ECOLOGICAL BASIS OF EXPLOITATION OF THE RESOURCES OF ANTARCTIC KRILL

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Abstract: The analysis of long-term Soviet investigations and literary data have revealed two natural zones in the Antarctic region of the Southern Ocean: A zone of open Antarctic Waters and a zone of drifting ice, which differ by climatic and ice conditions, the distribution patterns of physico-chemical characteristics, biogenic elements, water masses, horizontal and vertical circulation as well as by the character and rhythm of bioproductive processes at the initial level of the production cycle. The series of the differences is, to a considerable extent, responsible for characteristics of the qualitative and quantitative composition of communities, particularly of dominating species in each natural zone. The Antarctic krill is an important link in the trophic structure of the epipelagic community of marine organisms in the natural zone of drifting ice which is the area of its domination. Taking into account peculiarities of the production cycles in this zone the conclusion can be made that a certain part of the krill production is not used. The estimated value of the amount taken by consumers is not equivalent to the value of annual production of krill. The annual production is estimated to be 24–47 g/m^2 in the area where krill dominates and it is equal to 15 million km^2, consequently the total annual production is 360–700 million t and the annual amount eaten by principal consumers is a little over 200 million t.

As a result of the analysis of long-term Soviet investigations of the oceanographic and biological structure of the Southern Ocean together with the analysis of the scientific inheritance of the past years (the results of the investigations made by the Discovery Committee expeditions in 1925–1939) we have come to the conclusion that the study of antarctic ecosystems and therefore the management of biological resources should be based on natural zonation of the Southern Ocean in accord with differences in natural conditions in the area.

The evidence in favour of the approach to the study of marine living resources of the World Ocean on the basis of natural zonation of its area is supported by many prominent scientists including SCHOTT (1935), HELA and LAEVASTU (1961), DIETRICH (1963) and GERSHANOVICH and MOISEEV (1976).

Based on the analysis of a great amount of data available we have ascertained that peculiarities of the oceanographic and biological structure of the Southern Ocean manifest themselves in full accord with differences in its climatic zones. It is found that the regularities of formation of bioproductivity, species composition, distribution of biological resources, the pattern of food webs and trophic relations of marine organisms are closely associated with the *latitudinal* (physical-geographical), *vertical* (a range of depths) and *circumpolar* types of zonation in the Southern Ocean (LUBIMOVA, 1981, 1982 a, b). The latitudinal zonation is displayed in differences in the climatic latitudinal zones of the Southern Ocean, the vertical zonation is shown by characteristics of the meridional exchange between the inshore and offshore waters of the Ocean and finally the circumpolar zonation manifests itself in differences in the character of meandering in the Antarctic Circumpolar Current, in orographic factors and in the extent of interaction between the horizontal flow of the Antarctic Circumpolar Current and coastal water of the high-latitudinal modification.

We distinguish two natural latitudinal zones in the Antarctic region of the Southern Ocean, which differ by climatic and ice conditions, by the distribution patterns of the main physical-chemical characteristics, of biogenic salts, water masses, horizontal and vertical circulation of water and therefore by the character and rhythm of bioproductive processes at the initial levels of the production cycle.

The combination of the differences involved governs, to a large extent, the specificity of the qualitative and quantitative composition of marine communities, particularly of the dominating groups and species as well as their functional characteristics in each natural zone.

The natural zones distinguished in the Antarctic region of the Southern Ocean are called according to the climatologic classification of the Antarctic suggested by BUGAEV (1963) and accepted in the Soviet Atlas of the Antarctic (1969). The boundary between them is the winter position of the negative radiation balance isoline (-2 kcal/cm^2 month) passing around the Antarctic Continent approximately along 60° S.

In general, with regard to the main parameters of the oceanographic structure, the natural latitudinal zones may be characterized as follows:

Natural zone of open Antarctic Waters covering an area of some 27 million km^2 is free from ice all the year round and is subject to the permanent influence of the Antarctic Circumpolar Current with which, as a rule, the zonal distribution of physical-chemical characteristics and biogenic elements is associated. Water-sinking processes prevail in most part of this natural zone, and the Antarctic Deep Warm Water Mass is predominant in the vertical structure (KORT, 1969; BOGOYAVLENSKY, 1969; VOLKOVINSKY, 1971; MAKEROV, 1956; SARUKHANYAN, 1980). The bioproductive process pattern of the zone at early stages of the cycle is similar to that of boreal regions, two peaks of phytoplankton vegetation are observed throughout the year. Copepods are predominant in the zooplankton composition, their high biomass is recorded down to the depth of 700–1000 m for most part of the year (HART, 1942; FOXTON, 1956; VORONINA, 1963, 1971; VORONINA *et al.*, 1980).

Natural zone of drifting ice covering an area of some 19 milln kmio^2 is free from ice only in summer. It is under the influence of large-scale cyclonic circulations of precontinental seas (BUJNITSKY, 1973; TRESHNIKOV, 1964) with the exception of stationary compact ice existing all the year round. The processes of upwelling and azonic patterns of the distribution of physical-chemical characteristics and biogenic salts prevail over a larger part of the zone. The Antarctic Bottom and Antarctic Surface Cool Water Masses formed as a result of the interaction of shelf and deep waters are more developed in the vertical structure. Practically there is no deep warm water mass in the coastal shelf part of the zone (KORT, 1969; LEDENEV, 1969; KOROTKEVICH and LE-

DENEV, 1962; KLEPIKOV, 1958; BOGOYAVLENSKY, 1969). The bioproductive processes are of a distinctly-seasonal character. The peak of phytoplankton vegetation is recorded only once a year, in spring. Macroplankton (by biomass) prevails in the composition of zooplankton which is concentrated in the surface 0–100 m layer, macroplankton is mainly represented by euphausiids (*E. superba* and other species) (HART, 1942; VORONINA, 1971, 1977; VORONINA *et al.*, 1980).

The natural zone of open Antarctic Waters is, thus, characterized by high productivity chiefly in the mesopelagic layer on account of highly abundant copepods throughout the year. In the natural zone of drifting ice high productivity is recorded in the epipelagic layer only in the warm period of the year where macroplankton (primarily *E. superba*) is concentrated. According to the latest data obtained on the basis of modelling the populations of mass species of copepods and the quantitative ratio between copepods and euphausiids it has been ascertained that the secondary production of copepod plankton in the area of its domination (the natural zone of open Antarctic Waters) is equal to 70 g/m^2/year and the production of krill in the area of its domination (the natural zone of drifting ice) ranges from 24–47 g/m^2/year (VORONINA *et al.*, 1980).

The interzonal differences in the oceanographic structure of the Antarctic region of the Southern Ocean are responsible for the existence of various ecologic communities of marine organisms dominating in each natural zone.

The highly productive mesopelagic layer of the natural zone of open Antarctic Waters is inhabited by abundant plankton-eating fish from the family Myctophidae, this area is the centre of their habitat. As it is ascertained the reproduction and formation of spawning concentrations of many mass species of myctophids occur within the zone (BOGDANOV and LUBIMOVA, 1978; LUBIMOVA, 1980a, b; EFREMENKO, 1972, 1980; LUBIMOVA *et al.*, 1982). The meso- and bathypelagic layers of the zone are inhabited by a number of species of notal and Antarctic cephalopods which eat mainly mesopelagic plankton-eating fish, such as *Moroteuthis ingens*, *M. knipovitchi*, *Gonatus antarcticus*, *Galiteuthis aspera*, *Batoteuthis scopols*, *Mesonychoteuthis hamiltoni* and some other species known primarily from the analysis of the stomach content of sperm whale (KLUMOV, 1971; KLUMOV and YUKHOV, 1975; FILIPPOVA and YUKHOV, 1979). In view of the fact that according to the data available (information of I. W. C. for 1931–1967; BERZIN, 1971; LAWS, 1977) the highest abundance of sperm whale in the Antarctic is registered in the band between 40° and 60° S and as is known sperm whales eat in places where squids are concentrated it is very likely that the abundance of meso- and bathypelagic squids inhabiting the natural zone of open waters is fairly high. The review of data available on the distribution and biology of the species involved as well as of other groups and species which are predominant in the zone of open Antarctic Waters, supports the evidence that the pelagic community is mainly represented by the mesopelagic group of marine species and their trophic structure is developed on the abundance of copepod plankton in the 0–1000 m layer, and the Antarctic krill is not significant here. The exception is local waters off South Georgia, an area of expatriation of krill beyond the habitat of the Weddell Sea population (MAKAROV and SHEVTSOV, 1969) where high productivity is formed in the epipelagic layer. It is worth mentioning that some scientists (DELL, 1952; KNOX, 1970) suggest the existence of an independent food web in the Antarctic, *i.e.* copepod plankton–meso- and bathypelagic fish–squid–sperm whale.

The Antarctic krill *E. superba* is an important link in the trophic structure of the community of marine species in the natural zone of drifting ice which is the centre of its habitat. It is ascertained that the northward distribution of krill aggregations which are formed in the feeding and reproduction seasons in the warm period of the year, is restricted by 60° S practically all over the Southern Ocean (MASLENNIKOV, 1980; LUBIMOVA and SHEVTSOV, 1980) which corresponds to the north boundary of the natural zone of drifting ice. Within the boundaries of the zone getting free from ice in summer krill is eaten by baleen whale, pinnipeds (except for southern elephant seal), fish, birds and mesopelagic squid capable to rise into the epipelagic layer where krill aggregations occur. The extent of accessibility of krill, however, as a food item is not the same for all groups of consumers due to peculiarities of the vertical and spatial distribution of both krill and its consumers. Krill is most available to baleen whale and pinnipeds distributed widely in the epipelagic layer of the zone of drifting ice in summer, and among them krill is the most accessible to permanent inhabitants of the zone, *i.e.* to minke whale and crabeater seal and less available to some migratory species of baleen whale, *e.g.* sei whale which do not occur practically south of 60° S (LAWS, 1977; BUDYLENKO, 1970) and ice forms of seal (Ross's seal and Weddell's seal). By far less is the extent of accessibility of krill to the high-latitudinal Antarctic fish inhabiting mainly the off-bottom layer of the insular and continental shelves. It is only a few species from the high-latitudinal fauna inhabiting the shelf water that adapted themselves to using rich food resources from the pelagic layer during their vertical migrations to mid-water where krill is concentrated. They are so-called demersal-pelagic or secondary pelagic shelf species of fish from the family Nototheniidae (*Pleurogramma antarcticum*, *Notothenia rossi marmorata*, *N. squamifrons*) and from the family Chaenichthyidae (*Champsocephalus gunnari*, *Pagetopsis macropterus*, *Neopagetopsis ionah*, *Chaenodraco wilsoni*, *Chionodraco hamatus*, etc.) (ANDRIYASHEV, 1964; LUBIMOVA, 1980a, b; SHUST, 1980; ABE and SUZUKI, 1978). It is worth saying that the extent of accessibility of krill and therefore the feeding rate of its consumers are higher in the West Antarctic rather than in the East Antarctic. Owing to the circumpolar zonation mass aggregations of krill in the West Antarctic are formed in the shelf waters of the Antarctic Peninsula, off South Shetland and South Orkney Islands, in the East Antarctic, mainly beyond the shelves of pre-continental seas, over the continental slope and in the deep ocean. The investigation of the quantitative composition of food consumed by shelf fish from the zone of drifting ice in the East Antarctic (the case study of the most abundant *P. antarcticum* which adapted themselves to intermittent habitation in the pelagic layer) has indicated that krill constitutes about 50% of the total ration of all age groups of fish (GORELOVA and GERASIMCHUK, 1981).

Krill is by far less accessible for mesopelagic fish from the family Myctophidae, the centre of their habitat lies in the natural zone of open Antarctic Waters. Inhabiting the Antarctic Circumpolar Current water some specimens, however, penetrate into the zone of drifting ice from the south outlying part of the Antarctic Circumpolar Current, in the West Antarctic in particular where the boundaries of the two different natural zones are near. Thus the food contacts of myctophids and krill revealed in the investigation are restricted by the north boundary of the zone of drifting ice chiefly in the

West Antarctic, in the Sea of Scotia in particular (PERMITIN, 1970; REWWEDER, 1979; LUBIMOVA, *et al.*, 1982).

Of meso- and bathypelagic squid known in the Antarctic region of the Southern Ocean only *Brachioteuthis riisei* is identified by biologists as a surface from which eats krill in the Sea of Scotia and occurs in the stomach content of sei whale and fin whale. It is assumed that mesopelagic squids *Kondakovia longimana* and *Psychroteuthis glacialis* are able to rise to the lower epipelagic layer, but there is still no evedence that they eat krill. All other species of squid encountered in catches taken in the zone of drifting ice belong to typical meso- and bathypelagic deep-water forms and krill, as a food item, is inaccessible to them (KLUMOV, 1971; KLUMOV and YUKHOV, 1975; FILIPPOVA and YUKHOV, 1979).

Analysing information available in literature and the author's data on the distribution of biological resources in the Southern Ocean and on the consumption of krill by principal groups of consumers we estimated that the total consumption rate is equal to 209 million metric tons of krill per year (LUBIMOVA and SHUST, 1980). As a result of the addition of new data on productivity of demersal-pelagic fish inhabiting the insular and continental shelves in the zone of drifting ice and mesopelagic myctophids in the area of their possible contacts with krill in the northern part of the zone a similar value of the annual consumption of krill (a little over 200 million metric tons) has been estimated.

Proceeding from the characteristics of production cycles in the zone of drifting ice it is safe to say that a certain part of krill production is not used and the estimated value of krill eaten is not equivalent to the annual production of krill. According to principles stated by scientists (CUSHING, 1959, 1975; GEINRIKH, 1971; STEEMAN-NIELSEN, 1962) the production cycles at the initial levels in the zone of drifting ice are distinctly unbalanced. The main characteristics of the production cycles in the high-latitudinal Antarctic are as follows:

1) The distinctly pronounced stratification of waters results in a higher growth rate of algae, spring outburst of phytoplankton and a wide range in the grazing rates of herbivores.

2) The duration of the "delay period" (D. H. Cushing's term) between the development of phytoplankton and herbivores, particularly *E. superba* in the zone of drifting ice is over two months, consequently the complete productive cycle lasts longer here than in temperate waters of the World Ocean and the volume of primary production is greater, so it is under-exploited by herbivores.

3) When the amplitude of seasonal variations in the standing crop of algae is high non-exploited algal cells sink to the bottom, *e.g.* the quantity of diatoms in samples taken from the suspension in the zone of drifting ice reaches 1 milliard cells per $1 m^3$ (LISITSYN, 1969; KOZLOVA, 1962).

4) A pronounced domination of one species among herbivores (*E. superba* in this case study) in the vegetation period leads, in the long run, to a very high level of production.

The unbalance observed between the production cycles of algae and herbivores in a certain period of concentration of consumers in areas rich in zooplankton leads, according to CUSHING, to a variable rate of grazing and to unbalanced production cycles of herbivores and carnivores, *i.e.* carnivores under-exploit the production of herbivores.

In accordance with this, in summer, when mass aggregations of *E. superba* are formed and the abundance of carnivores of the first level consuming krill as highly aggregated food is the highest the production of krill is under-exploited.

At the present stage of our knowledge it is difficult to evaluate the part of krill which remains unexploited since values suggested in literature vary greatly, *e.g.* 750 million t (HEMPEL, 1970; GULLAND, 1970), 450 million t (GREEN, 1977), etc. Using, however, the recent data on the average production of krill in the area where *E. supreba* dominates, *i.e.* in the zone of drifting ice it is possible to obtain a fairly true value of the unexploited part of the production of krill within this zone. The mean annual production of krill in the area of its domination is equal to 24–47 g/m^2 (VORONINA *et al.*, 1980) and the area of the zone (except for the coastal shelf water) is 15 million km^2, so the total annual production of krill is equal to 360–700 million t. The principal consumers take 200 million t of krill, consequently a substantial part of its annual production remains unexploited.

At present we are making an attempt to estimate the unexploited part of the annual production of krill in the Antarctic on the basis of regularities of its population dynamics.

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(*Received November 16, 1982*)