Oceanographic Conditions in the Central Subarctic Pacific Region,
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by

A.J. Dodimead

FISHERIES RESEARCH BOARD OF CANADA
Biological Station, Nanaimo, B.C.

Pacific Oceanographic Group

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INTRODUCTION

Prior to 1962, autumn and winter oceanographic conditions in the central and western Subarctic Pacific could not be described because of the lack of oceanographic data. However, as a result of a number of recent surveys in these areas, data are now available for these periods, and some reports have been published (Favorite et al., 1964 and 1966; Ingraham, Jr., 1966; Reid, 1966; U.S. Navy Oceanographic Office, 1967). One of the most extensive of the surveys was the Boreas Expedition completed in early 1966, in which the author participated (Reid, 1966; University of California, SIO Reference 66-24). A substantial part of the temperature and salinity data was obtained for the first time in these waters from continuous profiles of temperature and salinity with depth. These data, along with relatively closely spaced stations in boundary regions, have made it possible to provide an excellent definition of the distribution of these variables and the associated calculated parameters for the winter of 1966.

In this report, two sections along long. 175°E and 165°W are presented and discussed. These sections transect the major current systems and sub-regions of the central Subarctic Pacific, namely, the westward-flowing Alaskan Stream, the Alaskan Gyre, the eastward-flowing Subarctic Current and West Wind Drift, the Transitional Domain and the Subarctic Boundary (Fig. 1). The temperature, salinity, density, water masses and geostrophic currents associated with these systems and with their boundaries are discussed. Comparisons are made with observations reported recently for other periods at about the same longitudes (Dodimead et al., 1963; Favorite and Hanovan, 1963; Ohtani, 1965 and 1966; Ingraham, Jr., 1967; Park, 1967).

DISCUSSION

The temperature and salinity distributions were drawn using values read from the published salinity-temperature-depth curves. Temperature-salinity curves were drawn from the tabulated data, while density and geostrophic current sections were constructed from computed values at standard depths (University of California, SIO Reference 66-24). The results are presented in Fig. 3-11.

As a brief review, the main feature of the vertical salinity structure of most of the waters of the Subarctic Pacific is the presence of three distinct zones: an upper (seasonal) zone, a halocline and lower (non-seasonal) zone. The structure and dimensions of the zones vary over the region and have been well described by Dodimead (1961) and Dodimead et al. (1963). Typical salinity
and associated temperature structures and the zones are shown in Fig. 2. In subsequent discussions, reference is made to these zones and structures.

1. Depth of upper (seasonal) zone

In winter, in the Subarctic Pacific, a homogenous upper zone (surface-mixed layer), generally less than 150 m in depth, is formed by mixing as a result of winter convective overturn (Dodimead et al., 1963; Tully and Giovando, 1963). The depth of the layer is primarily dependent upon the degree of cooling and evaporation, and the stability of the underlying halocline waters. However, near and between the Aleutian Islands, especially in the relatively narrow and shallow passages, convective overturn is enhanced by turbulent mixing due to tides. Here, a relatively deep mixed layer is formed. Dodimead et al. (1963) have reported that this layer may extend to a depth of 275 m. In these sections, the mixed layer was deepest (170 m) between the Aleutian Islands, and in mid-ocean at approximately lat. 45°N along 175°E (Fig. 3, 6 and 8). The shallowest depths (40-80 m) were in the relatively dilute and cold surface waters of the coastal area along 165°W, where the upper zone and halocline waters are always relatively stable (Fig. 4, 7 and 9). Generally, the mixed layer was deeper along 175°E than along 165°W (cf. Fig. 3 and 4).

2. Temperature

The upper-zone or mixed-layer temperatures appear to be normal for these areas for this time of year (Fig. 3 and 4). The coldest waters (≤ 2.6 °C) occurred as a cell at lat. 48°N along 175°E (Fig. 3). The cell is considered to indicate the eastern edge of the Western Subarctic Gyre (Fig. 1), where temperatures are relatively low. In general, temperatures increased southward. The surface gradient was similar to that observed in summer. The surface fronts, cold and warm cells are characteristic features of the Transitional Domain.

The underlying halocline waters were generally warmer than the upper-zone waters, particularly along 175°E, where positive gradients were present at all stations except sta. 116. This is a common characteristic of the temperature structure in this area. Along 165°W, the continuity of positive gradients was broken from sta. 7 to 11, where small negative thermoclines occurred (Fig. 4). There appear to be two distinct regimes, a northern and southern regime, in which positive gradients occur. In each of the regimes the mechanism for the formation of the positive gradients is considered to be different. The northern regime extends from sta. 101-115, along 175°E (Fig. 3) and from sta. 1-6, along 165°W (Fig. 4). In this regime, the temperature inversions are thought to be a result of local surface cooling to a temperature below that of the halocline waters. This results in a positive gradient with depth, accompanied by a temperature maximum (Fig. 2) (Uda, 1963; Dodimead et al., 1963). Here, the positive gradients were largest (1.5 °C) along the axis of the Alaskan Stream, where the halocline waters were warmest (Fig. 4) and in the Subarctic Current (Fig. 3).
southern regime extends from sta. 117-124, along 175°E (Fig. 3) and from sta. 12-19, along 165°W (Fig. 4). Here, the positive thermoclines and temperature maxima are considered to be formed through lateral advection (see page 4 for full explanation). The magnitudes of the positive thermoclines were also about 1.5°C. In either case, the positive thermoclines were stable features, being coincident with the top portion of the halocline.

Below the mixed layer, a significant and characteristic feature is the doming or ridging of the isotherms, which occurred between lat. 45°N and 51°N along 175°E (Fig. 3), and between lat. 48° and 53°N along 165°W (Fig. 4). The dome can usually be defined conveniently by the area enclosed by the 4°C isotherm as seen in Fig. 4. However, to the north along 175°E, waters of this temperature and greater were absent in early 1966, except for the presence of a small cell (Fig. 3). Favorite et al. (1967, p. 92 and 95) have suggested that the absence of these waters was due to their near-complete recirculation at about long. 170°W into the Gulf of Alaska during the winter period. It may have been that there was a reduction of warm-water flow into the Alaskan Stream, accompanied by a relatively large outflow of cold high-salinity water from the Bering Sea. Through mixing, the temperature of the Alaskan Stream was then lowered below a temperature of 4°C.

Another feature that has been noted in other data is a weak minimum-maximum stratum at 200-300 m depth which occurs within the temperature dome (Fig. 3 and 4). It is considered to be a result of seasonal overturn in the western Subarctic, where vertical mixing to greater depths occurs, resulting in a temperature minimum of about 0°C. The minimum is gradually increased as this water is advected eastward in the Subarctic Current (Favorite and Hanovan, 1963; Favorite, 1967). It will be shown later that these are relatively low-salinity waters. In winter 1966, the value of the minimum was 3.1°C at 175°E. It changed by only about 0.3°C between 175°E and 165°W. In contrast, the value of the temperature maximum in the halocline of the Alaskan Stream changed by 1°C, but in this case, the values decreased westward. Similar changes over comparable distances in these two systems and zones have been reported by Favorite et al. (1964).

Southward of the dome, the marked horizontal and vertical gradients are characteristic of these areas. The sharp gradient below 150 m depth between sta. 116 and 117, along 175°E (Fig. 3), and the gradient between sta. 9 and 10, along 165°W (Fig. 4), are considered to be the northern boundaries of the Transitional Domain. The water masses on either side of the boundary were markedly different, except in the deep lower-zone waters, as shown by the temperature-salinity relationships presented in Fig. 5. The demarcation between sta. 116 and 117 along 175°E and between sta. 9 and 10 along 165°W is clearly evident. The position of the boundary is similar to that observed in summer 1958 along 175°E (Favorite et al., 1964). However, Favorite and Hanovan (1963) showed that the boundary occurred at about 47°N, along 175°E in the summer of 1956, indicating that there can be fairly marked shifts in these water masses at this longitude. Along 165°W, the position of the boundary seems to be relatively permanent.
3. Salinity

The salinity profiles are characteristic of the Subarctic Pacific (Fig. 6 and 7). The isohaline upper zone, the halocline at 100-150 m depth, and the doming of the isohalines in the halocline and in the lower zone south of the Aleutian Islands and of the Alaskan Peninsula are permanent features (Dodimead et al., 1963).

The peak of the salinity dome in the halocline waters at sta. 110 (Fig. 6) and at sta. 5 (Fig. 7) is considered to be the southern boundary of the Alaskan Stream or the northern boundary of the Subarctic Current. These positions approximate the centre of the salinity ridge, which Favorite (1967) used to locate the southern boundary of the Stream.

Within the halocline and lower zone, the downward slopes of the isohalines and isotherms were coincident on the northern sides of the salinity and temperature domes. However, on their southern sides, the temperature dome extended about 180 miles further south than the salinity dome (cf. Fig. 4 and 7). In fact, in the intermediate-depth waters (200-400 m), there were troughs in the salinity structure at the peaks of the temperature dome, at sta. 113 and 7 (cf. Fig. 3 and 6; Fig. 4 and 7). The salinity trough, and the deeper relatively weak temperature minimum-maximum stratum, which occurred at these stations, appear to be the best indications of the axis of the westward-flowing Subarctic Current.

In the Transitional Domain, the outstanding features were the surface salinity gradients, which were most marked near its southern boundary along 175°E (Fig. 6), and the inversions at depth (Fig. 6 and 7). The salinity-maximum strata were coincident with the temperature maxima and associated positive thermoclines (cf. Fig. 3 and 6). It is suggested that this temperature maximum is formed by lateral mixing at depth along the isohalines or isopycnals, and not by local surface cooling of the mixed layer to temperatures below that of the halocline waters, as described on page 2. Further, it is suggested that it is formed by a northward lateral mixing within a small depth interval of 20-25 m. These warm waters appear to have their origin at the southern limit of the Transitional Domain, coincident with the sharp surface temperature and salinity gradients.

The Subarctic Boundary is usually positioned by the nearly vertical isohaline of 34.0 ‰, at about 200-400 m depth (Dodimead et al., 1963). Along 175°E it is considered to lie at approximately 41°N (Fig. 6), while along 165°W it appears to lie at about 42°N (Fig. 7). The former position is about 60 miles south of the position reported previously (Dodimead et al., 1963; Favorite and Hanovan, 1963; Favorite et al., 1964; Park, 1967).
4. Density

The vertical profiles of density, expressed as $\sigma - t$ are shown in Fig. 8 and 9. A significant feature is the stability of the water column coincident with the position of the halocline (cf. Fig. 7 and 9). In the Transitional Domain, the isopycnals and isotherms below the halocline have similar configurations, indicating that density is temperature dominated. Over the remainder of the area, the density is primarily salinity dominated, because the temperature gradients were relatively weak. In particular, the density dome is coincident with the salinity dome (cf. Fig. 6 and 8). The peak of the density dome shifted slightly southward with depth.

The density (and salinity) dome identifies the Alaskan Gyre, which represents the shear zone between the westward-flowing Alaskan Stream and eastward-flowing Subarctic Current. The peak of the density dome is considered to denote the area of maximum upward movement.

5. Geostrophic currents

The geostrophic currents varied markedly along both sections (Fig. 10 and 11). Along 175°E, the westward flowing Alaskan Stream extended south of the Aleutian Islands to lat. 49°N. Moving along an axis at lat. 51° the surface geostrophic currents were in excess of 24 cm/sec (11.2 miles/day), decreasing to 12 cm/sec (5.6 miles/day) at 500 m depth (Fig. 10). Comparison with other reports (Ingraham, Jr., 1966) indicates that the axis has a relatively permanent position in this area.

Along 165°W, the axis of the Stream occurred at lat. 53°30'N, with speeds of 28 cm/sec (13.1 miles/day) (Fig. 11), slightly higher than those to the west (Fig. 10). Favorite (1967) has reported that in the Alaskan Stream direct current observations have given average surface speeds of 75 cm/sec (35 sea miles/day), about 3 times the speeds deduced from the present geostrophic calculations. Ingraham, Jr. (1966) has shown that with station spacing of 5 miles, geostrophic currents in excess of 40 cm/sec (18.7 miles/day) have been calculated, but still only about one-half the speed from the direct observations.

In the Subarctic Current and West Wind Drift, geostrophic velocities varied between 4 and 18 cm/sec (1.9 and 8.4 miles/day), with maximum velocities observed across 175°E (Fig. 10 and 11). In the Subarctic Current, maximum velocities occurred along its axis. Velocities were calculated to be 8 cm/sec (3.8 miles/day) on the 175°E section. The location and speed along the axis of the Subarctic Current were similar to those reported by Ingraham, Jr. (1966) for the autumn of 1965.

Maximum velocities encountered in the West Wind Drift along 175°E were about 18 cm/sec (8.4 miles/day) at lat 41°N (Fig. 10). Velocities of this magnitude were present at lat. 43°N in the autumn of 1965 (Ingraham, Jr., 1966).
Relatively large geostrophic currents (10 cm/sec) along long. 175°E (Fig. 10) occurred at lat. 45°N, coincident with the area where the mixed layer was deepest (Fig. 3).

Geostrophic current speeds in the Subarctic Current and West Wind Drift agree well with speeds (4-5 miles/day) calculated from drift experiments conducted by Favorite (1964). Thus, geostrophic calculations appear to give reliable estimates of actual surface speeds in the Subarctic Current and West Wind Drift. Similar conclusions were made by Reid (1961) from comparisons of ships' drift and geostrophic currents.

The variation in directions between sta. 109-112 along 175°E (Fig. 10) is considered to be associated with the northern and southern boundaries of the eastern extremity of the Western Subarctic Gyre (Fig. 1). The Gyre extended further eastward than in some of the other years, possibly to compensate for the apparent southward shift of the other systems that occurred along 175°E.

It appears that the positions of the systems along 175°E were similar to those found in summer, 1958; and extended further southward than during various seasons of other years for which data are available.

SUMMARY

1. Alaskan Stream

The Alaskan Stream flows westward along the southern side of the Aleutian Islands. It is continuous as far westward as long. 170°E where it divides, sending one branch northward into the Bering Sea and one southwestward to rejoin the eastward-flowing Subarctic Current (Favorite, 1967) (Fig. 1). Ohtani (1965) has suggested that a third branch may exist, extending westward, and that this branch may be a permanent feature, while the other branches may vary in shape and position seasonally. It is apparent that the western extremity of the Alaskan Stream is a complex system, and there is need for further work.

The southern limit of the Alaskan Stream is best defined by the peak of the salinity or density dome, or by the southern extent of westward-flowing surface waters, as determined from geostrophic calculations. Its axis at 175°E and 165°W appears to be relatively permanent in position. Geostrophic currents in excess of 40 cm/sec have been calculated from stations of 5-mile spacing (Ingraham, Jr., 1966) which is about one-half of the speeds determined from direct current observations. This shows the necessity for very close station spacing if any reliable measure of currents is to be obtained from geostrophic calculations.
In winter, surface waters are relatively cold. The underlying halocline waters are warmer than the surface waters. The magnitude of the resulting positive thermocline (generally between 1 and 2°C) is dependent upon the degree of local cooling and the temperature of the halocline waters. The largest temperature gradient at depth occurs in the axis of the Stream where the halocline waters are relatively warm. The subsurface temperature maximum is highest in the eastern part of the Alaskan Stream. It decreases by about 1°C by mixing over a path of about 750 miles. At the same time, surface waters are colder to the west so that the magnitude of the positive thermocline remains relatively constant.

2. Subarctic Current

The Subarctic Current is a comparatively cold, low-salinity, weak eastward-flowing current, originating in the western Subarctic Pacific and extending eastward into the Gulf of Alaska (Fig. 1) (Dodimead et al., 1963). Its axis can be identified either by the peak of the temperature dome, by the deep (200-300 m) temperature minimum-maximum stratum (Fig. 3 and 4) or by the salinity trough (Fig. 6 and 7). Its southern extent is considered to lie just north of the vertical 4°C isotherm, so that, within the Subarctic Current, temperatures are less than 4°C in the lower-zone waters.

Local cooling is generally sufficient to form a temperature-maximum stratum below the mixed layer, particularly along 175°E. The magnitude of the winter positive thermoclines may be as large as those in the Alaskan Stream.

3. Alaskan Gyre

The Alaskan Gyre represents the shear zone between the Alaskan Stream and the Subarctic Current. It encompasses the relatively slow westward and eastward portions of these two systems (Fig. 1). The Alaskan Gyre is associated with the salinity and density dome (Fig. 6 and 8) but not with the entire temperature dome (Fig. 3). At its centre, the temperature change between 150 and 1500 m depth is remarkably linear, brought about by upward movement, which is presumably a maximum at the centre of the dome.

4. West Wind Drift

The West Wind Drift has as its origin the confluence of the Oyashio and Kuroshio (Fig. 1). It moves eastward with a slight northward component which carries it to about lat. 45°N in the vicinity of long. 180°. It continues in a near-zonal path to approximately 300 miles from the Washington-Oregon coasts, where part turns southward to form the California Current; a small part intrudes into the area off the Coast of Vancouver Island and then moves southward off the coast; and the remainder flows northward into the Gulf of Alaska (Dodimead et al., 1963) (Fig. 1). The northern boundary now appears
to shift northward as the West Wind Drift moves eastward, so that its northern extent lies at lat. 48° along 165°W.

Velocities decrease toward the east. Maximum velocities, approximately 18 cm/sec, occur near the Subarctic Boundary. Cells usually identified with westward flow are common features of the West Wind Drift.

5. Transitional Domain

In the Transitional Domain, surface salinities and temperatures are relatively high, and the magnitude of the halocline is comparatively small. Surface gradients are usually present. A sub-surface salinity minimum may occur beneath the halocline. The northern limit of the Domain is considered to be defined by the sharp horizontal surface and subsurface temperature discontinuity near lat. 45°N along 175°E (Fig. 3) and the relatively sharp subsurface temperature boundary near lat. 47°30'N along 165°W (Fig. 4). The T/S relationship of these waters are quite distinct from those immediately to the north, although along 165°W they do approach those in the Alaskan Stream, particularly in the halocline and lower-zone waters (Fig. 5). The T/S relationships are considered to be the best means of identifying the northern limit of this domain along these longitudes.

It appears that the winter temperature structure will exhibit a fairly marked positive thermocline brought about by lateral northward movement at depth, as opposed to those formed by local surface cooling below the temperature of the halocline waters.

The Subarctic Boundary denotes the southern limit of the Transitional Domain and of the Subarctic Pacific Region.

REFERENCES


FIGURES

Fig. 1. Major current systems of the North Pacific Ocean and station positions along long. 175°E and 165°W.

Fig. 2. Structures in the Subarctic Pacific Region.

Fig. 3. Temperature (°C) distribution along long. 175°E.

Fig. 4. Temperature (°C) distribution along long. 165°W.

Fig. 5. Temperature-salinity relationships along (A) 175°E and (B) 165°W.

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Fig. 7. Salinity (%) distribution along long. 165°W.

Fig. 8. Density (σt) distribution along long. 175°E.

Fig. 9. Density (σt) distribution along long. 165°W.

Fig. 10. Geostrophic currents (cm/sec) along long. 175°E. (Westward-setting currents are stippled).

Fig. 11. Geostrophic currents (cm/sec) along long. 165°W. (Westward-setting currents are stippled).
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