Summer-winter comparisons of oxygen content in the polar seas

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Until very recently, marine chemistry studies in the polar seas were mainly performed in summer. Little or no chemical data were collected in winter because of logistical problems. Yet, deep and bottom waters of the world oceans are formed mainly in winter in the polar regions. The lack of winter data in such regions has prevented scientists from accurately estimating the variation of chemical properties of deep and bottom waters as they move away from their formation regions.

Winter oxygen data have now been collected in the Weddell, Bering, Greenland, and Norwegian seas. The concentrations of oxygen were found to differ drastically from summer values. Surface waters were undersaturated, because the air-sea exchange rate is comparatively lower than the cooling rate. What follows will be the comparison between my winter data and the summer data collected by me and by other investigators.

In 1982 Levitus summarized all data from the National Oceanographic Data Center as of 1978 and published the annual and seasonal mean oxygen saturation levels at the sea surface. The southern ocean annual mean was shown to be a few percent undersaturated, but at that time sufficient winter data were not available. The recent winter data, to be discussed later, indicate an even lower degree of saturation. The then-available and recent winter data also show undersaturation in the Bering Sea and the northern North Atlantic.

As early as 1963, Smetanin reported that wintertime northeast Pacific surface water is slightly undersaturated with oxygen. In 1964, Ivanenkov reported that nearly all of the Bering Sea in winter absorbs oxygen. He reported an average of 6 percent undersaturation in the western Bering Sea, a value later confirmed by Reid (1973). A similar degree of oxygen undersaturation exists in the northwestern North Pacific Ocean in winter (Hakodate Marine Observatory 1967; Reid 1973, 1982). The wintertime northern Gulf of Alaska surface water data and my *Polar Sea* data on the eastern Bering Sea shelf also show systematic undersaturation in winter (SIO Reference 70–5 1970; Chen 1985; Chen et al. 1985). The oxygen content of the *Polar Sea* winter surface layer is higher than that of the deep layer on the ice-covered shelf, but the degree of saturation is reversed, i.e., most of the deep shelf water is more highly saturated than that of the surface water. This phenomenon is not observed in summer when both the oxygen content and the degree of saturation of the surface water are higher than those of the deep shelf water (e.g., Hattori 1977, 1979).

In summer, shelf oxygen data show extreme variability, governed by biological processes. Winter oxygen, however, seems to mix conservatively regionally as suggested by segments of linear temperature vs. oxygen correlations, discussed in detail in Chen (1985).

Deep water for *Polar Sea* stations (104 and 105) in the Aleutian Basin shows a minimum in oxygen (figure 1a). The homogeneous, ice-free surface layer is also undersaturated with respect to oxygen by about 8 percent (figure 1b). The winter surface-water oxygen concentration is similar to the value found in the minimum temperature layer in the summer. Summer data from the same locality (stations KH78-3-8 and KH78-3-9 of the *Hakuho Maru* cruise; Hattori 1979) are plotted in figures 1c and 1d for comparison. Seemingly, summer warming raises the temperature, but the oxygen content of the surface layer does not increase by much except in the top 30 meters, where supersaturation is obviously caused by enhanced photosynthesis. In winter, enhanced vertical mixing and rapid cooling, unmatched by slower air-sea oxygen exchange and photosynthesis, produce undersaturation in the surface layer (Ivanenkov 1964; Reid 1973; Chen 1985). Brujewiez, Bogoyavlensky, and Mokievskaya (1960) also found an undersaturation as much as 20 percent in the summer minimum-temperature layer in the Sea of Okhotsk,

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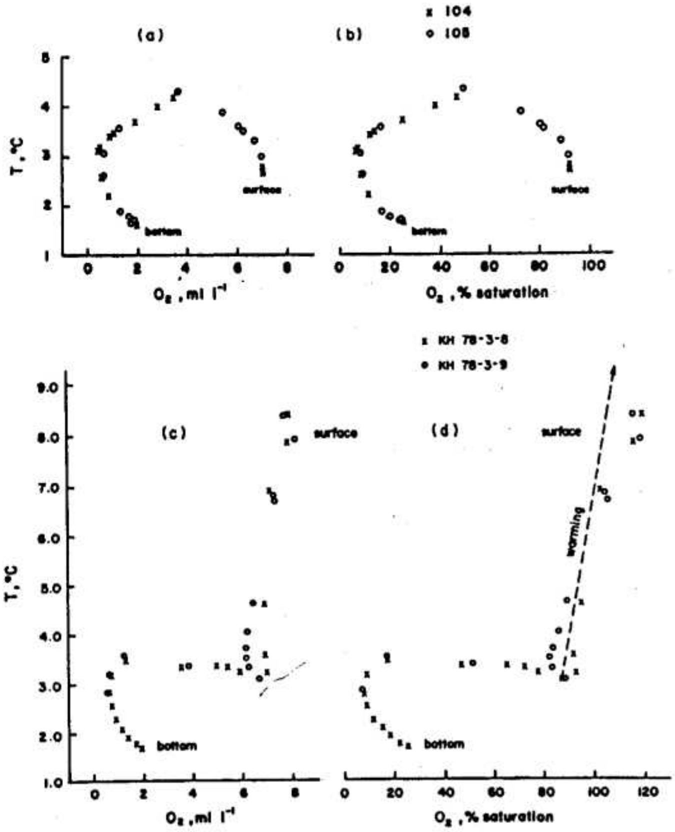

Figure 1. Correlation between (a) temperature (T°C) and oxygen (O_2), (b) temperature and percentage of oxygen saturation of my winter Aleutian Basin data, and correlation between (c) temperature and oxygen, (d) temperature and percentage of oxygen saturation of the summer *Hakuho Maru* data from the same location. The broken line shows the theoretical slope (taken from Chen 1985).

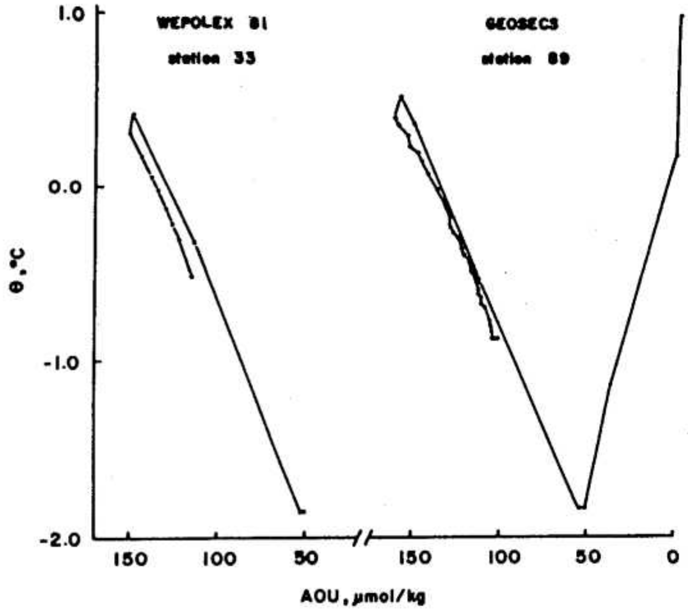

Figure 2. θ/AOU plot for WEPOLEX station 33 and GEOSECS station 89 in the Weddell Sea (taken from Chen 1984). ("AOU" denotes "apparent oxygen utilization." "μmole/kg" denotes "micromoles per kilogram.")

with the lowest degree of saturation on the continental shelf off Siberia and Sakhalin Island where intensive cooling occurs in winter.

The situation is similar in the Weddell Sea, based on the comparison of the SOMOV (Chen 1982a, 1984; Huber et al. 1983; Gordon, Chen, and Metcalf 1984), GEOSECS (Takahashi, Broecker, Bainbridge, and Weiss, unpublished data, Lamont-Doherty Geological Observatory, 1980), and other data in the literature (IGY 1961). An ice-free sumertime GEOSECS Atlantic station, GS 89, is located at 0.0°E 60.0°S which is very close to the ice-covered SOMOV station 33 (0°0.20'E 60°S). The potential temperature/salinity (θ/s) plot for waters below the minimum potential temperature (θmin) layer at GS 89 is essentially the same as the plot at SOMOV 33. The θ/AOU (apparent oxygen utilization) plot (figure 2) below the min layer at GS 89 is also similar to the plot at SOMOV 33. The SOMOV 33 data show a high AOU value of 50 micromoles per kilogram at the surface because the surface water is mixed with low-oxygen Weddell deep water, while the ice blocked the input of atmospheric oxygen (Gordon et al. 1984).

My winter data in the Bering Sea also suggest some air-sea exchange, but the exchange could have happened in the numerous leads and polynyas that I encountered in the Bering Sea but not in the Weddell Sea. The recent winter *Hudson* data (CSS *Hudson* 1984) in the northern North Atlantic Ocean also show systematic oxygen undersaturation (as low as 10 percent undersaturation) within or out of the ice field.

The above discussion clearly indicates that the high-latitude regions are probably undersaturated with oxygen in winter, although water chemistry beneath the ice varies from place to place, and I cannot yet generalize the findings in one area to represent other regions. As a further note, Anderson and Dyrssen (1980) reported surface oxygen supersaturation within the summer Barents Sea ice field, which is, no doubt, due to photosynthesis.

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