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RELATIONSHIP BETWEEN THE MUCILAGE PHENOMENON AND SOME CONCOMITANT ENVIRONMENTAL VARIABLES IN THE NORTHERN-ADRIATIC LAGOON OF STELLA MARIS, UMAG, CROATIA

The appearance of mucilage episodes and some meteorological and oceanographic variables were daily monitored during a 1-year period in the shallow macro-tidal northern-Adriatic lagoon of Stella Maris, Umag (Croatia). The phenomenon than appeared in the seawater in the form of gelatinous flocks, patches and stringers of various size and colour was recorded from April to September 2005. The environmental data collected during that period (air and water temperature, wind force and wind direction, tides, water density and salinity, current speed and current direction) were compared by means of Principal Component Analysis (PCA) to the winter parameters when the mucilage was absent. From the results obtained using the PCA method, we assumed that the changes in current speed, wind force and wind direction during the spring and summer period were able to affect density, tides and salinity which then became decisive factors that contributed to the accumulation of the mucilage aggregates. Similar findings documented in the whole northern Adriatic are discussed in this paper.

Key words: *northern Adriatic, mucilage, oceanographic conditions, PCA*

1. INTRODUCTION

The floating mucilage aggregates are well known in seas and oceans worldwide [1]-[4], but it seems that elsewhere they never come to such an extent as they appear in the northern part of the Adriatic Sea. The northern-Adriatic phenomenon of massive floating gelatinous aggregates, which appears in the water column in the form of flocks, strings, clouds, creamy and/or thick gelatinous surface layer [5], has been observed and well documented in the scientific literature for over two centuries [6]-[11]. The mucilage episodes usually occur in summer during calm and sunny weather and may cause serious problems to fishery and tourism. It seems that the phenomenon is of autochthonous, marine origin [12], [13] and no connection to anthropogenic eutrophication has been confirmed so far [14]. Despite recent intensive studies - performed since 1988, when the phenomenon suddenly reappeared after many decades - the gelatinous aggregates still remain the subject of debate. The mucilage appearance has been related to specific meteorological and oceanographic conditions [15], altered geostrophic circulation and current regime [16] and/or stress conditions for organisms that produce gel substances [17], [18].

The aim of this study was to verify whether the hypothesis that certain specific meteorological and oceanographic conditions trigger the evolving of mucilage could also be valid in the small and shallow, easily accessible northern-Adriatic lagoon. For this purpose we registered every single event of mucilage that appeared during the one-year research period and measured the concomitant environmental variables (air and water temperature, density, salinity, tides, wind force and direction, as well as current speed and direction) on a daily basis.

2. MATERIALS AND METHODS

2.1. Study site

The study site is the small, natural macro-tidal northern-Adriatic lagoon of Stella Maris, near Umag in Istria (Croatia), 15000 m^2 of surface and 2 m deep in most parts (Fig. 1). The lagoon is permanently connected to the adjacent sea by a narrow channel and during the tourist season in spring and summer it serves as a small marina with approximately a hundred moorings for smaller boats and yachts. There are several bottom freshwater springs, active in 30% of the cases, mostly during late autumn and winter. The climate of the region is a sub-Mediterranean one, with the average annual air temperature of 16.4°C and a rainfall of up to 1000 mm per year, distributed mostly during autumn and winter. From October 2004 to October 2005 visual observations were performed daily in order to detect any appearance of mucilage.

2.2. Atmospheric and oceanographic data

During the research period, daily *in situ* measurements of the air temperature and monitoring of the wind force and direction, tides, as well as current speed and current direction in the connecting channel were performed. In the absence of appropriate equipment, descriptive features of wind force and direction, tides, current speed and direction were registered on a daily basis and were additionally codified in accordance with their frequency. In addition, water temperature and water density data (measured by an aerometer) were collected from the sampling site. The conversion of density values to salinity was made using the Knudsen tables. The data regarding sunshine hours were obtained from the DHMZ (Meteorological and Hydrological Service of Croatia).

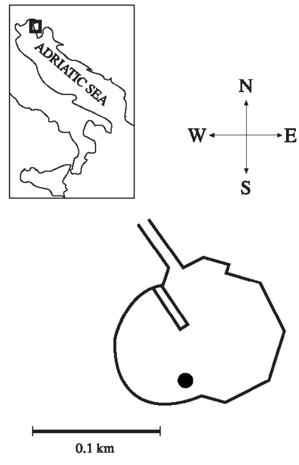

Fig. 1: Location of the Stella Maris lagoon with sampling site

Source: Authors

2.3. Data analysis

To determine in which way various variables might contribute to the mucilage episodes, we used the Principal Component Analysis (PCA). Thus, we were able to reduce a large number of dimensions without much loss of information.

For better understanding of the mathematical procedure, let X be the matrix with n rows and p columns. Rows are samples, while columns are variables. Some pairs of variables will be highly correlated compared to others, and some variables will have larger variability measured as variance. Let *cov(X)* be the variance–covariance matrix of variables $X_1, X_2, ..., X_p$ and $\mathbf{e}_1, \mathbf{e}_2, ..., \mathbf{e}_p$ the eigenvectors of this matrix in descending order, corresponding to the eigenvalues. These vectors constitute the new basis in the p – dimensional vector space. The transformation of the original variables on such basis generates p new variables – *the principal components* $PC_1, PC_2, ..., PC_p$. The principal components are the linear combinations of the original variables:

$$PC_1 = a_{11}X_1 + a_{12}X_2 + ... + a_{1p}X_p$$

$$PC_2 = a_{21}X_1 + a_{22}X_2 + ... + a_{2p}X_p$$

$$\vdots$$

$$PC_p = a_{p1}X_1 + a_{p2}X_2 + ... + a_{pp}X_p$$

matching [19], [20] the following criteria:

1. the eigenvalues of $cov(X)$ are the variances of $PC_1, PC_2, ..., PC_p$;
2. the total variance of the original variables is equal to the total variance of the principal components:
   $var(X_1) + var(X_2) + ... + var(X_p) = var(PC_1) + var(PC_2) + ... + var(PC_p)$;
3. the coefficients $a_{11}, a_{12}, ..., a_{1p}$ were calculated to obtain $var(PC_1)$ as large as possible, then $a_{21}, a_{22}, ..., a_{2p}$ to obtain $var(PC_2)$ as large as possible after $var(PC_1)$ was extracted, etc.
4. every principal component is orthogonal to all the others, and because of this property there is no redundant information.

The first principal component PC_1 explains the same percentage of total information as the percentage of $var(PC_1)$ is in the total variance, the second principal component PC_2 explains the same percentage of total information as the percentage of $var(PC_2)$ is in the total variance, etc. The percentage of explanation of the first k principal components $PC_1, PC_2, ...PC_k$, $k \in \{1, 2, ..., p\}$ together is the corresponding cumulative sum.

3. RESULTS AND DISCUSSION

Two sets of data were selected for the PCA: 19 series of data registered in spring and summer during the days when the mucilage appeared (from April 21 to September 23, 2005), and another 19 series of data, randomly chosen during winter days when no mucilage was recorded (from January 25 to February 15, 2005). The data analysis was made using the MathWorks MATLAB R2007b (Ver. 7.5) and MS Office Excel 2003.

In the year 2005, the appearance of mucilage started in late April. On April 21, the first two yellow patches, about one half of a square meter in size, remained on the surface of the SE quadrant only for one day and then disappeared. One week later, on April 29, many yellow, brown and red patches in the whole water column, including the surface layer, were seen in the SE quadrant again, and remained there for two days. In the following month numerous episodes of mucilage were registered, once or twice per week. The marine snow, in the form of yellow flocks of few cm in size, was observed on May 6, then again on May 12 as brown flocks, and on May 15 as yellow, brown and pink flocks, again in the E quadrant. A week later, on May 22, the flocks were again only yellow in colour and three days later they reappeared as white and brown/pink patches. On May 27 small white and brown flocks were seen again on the surface. On May 29 and 31 white strings, one meter long, came into sight. On June 1 the strings and patches were still seen and then disappeared, while on June 5 only yellow patches showed. On June 18 a new episode occurred: 10 cm long gelatinous transparent strings appeared in the W quadrant of the lagoon. They disappeared the next day and reappeared for one day only on June 21 in various shapes, from 10 cm to 2 m in size, again in the W quadrant. In July there were only two mucilage events: on July 11 as small white patches floating on the surface and on July 23 as small yellow patches. The last two episodes occurred in August and September respectively. On August 2 very small light green patches were recorded on the surface and finally on September 23 the gelatinous transparent strings were seen in S quadrant.

During the investigation period, the air temperature varied in a wide range from -0.2 °C on February 28 to 31 °C on July 15 (Fig. 2).

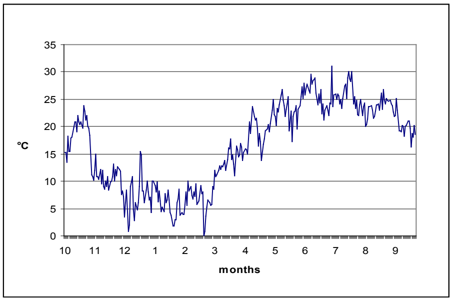

Fig. 2: Daily values of air temperature from October 2004 to October 2005

Source: Authors

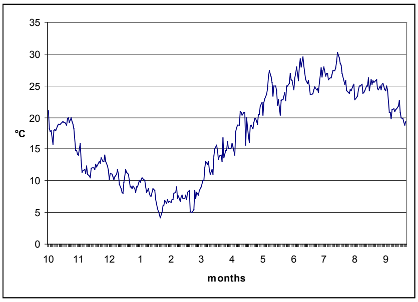

Fig. 3: Daily values of water temperature From October 2004 to October 2005

Source: Authors

The water temperature showed a similar seasonal pattern (Fig. 3), except for the minimum value which was registered one month earlier. The minimum of 4.2 °C was registered on January 30, while the maximum of 30.2 °C on July 30. The water density was higher in winter and lower in summer and the sporadic extreme low values were directly influenced by daily events: by the heavy rain of the previous night rather than by the bottom freshwater spring activity. However, salinity ranged from 23, registered on October 18 to 37.1 on June 27 (Fig. 4), with lower values in winter and higher in summer.

The level and water exchange inside the lagoon are generally influenced by the tides that range from up to 2.04 m, while the prevailing west and southwest weak and medium winds represent the additional forcing factor.

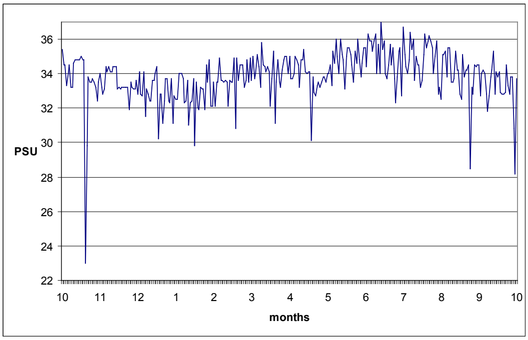

Fig. 4: Daily values of salinity from October 2004 to October 2005

Source: Authors

The frequency pattern of the wind force, wind direction, tides, current speed and current direction during the two distinct periods (winter days without mucilage and spring and summer days with mucilage) are shown in Table 1.

Tab. 1: Frequency of original variables in two selected periods: Winter (without mucilage); Spring-Summer (with mucilage)

Tides	Winter	Spring – Summer
High	4	8
Low	6	11
very low	6	0
extremely low	3	0

Wind Force	Winter	Spring – Summer
Strong	7	2
Medium	4	7
Light	2	6
no movement	6	4

Wind Direction	Winter	Spring – Summer
N	6	5
NE	2	1
SW	0	3
W	1	4
NW	4	2
no movement	6	4

Current Speed	Winter	Spring – Summer
Fast	5	9
Medium	3	4
Slow	8	3
no movement	3	3

Current Direction	Winter	Spring – Summer
Entering	9	9
Exiting	7	7
no movement	3	3

Source: Authors

The original data used for the PCA are shown in Table 2a and Table 2b:

Tab. 2a: Original data of 9 selected variables (Winter – mucilage absent)

Date	Temp.	Density	Salinity	Sunshine Hours	Tides	Wind Force	Wind Direction	Current Speed	Current Dir.
Jan 25	7	26	33,5	1	6	7	2	3	7
Jan 26	5,6	25,4	32	0,3	6	4	6	3	9
Jan 28	5,2	26,2	31,9	2	4	7	6	3	9
Jan 29	4,8	26,4	33,2	7	4	7	6	5	7
Jan 30	4,2	26,2	33,1	8,7	4	7	6	8	9
Jan 31	5	26,2	33,1	6,5	6	6	6	8	7
Feb 1	6	25,2	31,9	4,5	6	6	6	5	9
Feb 2	6,2	27	34,5	5,6	6	2	4	3	3
Feb 3	6,9	26,4	33,5	6,9	6	2	4	8	9
Feb 4	6,4	26,8	34,8	7,5	6	4	4	8	7
Feb 5	7	25,2	32,1	8,7	6	7	6	5	9
Feb 6	6,6	25,2	32,1	8,8	6	6	6	8	9
Feb 7	6,8	26,2	33,5	8,6	6	4	4	3	3
Feb 8	6,6	25,4	32,1	8,8	3	4	1	8	9
Feb 9	7	26,2	33,5	8,9	3	7	6	3	3
Feb 10	7	26,4	33,5	9,1	3	6	6	8	7
Feb 11	8	27	34,9	2,2	6	6	6	8	7
Feb 13	8,2	26,2	33,6	4,1	4	6	6	5	7
Feb 15	7,2	26,2	33,5	2,5	6	7	2	5	7

Tab. 2b: Original data of 9 selected variables (Spring-Summer – mucilage present)

Date	Temp.	Density	Salinity	Sunshine Hours	Tides	Wind Force	Wind Direction	Current Speed	Current Dir.
Apr 21	15,2	25,2	33,7	7,8	11	7	5	9	7
Apr 29	18,8	25	34,8	5	11	4	4	3	3
Apr 30	21	24,8	35,4	11,6	11	6	3	3	3
May 6	15,6	22	30,1	9,3	8	7	5	4	9
May 12	18,8	24,2	33,5	13,5	11	2	3	9	9
May 15	19,2	23,8	33,5	7,4	11	6	4	9	9
May 22	22,4	23,4	33,3	10,8	11	6	3	3	9
May 25	23	24,8	36	14	11	7	2	4	9
May 27	24,6	23,2	34	13,8	11	4	4	9	9
May 29	27,4	23	35,1	13,9	8	4	4	9	7
May 31	25,6	24	33,1	6,8	8	2	5	9	7
Jun 1	23,4	24,4	35	11,7	11	6	1	9	7
Jun 5	22	24,2	34,5	2	8	6	4	3	3
Jun 18	27	23,6	36,3	9,9	8	7	4	4	9
Jun 21	24,4	23,8	35,3	13,5	11	7	5	4	9
Jul 11	24,4	22,2	32,7	6,6	11	7	2	9	9
Jul 23	26,2	23,2	34,5	12,2	8	4	4	9	7
Aug 2	28,2	22	34	13,6	8	7	4	3	7
Sep 23	21,4	23,2	32,9	9,5	8	6	5	3	9

Source: Authors

The PC_i variables ($i = 1, 2, \dots, 9$) are linear combinations of original variables. The coefficients in linear combinations that are obtained from the variance-covariance matrix are given in Table 3a. and Table 3b.

Tab. 3a: Principal component coefficients (Winter – mucilage absent)

	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	PC_7	PC_8	PC_9
Temperature	-0.2730	0.1389	0.1479	0.3155	-0.6964	0.4385	-0.2618	0.1105	-0.1636
Density	-0.5077	-0.1940	-0.1548	-0.3486	0.0088	-0.2998	-0.0963	0.3406	-0.5864
Salinity	-0.5650	-0.1519	-0.0091	-0.2393	-0.1554	-0.0452	0.1315	0.0975	0.7399
Sunshine Hours	0.0338	-0.6303	0.0984	0.3597	0.2270	0.3493	0.3054	0.4414	-0.0295
Tides	-0.1179	0.4543	0.3666	-0.3847	0.1781	0.4306	0.4953	0.1040	-0.1547
Wind Force	0.2811	-0.0401	-0.4810	-0.1166	-0.5362	-0.0908	0.6098	0.0445	-0.0697
Wind Direction	0.1983	-0.2123	-0.3945	-0.5193	0.0523	0.5862	-0.3739	-0.0359	0.0531

Current Speed	0.0589	-0.5186	0.5207	-0.2823	-0.2559	-0.0495	0.0847	-0.5288	-0.1486
Current Direction	0.4601	0.0269	0.3898	-0.2851	-0.2276	-0.2323	-0.2178	0.6113	0.1656

Tab. 3b: Principal component coefficients (Spring-Summer – mucilage present)

	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	PC_7	PC_8	PC_9
Temperature	0.1847	-0.4634	0.4556	-0.2110	0.2206	-0.1591	0.2661	0.3186	-0.5027
Density	-0.6042	0.1057	-0.0321	-0.1330	-0.3195	-0.2015	0.0866	-0.3748	-0.5607
Salinity	-0.4036	-0.3371	0.4389	-0.0750	-0.1869	-0.3350	0.0290	-0.0272	0.6136
Sunshine Hours	0.0957	-0.5622	-0.0151	0.0959	-0.5114	0.4220	-0.4546	-0.0479	-0.1294
Tides	-0.4458	-0.1549	-0.4178	0.2747	-0.0544	0.0645	0.2204	0.6867	-0.0073
Wind Force	0.0292	0.0585	0.1905	0.7410	0.1055	-0.4494	-0.4017	0.0291	-0.1873
Wind Direction	0.3123	0.3877	0.0952	-0.2008	-0.6590	-0.3045	-0.0385	0.4170	-0.0209
Current Speed	0.0329	-0.2509	-0.4991	-0.4316	0.2100	-0.4941	-0.4586	0.0440	0.0059
Current Direction	0.3614	-0.3221	-0.3599	0.2680	-0.2455	-0.3175	0.5408	-0.3268	0.0629

Source: Authors

From the first principal component

$$PC_1 = -0.2730 \times Temperature - 0.5077 \times Density - 0.5650 \times Salinity + \\ +0.0338 \times SunshineHours - 0.1179 \times Tides + 0.2811 \times WindForce + \\ + 0.1983 \times WindDirection + 0.0589 \times CurrentSpeed + 0.4601 \times CurrentDirection$$

it can be seen that salinity, density and current direction had the most pronounced influence in the case when the mucilage was not present (winter samples). On the other hand, in the summer samples, when the mucilage was present, the first principal component appeared to be:

$$PC_1 = -0.1847 \times Temperature - 0.6042 \times Density - 0.4036 \times Salinity + \\ +0.0957 \times SunshineHours - 0.4458 \times Tides + 0.0292 \times WindForce + \\ + 0.3123 \times WindDirection + 0.0329 \times CurrentSpeed + 0.3614 \times CurrentDirection$$

suggesting that the variables with the most prominent influence on the first principal component were density, tides and salinity. Figures 5a. and 5b. represent the biplots accorded to the two first principal components for both cases (with and without mucilage).

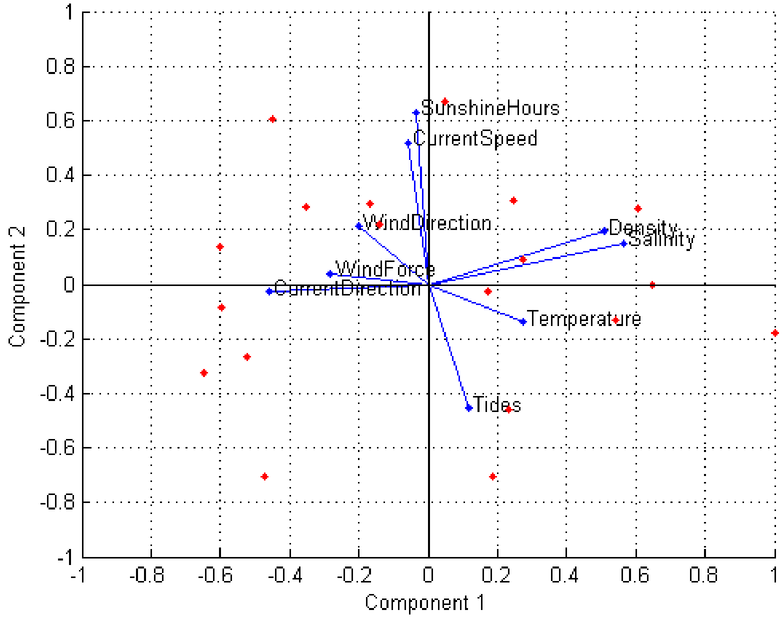

Fig. 5a: Biplot according to the two first principal components (Winter – mucilage absent). Dots represent single days, vectors are original variables.

Source: Authors

In the first case, when the mucilage was absent, PC_1 and PC_2 cumulatively explain 47.72% of total information. On the other hand, in the case when the mucilage was present, PC_1 and PC_2 cumulatively explain 46.56% of total information.

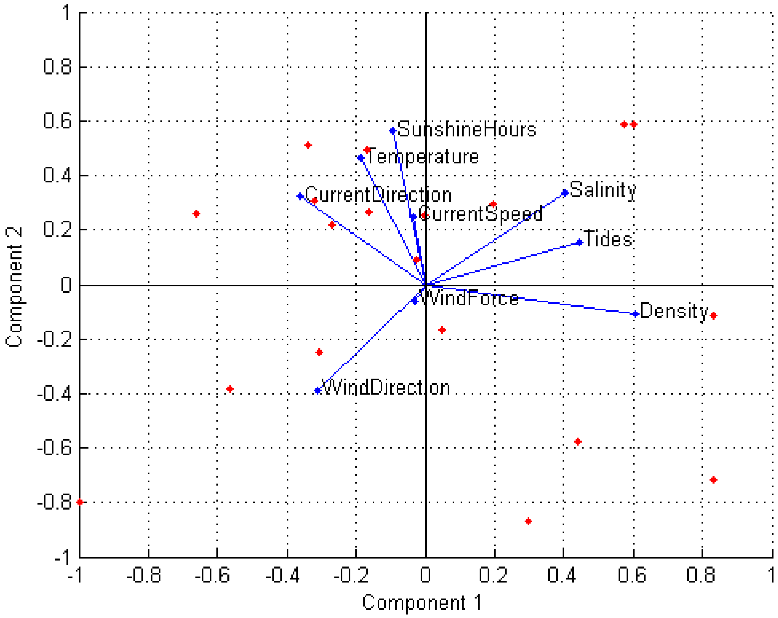

Fig. 5b: Biplot according to the two first principal components (Spring-Summer – mucilage present). Dots represent single days, vectors are original variables.

Source: Authors

In accordance with the results mentioned above, Euclidean lengths of the original variables were computed, as well as their differences. The differences in descending order and the ranking list of the variables are given in Table 4. It can be seen that in the case of mucilage events the most pronounced changes occurred in three variables: current speed, wind force and wind direction.

From the results obtained using the PCA method we can assume that the changes in the current speed, wind force and wind direction during the spring and summer period were able to affect density, tides and salinity which then became the decisive factors that contributed to the accumulation of mucilage. The same method, considered as exploratory rather than predictive [21], could not explain the earlier massive mucilage events, which occurred in the northern Adriatic basin in 2000 and 2002 and the sampling periods before and during mucilage formation did not show any difference in the distribution in the scatter plot [22].

Tab. 4: Differences of Euclidean lengths in both cases (with and without mucilage) and the ranking list of variables

Rank	Variable	Differences of Euclidean lenghts
1.	CurrentSpeed	0.2689
2.	WindForce	0.2186
3.	WindDirection	0.2073
4.	Temperature	0.1926
5.	Density	0.0699
6.	SunshineHours	0.0609
7.	Salinity	0.0592
8.	CurrentDirection	0.0232
9.	Tides	0.0025

Source: Authors

Our results corroborate those obtained at large scale for the whole northern Adriatic [16], where during certain years different current regimes of the basin, producing an anticyclonic gyre, coincide with the mucilage events. Thus, the circulation might play a major role in the processes of mucilage accumulation. The statistically increased temperature in the whole water column in the off-shore waters of the Gulf of Trieste measured in 1988, when the first massive mucilage phenomenon occurred after many decades, was considered as the main triggering factor for the mucilage formation [23]. However, the recent observations for the whole northern Adriatic [15] suggest that an increased air and sea temperature could play a role, even though secondary, and that a combination of several unusual conditions: sharp heating of the sea surface in May-June, domination of eastward transport of freshened waters formed in the Po Delta area, and intrusion of very high salinity intermediate waters originating in the eastern Mediterranean, could be the principal triggering factor of mucilage events.

4. CONCLUSION

Based upon our short-term observations of the mucilage episodes and the concomitant environmental variables, it seems that seasonality was the dominant factor in controlling the appearance of gelatinous aggregates. Time-limited meteorological parameters (wind force and wind direction) as well as current speed were probably the environmental conditions which induced water density, tides and salinity to become the most prominent agents for the mucilage formation.

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Sažetak

MEĐUZAVISNOST IZMEĐU POJAVE CVJETANJA MORA I NEKIH POPRATNIH EKOLOŠKIH PARAMETARA U SJEVERNOJADRANSKOJ LAGUNI STELLA MARIS KRAJ UMAGA, HRVATSKA

U jednogodišnjem istraživačkom razdoblju u plitkoj je sjevernojadranskoj laguni Stella Maris, kraj Umaga (Hrvatska), karakterističnoj po izrazitom rasponu plime i oseke, praćena pojava tzv. cvjetanja mora - sluzastih nakupina u morskoj vodi. Istodobno su vršena dnevna mjerenja nekih popratnih meteoroloških i oceanografskih parametara. Pojavljivanje sluzastih pahulja, krpa i niti različitih veličina i boja zabilježeno je od travnja do rujna 2005 godine. Usporedbom ekoloških podataka (temperature zraka i vode, jakosti i smjera vjetra, plime i oseke, gustoće i slanosti, te brzine i smjera morske struje), sakupljenih u tom razdoblju sa zimskim uzorcima kada u vodi nije bilo sluzi, metodom analize osnovnih komponenata (PCA) uočena je u proljetnom i ljetnom razdoblju, kada se sluz pojavljuje, najveća promjena brzine morske struje te jakosti i smjera vjetra. Te su promjene mogle utjecati na najjače izraženi doprinos cvjetanju mora drugih triju varijabli: gustoće, plime i oseke te slanosti. U radu se raspravlja o sličnim rezultatima dobivenim i za otvorene vode sjevernog Jadrana.

Ključne riječi: *sjeverni Jadran, cvjetanje mora, oceanografski parametri, PCA*

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