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Main Features of Water Chemical Structure in the Southern Ocean

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Abstract : To better understand water stratification, chemical element redistribution due to dynamic processes, trends and intensity of biochemical synthesis processes and organic matter distribution in the Southern Ocean, the distributions of major hydrochemical parameters, such as dissolved oxygen, dissolved phosphates, pH values and total alcalinity, are described. A set of data on each element were averaged into the rectangular grid points to construct maps of the spatial distributions of hydrochemical parameters.

Key words : chemical structure, Southern Ocean, distribution, dissolved oxygen, phosphates, pH, alcalinity

Introduction

To study the regularities in the spatial distribution of major hydrochemical parameters in the Southern Ocean, as also in any other region of the World Ocean, appears to be of great importance in addressing a number of problems, related to the dynamic, physical-chemical and biogeochemical processes, occurring in the water column. In particular, such data allow us to better understand water stratification, chemical element redistribution due to dynamic processes, trends and intensity of the biochemical synthesis processes and organic matter distribution. The distirubiton of the dissolved oxygen and nutrients in the ocean water characterizes the level of biological productivity, being an indirect indicator of food resources in the water region. Knowing the variability of the fields of hydrochemical parameter distribution, one can describe the hydrochemical regime of the region, which in turn can serve as the basis for theoretical prediction of the ocean bioproductivity.

After a comprehensive analysis of the data a set of data on each element were averaged into the regular grid points with 2° spacing by longitude and 1° by latitude to construct maps of the spatial distributions of hydrochemical parameters. In the surface layer the preference was given to the observations, carried out during the antarctic spring and summer, if there were data, collected in different seasons of the year. In the construction of the meridional sections the data were averaged by standard levels and referred to the nearest whole degree by the section longitude. The latitudinal sections were made practically without averaging due to a small amount of data. The observations with an interval of not more than 1° (in some cases not more than 2°) by longitude from the section latitude were used.

General Water Chemical Structure

The intensity of biochemical processes at different depths and the form of the curves of vertical distribution of the concentrations of dissolved oxygen and carbonate system elements are commonly used as major criteria in classification of ocean water by chemical characteristics. The form of the latter is affected not only by the geochemical processes of synthesis and destruction of organic matter, but by physical processes, governing water stratification and circulation, as well.

Depending on the prevailing biochemical process in the vertical chemical structure of the Southern Ocean water it seems to be desirable to distinguish three main layers: surface, intermediate and deep.

The processes of photosynthesis and assimilation of the nutrients prevail in the surface layer. This layer is characterized by lower concentrations of the mineral forms of phosphates, nitrates and silicic acid and by a maximum content of the dissolved and weighted organic matter. In the surface layer one observes a maximum of the dissolved oxygen, governed by the presence in the layer of two main (for the ocean) sources of oxygen. During the vegetation period these are the processes of the photosynthesis, and for the other time of the year – the processes of oxygen invasion from the atmosphere. The upper boundary of the layer of maximum gradients of the concentrations of the dissolved oxygen and nutrients is assumed to be the lower boundary of the surface layer. Usually this boundary coincides with the "pycnocline" layer. In the intermediate layer of the ocean water the processes of the biogenic element regeneration prevail. This is a layer of large vertical gradients of hydrological and hydrochemical characteristics, particularly in its upper part. The depth of the intermediate layer is mainly governed by the rate of the nutrients regeneration and by dynamic conditions. The depth of decreasing vertical gradients of the dissolved oxygen, phosphates and nitrates where the concentrations of these compounds reach their extreme values is assumed to be the lower boundary of the intermediate layer. One can indicate the lower boundary of the intermediate layer more accurately, using O–P (dissolved oxygen-phosphates) diagrams. Table 1 gives depths of the lower boundary of the intermediate layer in various regions of the Southern Ocean, obtained from the mid-latitudinal vertical distributions of the concentrations of the dissolved oxygen and phosphates. They reflect qualitative regularities in variations of the intermediate layer thickness over the Southern Ocean water area, which are in a good agreement with the features of the meridional water cir-

Table 1. Mean latitudinal depth of the lower boundary of the intermediate water layer in various regions of the Southern Ocean.

meters

Latitudes	Atlantic Sector			Indian Ocean Sector			Pacific Ocean Sector		
	West. part	Central part	Eest. part	West. part	Central part	Eest. part	West. part	Central part	Eest. part
40	1500	1400	1300	1500	1700	1700	1800	2400	1500
45	1100	1200	1300	1300	1500	1700	1600	2500	1500
50	1000	700	600	700	900	1200	1600	2100	1600
55	1000	400	350	450	450	500	1200	1400	1800
60	300	300	250	300	250	250	800	250	1200
64	200	200	150	200	350	400	250	200	600
70	400	250	–	–	–	–	400	300	250

culation. The depth of the lower boundary of the intermediate layer decreases almost everywhere in the direction from the north to the south, reaching minimum in the antarctic convergence area.

The rate of biochemical processes in the deep layer is very small. The biochemical oxygen demand in this layer is by 2−3 orders of magnitude less than in the photosynthesis layer and lower than 2000m. It is several thousandths of mℓ/ℓ per year. The deep layer is characterized by high concentrations of nutrients and small vertical and horizontal gradients of all hydrochemical parameters.

The surface, intermediate and deep layers of the chemical water structure of the ocean are also in turn subdivided into parts by vertical in accordance with the water structure masses. Lower than the photosynthesis layer in the vegetation period and in the entire thickness of the water during the rest of the year, the redistribution of the hydrochemical properties over the ocean water area is mainly governed by physical processes of the water transport. In accordance with the features of water circulation in the Southern Ocean one can define two main latitudinal zones with a well-pronounced chemical structure. These are the Antarctic structural zone; from the shores of Antarctica to the antarctic convergence area, and from the antarctic convergence area to the subtropic convergence area.

The zones of the antarctic convergence and divergence have some typical features in the chemical structure. In descriptions of the hydrochemical regime these zones should be considered as the areas of the most strong vertical motions and transformation of waters. The areas of the antarctic convergence and divergence can be quite well observed at the maps of the horizontal distribution of hydrochemical parameters. The antarctic convergence area is characterized by the noticeable density of isolines (0 m and 200 m levels), and silicic acid distributions. The area of the antarctic divergence can be identified from a number of the features, which accompany the upwelling to the surface of relatively warm deep waters. As the rising water is strongly depleted of oxygen, then in the identification of the divergence zone location the distributions of the dissolved oxygen are most indicative of all hydrochemical characteristics. At the vertical sections of hydrochemical parameters in the convergence area the slope angle of isolines in the subsurface water dramatically increases. Southward and northward of the convergence zone the position of the isolines is more close to the horizontal one. The divergence area is characterized by an extremely high location of the oxygen minimum and nutrients maximums.

The Dissolved Oxygen Distribution

The distribution of the dissolved oxygen in the Southern Ocean water should be considered according to the existing water classification by vertical and latitudinal structural zones.

In the surface water layer the level of the dissolved oxygen is governed mainly by the processes of gas exchange with the atmosphere, being close to equilibrium during the whole year. The absolute oxygen content varies over the ocean area approximately in accordance with the dissolution value. In the surface water of the antarctic zone due to low temperatures the amount of oxygen is comparatively large and decreases from the south to the north from 700−750 μg−at/ℓ in the most cold shelf waters at 600−650 μg−at/ℓ in the antarctic convergence area. In a warmer subantarctic water the absolute content of the dissolved oxygen is somewhat less, being in the range of 500−650 μg−at/ℓ.

During the vegetation period the oxygen

content in the photosynthesis layer may exceed the equilbrium concentrations. The over-saturation of the surface water occurs in the case, when the oxygen income, resulting from the photosynthesis processes exceeds its decrease due to oxidation of organic matter, outflow to the lower water layers and loss of some excessive oxygen to the atmosphere.

From available data the largest saturation of the surface antarctic water by oxygen is observed approximately in the middle between the convergence and divergence zones and near the edge of the melting ice. In the antarctic divergence area even during the intensive photosynthesis processes there is a marked decrease in the saturation of water by oxygen as compared with the waters, situated northward and southward of the divergence area. Some decrease in the water saturation by oxygen, observed near the convergence zone appears to be connected with the enhanced vertical mixing of the surface waters in this region, which produces an unfavourable influence on the development of phytoplankton. At the present time there are data, indicating, that in summer the growth of the primary production and hence the intensity of photosynthesis in the antarctic and subantarctic regions of the Southern Ocean are limited mainly by the depth of the intensive vertical mixing of the surface water, rather than by sunlight. At low height of the sun the photosynthesis layer thickness is only 25−30 m in the antarctic waters and 30−50 m in the subantarctic waters. It is obvious, that the deeper the intensive vertical mixing, the lesser part of phytoplankton is in the photosynthesis layer, participating in photochemical reactions. The oxygen increase near the melting ice edge can be related to the fact, that directly in the melt area the ocean phytoplankton is joined by photosynthesizing algae populations, developing on the ice bottom surface, which in turn increases oxygen production.

The period of the rapid blooming of phytoplankton in the antarctic waters is not long. The maximum of the intensity of the photosynthesis processes falls on November and December. From late May to early October the photosynthesis processes are actually completely absent. During the other part of the year, in spite of the low height of the sun there is quite enough light for the photosynthesis processes in the surface antarctic water. Also already by midday the plants receive more light, than they can absorb without harm for themselves. The so-called effect of the photodepression occurs. As a result, the photosynthesis maximum and respectively associated oxygen maximum is observed not at the surface, but by 5−10 m lower. The oxygen content in the subsurface maximum of the photosynthetic origin in the antarctic waters occurs usually within 700−750 $\mu g-at/\ell$ at saturation of 102−109%, although it can reach 120 % and more for a short period of time. The effect of photodepression occurs in the subantarctic water too, but the depth of the maximum photosynthesis processes is greater from 10 to 50 m. The value of the subsurface oxygen maximum in the subantarctic water is usually 102−119% of equilibrium concentrations, but briefly it can reach 120 % and more in the areas of especially rapid blooming.

The only source of the dissolved oxygen income to the intermediate water layer appears to be its income during the process of the turbulent exchange with the surface water. A rapid decrease of the oxygen level with depth is observed in the intermediate layer, and a layer of the main oxygen minimum is formed at its lower boundary. The depth of the minimum layer, as a rule, decreases from the north to the south, reaching the lowest values in the antarctic divergence zone. When crossing the antarctic convergence area one observes a sharp rise of the layer with the minimum oxygen concentrations by several hundred meters. To the south of the antarctic divergence area the depth of the minimum layer increases again, with the minimum itself becoming less pronounced. Directly near the land slope it actually disappears completely. The layer of the oxygen minimum is also absent in the shelf water, which is characterized by a strong uniformity.

The distribution of the dissolved oxygen content in the minimum layer is in full agreement with the oxygen distribution in the lower deep layers. In the meridional direction from the northern limits of the Southern Ocean up to the land slope of Antarctica the oxygen level in the minimum layer increases. In the zonal direction with the water movement from the west to the east decreases. The latter tendency is more pronounced in the subantarctic latitudinal zone. The largest mean concentrations of oxygen in the minimum layer are observed in the central Atlantic sector, the lowest being found in the central and eastern Pacific Ocean sector. The local increases of the oxygen deficit can be attributed both to the features of water dynamics and serve as an indirect indicator of enhanced bioproductivity in the surface water.

The ocean depths lower than the layer with minimum oxygen content are aerated only in the regions of the deep and bottom water formation. The conditions for these waters formation and their further circulation in the whole World Ocean govern to a large extent the oxygen regime of deep and bottom layers of the Southern Ocean water. Major mass of the deep circumpolar water is formed in the western Indian Ocean sector when the North Atlantic deep, subantarctic intermediate and bottom antarctic waters mix. The deep water of the Southern Ocean move in a general zonal flow eastward, having some southern constituent of the current velocity. In the motion to the south one observes a general upwelling of the deep water with approaching the land slope of Antarctica. Deep circumpolar waters contain a relatively small amount of the dissolved oxygen which is particularly characteristic of the upper layer of this water. The deep water of the adjacent oceans is more poor in oxygen, the only source of the oxygen supply for the deep water of the Southern Ocean being from the bottom antarctic water. The bottom antarctic water is formed at the land slope of Antarctica or very close to it, when the well-aerated shelf water mix with the deep circumpolar water. The bottom water formation is most active in the south-western Weddell Sea. There are data about the existence of bottom water sources in the Ross Sea, Davis Sea, Prudes Bay and in some other coastal regions of Antarctica.

The level of the dissolved oxygen in deep and bottom waters increases with depth, reaching maximum values near bottom, over the entire Southern Ocean. The value of the bottom maximum is greater, the smaller the distance of the bottom water from the area of its formation, and in most cases, the nearer its position to the land slope of Antarctica. Directly in the areas of the bottom water formation the oxygen level down to the bottom almost does not change.

The distribution of the values of the water saturation by the dissolved oxygen in deep and bottom waters preserves the general features of the distribution of the absolute oxygen content in these layers, but in a smoothed form to some extent. The latter is related to the fact, that the decrease of the oxygen content in deep and bottom waters of the Southern Ocean, not connected with its biochemical demand, as a rule is accompanied by an increase of water temperature, and hence by a decrease of the oxygen solubility value.

The Distribution of Dissolved Phosphates

The compounds of phosphorus, as of some

other nutrients participate in all vital processes of sea plants and animals, and their content may serve as one of the indicators of the water region bioproductivity.

High concentrations of the dissolved phosphates in the entire water column, including the surface layer, are characteristic of the hydrochemical structure of the Southern Ocean water.

The upwelling of deep waters, rich in phosphates to the lower boundary of the surface layer, occuring southward of the convergence area, governs the comparatively high concentrations of phosphates in the surface antarctic waters. At most of the hydrological stations, occupied in this area, these concentrations are within 1.5 – 2.0 μg-at P/ℓ. The deep water rises most near to the surface in the antarctic convergence area. It is here at these latitudes one can distinguish a ring of waters with a maximum content of phosphates at the surface around all Antarctica. Northward of the divergence area the phosphate concentrations decreases with the distance from the water upwelling zone. Some decrease in the phosphate level is observed also to the south of the divergence area, which is most marked in the absence or attenuation of the photosynthesis processes. The largest meridional gradients of phosphates are found in crossing the antarctic convergence area, where the downward water flows prevail in the surface layer. In the subantarctic structural zone the phosphate concentrations in the surface layer change within: from 0.2–0.5 μg-at P/ℓ at the northern limits of the Southern Ocean water to 1.0–1.5 μg-at P/ℓ in the convergence area.

The other source of the phosphate income to the surface layer over the entire Southern Ocean area appear to be the processes of the convective mixing during water cooling and formation of the ice cover. A seasonal character of these processes, as well as the change in the photosynthesis intensity during the year govern seasonal variations of the dissolved phosphates in the surface layer which are about 0.3–0.5 μg-at P/ℓ for the Southern Ocean water. A dramatic increase in the phosphate concentrations is observed in November–December and preserved at low level during the entire antarctic summer. In April the level of the dissolved phosphates increases again up to the winter values. It is characteristic of the antarctic and most subantarctic surface water that even in the periods of the intensive development of the photosynthesis processes the content of phosphates in them is higher than the level of the concentrations, limiting the growth of phytoplankton. In the intermediate water layer a sharp increase of the phosphate concentration with depth is observed and a maximum of dissolved phosphate layer is formed at its lower boundary. The mechanism for the formation of this maximum and main regularities in the change of its depth over the Southern Ocean area are similar to those for the main oxygen minimum. The phosphate concentrations in the layer of their maximum are mainly in the range of 2.3–2.8 μg-at P/ℓ.

The distribution of the dissolved phosphates in the deep layer of the Southern Ocean is characterized by a comparatively strong uniformity, both vertically and in latitudinal and meridional directions. The latter is particularly typical for the antarctic structural zone, where the phosphate level actually does not change from the layer of their maximum down to the bottom, as a result of the intensive vertical motions of water. For the most part of the Southern Ocean area the level of the dissolved phosphates in the deep layer is equal to 2–2.5 μg-at P/ℓ.

Distribution of pH–Values and Total Alcalinity

The pH–parameter characterizes acid conditions of the medium and influences many chemical and biochemical processes, thus being an important factor, governing the appearance and maintenance of life in the ocean water. The pH value is related to some extent to the whole set of the parameters, forming chemistry of sea water and along with the total alcalinity value serves as the most–easy–to determine parameter of the state of the carbonate, borate, phosphate and other equilibrium systems in the ocean. The upsetting of these equilibriums caused by the chemical and biochemical processes and also by the change of the physical parameters of sea water state immediately affects the pH value.

Most typical feature of the pH value distribution in the surface water of the Southern Ocean appears to be its decrease from the north to the south. This tendency is revealed in the entire ring of the surface waters and is governed first of all by the increase of the dissolved CO_2 level in the surface water with the decrease of temperature. In latitudinal direction the differences in the pH values and total alcalinity estimates between some sectors of the Southern Ocean are quite small, being within the error of constructing the maps of these parameter distribution. The pH value in the surface layer of the subantarctic structural zone is equal to 8.05–8.20, with total alcalinity value being equal to 2.30–2.40 mg-eq/ℓ. In the antarctic structural zone the pH value at the surface is within 8.00–8.10 with total alcalinity being equal to 2.25–2.35 mg-eq/ℓ. During the periods of the intensive development of the photosynthesis processes the pH value can reach quite significant values (8.25 and more) even in the vicinity of the shores of Antarctica.

The features of the water circulation have a distinct effect on the pH value distribution in the intermediate and deeper waters. In the subantarctic structural zone in the upper 1.5 km layer the downward water motion prevails. Due to this the entire intermediate layer is quite strongly affected by surface water. The latter can be seen from comparatively large estimates of pH value down to the depths of 1000–1200 m. In the antarctic structural zone and in particular in the antarctic divergence area the upward water motion prevails at these depths and low pH values are more near to the surface, than in the Subantarctic. The differences in the pH values between some sectors of the Southern Ocean in the intermediate and deep water layers are small, both for the subantarctic structural zone and the antarctic waters. They reach maximum (about 0.10) between the eastern Pacific and Atlantic sectors of the Southern Ocean.