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Distribution of Dissolved Oxygen in the Summer Thermocline

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ABSTRACT

In summer the maximum concentration of dissolved oxygen is nearly always found at a depth corresponding to the lower part of the winter mixed layer. This subsurface maximum is widespread and in some areas may exceed the surface concentration by an increment of more than one milliliter per liter. It is shown that at and above the depth of the summer maximum the oxygen concentration remains very near the saturation concentration throughout the year, and hence depends principally upon the temperature. Seasonal variations in the thermal structure are shown to account for the formation of the subsurface maximum in summer.

Introduction. Over the greater part of the ocean in summer the maximum concentration of dissolved oxygen is found at a depth corresponding to the deeper part of the winter mixed layer. Kitamura (1958) mapped the amount by which the subsurface oxygen maximum exceeds the surface concentration in the North Pacific and found that it exceeds one milliliter per liter in some areas. He has also pointed out that the high values do not correspond to areas where photosynthesis is expected to be high. Reid et al. (1958) described the summer subsurface oxygen maximum in the region of the California Current and offered a preliminary hypothesis, as follows:

If all the water in a layer above a level that corresponds to the bottom of the winter mixed layer remained exactly saturated with oxygen throughout the year, the seasonal thermal changes would require that in summer the oxygen concentration in the lower part of the layer exceed that in the upper part.

The purpose of this study is to present, by examination of various data, the following conclusions: oxygen concentration throughout the upper layer

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remains sufficiently near the saturation value to be consonant with the above hypothesis; a subsurface oxygen maximum appears in the warmer months; this maximum is widespread, and the amount by which it exceeds the shallower concentrations corresponds fairly well to what might be expected from the seasonal range of surface temperature over the ocean; the alternative hypothesis, that the subsurface oxygen maximum might result from photosynthesis, seems unlikely.

Units and Definitions. Oxygen saturation concentration was determined from the nomogram of Richards and Corwin (1956) prepared from the work of Truesdale et al. (1955). Oxygen concentration is referred to in two ways: (1) as absolute concentration in milliliters of oxygen per liter of water (henceforward ml/L), and (2) as the ratio of the absolute concentration to the oxygen saturation concentration at in situ temperature and salinity, but at pressure of one atmosphere regardless of in situ pressure. The saturation ratio is expressed in per cent to avoid confusion with other units. Although the defined ratio is a convenient measure, it must be noted that subsurface samples with ratio above 100°/o are not necessarily supersaturated when in situ pressure is considered.

"Surface" concentration is understood to mean that concentration measured in a sample collected by a bottle closing at least half a meter below the surface and, in conditions of high waves, perhaps as much as three meters below the surface.

The "oxygen increment" or simply the "increment" is understood to mean the amount by which the absolute concentration of oxygen at the depth of the subsurface oxygen maximum exceeds the surface concentration.

Seasonal Variations near the Surface. Four examples of the seasonal variations of temperature, salinity, oxygen, and oxygen saturation ratio are presented in Figs. 1–4. The measurements were at fixed positions and the water was flowing past at speeds that varied with depth. The changes observed are produced partly by horizontal and vertical advection as well as local processes. This limitation must be kept in mind in any conclusions based on local data.

In all of the examples there is a relatively deep mixed layer in the colder months, with a saturation ratio near 100°/o. The ratio increases slightly in summer, but the greatest increase is above the level of the subsurface oxygen maximum that has appeared concurrently.

The Summer Subsurface Oxygen Maximum in the North and Equatorial Pacific. Kitamura's (1958) map of the oxygen increment has been extended in Fig. 5 by including northern summer data from the Bering Sea and from the area between the Tropics. Stations not showing the maximum are indicated by open circles. North of 15°N there are only a few of these and
Figure 1. Seasonal variation of temperature, salinity, dissolved oxygen and saturation ratio (per cent) in the upper 150 m at 26°32’N 117°48’W (CCOFI 120.80), 1950-1953 mean. Data are from Scripps Inst. Oceanogr. (1957, 1960) and unpublished Calif. Coop. Fish. Invest. cruises.

Figure 2. Seasonal variation of temperature, salinity, dissolved oxygen, and saturation ratio (per cent) at 50°N 145°W (Weather Station Papa) in 1957. Data are from the Fish. Res. Board Canada (1958).
Figure 3. Seasonal variation of temperature, salinity, dissolved oxygen, and saturation ratio (percent) in the upper 150 m at 29°N 135°E (Station TANGO), 1948–1953 mean. Data are from the Japan Meteorological Agency (unpublished) and from Okubo (1959).

Figure 4. Seasonal variation of temperature, salinity, dissolved oxygen, and saturation ratio (percent) in the upper 150 m at 39°N 135°E (Station EXTRA), 1948–1953 mean. Data are from Koizumi (1955) and Okubo (1959).
they have been ignored in the contouring. The rejected values are indicated by crosses.

A substantial increment was detected north of 15°N at nearly all of the stations, at depths varying irregularly from 20-100 m. The distribution of the increment is relatively coherent: a zone of high values is found along 40°N; a band of low values extends from the summer upwelling region off California to the Hawaiian Islands; and an area of high values is seen off Baja California.

The maximum is found in less than half of the data south of about 7°N, and with few exceptions the increment recorded there is less than the 0.05 ml/L which is approximately the range of analytical error.

The map of the increment (Fig. 5) is remarkably similar to the map of seasonal range of surface temperature presented in Fig. 6. However, the saturation concentration of oxygen does not vary linearly with temperature, and the two fields reflect the nonlinearity to some extent. For example, the 8°C range (Fig. 6) results at 50°N 160°E from a seasonal change of about 0°-8°C, and at 25°N 150°E from a seasonal change of about 20°-28°C. In the first case the corresponding change in saturation concentration is about 1.5 ml/L and the oxygen increments (Fig. 5) fall between 1.0 and 1.5 ml/L. In the second case the corresponding change in saturation concentration is about 0.6 ml/L and the observed increments fall near 0.5 ml/L. In the Bering Sea the fit is less satisfactory. For the mean temperature variation (Fig. 6), the corresponding change in saturation is about 1.5 ml/L, but the observed increment is less than 0.5 ml/L over much of the area, particularly along the Aleutian Islands. In an area centered at 40°N 160°W the increment is about 2 ml/L, but for the mean temperature range the change in saturation concentration is only 1.1 ml/L. Furthermore, the absolute concentrations at the maximum there are as high as 7.5 ml/L; these cannot have been in equilibrium with the atmosphere at temperatures higher than 2.3°C, and water as cold as this is never found in the mixed layer in that area. On the other hand, there is little reason to believe that the area is more productive than its surroundings, and that the high values might have been produced by photosynthesis. The 14 increments of about 2 ml/L were all determined from measurements made by two vessels in 1955 (Norpac Comm., 1960). Although they have not been rejected, it is noteworthy that the 10 other measurements made in that area in July-August 1956 (Fish. Res. Bd. Canada, 1957; Scripps Inst. Oceanogr., 1958) found that the concentration at the maximum did not exceed 6.5 ml/L, and that the increment did not exceed 1 ml/L.

The subsurface maximum is restricted to the warmer part of the year. No maxima are evident in observations made from January through March 1954 between 25°-40°N, 140°-165°W (McGary and Stroup, 1956) and none were found in the South Pacific in southern winter (May-July 1932) by the
Figure 5. The increment of dissolved oxygen concentration (ml/L) from the sea surface to the depth of the summer subsurface oxygen maximum. Open circles indicate stations not showing the maximum; these were ignored in contouring north of 15°N. Crosses indicate rejected data. Data are from the Norpac (Norpac Comm., 1960) and Equapac (Equapac Comm., in press) expeditions, from the early part of the Eastropic expedition (west of 110°W only) (Scripps Inst. Oceanogr. 1956), from the Albattross (Bruneau et al., 1953) and the Scot expedition (Holmes and Blackburn, 1960).
Figure 6. Seasonal range of surface temperature (°C) in the North Pacific Ocean; after Schott (1935), modified in part from data made available by the U.S. Navy Hydrographic Office.
Figure 7. Oxygen saturation ratio (per cent) at the sea surface in northern summer. Data sources are as in Fig. 5.
Discovery II (Disc. Comm., 1941). However, the Dana (Carlsberg Foundation, 1937) and the Downwind (Scripps Inst. Oceanogr., 1958) found maxima in southern summer in the South Pacific.

Summer Subsurface Oxygen Maxima in the Atlantic Ocean. The maximum is seen in various Atlantic data; among them are the I.G.Y. data of the Discovery II (Worthington, 1958) and the Crawford (Fuglister, 1957) as well as the Meteor data (Wattenberg, 1939, Beilage LXV). It is interesting to note that there was a similar oxygen maximum in summer data used by Redfield (1948) from the Gulf of Maine, though he does not refer to it. Riley (1951: fig. 4) has plotted a maximum on an oxygen profile in the South Atlantic, but he deals mostly with the deeper, steady-state distribution, and does not mention it.

The Possible Effect of Photosynthesis. Rakestraw and Emmel (1938) have computed the “original” value of oxygen from the dissolved nitrogen concentration at six stations in the North Atlantic and have compared this with the observed oxygen as an indicator of net production or assimilation. They concluded (p. 211) “... predominance of oxygen production over assimilation occurs more rarely than hitherto supposed.” Their data were taken in summer and showed the subsurface oxygen maximum, at increments from 0.55-1.11 ml/L. From consideration of the “original” value at the depth of the maximum it appears that a net production of 0.06-0.23 ml/L at three stations and net assimilation of 0.09-0.64 ml/L at the other three had taken place. In each case the maximum value was nearer to the “original” value at that level than to the actual surface value. This may indicate that the seasonal change of temperature was more effective than organic processes in creating the oxygen maximum.

Redfield (1948) found the upper waters of the Gulf of Maine to be undersaturated in winter and oversaturated in summer. By considering the phosphate variation also, he concluded that the major cause of the fluctuation of oxygen during most of the year is the seasonal variation of temperature, and that only at the period of minimum temperature (that is, low temperature change) is the effect of photosynthesis dominant. Some marginal evidence that his findings may apply to the surface water in particular as well as to the average of the upper 50 m is seen by comparing the saturation ratio at the surface in summer (Fig. 7) with the seasonal range of surface temperature (Fig. 6). The highest ratio at the surface occurs approximately along the zone of greatest seasonal temperature range. This may be partly the result of summer heating at such a rate that the saturation concentration decreases faster than oxygen concentration can decrease by escape to the atmosphere.

Measurements of the variation in productivity with depth are very sparse in the Pacific. The only measurement in the California Current in summer
(Blackburn et al., in press) showed productivity at the depth of the oxygen maximum (29 m) to be only 0.15 as high as at the surface.

Okubo (1959) has calculated that the average depth of compensation throughout the year is 40 m at Station TANGO and 20 m at Station EXTRA. The oxygen maximum at these stations lies between 50 and 70 m, where net production must be negative; thus, photosynthesis of an oxygen maximum at these depths does not seem likely.

It is difficult to see how the observed horizontal distribution of the oxygen increment (Fig. 5) could be accounted for by photosynthesis alone. What little may be surmised about the space variation of photosynthesis from the standing crop of zooplankton (Reid, in press) would indicate that photosynthesis should be relatively high along the California Current and relatively low in the central North Pacific. However, the oxygen increment does not follow this pattern. Certainly some production of oxygen takes place near the Equator (probably much more than at 30°N in midocean), but the data (Fig. 5) show little evidence of a maximum there.

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