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INTRODUCTION

As a part of the International Biological Programme, Yugoslavia has included studies of marine communities. The Institute of Oceanography and Fisheries, Split, established permanent stations in the Central and South Adriatic to collect monthly and seasonal data on physical, chemical, meteorological and biological parameters. Such data combined with other data such as the CICLOPE (1911—1914) and NAJADE (1911—1914) expeditions and the later Yugoslav expedition during the IGY 1957—1958 provided the basis for the formulation of a model to predict secondary production in the Adriatic (Buljan, 1953, 1968; Zore-Armanda, Pucher-Petković and Kačić, 1971; Pucher-Petković and Zore-Armanda, 1973). This scheme with some new quantitative estimations will be discussed and it will be shown how it could be applied to the other areas of the Eastern Mediterranean Sea.

WATER EXCHANGE AND METEOROLOGICAL FACTORS

The Adriatic Sea is the main source region for the deep water of the Eastern Mediterranean. On the other hand, the Levant basin is the source region of very saline intermediate (A) water (Lacombe and Tchernia, 1960; Zore-Armanda, 1963; 1974b). Water exchange between the Adriatic and other basins of the Eastern Mediterranean takes place through the Otranto Strait as identifiable characteristic layers, surface, intermediate and bottom water. The degree of exchange is regulated by the water characteristics and by meteorological factors. Concerning these factors, it seemed useful to analyze the climatic parameters influencing an area larger than the Adriatic Sea or even larger than the whole Mediterranean. It has already been noted that the quantity of ice in the North Atlantic exercises a certain influence upon the oceanographic characteristics of the Eastern Mediterranean (Zore-Armanda, 1971, 1974a, b). It apprears that this parameter might be related to the properties of the baric field over the northern North Atlantic, Europe and Mediterranean, especially the position of the Iceland low, which extends northeastward with the heavy ice appearance in the North Atlantic. At the same time, a high over Europe is more frequent, resulting in north winds over the Mediterranean along with frequent penetration of cold and dry air masses from the continent. Under such conditions, the average winter sea surface temperature decreases and the salinity increases in the central Adriatic. The quantity of ice in the Iceland region could well indicate the general ice conditions in the North Atlantic and likewise could be related to the meteorological and oceanographic conditions of the Mediterranean and the Adriatic.

The amount of advection of eastern water into the Adriatic is also important in the formation of deep water. Air pressure gradients over the Eastern Mediterranean exert an important influence (Zore-Armanda, 1968, 1974a). It seems that air pressure gradients exert a direct influence upon the flow, acting on the sea-level slope. The zonal air pressure gradient prevails over the Eastern Mediterranean in summer. For water advection into the Adriatic to occur, it is necessary that the air pressure gradient be higher in the most western part, such as the vicinity of Trieste. In winter, the meridional gradient is prevalent in the Eastern Mediterranean. For water advection into the Adriatic in winter, it is necessary that air pressure in the most northern part (Trieste) be higher. The winter meridional and summer zonal air pressure gradients over the Adriatic are well represented by annual diagonal gradients, which correspond roughly to the sum of their vectors. Because Trieste is situated in the most northwesterly area, and Athens southeasterly of the Adriatic, it is assumed that the annual differences in air pressure between these two places are characteristic of the air pressure gradients responsible for water exchange between the Adriatic and the Ionian Sea. Thus the Adriatic as well as other basins of the Eastern Mediterranean could be looked upon as continental seas, whose characteristics can change significantly from year to year and regulated by climatic conditions.

In the Adriatic, significant year-to-year variations, in primary production, by as much as a 100 percent change from the previous annual value, has been observed. Pucher-Petković and Zore-Armanda (1973) have shown that such variation depends on the previously described climatic factors (Figure 1). On the other hand, it has been repeatedly noted that the East Mediterranean has low levels of nutrients (Sournia, 1973). The main sources of nutrients for the Eastern Mediterranean are the Nile and Po Rivers, as well as the inflow from the western Mediterranean. The contribution of nutrients from the Black Sea is restricted to the most northern part of the Aegean Sea. The quantity of the nutrients as well as primary production decreases going from Gibraltar to the Levant and possibly to the Adriatic. Thus the amount of the water exchange between basins is of great importance. Obviously it is difficult to express such relations quantitatively due to the lack of sufficient data on currents for the various regions. It should also be mentioned that along with the permanent biological nutrient consumption, the nutrients are subject to the diffusion processes, but the knowledge of water transport is not sufficient for the nutrient transport calculations. In spite of these limitations, a nutrient distribution for four seasons for the Otranto Strait has been calculated. It is based on certain approximate assumptions that the currents in the Central Adriatic and Otranto Strait are similar and there is permanent vertical distribution of nutrients and, therefore, should be considered as strictly preliminary.

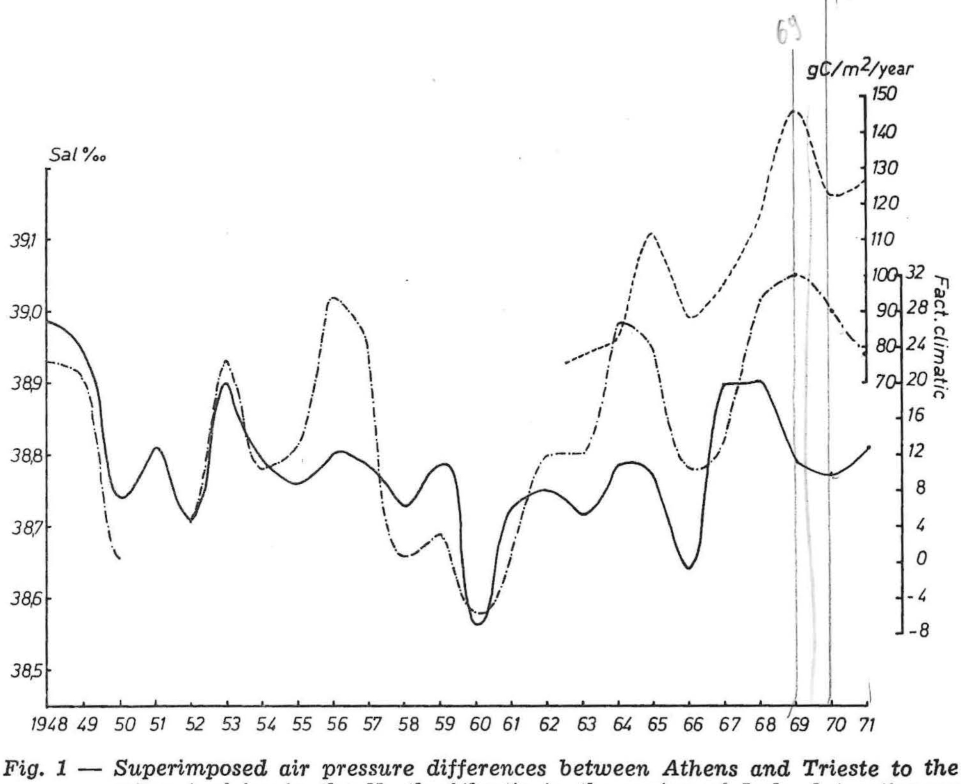

Fig. 1 — Superimposed air pressure differences between Athens and Trieste to the amount of ice in the North Atlantic in the region of Iceland (continuous line), the maximum annual values of the salinity in the Central Adriatic (dashed-dotted line) and the gross annual primary production in g C/m² surface in the Central Adriatic (broken line).

Data on the currents of the Central Adriatic are sufficient to understand the major aspects of the current system (Zore-Armanda, 1968). A surface current develops to a depth of 40 m, an intermediate current (»A« water) between 40 and 400 m depth and deep (bottom) current from 400 m to the bottom. It is assumed that in the Strait, the resultant current velocities are similar to those in the Central Adriatic, although they are possibly larger. However, the lowest values have been used to avoid periodic current fluctuations.

For the surface layer the velocity of the 10 cm/sec is used, for the intermediate 4 cm/sec and for the deep (bottom) layer 3 cm/sec. Taking into account the cross sectional area for each layer (surface: $2{,}8 \times 10^{10}$ cm^2; intermediate: $12{,}2 \times 10^{10}$ cm^2; deep: $5{,}4 \times 10^{10}$ cm^2) and supposing a constant current direction, the water transport determined for each layer and for each season (three months = 90 days) is as follows: surface layer, 2.17×10^{18} cm^3/season; intermediate, 3.72×10^{18} cm^3/season; bottom, 1.26×10^{18} cm^3/season.

For each season and layer, the current rose of Zore-Armanda (1968) and unpublished are used to determine the percent of incoming, northwest (NW) and outgoing southeast (SE) current. It is assumed that the same percent of the previously calculated transport represents the net incoming and outgoing water transport. For the exit transport, the difference between evaporation and fresh water inflow (E-P) for the Adriatic has been subtracted. Evaporation was determined from heat budget calculation for the whole Adriatic (Zore-Armanda, 1969).

Table 1 gives the value of about 7.8×10^3 km^3 of water that enters or leaves the Adriatic in one year. As the volume of the Adriatic is about 35,000 km^3 of water, the calculated water renewal takes 5 years. But as the deep Eeastern Mediterranean water is formed almost entirely in the vicinity of the Otranto Strait (Zore-Armanda, 1974b) it is possible that the Adriatic renews its

Table 1. Water exchange (in 1000 km^3) in the Otranto Strait

Season	Layer	Percent Northwest Current	Income to the Adriatic	Percent Southeast Current	Exit from the Adriatic
Spring	Surface	13	0.28	13	0.28
	Intermediate	36	1.02	13	0.50
	Bottom	0	—	47	0.60
	Total		1.30		1.38
Summer	Surface	9	0.62	41	0.90
	Intermediate	47	1.76	20	0.75
	Bottom	0	—	39	0.50
	Total		1.96		2.15
Autumn	Surface	14	0.30	14	0.30
	Intermediate	27	1.00	13	0.50
	Bottom	0	—	55	0.70
	Total		1.36		1.50
Winter	Surface	54	1.19	20	0.44
	Intermediate	53	1.96	29	1.10
	Bottom	0	—	95	1.20
	Total		3.15		2.74
Whole year	Surface		1.97		1.92
	Intermedite		5.74		2.85
	Bottom		—		3.40
	E — P				—0.07
	Total		7.71		7.70

water over a longer period, as the exchange of water in the Strait may be faster than in the rest of the basin.

Annual average income and exit in the surface layer is in equilibrium; in the intermediate layer the income exceeds the exit. The higher income in the intermediate layer is compensated by the high exit in the deep (bottom) layer.

NUTRIENT BUDGET AND PRIMARY PRODUCTION

The assumption is made that there is a rather permanent vertical distribution of phosphate, nitrate and silicate in both the Adriatic and Ionian Seas. The data of McGill (1965) have been used to determine average values for the three layers. These values multiplied by the water income and exit in the Otranto Strait for all seasons and layers gave an annual budget for nutrients. Values which are attributed to nutrient income from the Po River (Sournia, 1973) are added to the income.

Table 2 shows an approximate annual balance for phosphate and nitrate, but not for silicate. This can be accounted for to the fact that the silicate which is supplied by rivers in relatively high quantity, is subject to intensive consumption by diatoms, which represent, especially in the coastal region of the Adriatic Sea, the most important phytoplankton group. As for the seasonal distribution of the phosphate and silicate, it is interesting to note that the Adriatic has a positive balance only in winter and in the other seasons, a negative balance. Recent data taken during four seasons in the South Adriatic (Vukadin, 1972) show that the maximum appears in winter. For nitrate the positive balance is observed in summer.

Table 2. Nutrient exchange in the Otranto Strait

Season	PO_4-P (10^3 tons)		NO_3-N (10^3 tons)		SiO_3-S (10^3 tons)	
	In	Out	In	Out	In	Out
Spring	4.64	5.65	24.67	34.30	92.00	106.70
Summer	7.13	7.76	42.17	40.25	144.00	146.40
Autumn	4.63	6.24	24.22	38.08	91.60	117.60
Winter	10.94	9.08	48.32	69.86	211.50	188.60
Po River	1.80		41.39		110.10	
Whole year	29.14	28.73	180.77	182.49	649.20	559.30

It is evident that the unequal water exchange in different seasons may well effect the production. But the seasonal changes in production depend also from many other factors (light, sea temperature, grazing, etc.) and further studies to understand such a complicated relationship are needed.

What would the nutrient budget be if the water exchange in the Otranto Strait is more rapid? Based on T-S diagrams, Zore-Armanda (1963) has shown that in such a case the intermediate (A) water enters to the Adriatic in a larger quantity and it occupies the surface layer. The T-S diagrams also show that the average volume of intermediate (A) water is 60 percent of the whole water body and it could vary from 50 to 70 percent. Thus it can be assumed that the intermediate water completely occupies the surface layer. The latter calculations are made with the assumption that in the years with more intensive water exchange, characteristics of the intermediate water could be attributed to the surface water. For phosphate, this gives the increasing income of 1.18 $\times 10^3$ tons or 40 percent. For nitrate, the increasing income would be 46.89 $\times 10^3$ tons or 30 percent and for silicate 43.8 $\times 10^3$ tons or 8 percent. It is noted that as far as nitrate is concerned, the increasing income is of the same order of magnitude as annual contribution of the Po River while for phosphate and silicate it reaches 50 percent of the annual contribution. For nitrate, the increase is most marked. Therefore, nitrate could be, under certain circumstances, a limiting factor for production, as pointed out by Nümann (1941) and Buljan (1964, 1968). The very low N/P ratio, which McGill (1965) found in the Jabuka pit supports this opinion, whereas the high N/P ratio found by Scaccini Cicatelli (1967) on the Italian coast (from the Po River to Ancona) and by Poli Molinas and Olmo (1969) near Fano may be due to the proximity of the Po River. Sournia (1973) and Ercegović (1936) emphasized the phosphorous deficiency in the Adriatic.

Silicate, which is necessary for diatom frustule formation, could limit primary production (Yentsch, 1963). The Po and other fresh water sources contribute much of silicate to the Adriatic Sea. A survey of silicate in the Central Adriatic by Buljan and Marinković (1956) showed 192 mg/ton as the average content for the surface layer in the coastal region, 170 mg/ton for the same layer in channels and 114 mg/ton for the surface water of the open Central Adriatic. These values are higher than those found in the South Adriatic and Ionian Sea by McGill (1965). It appears that such distribution of silicate is in agreement with the silicate budget (Table 2). Pucher-Petković (1966) estimated that silicate could not be a limiting factor for the Adriatic production, based on the generally high percentage of diatoms in the phytoplankton population.

In the open Middle Adriatic, a very interesting relationship between the maximum salinity values and the presence of coccolithophores was found as shown in Figure 2. As mentioned above, higher salinity of the Adriatic water is due to a larger advection of Eastern Mediterranenan intermediate (A) water from the Levant basin. With higher salinity in the Adriatic, the percentage of coccolithophores is augmented. Thus it is obvious that coccolithophores prefer the more saline environment and that there exists an excellent relationship between the proportional occurrence of this group and the trend of salinity, but with a time delay of one year. Therefore, coccolithophores are considered as an indicating group of the Eeastern intermediate water (Pucher-Petković and Zore-Armanda, 1973). Thus with more intermediate (A) water and higher concentration of nitrate (up to 30 percent), the greater the abundance of coccolithophores. This leads to the assumption that low coccolithophore abundance is related to a definite nutrient relationship as well as other factors including temperature, salinity and nutrient concentration. In the other areas of the Mediterranean, the coccolithophores occur in higher percentage than previously found (Pucher-Petković, 1966; Vučetić and Pucher-Petković, 1969). This finding could also be inter-

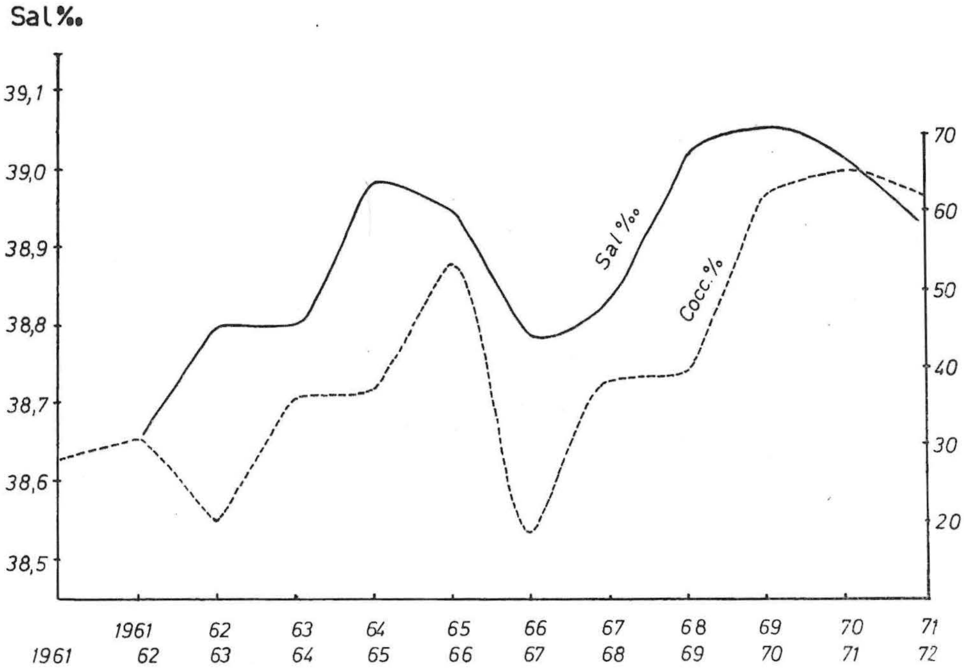

Fig. 2 — Coccolithophore percent and maximum annual values of salinity in the Central Adriatic. The first row of years on the ordinate relates to the salinity and the second row to the percent of the coccolithophores in the phytoplankton population.

preted as the result of different relationships. The percentage of coccolithophores, which increases from the coast to the open sea (Pucher-Petković, 1963, 1964) and where the Eeastern Mediterranean (A) water influence is more intensive, could support such an opinion. The same increase and influence is found from the North Adriatic towards the Central Adriatic. Thus it appears that percent of coccolithophores and other groups within the phytoplankton population could indicate a specific relationship between silicate, nitrate and phosphate in the sea.

SECONDARY PRODUCTION

The level of primary production and relationship to the volume of the inflow of eastern intermediate (A) water into the Adriatic was analyzed. On the basis of long-term data (Pucher-Petković and Zore-Armanda, 1973) the total annual pimary production of the Adriatic was estimated to be 8.7×10^6 tons C, with a maximum of 13.9×10^6 tons C and the minimum of 6.5×10^6 tons C. Using these values and assuming three trophic levels and an ecological efficiency of 15 percent for each trophic level, the average annual fish production of the Adriatic was estimated to be about 300,000 tons with a maximum of 470,000 tons and a minimum of 220,000 tons. Relating these values to the total catch, which in the recent years did not exceed 120,000 tons, shows that the Adriatic has fish reserves in high productive years only, if the assumption that not more than 50 percent of the annual production is caught, is accepted. Therefore, it is important to determine which are the high productive years. As discussed above, under certain climatic circumstances, the Adriatic could receive higher concentrations of nutrients, especially nitrate and achieve a higher level of primary production. Such years are also characterized by higher salinity and, therefore, the relationship between the total annual catch, maximum salinity and climatic factors was determined (Zore-Armanda, 1970). Statistical analyses showed that changes in the climatic factors as well as in water characteristics could be related to secondary production three years later. In addition, the total annual catch has been analyzed for the entire Eastern Mediterranenan and the analysis shows it could be related to the same climatic factors. This suggests that the climatic factors that favor increased production in the

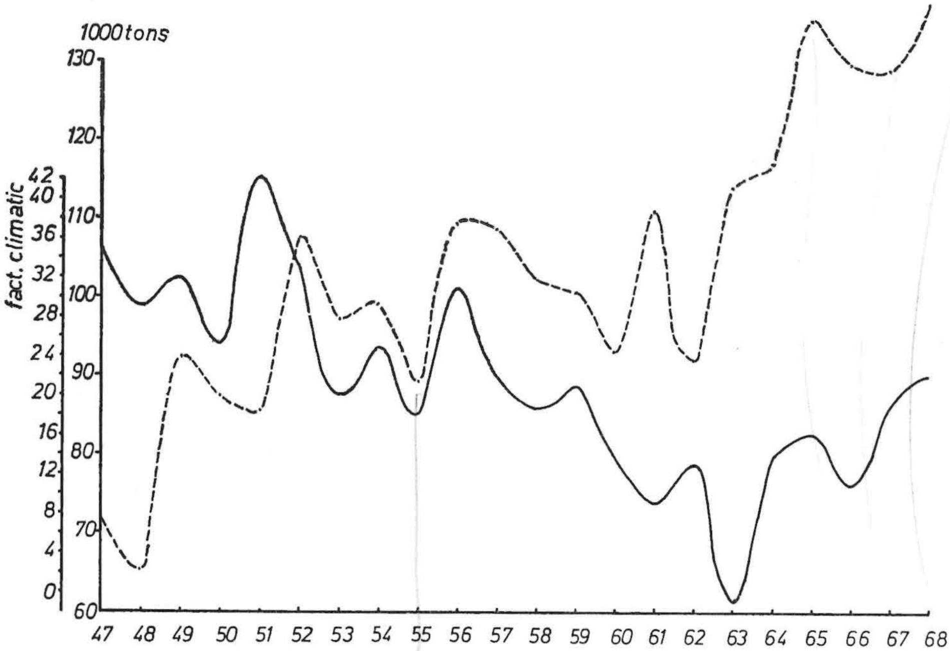

Fig. 3 — Climatic factors as in Figure 1 but summed for the three years before the catch and in a way that the higher consideration is given to the year of spawning to zero year — continuous line. If the meteorological factors are marked mt, and the years 0, 1, 2 and 3, the sum is:

$$mt\,(3') = mt\,(0) + \frac{mt\,(1) + mt\,(2) + mt\,(3)}{3}$$

The broken line shows the total catch of the small pelagic fish in the Eastern Mediterranean in Yugoslavia, Italy, Greece and Israel. (Data from FAO Yearbook of Fisheries Statistics, 1947—1968.)

Adriatic have similar influence in the entire Eastern Mediterranenan. It has been noted that in the Adriatic there is uneven exchange of water in the Otranto Strait and uneven influence of the Eastern intermediate (saline) water. A similar situation could have an influence on the water exchange and water mixing in the other basins of the Eastern Mediterranean and influence the production in the same way (Figure 3). This could be especially true for the Ionian and Aegean Seas where normally vertical mixing is rather poor (Bumpus, quoted by Sournia 1973).

One more point has been studied. It is certain that climatic conditions, which influences the secondary production three years later, plays a certain part in the final production during the interval. However, it seems that the conditions in the year of spawning are the most important. Therefore, an attempt was made to show the meteorological factors in such a way that the factors from several years were summed up in a special way. These factors were taken into full account for the year of spawning (0 year) and one part of them in the following years. Figure 3 shows that climatic factors presented in such a way could be well compared with the fish catch of the entire Eeastern Mediterranean.

In conclusion, climatic factors are of great importance in that they regulate intensity of horizontal and vertical water exchange in the Eastern Mediterranean and that their role in the nutrient enrichment is of the same order as the river input.

SUMMARY

A model to predict secondary production in the Adriatic and its possible application to the other basins of the Eeastern Mediterranean has been discussed.

It has been shown how some climatic factors, such as air pressure gradients and ice conditions in the North Atlantic influence some oceanographic parameters in the Adriatic. An important parameter is the uneven advection of the Eastern intermediate water into the Adriatic which brings into this sea an important quantity of nutrients and thus influencing the rate of primary production. Some assumptions on the current velocities and their distribution permit the calculation of the average annual income and exit of water in the Otranto Strait in three different layers. This provided a basis for the calculation of the annual nutrient budget and to make an estimation for the rate of increase of nutrients if water exchange in the Otranto Strait is more rapid. It has been shown that such an increase of nutrients is of the same order as the river input. The calculated water renewal for the whole Adriatic takes five years, but renewal may be over a longer period.

Some observations show that coccolithophores could be considered as an indicating group of the Eastern intermediate water and that their percent within the phytoplankton population could indicate a specific relationship between silicate, nitrate and phosphate in the sea. At the same time, a high level of primary production is found. Statistical analyses show that the changes in the climatic factors and in the level of primary production could

be related to secondary production but with a delay of three years. The total annual catch of fish has been analyzed for the entire Eastern Mediterranean showing that it could be related to the same climatic factors. The climatic factors are of great importance in that they regulate intensity of horizontal and vertical water exchange and the nutrient enrichment.

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NEKE DINAMIČKE I BIOLOŠKE KARAKTERISTIKE JADRANA I DRUGIH BAZENA ISTOČNOG MEDITERANA

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KRATAK SADRŽAJ

U radu se iznosi model koji može poslužiti za predskazivanje sekundarne proizvodnje u Jadranu kao i njegova moguća primjena na druge bazene istočnog Mediterana.

Klimatski faktori, kao gradijenti tlaka zraka i led u sjevernom Atlantiku, utječu na neke oceanografske parametre u Jadranu. Značajan faktor je i nejednaka advekcija istočne intermedijarne vode u Jadran koja donosi u ovo more znatne količine hranjivih soli i tako utječe na visinu primarne proizvodnje. Na osnovi nekih pretpostavki o brzini struja i njihovoj raspodjeli učinjen je proračun srednjeg godišnjeg ulaza i izlaza vode u Otrantskim vratima u tri različita sloja. Ti elementi su poslužili za proračun godišnjeg budžeta hranjivih soli i za procjenu njihovog porasta u slučaju brže izmjene vode u Otrantskim vratima. Taj porast je istog reda veličine s doprinosom rijeka. Proračun je pokazao da se voda u Jadranu obnovi u pet ili nešto više godina.

Neka opažanja ukazala su da kokolitineje mogu biti promatrane kao indikatorska grupa istočne intermedijarne vode. Njihov postotak unutar ukupnog fitoplanktona može ukazivati na specifičan odnos između silikata, nitrata i fosfata u moru. Istovremeno je nađena visoka primarna proizvodnja. Statističke analize ukazuju da se promjene klimatskih faktora odrazuju na visini primarne i sekundarne proizvodnje, ali na posljednjoj s pomakom od tri godine. Analiza ukupnog godišnjeg ulova ribe za čitav istočni Mediteran pokazala je da i on može ovisiti o istim klimatskim faktorima. Oni su od velikog značenja jer reguliraju intenzitet horizontalne i vertikalne izmjene vode i količinu hranjivih soli.