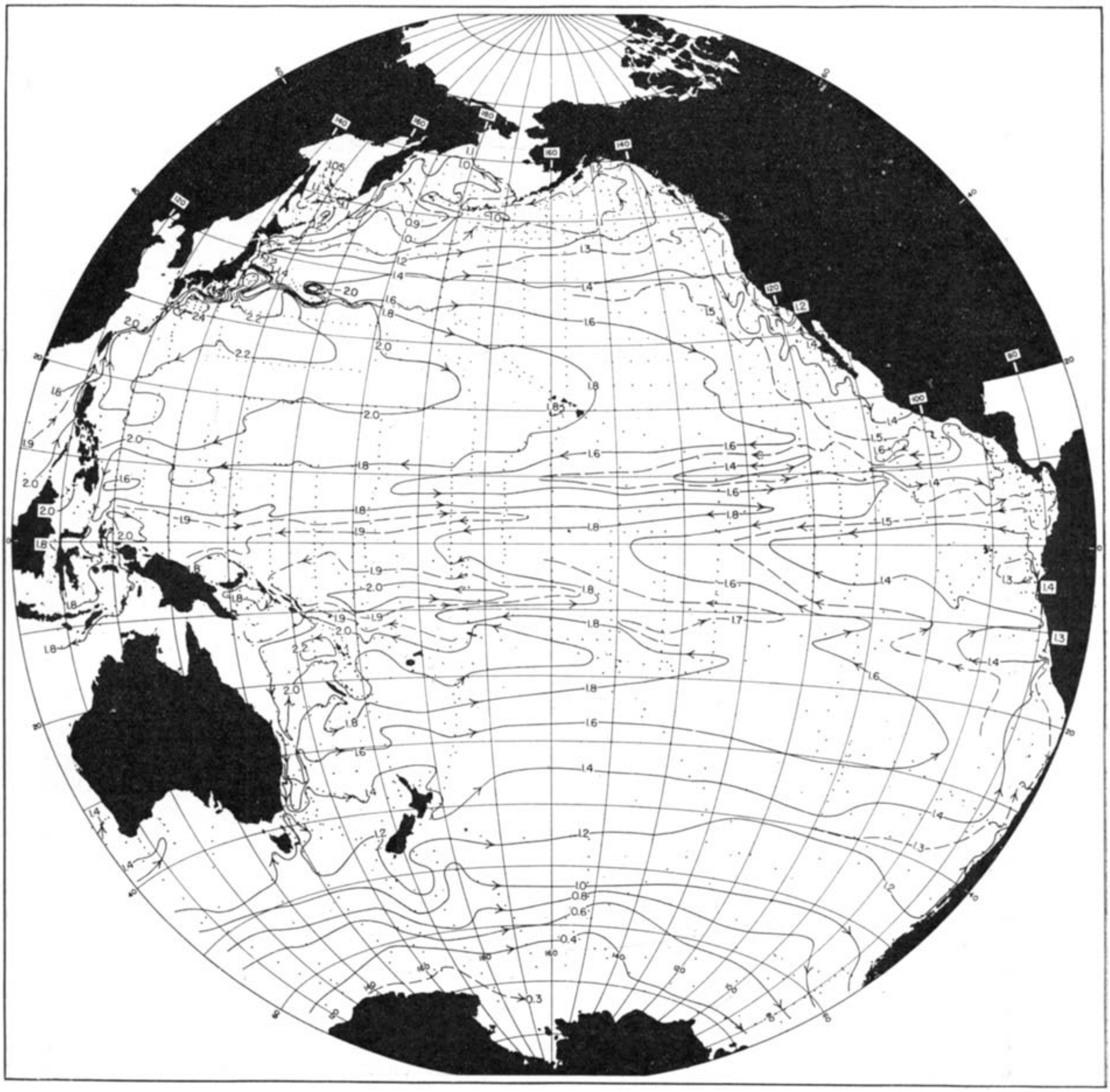

Fig. 1. The anomaly of geopotential distance betweenthe zero- and the 1,000-decibar surfaces in the Pacific Ocean, in dynamic meters.

The major surface currents of the Pacific Ocean as given in the atlases are all indicated by the field of geopotential anomaly. The northern subtropical anticyclone, and its components (the Kuroshio Current, the west wind drift, the California Current, and the North Equatorial Current) are all indicated by the appropriate direction of the contours.

The southern subtropical anticyclone, which consists of the East Australia Current, part of the west wind drift, the Peru Current, and the South Equatorial Current, is also quite clearly defined. The geographical variation in slope of the sea surface is about the same as in the northern gyre except that across the East Australia Current it is not so great as across the Kuroshio.

Along the coast of South America there is a well-defined equatorward eastern boundary current. To the south there is some evidence of a poleward flow analogous to the poleward flow along Canada and Alaska. The data do not give an explicit answer, and the Atlas of Pilot Charts (U.S.N.H.O., 1950) gives only marginal evidence of such a poleward flow.

The northern high-latitude cyclone, which consists of part of the west wind drift, the Alaska Current and the Oyashio Current, is also quite clearly defined, as is the great circumpolar flow of the Southern Ocean. In these data little evidence is found of any westward flow along the coast of Antarctica.

In the equatorial region the west-flowing currents are seen to be separated by the east-flowing (North) Equatorial Countercurrent, and an east-flowing current south of the equator, equally well-defined in these data in the western ocean. If this slope downward to the south is geostrophically balanced, then there is an eastward flow in this region, approximately symmetrical to the (North) Equatorial Countercurrent (REID, 1959). It is strong in the west and becomes weaker toward the east. The data in the eastern Pacific are not spaced in a fashion to answer very well whether it extends to the longitude of the Galapagos Islands, but there is a suggestion of a weak eastward flow almost that far. The various atlases of sea surface currents are of limited value in this region because the data are so sparse. The *Current Charts of the Southwestern Pacific Ocean* (U.S.N.H.O., 1944a) show an average of about one observation per month per one-degree square in the region between 5° and 10° S and between New Guinea and 165° W. The monthly pilot charts (U.S.N.H.O., 1950) show no good indication at any time of year of an eastward flow at 10° S in the eastern Pacific.

The charts prepared by the AIR MINISTRY (1939) include all of the South Pacific Ocean by seasons. An eastward flow at 10° S is seen from November through April starting from the Solomon Islands. It reaches 140° W on the November through January chart, when some west winds are indicated at 10° S in the western Pacific (McDONALD, 1938), and 160° W on the February through April chart. Although this chart includes the Southeastern Pacific there are areas covering more than 20 degrees of latitude and longitude which contain no data. The triangle with corners at 1° S and 55° S on the American coast and at 50° S 158° W contains practically no data at all except in a narrow band along the coast of South America.

The distribution of eastward flow near the equator (Figure 1) is not entirely inconsistent with the conventional concept of the countercurrent as a return flow in the doldrums. The data on Figure 2 reveal that when wind stress is averaged all across the ocean throughout the year the doldrums are centered very nearly at the equator. But if the area is broken into eastern and western parts at the 160° W meridian, then the average doldrums position is found about five degrees north in the eastern part and five degrees south in the western part. In the west the doldrums are even weaker in the southern part than in the northern part.

The seasonal variation of the winds is such that in the eastern Pacific the doldrums are, on the average, north of the equator in all seasons. In the west, however, the average position of the doldrums is slightly north of the equator in the season June through August.

The eastern doldrums do lie very near the equator in the season December through February when minimum wind stress computed by HIDAKA (1958) at five degree intervals is at 2.5° N. It is possible that this south equatorial countercurrent extends farthest eastward at this period and in some years might carry warm central-ocean water across the cold Peru Current to the coast. It might thus be the source of the warm water phenomenon known there as *El Niño*, which occurs occasionally in December or January.

Over large areas, however, the limitations of the geostrophic approximation are obvious. That the contours alone do not describe the flow at the equator is to be expected; the arrowheads are placed there to emphasize the discontinuity. But even in higher latitudes only a few of the contours are closed curves; the others begin and end at the continents.

B. *The speed of the surface flow.*

The Figure 1 is a graphical interpretation of the computed values of geopotential anomaly. A few of the points have been violated by one dynamic centimeter in the interest of smooth-

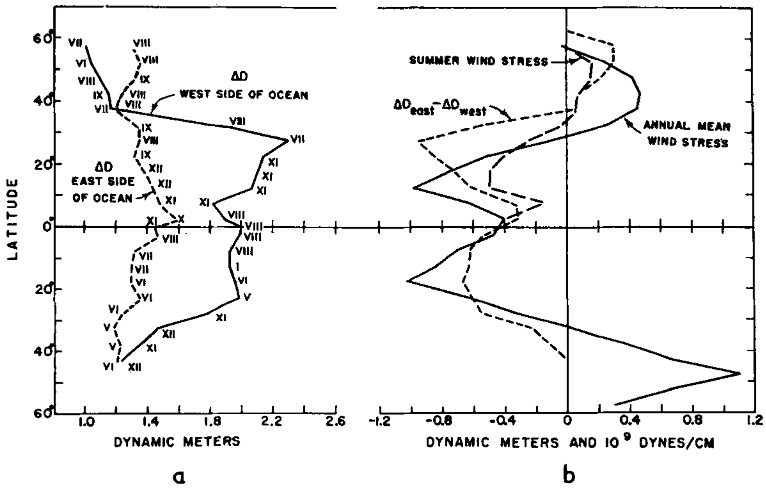

Fig. 2. a. The anomaly of geopotential distance (ΔD) between the zero- and the 1,000-decibar surfaces along the eastern and western sides of the Pacific Ocean, in dynamic meters. The western side is taken here to be Kamchatka, the Kurile Islands, Japan, and Ryukyu and Philippine Islands, New Guinea and Australia. Roman numerals indicate the month in which each datum was taken.

b. Difference in geopotential anomaly at the eastern and western boundaries of the Pacific Ocean, and the total zonal wind stress (dynes per cm of latitude) across the Pacific Ocean.

ness. Wooster and Taft (1958) have estimated the errors in measurement of temperature, salinity, and depth and concluded that they result in a standard error of 0.004 dynamic meters in the geopotential anomaly at the sea surface with respect to 1,000-decibars. This is much less than the periodic and non-periodic variations reported by Reid (1956), in which values differing by as much as 0.08 dynamic meters were found at one position one week apart. The data on Figure 1 suggest that such wide fluctuations are rare, since the field is relatively free of local disturbances of this order over most of the area. Because there is some roughness which may not be real, the geostrophic speeds in the following discussion have been measured from the spacing of adjacent contours rather than from the difference from station to station within the two contours.

A comparison of the geostrophic speeds with the atlases (U.S.N.H.O., 1944b and 1947) has been made and the results are summarized as follows.

1. In the Kuroshio the geostrophic speed of 1.3 to 1.6 knots is slightly higher than most of the atlas averages. The averages may have been damped by the shifting of the axis of the stream (Masuzawa, 1957, and Fukuoka, 1958).

2. In the slower west wind drift and California Current the agreement is to about 0.1 knot, averaged over large areas.

3. In the North Equatorial Current the agreement is to about 0.1 knot averaged over large areas except in the west where Figure 1 shows a southward shift of the main stream, resulting in a reduction in speed at about 15° N of 0.4 knot.

4. The northward flow past Formosa is computed as about 1.3 knots, while the atlas average is about 1.15.

5. The westward flow south of the Aleutian Islands appears to be about 0.1 knot, from both methods.

6. In the southern part of the Oyashio Current the atlas indicates about 0.2 knot to the east, but the geostrophic flow, as contoured, is about 1 knot.

7. In the (North) Equatorial Countercurrent at latitudes below 5° and in the westward flow nearer the equator the geostrophic speed is consistently higher than the atlas speed.

5. The effect of wind stress

One consequence of the neglect of the other terms (probably, in this case the stress associated with the vertical shear of velocity) is that the difference in geopotential anomaly between the eastern and western sides of the ocean (Figure 2) must be interpreted as north-south flow at the surface. In Figure 2 a mean equatorward flow is indicated between 37° N and 42° S, and a mean poleward flow north of there.

Along the east side of the ocean (Figure 2a) the geopotential anomaly is greatest near the equator. This is in accordance with what one might expect from the latitudinal distribution of solar radiation. Along the west side (here defined as Kamchatka, the Kurile Islands, Japan, the Ryukyu and Philippine Islands, New Guinea and Australia) the variation is much greater, with maxima near the tropics as well as at the equator. Although the variation is also a consequence of the temperature distribution (since salinity is highest near the tropics and low near the equator and in high latitudes) some other factors must operate as well as local heating or the maxima would not be found so far from the equator. Among these one might consider the direct effect of the zonal wind stress (MONTGOMERY AND PALMÉN, 1940). Values of wind stress have been computed by HIDAKA (1958) for each 5° of latitude and longitude by seasons and by annual mean. From these the total zonal wind stress across the ocean has been calculated as a function of latitude and plotted over the latitudinal range of the data (Figure 2b). North of the equator the seasonal value for June through August is plotted also, since most of the oceanographic data north of the equator were from the period June through September. The oceanographic data south of the equator are from various months on either side of the ocean, and therefore no seasonal curve has been included. There is enough similarity in the curves to suggest that the wind stress is of great importance in accounting for the difference in geopotential anomaly.

If one integrates equation 2a zonally from the western to the eastern edge of the ocean and from some depth Z where the vertical shearing stress can be neglected, the velocity term will be negligible (since one may assume a negligible net meridional transport) and

$$\int (p_2 - p_1)dz = \int (\tau_x)_0 dx \qquad (2)$$

where $(\tau_x)_0$ is the surface wind stress. The term on the right can be evaluated from Hidaka's results and is plotted in Figure 2. The term on the left is the vertically integrated pressure difference across the ocean. In the data a value of Z can be found for each zone such that the pressure gradient and wind stress are balanced. If one assumes that the horizontal pressure difference is constant down to Z and negligible below, then the data in Figure 2 suggest that an average value of Z would be about 100 meters. Both MONTGOMERY AND PALMÉN (1940) and AUSTIN (1958) have shown that the pressure differences extend to greater depths, however.

More specifically, the velocity computed from the simplified equations does not satisfy the equation of continuity with a steady distribution of density unless the flow is east-west only. Since north-south flow also occurs in the ocean, the actual transport contains non-geostrophic flow, and transport calculated from the geostrophic equation will be incomplete. The same degree of incompleteness will be present in the geostrophic flow at the surface and is most immediately apparent in the appearance and disappearance of the contours at the coasts and in the indicated convergence at the equator.

These discrepancies, however serious, are not unexpected, and their nature might have been anticipated, in part, from a qualitative consideration of some of the neglected terms. MONTGOMERY AND PALMÉN (1940, Figure 41), considering wind stress, the earth's rotation, and the known surface currents, have prepared a schematic representation of the resulting shape of the sea surface near the equator that compares quite well with the corresponding part of Figure 1.

If one includes the vertical shear stress terms in equations 1a and 1b, and multiplies the first by u and the second by v and substracts, one obtains

$$u\alpha\partial p/\partial x + v\alpha\partial p/\partial y = u\alpha\partial\tau_x/\partial z + v\alpha\partial\tau_y/\partial z. \qquad (3)$$

If the local rate of change of geopotential difference is zero, the left side of (3) represents the time-derivative of the geopotential difference or sea level along a streamline (in this case, with respect to the 1,000-decibar surface).

If τ_x and τ_y are neglected, there is no change along a streamline. If they are included (and one notes that near the sea surface $\partial\tau_x/\partial z$ and $\partial\tau_y/\partial z$ will have the same signs, respectively, as $(\tau_x)_0$ and $(\tau_y)_0$, the surface wind stress), then it is seen that along a streamline sea level will rise where the products of wind stress and velocity are positive. That is, in downwind flow there is an uphill component and in upwind flow there is a downhill component.

If one considers that the North Pacific is a series of narrow gyres, each extending zonally across the ocean, then the centers of the anticyclones would be expected to stand higher and the centers of the cyclones lower than the adjacent areas. Except in the western boundary currents where MUNK (1950), CHARNEY (1955) and MORGAN (1956) have shown that more complex processes dominate, the wind field that lies above these gyres will drive the water uphill or downhill as it reinforces or opposes the flow, and the contours will therefore undergo certain excursions with regard to the actual flow.

In the northern subtropical anticyclone (California and Kuroshio Currents and parts of the west wind drift and North Equatorial Current) the wind is everywhere in approximately the same direction as the flow. In the greater part of this anticyclone (except in the western boundary current) the streamlines must be directed uphill and the contours must spiral outward from the center of the gyre. Those contours (1.5 to 1.8 dynamic meters) which spiral outward to the south far enough to cross the North Equatorial Current and reach the North Equatorial Countercurrent will have entered that part of a cyclonic gyre which flows upwind. Since the water will then be moving downhill, the contours must spiral outward again from the center of the cyclone, and some (1.6 and 1.9 dynamic meters) extend southward across the countercurrent to the Equatorial Current. They are now again in an anticyclone in which the westward flow is downwind and uphill. Therefore the contours spiral outward again, and some of them (1.4 through 1.9 dynamic meters) intersect the equator, meeting their counterparts from the southern hemisphere.

By a similar qualitative argument the disappearance of the contours (1.1 through 1.2) in the westward flowing limb of the subarctic cyclone might have been anticipated. This flow is upwind, the height along a streamline must decrease, and if one considers a streamline near the coast in the Southeast Alaska Current this can occur only if the contours intersect the coast.

6. Comparison with the Atlantic

It is interesting to compare this chart with the corresponding one for the Atlantic Ocean prepared by DEFANT (1941, Beilage XIV). He used METEOR data in the South Atlantic and a combination of data from several expeditions in the North Atlantic.

One first notes that the Pacific values seem to be higher than the Atlantic values. It has been calculated (REID, 1961) that the average value of the geopotential anomaly at the sea surface with respect to the 1,000-decibar surface in the Pacific is higher than in the Atlantic by 40 dynamic cm, and that with respect to the 1,000-decibar surface the Pacific must stand 40 cm higher than the Atlantic.

A second feature of interest is the difference in complexity of the two charts. Part of the additional complexity of the North Atlantic may be the result of having to use data taken at quite different times. The South Pacific chart is also composed of data from many different years, yet does not have so many irregularities. The relatively simple pattern of large cyclones and anticyclones, roughly symmetrical about the equator, which characterizes the Pacific is apparent in the Atlantic also, but is confused by many small hills and valleys.

The appearance and disappearance of contours at the coast that characterize the Pacific chart are found also in the Atlantic chart, to about the same extent.

Acknowledgements

The author wishes to express his appreciation to Dr. N. P. Fofonoff and Professors R. B. Montgomery and R. S. Arthur for various suggestions and discussions. This work was supported by the Marine Life Research Program, the Scripps Institution of Oceanography's component of the California Cooperative Oceanic Fisheries Investigations, a project sponsored by the Marine Research Committee of the State of California.

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APPENDIX

The materials used in preparing the chart of geopotential anomaly at the sea surface with respect to the 1,000-decibar surface.

From the available materials choices were made on the basis of the area and time of each expedition. The NORPAC, EQUAPAC, and EASTROPIC expeditions each covered large areas in relatively short (although different) periods. Stations from these three were chosen in preference to those stations of other extensive cruises (the Carnegie, for example) which overlapped them. From expeditions such as the Discovery II, Snellius, William Scoresby, and Derwent Hunter that covered the same area more than once, selections were made on the basis of season and need. In areas where data were scanty, overlapping was permitted.

It is not possible to explain in detail each choice, partly because there are so many, and partly because even though some more suitable data became available during the work, the older choices were in some cases allowed to stand.

The list contains those stations which were used and those stations which were considered and rejected without apparent fault except that the value seemed not to fit the field. For any cruise the stations not listed were either too shallow (a few of the listed ones have been extrapolated the last hundred meters), redundant, or obviously in error (showing instability or extremely unlikely values of temperature or salinity).

T. S. Austin (in press) has reported a consistent depth error in the data from the HUGH M. SMITH. The error has been corrected in the data used in this study. Part of the corrections were made through the facilities of the department of Oceanography, Texas A. and M. College.

The NORPAC Stations used (June—October 1955)

Vessel	Stations considered	Number to 1,000 m	Number used	Station rejected	Reference
All C.C.O.F.I.	1—162	143	142	No. 154	NORPAC COMMITTEE (1960) Oceanic Observations of the Pacific: 1955, The NORPAC DATA, pp. 1—582. University of California Press and University of Tokyo Press, Berkeley and Tokyo.
Tenyo Maru	6—36 45—51	38	38		
HMCS Ste. Therese	1—39 41—85	82	82		
Umitaka Maru	5—59	44	43	No. 47	
Kagoshima Maru	521—531	11	11		
Keiten Maru	565	1	1		
Kaiyo Maru	D1—D11	7	7		
Brown Bear	1—69	43	43		
H. M. Smith	1—114	76	76		
Oshoro Maru	1—19 21—37	29	29		
Satsuma	2—19 21—49	47	47		
Ryofu Maru	448—496	33	31	No. 458, 493	
Yushio Maru	1001—1031	22	22		
Shumpu Maru	1—85	32	32		
Meiyo Maru	C1—C5 B3—B13 303[1] 303—305	16	16		
Total NORPAC			620	4	
The EASTROPIC Stations used (September—December 1955)					
H. M. Smith	1—24	20	20		KING, J. E., AUSTIN, T. S., and DOTY, M. S. (1957) Preliminary Report on Expedition EASTROPIC. U.S. Fish Wildlife Serv. Spec. Sci. Rep., Fish. No. 201: 1—155.
Horizon	7—24 26—34 36—42 44—55 57—97	76	76		UNIV. CALIF., SCRIPPS INST. OF OCEANOGRAPHY (1956) Data collected by Scripps Inst. Vessels on EASTROPIC Expedition, September—December 1955. Unpub. Rep., SIO Ref. 56—28.
Baird	1—24 32—33 35—42 44—55 58—74 76—91	70	70	No. 5	
Total EASTROPIC			166	1	

The EQUAPAC Stations used

Vessel	Stations considered	Number to 1,000 m	Number used	Station rejected	Reference
H. M. Smith	1—79	79	79		AUSTIN, THOMAS S. (1957) Summary Oceanographic and Fishery Data, Marquesas Islands Area, August—September, 1956 (EQUAPAC) U.S. Fish Wildlife Serv. Spec. Sci. Rep., Fish. No. 217: 1—186.
Stranger	1—46	45	45		UNIV. CALIF., SCRIPPS INST. OF OCEANOGRAPHY (1957) Data collected by Scripps Inst. vessels on EQUAPAC Expedition, August 1956. Unpub. Rep., SIO Ref. 57—25.
Horizon	1—47	43	43		
Orsom III	1—19	18	18		INSTITUT FRANÇAIS D'OCÉANIE, Orsom III, Croisière EQUAPAC, September—October 1956. Unpub. Rep.
Satsuma	1—46	44	44		SUDA, K., EQUAPAC Oceanographic and Meteorological Data (Preliminary Report), Satsuma, July—August 1956. Japanese Hydrographic Office, Unpub. Rep.
Umitaka Maru	1—20	8	8		TOKYO UNIV. FISH., EQUAPAC: Umitaka Maru, EQUAPAC Expedition, October—November 1956. Unpub. Rep.
Shoyo Maru	5—15	10	10		JAPAN FISHERIES AGENCY, EQUAPAC Oceanographical and Meteorological Data, Shoyo Maru, August 20-November 3, 1956, Unpub. Rep.
Kagoshima Maru	614 616—618 620—634	19	19		KAGOSHIMA UNIV. FACULTY OF FISH., Oceanographical Observations made during the International Cooperative Expedition EQUAPAC in July—August, 1956, by M. S. Kagoshima Maru and by M. S. Keiten Maru, Unpub. Rep.
Keiten Maru	601—622	19	19		
Total EQUAPAC			285	0	

The stations used from expeditions made by single vessels

Vessel	Stations considered	Number to 1,000 m	Number used	Station rejected	Reference
Challenger (8 Sept.—23 Oct. 1875)	272, 276 280—281 283—287 289	10	10		OFFICERS OF THE CHALLENGER EXPEDITION (1884) Report on the Deep-Sea Temperature Observations of Ocean Water, Report on the scientific results of the voyage of H.M.S. Challenger during the years 1873—1876. Physics and Chemistry Vol. 1, Part III, pp. 1—2, pl. I—CCLVIII, Tables I—VII. *also* WÜST, G. (1929) Schichtung und Tiefenzirkulation des Pazifischen Ozeans: Institut für Meereskunde, Berlin, N. F., A. Geograph.-Naturwissensch. Reihe, Heft 20, pp. 1—64.
Planet (28 May—3 July 1908)	12, 13 22	3	3		REICHAR, A. C. (1911) Temperatur- und Salzgehaltbestimmungen im südwestlichen Stillen Ozean, 1910. Ann. der Hydrogr. und Mar. Meteor., XXXIX, Heft X, pp. 521—527.
Carnegie (26 Oct. 1928—28 April 1929)	35—97	62	61	No. 92	FLEMING, J. A., ENNIS, C. C., SVERDRUP, H. U., SEATON, S. L., and HENDRIX, W. C. (1945) Observations and results in physical oceanography, Scientific Results of Cruise VII of the Carnegie during 1928—1929 under Command of Capt. J. P. Ault. Oceanogr. IB, pp. 1—315.
Dana (9 Nov. 1928—10 Aug. 1929)	3592—3655 3666—3788	43	43		CARLSBERG FOUNDATION (1937) Hydrographical observations made during the Dana expedition 1928—1930. Dana-Report Vol. II, No. 12, pp. 1—46.
Snellius (29 July—27 Nov. 1929)	30 33—35 90, 95, 100 104—113 115—118 122, 128 131, 146 147	40	40		VAN RIEL, P. M., GROEN, P. and WEENINK, M. P. H. (1957) Oceanographic results, quantitative data concerning the statics of the East-Indonesian waters; depths of standard pressures and stability values. The Snellius Expedition in the eastern part of the East Indian Archipelago 1929—1930. Vol. II, Part 7, pp. 1—45.
			157	1	

Vessel	Stations considered	Number to 1,000 m	Number used	Station rejected	Reference
			157	1	
(7 March—5 Nov. 1930)	201, 205 208, 218 240, 262 263, 272 276, 301 303, 310 312 324—327 334, 349 350, 353 354a, 382				
William Scoresby....... (19 May—27 Aug. 1931)	597, 606 609 612—616 629, 638 646, 653 668 671—688 694, 701 703 705—711 719—722 734—737	27	27		DISCOVERY REPORTS (1949) Hydrographical observations made by R.R.S. William Scoresby 1931—1938. Vol. 25, pp. 143—280, Cambridge.
Discovery II.......... (8 May—2 July 1932)	873—926	150	150		DISCOVERY REPORTS (1941) Discovery Investigations Station List, 1931—1933, Vol. 21, pp. 1—226, Cambridge.
(9 Sept.—29 Oct. 1932)	956—994				
(28 Jan.—7 Feb. 1936)	1662—1679				(1944) Station List, 1935—1937, Vol. 24, pp. 1—196.
(12 Jan.—9 March 1938)	2174—2220 2226—2280				(1947) Station List, 1937—1939, Vol. 24, pp. 198—422.
(20 Oct. 1950—22 June 1951)	2728 2734—2741 2768—2771 2780—2782 2789—2798 2817—2821 2831—2841				(1957) Station List, 1950—1951 Vol. 28, pp. 300—398.
USS Gannet........... (10—11 Aug. 1933)	26, 28 32, 34	4	4		BARNES, C. A., and THOMPSON, T. H. (1938) Physical and chemical investigations in Bering Sea and portions of the North Pacific Ocean.
USCGC Chelan......... (18—24 Aug. 1934)	102, 105 106 117—119	6	6		Univ. Wash. Pub. in Oceanogr., Vol. 3, No. 2 pp. 35—79 and Appendix, pp. 1—164.
Albatross.............. (29 Aug. 1947—12 Jan. 1948)	43—101 103—112 114—125 127 130—132 134—136 138—142 144—150	34	33	No. 93	BRUNEAU, L., JERLOV, N. G. and KOCZY, F. F. (1953) Physical and chemical methods, Appendix Table 2, Rep. Swed. Deep-Sea Exped., Vol. III, Physics and Chemistry, No. 4, pp. XLII—LV.
			377	2	

Vessel	Stations considered	Number to 1,000 m	Number used	Station rejected	Reference
			377	2	
H. M. Smith.......... (Cruise 5) (30 June—6 Aug. 1950)	1—12 50—51	14	14		CROMWELL, T., and AUSTIN, T. S. (1954) Mid-Pacific Oceanography, Parts II and III, Transequatorial Waters, 1950—1951. U.S. Fish Wildlife Serv. Spec. Sci. Rep., Fish. No. 131.
USS EPCE(R) 857 (Shuttle)	39—54	16	16		U.S. NAVAL ELECTRONICS LABORATORY, Shuttle Expedition, 24 April to 4 June 1952. Unpublished material.
Oshoro Maru.......... (31 May—20 June 1954)	11—28	14	14		MISHIMA, S., and NISHIZAWA, S. (1955) Report on the Hydrogr. Invest. in Aleutian Waters and the Southern Bering Sea in the Early Summers of 1953 and 1954. Bull. Fac. Fish., Hokkaido Univ., Vol. 6, No. 2, pp. 85—124.
Derwent Hunter........ (23 Nov.—13 Dec. 1954)	160—195	21	21		COMMONWEALTH SCIENTIFIC INDUSTRIAL RESEARCH ORGANIZATION, AUSTRALIA, DIV. FISH (1956) Oceanogr. Station List, Onshore Hydrological Invest. in Eastern and Southwest Australia, 1954. Vol. 24, F.R.V. Derwent Hunter, pp. 54—109.
(29 Aug.—13 Dec. 1955)	96—194	29	29		(1957) Vol. 27, 1955, pp. 66—145.
Ob.................. (13 April—5 May 1956)	79—98	15	15		IGY REPORTS OF THE COMPLEX ANTARCTIC EXPEDITION OF THE ACADEMY OF SCIENCES OF THE USSR (1958) Hydrological, Hydrochemical, Geological and Biological Studies, Research Ship Ob 1955—1956. Hydro-Meteorological Publishing House, Leningrad, pp. 1—214
Orsom III .... (Astrolabe) (5—17 May 1958)	1—14	12	12		ROTSCHI, H. (1958) Orsom III, Océanographie Physique, Croisière Astrolabe. O.R.S.T.O.M., I.F.O. Rapp. Sci. No. 8, pp. 1—79, Nouméa.
Orsom III............ (56—5) (13 Oct.—14 Nov. 1956)	1—23	22	22		ROTSCHI, H. (1958) Orsom III, Océanographie Physique, Croisière 56—5. O.R.S.T.O.M., I.F.O., Rapp. Sci. No. 5, pp. 1—34, Nouméa.
			520	2	

Vessel	Stations considered	Number to 1,000 m	Number used	Station rejected	Reference
			520	2	
Vityaz 25	3652—3683	21	21		136 stations in the W. Pacific, Vityaz Cr. 25, 28 June—11 Oct. 1957. Unpublished report made available through World IGY Data Center A.
Vityaz 26	3801—3875	57	55	No. 3855, 3856	102 stations in the W. Central Pacific, Vityaz Cr. 26, 5 Nov. 1957—27 Feb. 1958. Unpublished report made available through World IGY Data Center A.
Horizon (Downwind) (5 Nov. 1957—23 Feb. 1958)	10—11 13—44	31	29	No. 42 43	UNIV. CALIF., SCRIPPS INST. OF OCEANOGRAPHY (1958) Physical and chemical data. Chinook Expedition, 1956, Mukluk Expedition, 1957, and Downwind Expedition, 1957—1958, Unpub. Rep., SIO Ref. 58—85.
Ob Cruise 3	334—351 423—450	43	43		Cruise 3 of the Ob in the Indian, Pacific, and Atlantic Oceans, 15 Jan.—18 June 1958. Unpublished report made available through World IGY Data Center A.
Tiare (Bounty)	2 4—14	10	10		COMITÉ LOCAL D'OCÉANOGRAPHIE ET D'ÉTUDE DES COTES DE NOUVELLE-CALÉDONIE (1958) Resultats des observations scientifiques du Tiare, Croisière Bounty, 20—29 Juin 1958, Rapp. Sci.I.F.O., No. 7, pp. 1—20, Nouméa.
Umitaka Maru (Coral Sea)	1—27	13	13		Coral Sea Cruise, 7—14 Jan. 1959. Data kindly made available through Commonwealth Scientific Industrial Research Organization Marine Laboratory, Australia, and Tokyo Univ. of Fisheries, Japan, Unpublished Material.
Ryofu Maru (9—31 July 1942)	15—56	30	30		ASSOCIATION OF AGRICULTURAL TECHNOLOGY (1954) Northern area oceanographic data 1887—1953. Report of the invest. of long range cold weather forecasting. No. 1, pp. 1—556. Tokyo.
Total, single vessel expeditions			721	6	
Grand total of all stations			1,792	11	