Distribution of inorganic phosphate and dissolved oxygen and their relationship in the coastal upwelling area off Zhejiang

The change and distribution of inorganic phosphate and dissolved oxygen content in sea water possess a certain regularity and correlation, which are closely related to the direct influence of biological activities. During the period of phytoplankton bloom, phosphate content may be exhausted and, at the same time, oxygen content in sea water increases in the euphotic layer. With the decomposition of organic matter, phosphate content increases and oxygen content decreases in the deeper layer. In addition, the upwelling carries the "new" nutrients to the euphotic layer, which provides advantageous conditions to phytoplankton growth, while the contents of dissolved oxygen decline due to the mixing of upwelling with low oxygen content. Other factors, such as temperature, wind-induced mixing and wave can also change oxygen content.

In the sea water the utilization or regeneration of nutrients should be related to the changes of the apparent oxygen content which are produced and utilized accompanying the processes mentioned above. According to these correlations the stoichiometric model of photosynthesis and nutrient regeneration is drawn in the ocean. It can be expressed as follows:

\[(\text{CH}_3\text{O})_{106} (\text{NH}_3)_{16} \text{H}_3\text{PO}_4 + 138\text{O}_2 \xrightarrow{\text{Oxidation}} 106\text{CO}_2 + 16\text{HNO}_3 + \text{H}_2\text{PO}_4 + 122\text{H}_2\text{O}.\]

The model indicates that the apparent oxygen utilization in deeper water is linearly related to the amounts of inorganic nitrogen and phosphate released.

Inorganic phosphate as one of three essential nutrient elements affecting phytoplankton growth is closely related to the primary productivity in the ocean. Oxygen content is an important mark of the level of the primary productivity. Thus the study of the distribution of inorganic phosphate and oxygen content in the fishing ground and their correlation has important significance.

Survey area and analysis method

The data in this paper were obtained through the investigation at the twenty five stations in the coastal area off Zhejiang (west to 124°E and 27°30′~30°30′N) in August 1981. The stations are shown in Fig. 1.

The content of inorganic phosphate in the sea water was determined on board by phospho-molybdic blue method with a shipboard spectrophotometer (Model GLZ-1); the oxygen content, by Winkler method. Chlorophyll a was determined by the Biological Department of our Institute.
Results

**Inorganic phosphate (PO₄—P).** As shown in Figs 2 and 4, inorganic phosphate concentration is higher in the inshore and decreases gradually towards offshore. In the upper layer above 10 m the isoplethes of inorganic phosphate lie in the inshore and the northern domain with layer gradients. The concentration of inorganic phosphate in all the stations is lower than 0.05 μmol/L except those in the onshore area. The concentration is even undetectable at the surface layer of some stations. The isoplethes of phosphate content in the water layers below 10 m move gradually outward. The concentration of phosphate increases gradually with the increase of depth; around 29°N and 123°E the upwelling carries the deep water enriched with phosphate to that around 10 m layer and creates larger vertical gradients of inorganic phosphate content at the different depths of each station. For example, at Station 8142, phosphate concentration increases from 0.11 μmol/L at 20 m layer to 0.74 μmol/L at 30 m layer.

**Dissolved oxygen (O₂).** As shown in Figs 3 and 4, a general trend of dissolved oxygen distribution is high in the inshore and low in the offshore water. In the inshore region below 10 m, oxygen content changes have large gradients. For example, the dissolved oxygen content in the surface layer declines from 6.65 × 10⁻³ at Station 8141 to 4.83 × 10⁻³ at Station 8142. Dissolved oxygen contents are lower (less than 4.8 × 10⁻³) in the upper layer of offshore water. But there occur patches of greater than 5.2 × 10⁻³ in the depth of about 10 m at Station 8143. The greater vertical gradients of oxygen content emerge in the pycnocline layer and decline rapidly downward until less than 2.8 × 10⁻³ at the bottom layer.
The distribution trend of \( \Delta O_2 \) extremely coincides with that of \( O_2 \). The apparent oxygen production (AOP equals the negative value of apparent oxygen utilization) is very high, with very dense isoplethes above the upper 10 m in the inshore waters. For example, AOP in the surface water is \( 2.00 \times 10^{-3} \) at Station 8141. AOP is low in the upper layer of offshore waters (less than \( 0.40 \times 10^{-3} \)). The AOP declines rapidly to zero in the pycnocline layer. However, the AOU increases rapidly with the increase of depth below the pycnocline.
Fig. 3. Horizontal distribution of dissolved oxygen and apparent oxygen utilization.

**Relationship between PO₄ – P and ΔO₂.** According to the distribution characteristics of inorganic phosphate and dissolved oxygen mentioned above, a linear regression method is applied to describing further the relationship between PO₄ – P and ΔO₂. As shown in Figs 5 and 6, no relationship exists between AOP and inorganic phosphate as most of the points converge at the corner of the figure. However, there exists a positive linear relationship between AOU and inorganic phosphate. The phosphate concentration increases with the increase of AOU. The regression equation is expressed as follows:

\[ \text{PO}_4 - P = 0.08 + 0.0037 \text{ AOU} \]

their correlation coefficient is 0.866 (n = 61).
Fig. 4. Transect distribution of inorganic phosphate and dissolve oxygen content, o$_3$ and Chl. a.

Fig. 5. The relationship between AOP and PO$_4$-P content in the water column.
Fig. 6. The relationship between AOU and PO₄-P content in the water column.

**Discussion**

In the coastal area off Zhejiang, the complex distribution of inorganic phosphate and dissolved oxygen and their complex inter-relationship are closely related to Zhejiang Longshore Water, Upper Water and Deep Water of Taiwan Warm Current and rich biological resources in the studied region. As shown in the salinity distribution (Fig. 7), coastal water masses with low salinity (<30) meet Taiwan Warm Current and form the stronger coastal front in the onshore domain (at about 30 m isople-

Fig. 7. Horizontal distribution of salinity in the surface layer.

th). Impeded by this front, river-input nutrients are accumulated in the onshore area. On the other hand, around 29°N the upwelling carries the deep water with abundant nutrients into the euphotic layer, and makes the euphotic layer rich of phosphate. However, because no upwelling reaches the surface layer, the mixing of upper and deep waters of Taiwan Warm Current causes the formation of up-
upwelling fronts in different depths. Various elements in the fronts form great vertical gradients. This indicates that the upper water with lower phosphate and higher oxygen is separated by a steep pycnocline from the deep water with higher phosphate and lower oxygen.

The results indicate that the highest oxygen production occurs in the inshore area at the upper 10 m on the edge of central upwelling area which coincides with the highest values of chlorophyll a and zooplankton, as a result of intense photosynthesis and phytoplankton bloom at the upper layer of onshore area. The continuous input of inorganic phosphate and nitrogen from the continental runoff is one of the main causes promoting the growth of phytoplankton. In the inshore area below 10 m, the apparent oxygen utilization and phosphate concentration increase rapidly with depth. This mainly results from the degradation of organic matter rather the mixing of the deep upwelling water with lower oxygen content. This is confirmed by the transect of σθ. The content of inorganic phosphate is low in the subsurface layer off the coastal front and it is undetectable at individual stations. The ratio of N : P is more than 40 : 1. Therefore owing to insufficient supply of nutrients, the phytoplankton grow slowly (the average value of chlorophyll a is 0.52 mg/m³ in the surface layer at stations from 8143 to 8145). And the rate of oxygen produced by photosynthesis of the phytoplankton lowers. However, in the surface layer of the central upwelling area, a certain amount of nutrients could be sustainably transported upward into the euphotic layer by the eddy diffusion. The nutrient conditions, therefore, are much more advantageous for the phytoplankton growth than those in the outer domain. In the front area of upwelling, the nutrients are extremely rich enough for the uptake of phytoplankton growth. For example, the high value of chlorophyll a is 7.4 mg/m³ in the depth of 20 m at Station 8143. But no high content of dissolved oxygen occurs in this layer, probably due to the coverage by the mixing of the deep water of upwelling with the lower content of dissolved oxygen.

On the other hand, as shown in Fig. 8, inorganic phosphate relates closely to living organisms. The content of chlorophyll a and biomass increase with the increase of phosphate concentration, and the results are also satisfactory by the regression analysis for average 5 values (r_{chl.a} = 0.96, r_{phyno.} = 0.98).

![Graph showing the relationship between inorganic phosphate and chlorophyll a, phytoplankton biomass at the upper 30 m of Section 4.]

The dissolved oxygen in the euphotic layer of oceans is supersaturated as a result of the exceed-
ing oxygen content produced by the photosynthesis than that consumed by the respiration. At the same time the production of dissolved oxygen assimilates the nutrients at a certain proportion, which coincides with the simple proportion of the apparent oxygen utilization and the nutrients released in the deeper layer. However in this sea area no correlation exists between the inorganic phosphate and the apparent oxygen production. Because the detected contents of inorganic phosphate refers to that after the reduction of biological uptake, which is mainly influenced by the physical process. Figure 9 shows a better positive correlation between the apparent oxygen production and chlorophyll a in the water column at depth less than 10 m. The correlation coefficient is 0.75. The apparent oxygen production increases with the increase of the chlorophyll a content. It indicates further that the biological process is a major process controlling oxygen distribution in the water column at the depth less than 10 m. There is a more obvious linear relationship between the apparent oxygen utilization and the content of inorganic phosphate below the pycnocline and in the coastal subbottom layer. It indicates that the consuming dissolved oxygen released, at the same time, the inorganic phosphate in a certain proportion. And the ratios of N : P also approach to the normal ratio of 15 : 1. The ratio of $\Delta O_2 : \Delta P$ having a certain biological significance can be gained from the straight line slope in the figure of $P$ vs $\Delta O_2$. Its ratio is 200 : 1 (by atoms). In fact this ratio involves the effect of the mixing process and therefore causes larger deviation form Redfield ratio (276 : 1 ). But the former coincides basically with ratios of $\Delta O_2 : \Delta P$ in the data of Kuroshio Current water reported by C. Matsudaira and A. Okubo.

In conclusion the inorganic phosphate in the coastal area off Zhejiang in summer is one of the important nutrients in controlling the primary productivity. The intense photosynthesis in the upper 10 m is an important process in controlling the distribution of the oxygen content. The front formed by the mixing and converging of water masses with different properties is closely related to these processes mentioned above.