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Progress Report on the Oceanography of
the North Pacific Ocean
for 1960

by A.J. Dodimead

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This report summarizes the operational work and the preliminary assessment of the data collected during the past year. The similarities between these data and that collected in 1959 are emphasized. In addition a resume of the research work that has been accomplished or is in progress by the Pacific Oceanographic Group in the North Pacific Ocean has been included. A large number of figures are presented, first to substantiate some of the conclusions that have been deduced from these studies, and secondly, as reference material.

Operations

1. Winter oceanographic survey of the northeast Pacific Ocean (82 stations). Data record and Atlas published.

2. Summer oceanographic survey of the northeast Pacific Ocean (2 ships - 146 stations). Data published. Included in this data record are observations made in conjunction with the Pacific Naval Laboratory, Esquimalt, B.C. just prior to the survey.

3. Three - seven week patrols at Ocean Station "F" (lat 50° N, long 145° W). The program now includes a line of stations (6) en route to and from Station "F" every six weeks. Data processed and computed. Publication in early 1961.

4. Three surveys on the continental shelf off the coast of Vancouver Island. Emphasis was placed upon continuous observations, including current measurements, at selected positions. Data published.

The fourth consecutive mid-winter survey in the northeast Pacific Ocean was carried out during the period January 11 to February 10, 1960 aboard H.M.C.S. "Beacon Hill" (Navy frigate).

The observed temperature distribution at 10 metres depth (Fig. 1, dots represent station positions) was similar to that observed during the previous winter. The comparison is represented in Fig. 2 which illustrates the differences in temperatures between the mid-winter periods, 1959 and 1960 (hatched areas indicate colder water in 1960 than in 1959). Over most of the region the temperature anomalies were generally less than 0.4°C, except in the Gulf of Alaska where temperature differences greater than 0.5°C occurred and were colder in 1960 than in 1959. Temperatures were also slightly colder (less than 0.4°C) along the British Columbia coast and in the mid-ocean region in 1960 compared to 1959.

The intrusion of relatively warm water (Fig. 1) at 40° N latitude between 130° and 140° W longitude was again present, but slightly broader than previously. This intrusion appears to be a winter feature.

The salinity distribution at 10 metres depth (Fig. 3) confirms the features in the temperature distribution. There was an intrusion of relatively warm low salinity water westward along latitude 55° N. Northward of this, relatively cold saline water, generally associated with water from the Alaskan gyre, was present.

The distribution of temperature on the surface, $\sigma_t = 26.60$ (density = 1.02660) has been used in earlier reports to show the intrusion of warm water along the British Columbia coast below the level of seasonal influence. The temperature distribution on this surface
during winter of 1960, and the differences compared to winter of 1959, are shown in Fig. 4 and 5 respectively. The areas of the temperature anomalies (Fig. 5) generally agree with those at 10 metres depth (Fig. 2) and are of the same order of magnitude except in the Gulf of Alaska. Thus the intrusions of water mentioned previously are not limited to the upper zone but persist at least to the intermediate waters (100-200 metres).


This preliminary assessment is made from data collected during an oceanographic cruise (July 28 to September 6, 1960) using two vessels, C.N.A.V. "Oshawa" and "Whitethroat". The station positions are shown in Fig. 6.

The observed temperature distributions at 10 metres depth during summer 1959 and 1960 are very similar (Fig. 7 and 8 respectively). Slightly colder water was present westward of Queen Charlotte Sound in 1960. Relatively cold water apparently intruded from the west, resulting in a discontinuity in the 13°C isotherm.

The temperature distribution during these two periods on the surface \( \sigma = 26.60 \) are also similar; in particular, the location of the 6.5°C isotherm (Fig. 9 and 10). Warm water (6.0°C) in the form of a tongue did extend further northward than previously.

In 1959 there were two marked intrusions in the Gulf of Alaska outlined by the 4.0 and 5.0°C isotherms, resulting in a marked gradient in the temperature distribution at this level. These movements apparently relaxed during 1960 as shown by the gradual change in temperature in these regions.

It can be concluded that with conditions very similar in the seasonal (10 metres) and non-seasonal zone (\( \sigma = 26.60 \)), the distribution of
water masses and their movements, at least in the upper 200 metres were similar for these two periods, except for the two marked intrusions discussed above.

Data from Station "P" and the coastal lightstations suggest that these periods represent near-average conditions. The salinity distribution at 10 metres depth (Fig. 11) is also similar to that observed last summer. However, compared to the previous winter (Fig. 3) it is noted that relatively fresh water (less than 32.4%) extended further offshore in summer. This feature is primarily related to the presence of a marked thermocline in summer, whose stability conserves fresh water in the surface zone (10-30 metres depth).

In Fig. 12 and 13 are presented the temperature distributions at depth "D" (top of halocline) from winter and summer, 1960. They are quite similar in their distribution. This is further evidence that the winter temperatures of the upper zone can be recognized in the following summer's data (Dodimead, 1960).


Considerable effort during the past year has been devoted to the circulation and transport problems in the North Pacific Ocean. A final review of the drift bottles and calculated currents is near completion. In addition a theoretical study of the transport has been undertaken. These two studies are reviewed in the following sections.

(a) Drift bottles and the calculated currents.

In August, 1956 a drift bottle program was initiated as an aid to the study of the surface currents in the northeast Pacific Ocean. Batches of bottles were released every six weeks at Ocean Station "P"
until April, 1959. In addition, releases were made at selected positions in the northeast Pacific Ocean during the course of the oceanographic surveys. The position and dates of releases are shown in Fig. 14.

Forty-two releases (34,010 bottles) have been made, of which twenty-five (21,500) were made at Ocean Station "P". Most of the releases at Station "P" were made on the same date (within 3 days) each month in successive years. Besides suggesting the variations in surface drift throughout a particular period, the returns from these releases are extremely useful for showing the yearly variations that can and have occurred.

The bottles have been picked up on the ocean coast and in the coastal seaways around the North American coast. They have travelled northward and westward into the Bering Sea and to the end of the Aleutian Islands. They have also been picked up on the Hawaiian Islands, and as far westward as the Philippine Islands and the coast of Japan.

The average percentage returns for all releases is about 5% and has been as high as 18% for a particular release.

A progress report on the returns to April, 1958 has been published (Dodimead and Hollister, 1958). The more recent releases and returns substantiate the conclusions reached in that report. They were:

(i) The principal characteristics of the surface movement as shown by the estimated paths of the drift bottles were in agreement with the calculated currents, allowing for a component of movement to the right across the isobars.

(ii) The seasonal and yearly changes in surface movement implied by the calculated currents were in agreement with the drift bottle returns.

For reference material, the calculated currents (Fig. 15-21)
and a few of the drift bottle charts (Fig. 23-31) are presented for the periods studied.

The principal features of the circulation are summarized from the calculated currents:

(a) A mid-ocean movement from the west and toward the North American coast at a rate of about 2 miles per day (4 cm/sec);

(b) A division of this flow near the coast; part moving northeast and circulating around the Gulf of Alaska. The other part turns southward to form the California Current system, resulting in a region of divergence.

(c) The part that moves into and around the Gulf of Alaska continues westward along the Aleutian Islands. Most of this water moves into the Bering Sea, through and at the end of the Aleutian Islands. There is some evidence for a return flow south of the Aleutian Islands.

(d) In the Bering Sea most of the water continues in a counter-clockwise circulation around the Bering Sea, then flows southward and either re-circulates in a counter-clockwise gyre off the coast of Kamchatka, or moves eastward in the mid-ocean region.

These features are summarized in Fig. 22. A few of the drift bottle charts are presented which confirm some of these features and illustrate some of the yearly variations.

In Fig. 23 and 24 are shown the returns from releases made in the Gulf of Alaska. They suggest re-circulation in the Alaskan gyre, with a flow along the Aleutian Islands and into the Bering Sea. The path of
re-circulation into the main eastward flowing currents is only suggested. These particular bottles were in the sea from 2-3 years after date of release.

Figures 25-27 show the variations in the flow between Station "P" and the coast from releases made at Station "P" during the month of August.

It is interesting to note that generally there were marked variations in the location of returns in the corresponding months of the successive years. However, the distribution of returns from releases made in early November of successive year, have the same pattern (Fig. 28-30.). Figure 31 is presented to show the extent of the movement from the sub-Arctic region to the sub-Tropic and equatorial regions.

(b) Wind induced transport in the North Pacific Ocean.

We are aware that the main features of the circulation in the North Pacific Ocean have been established for a long time. Recently we have seen marked changes in the strength and distribution of currents. Our problem is to account for these.

Sverdrup (1947), Stommel (1948) and Munk (1950) have shown that the total steady-state transport of mass in the ocean depends primarily on the curl of the wind stress components acting on the surface of the ocean. Computations based on this theoretical result have yielded transport which agree quite well with the distribution and magnitude of transport inferred from oceanographic observations.

This steady-state model of mass transport has been applied to extensive calculations of transport in the North Pacific Ocean. These calculations were undertaken with two objectives in mind. First, to find out how long an averaging period is necessary to approach
steady-state conditions and second, to gain some idea of the variability, both with latitude and time, of the transport that is imposed on the ocean by the atmosphere.

The first part of the research, the calculations, is complete. They have been published in the form of monthly and mean charts for the years 1955 through 1959. It is planned to keep these calculations up to date and to publish them at the end of each year.

Examples of one month's calculations and their presentation is shown in Fig. 32-37.

It is realized that much study is required to evaluate this method of computing ocean circulations. However the study has opened up a large resource of information describing the driving forces in the ocean, that was not previously available in usable form.

4. Ocean Station "P"

Considerable data from Ocean Station "P" have been analyzed. One particular study has proposed a mechanism for the growth and decay of the thermocline in the Subarctic Pacific Ocean.

Growth and decay of the thermocline.

In the Subarctic Pacific Ocean, it has been observed that the waters are virtually isothermal to the depth "D" (top of the halocline, about 100 metres) at the end of the cooling season in late March. With the advent of the heating season in April a thermocline is formed. It is overlaid by a near isothermal (mixed) layer which continues to warm through the heating season until the end of August. Below it there is an unwarmed layer, which has been shown to be the remnant of the previous winter structure. Hence, the thermocline grows in some depth interval (between 20 and 60 metres at Ocean Station "P").
During the cooling season, from September, the surface mixed layer cools and deepens. The thermocline becomes ever more abrupt, deepens, and decays and may vanish in late February. The growth and decay of the thermocline is illustrated in Fig. 38.

The mechanics of the growth and decay of the thermocline are being studied in the semi-daily bathythermograph observations at Ocean Station "P" (Lat 50° N, Long 145° W). It has been concluded that the mechanics are similar in all oceanic areas, differing only in degree from place to place and time to time. This research is being prepared for publication. Meanwhile, it is convenient to summarize some of the principal conclusions.

Examinations of the data show that in the oceanic regions (away from the coasts) three dominant processes are involved in the growth and decay of the thermocline - heating, cooling, and wind mixing.

Heating is due to radiant energy from the Sun and occurs only during daylight hours. Cooling is due to evaporation, radiation and conduction of heat from the sea surface, and is continuous day and night. There is a net heat gain (from April to September at Station "P") and a net loss through the winter cooling season. The winds exist at all times and provide a mixing force where depth of influence varies with the wind speed.

The surface waters are warmed whenever the daytime heating exceeds the continuous cooling process. Usually, there is some wind so that a shallow (1-5 m) mixed layer is formed. Below this is a small thermocline separating the warmed surface waters from the deeper waters. The heat and the associated thermocline may vanish if the nighttime cooling exceeds the daytime heating. In this stage the thermocline is transient. If the heat is not lost it is mixed downward by the continuing wind, to
the limiting depth of wind influence. There, the thermocline becomes stable.

These processes are illustrated in Fig. 39. The position of the stable thermoclines are shown by cross hatching. The positions of the transient thermoclines as functions of time are shown by shaded transients through the mixed layer above the shallowest stable thermocline. The transients first occurred in April, and a stable thermocline was formed at the end of the month. Thereafter, the transients occurred with increasing frequency throughout the heating season. Each transient provided a small increase in the temperature of the mixed layer, and added to the magnitude of the stable thermocline.

Aside from oscillation because of internal waves the stable thermocline cannot ascend toward the surface. However, the mixed layer can deepen in the presence of any process which will increase the mixing, or remove the heat.

One sequence of events is illustrated in Fig. 39. The stable thermocline deepened through May. Then, at the end of June, in a period of light winds a second thermocline was formed, overlying the old one. Thereafter, all heat additions (transients) contributed to this second thermocline while the old thermocline remained constant. During a period of very light winds, the thermocline may find an even shallower depth of stability, so that a third thermocline may form. This occurred during August 9-17. However, as soon as the winds increased this descended to the next level and joined the second thermocline. Evidently the mean depth of the mixed layer is a measure of the maximum winds that have occurred since the level was established. Further, each thermocline forms a cover protecting the water below it from further heating from the surface.
At the end of the heating season two processes, cooling and increased wind mixing, become dominant. With the increasing autumnal winds there is a further redistribution of heat and modification of structure. The warmed waters, in the erstwhile shallow mixed layer, are mixed with the cooler waters in the thermocline. In consequence the mixed layer deepens and becomes truly isothermal; the thermocline becomes thinner, and its temperature gradient becomes abrupt (Fig. 38). This process is intermittent with the occurrence of storms.

Also, during the cooling season there is a net heat loss from the surface. Because the mixed layer is truly isopycnal convection currents occur. Hence the cooling is uniform throughout the mixed layer. This continuous process can only increase the depth of the mixed layer by erosion of the thermocline.

The two processes act together to increase the mixed layer and cool the water in the mixed layer, thus reducing the thermocline as shown in second diagram of Fig. 38.

In the limit, at the end of the cooling season, the mixed layer extends to some recognizable depth. It may be colder, have the same temperature, or be warmer than the underlying waters. Thereafter the cycle is repeated as a new thermocline is formed near the surface. When this occurs the remnants of the winter thermal structure are protected from any further local heat input from the surface. Hence this limit of winter cooling is the limit of seasonal surface influence. In the Subarctic region the limit of the process is the depth "D" (top of the halocline).
REFERENCES


NORTH PACIFIC PROJECT
JAN.-FEB. 1960
Temperature (°C)
at 10 metres depth

NORTH PACIFIC PROJECT
JAN.-FEB. 1960
TEMPERATURE ANOMALY (°C)
at 10 METRES DEPTH
JAN.-FEB. 1960 - 1959

[Map showing temperature and anomaly data]

FIGURE 1

[Map showing temperature anomaly]

FIGURE 2
FIGURE 3

NORTH PACIFIC PROJECT
JAN.-FEB. 1960
Salinity (‰)
at 10 metres depth
FIGURE 4

NORTH PACIFIC PROJECT
JAN.-FEB. 1960
Temperature (°C)
on \( \sigma_z = 26.60 \)

FIGURE 5

NORTH PACIFIC PROJECT
JAN.-FEB. 1960
TEMPERATURE ANOMALY (°C)
ON SURFACE \( \sigma_z = 26.60 \)

JAN.-FEB. 1960-1959
Colder in 1960 than in 1959
Figure 6
NORTH PACIFIC OCEAN

Temperature (°C) at 10 metres
August 1959

FIGURE 7
NORTH PACIFIC OCEAN
TEMPERATURES (°C)
AT 10 METERS DEPTH
SUMMER 1960

Figure 8
NORTH PACIFIC OCEAN

Temperature (°C) on the surface

\[ \sigma_t = 26.60 \]
August 1959

Figure 9
NORTH PACIFIC OCEAN
TEMPERATURE (°C)
ON SURFACE $\sigma_t = 26.60$
SUMMER 1960

Figure 10
NORTH PACIFIC OCEAN
SALINITY (%)
AT 10 METERS DEPTH
SUMMER 1960

Figure II
NORTH PACIFIC PROJECT
JAN.–FEB. 1960
Temperature (°C) at "D"
(top of halocline)
NORTH PACIFIC OCEAN

TEMPERATURE (°C) AT "D" (top of halocline)

SUMMER 1960

Figure 13
Figure 14

NORTH PACIFIC OCEAN

Positions of drift bottle releases

August 1956–1959

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S-148A
NORTH PACIFIC OCEAN

DYNAMIC HEIGHT ANOMALY (ΔD)
0/1000 DECIBARS
Contour Interval = 0.05

SUMMER, 1956

Figure 15
NORTH PACIFIC OCEAN
DYNAMIC HEIGHT ANOMALY (ΔD)
0/1000 DECIBARS
Contour Interval = 0.05
SUMMER, 1957

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Figure 17
Figure 21

NORTH PACIFIC OCEAN

DYNAMIC HEIGHT ANOMALY (ΔΔ)
0/1000 DECIBARS
Contour Interval = 0.05
SUMMER, 1959
Figure 23

NORTH PACIFIC OCEAN
Estimated path of drift bottles released on August 23, 1956
NORTH PACIFIC OCEAN
Estimated path of drift bottles released on February 17, 1957

Figure 24
Figure 25

NORTH PACIFIC OCEAN
Estimated path of drift bottles released at Station "P" on August 25, 1956
Figure 26

NORTH PACIFIC OCEAN
Estimated path of drift bottles released at Station "P"
on August 24, 1957
Figure 27

NORTH PACIFIC OCEAN
Estimated path of drift bottles released at Station "P" on August 23, 1958
NORTH PACIFIC OCEAN
Estimated path of drift bottles
released enroute Station "P"
on November 2, 1956

Figure 28
NORTH PACIFIC OCEAN
Estimated path of drift bottles released at Station "P"
on November 7, 1957

Figure 29
NORTH PACIFIC OCEAN
Estimated path of drift bottles released at Station "P"
on October 31, 1958

Figure 30
Figure 31

NORTH PACIFIC OCEAN
Estimated path of drift bottles
released on August 26, 1956

Base Map prepared by the Canadian Hydrographic Service, Surveys and Mapping Branch,
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Figure 31
Figure 32. Atmospheric Pressure

Figure 33. Meridional Component of Ekman Transport

Figure 34. Zonal Component of Ekman Transport
Figure 35. Meridional Component of Total Transport

Figure 36. Integrated Total Transport

Figure 37. Integrated Geostrophic Transport
GROWTH AND DECAY OF THERMOCLINE
OCEAN STATION "P"
(Lat. 50°N Long. 145°W)

FIGURE 38
FEATURES OF THE THERMOCLINE
Ocean Weather Station "P" 1956

FIGURE 39