Long-term warming effect to sprat stock quality characteristics in Crimea-Caucasian shelf of the Black Sea

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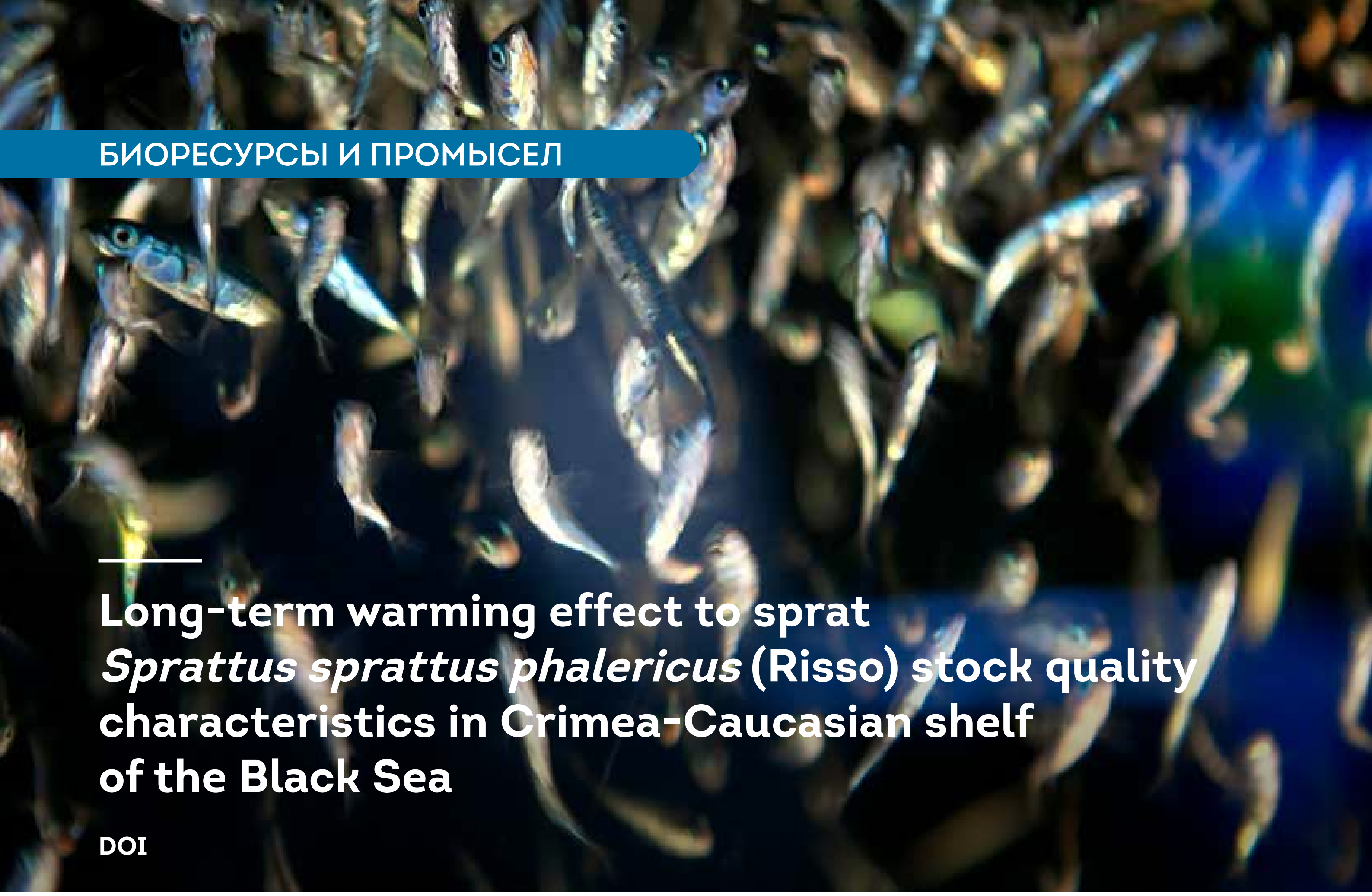

Long-term warming effect to sprat *Sprattus sprattus phalericus* (Risso) stock quality characteristics in Crimea-Caucasian shelf of the Black Sea

DOI

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ВЛИЯНИЕ ЭФФЕКТА ГЛОБАЛЬНОГО ПОТЕПЛЕНИЯ НА КАЧЕСТВЕННЫЕ ХАРАКТЕРИСТИКИ ПОПУЛЯЦИИ ЧЕРНОМОРСКОГО ШПРОТА *SPRATTUS SPRATTUS PHALERICUS* (RISSO) НА КРЫМСКО-КАВКАЗСКОМ ШЕЛЬФЕ ЧЕРНОГО МОРЯ

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Выполнено исследование связи между температурным фактором и популяцией черноморского шпрота *Sprattus sprattus phalericus* (Risso). Статистический анализ многолетней динамики взаимосвязи между температурным фактором и средней промысловой навески шпрота из уловов, как показателя качественного состояния популяции шпрота, выполнен за период 1951–2019 гг. Многолетние ряды данных были сглажены методом полиномиальной регрессии, после чего была построена линейная модель зависимости и выполнен кросс-корреляционный анализ, позволивший получить оценки коэффициентов корреляции Пирсона между исследуемыми факторами. Корреляционный анализ указал на наличие значимой связи между температурным фактором и средней навеской шпрота на промысле по возрастным когортам (коэффициент корреляции между средней навеской шпрота в возрасте 3+ и температурой поверхности воды в порту вблизи г. Ялта составил r = -0.86, в среднем по всем возрастам и точкам мониторинга r = -0.74). Результирующая линейная модель по сглаженным данным температуры поверхности воды (SST) и средней навески шпрота на промысле успешно прошла проверку надежности подгонки ($R^2 = 0.87$, RSE = 0.34), уравнение связи: $w = f(sst) = 22.23 - 1.263*sst$. Данное исследование позволяет подчеркнуть значимость температурного фактора, являющегося основным драйвером состояния качественных характеристик популяции шпрота.

The Black Sea sprat *Sprattus sprattus phalericus* (Risso) and temperature factor impact have been investigated. Statistical assessment of the long-term dynamics (1951–2019) of a relationship between the temperature factor and sprat mean weight in fishery catches used as a population quality characteristic has been performed. Pearson product-moment correlation and cross-correlation was evaluated, then data series was smoothed by the local polynomial regression and, finally, a linear model was fitted. The correlation test shows significant relationship between the temperature factor and sprat mean weight-at-age (mean weight in 3+ age group and SST in the port of Yalta resulted in $r = -0.86$, whereas average SST and average mean weight by age classes led to $r = -0.74$). The fitted linear model by smoothed data of average SST and average weight-at-age successfully passed diagnostics ($R^2 = 0.87$, $RSE = 0.34$), with the equation: $w = f(sst) = 22.23 - 1.263*sst$. As a result, this study allows to emphasize the temperature factor as a main driver of the sprat fishery quality characteristics. The global warming effect, starting since the 1990's has had a significant negative impact on the sprat population.

INTRODUCTION

The Black Sea sprat Sprattus sprattus phalericus (Risso) is a small pelagic cold-water fish. This species makes insignificant horizontal spatial migrations and is distributed at depths of over 10–100 m within the vertical layer [1]. Commercial fisheries have been carried out by all countries on the Black Sea shelf since the 1970s. In 1980–1990 the top annual fishery catches of sprat occurred in Ukrainian, Russian, Georgian, Bulgarian, and Romanian shelf waters and reached up to 100 ths. t (FAO Capture production statistics). In the mid-1990s sprat commercial fisheries in the Black Sea were started by Turkey [26] in spite of strong total catch reduction in the former Soviet Union countries. The maximum of annual catches by all the Black Sea countries fell on the period of 2007–2016 and made up to 120 ths. t. The current period (2017–2020) shows strong reduction in the annual catch of the sprat commercial fisheries value. The major annual fishery catch reduction in the latest years has been marked in the Turkish and Russian waters of the Black Sea.

Figure 1. Investigation area - stations of sea surface temperature measurements (points) and sprat biological data sources (red polygons)

Рисунок 1. Район исследования - станции измерения температуры поверхности моря (точки) и источники биологических данных о шпрот (красные полигоны)

There are a great number of local studies about the Black Sea sprat behavior in the South-East driven by the temperature factor [10, 22]. These investigations show the Black Sea sprat behavior dependence on the temperature factor while forming commercial aggregations. Another papers indicate that the sprat population parameters depend on temperature factor [2]. Most complex study [7] emphasizes the impact of temperature factor on the sprat SSB (spawning stock biomass) and recruitment growth success but no direct impact was detected. Another complex study [8] shows the importance of environment factor, including temperature, impact on the ecosystem variability and regime shifts.

The recent sprat stock assessment study using XSA on the Crimean-Caucasian shelf of the Black Sea [18] shows both SSB reduction during the period of 2017–2019 and minor overexploitation effect. SSB reduction during the period of 2017–2019 might have been caused by unexplained fluctuations in the recruitment number or by migrating bonito predation [27]. Preliminary studies of the ecosystem assessment [20] using the PCA method indicate that sprat SSB and recruitment reduction could have been caused by reduction of the food zooplankton availability and eutrophication changes. Ecosystem assessment evidences the importance of the sea surface temperature (SST) impact on the ecosystem variability within 1992–2019.

The main purpose of this study is to determine if the relationship between the long-term temperature factor and sprat quality characteristics in the Crimean-Caucasian shelf exist. Preliminary, non validated study of this research was published in conference papers [19].

MATERIAL AND METHODS

This assessment has been performed in two basic assumptions:

- mean weight-at-age sprat fishery statistics represent a quality population indicator;
- mean sea surface temperature dynamics in discrete points indicate global temperature changes in vertical layers;

According to these assumptions, the following hypothesis was tested: "Does a temperature factor is a main driver of the sprat population?". To check the main hypothesis on the long-term dynamics of temperature and sprat indicators, statistical assay was applied. Full data information, technical and observation details are presented below.

Study area

This research was performed based on the long-term historical observation data during the period of 1951-2019. The investigation area is presented in figure 1.

Data

In this paper, the authors used sea surface temperature data (*sst_**) collected by the Marine Hydrophysical Institute of RAS [12] and CMEMS Black Sea reanalysis data, where *sst_feo* is sea surface temperature in the vicinity of Feodosia, *sst_yalta* is sea surface temperature near Yalta and *sst_cher* is sea surface temperature near Chernomorskoye. Mean sprat weight-at-age value (*w**), where *w1* – 1+ age group, *w2* – 2+ age group, *w3* – 3+ age group were used. All these data were processed to obtain aggregative average temperatures between all observations in Feodosia, Yalta and Chernomorskoe by year and average weight between all observations in age groups by year.

Physical-geographical features

The Black Sea is the most eastern of all the Atlantic Ocean basin seas. The investigation area in this research was restricted, from the shoreline of the Crimean Peninsula to Konstantinovsky Cape (*Northern Black Sea, fig. 1*). This area is characterized by small depths. River flows here are not significant and represented primarily by low-water rivers of Crimea and Kuban. An exception in this case can be considered a western areain the north-western part of the Black Sea, where such big rivers as the Dnieper, Dniester and Danube are located, which significantly affects physical and chemical conditions of the water area.

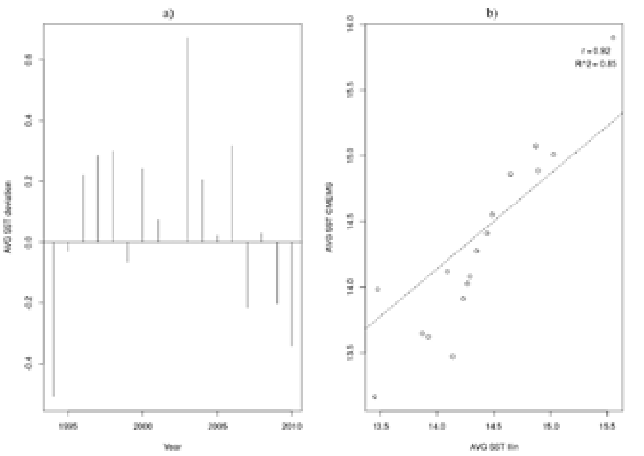

Figure 2. Validation test data series from different sources (Iliin and CMEMS project) for averaged SST. a) Relative average annual SST deviations; b) Linear model with correlation (r) and determination (R^2) statistics

Рисунок 2. Валидация рядов данных из разных источников (данные Ильина и проекта CMEMS) для усредненного SST. а) Относительные среднегодовые отклонения SST; б) Линейная модель с оценками коэффициента корреляцией (r) и детерминации (R^2)

Water temperature in various parts of the investigation area differs significantly. For example, in winter in the North-Western part it can make up 3–5 °C, while in the north-eastern part it can reach the level of 8–8.5 °C. In summer this pattern repeats: in the north-western part the temperature reaches 22–23 °C, while in the north-east 24–25 °C [13]. The same applies to the level of water salinity. In the north-west it reaches 7–16 ‰ in winter and 5–17 ‰ in summer, while in the north-eastern part it equals 17–18 ‰ and about 20 ‰ in summer. Currents here are directed from the east westwards along the coastline and reach the speed from 10 to 25 cm/s.

Sea surface temperature (SST)

Observations within 1951–1993 were done by [12] in the Southern Black Sea marine ports, close to Feodosia, Yalta and Chernomorskoe, fig. 1 (points). Average annual year SST was calculated. For the period of 1994–2019 annual average SST was processed from Copernicus marine project [14] data for the same location from BLKSEA_MULTIYEAR_PHY_007_004 spatial dataset.

Sprat quality characteristics

Sprat samples were obtained by the fishery and scientific monitoring in period of 1951–2019 in the Crimean-Caucasian shelf area of the Black Sea by YugNIRO [21], fig. 1 (crossed areas). The annual mean weight-at-age was calculated for age groups 1+, 2+, 3+.

Statistical analysis

Statistical data processing and modeling have been performed in R environment. All source codes and prepared input data are available in the authors' repository: https://bitbucket.org/phd-pm/sprat-temp-weight/src .

First of all, a validation test for different SST data series sources was performed. The annual SST observation by Iliin and CMEMS project had overlaps within 1994–2010. For this period, absolute and relative deviations were calculated; correlation, determination and normality tests were performed for each two time series from different sources. Next, successfully validated SST data series were joint in a long-time data series for the period of 1950–2019. The data series that failed validation were excluded from the assessment.

Preliminary raw data were visualized by anomaly diagnostics plot – long-term dynamics of absolute deviations against the mean value. Next, diagnostics was performed by linear correlation and cross-correlation product-moment Pearson test [17] with p-value significance test. For biological research, p-value lower than 0.05 (biological tests significance level) indicate significant linear relationship between the tested factors.

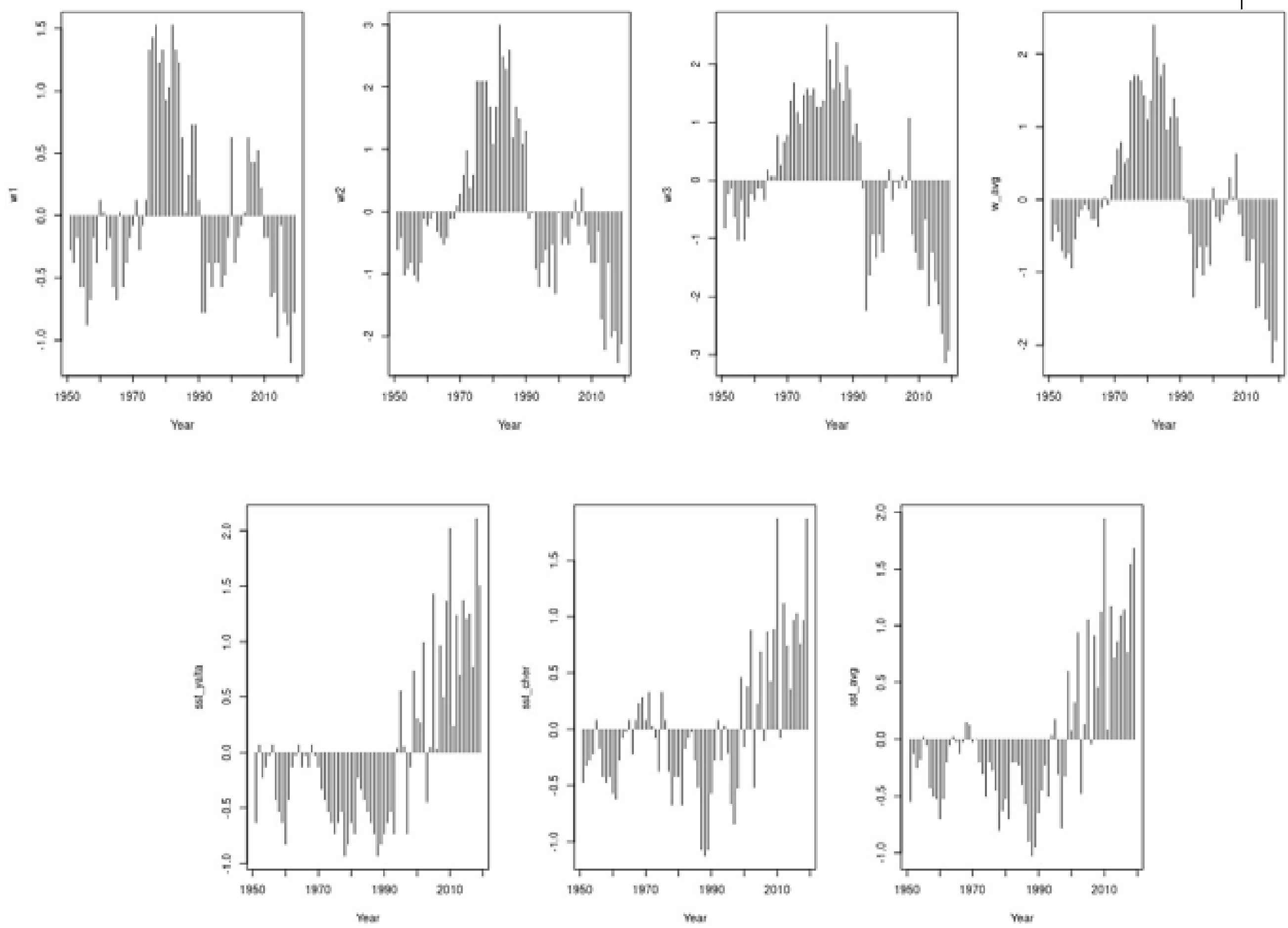

Figure 3. Anomaly diagnostics visualization. Top row - weight-at-age and average weight dynamics, bottom row - SST dynamics in points (ports) and average SST

Рисунок 3. Визуализация диагностики аномалий. Верхний ряд - динамика средних навесок по возрастным классам, нижний ряд - динамика SST в точках мониторинга и общий усредненный ряд SST по всем точкам мониторинга

After the preliminary diagnostics, all data series were smoothed by local polynomial regression with span = 0.5 [6], in order to reduce the influence of inter-annual factor variability. Fitted local regression by each data series was tested by residuals standard error value (RSE) and Shapiro-Wilk residuals normality test. High RSE values indicate the worst fitting. Residuals distribution normality test count as "successful passed" if p-value is higher than 0.1 (no evidence was found to decline distribution normality).

The smoothed data series were tested again by the correlation test. Finally, after determination of the relationship significance, a linear model was fitted [5] for grouped (by SST intervals) data series of SST and mean weight according to diagnostics of the best fitting.

RESULTS

Validation of the correspondence of two SST data series from different sources has proved that there were no significant differences between observations in points close to Yalta and Chernomorskoe. Absolute annual average (per year) deviation was the following: for Yalta – 0.07 °C (1.12°C for 17 years), for Chernomorskoe - 0.43 °C (7.25°C for 17 years). Deviations had no pronounced evidence for long-time overestimation or underestimation from different data sources: all deviations were randomly distributed against zero on y-axis. Finally, the linear correlation coefficient equaled: r_{yalta} = 0.98, $r_{chernomorskoe}$ = 0.6.

Validation of the correspondence in the point close to Feodosya failed and showed significant bias in two different sources of observations. Absolute annual average deviation made up 0.76 °C (13.01 °C for 17 years). Deviations have a strong signal of annual SST overestimation by CMEMS data against Iliin (all deviations are above zero y-axis). Finally, the linear correlation was non-significant, $r_{feodosya}$ = 0.32, determination was critically low: $R^2_{feodosya}$ = 0.10.

Based on the validation of different data source results, time series were joint for Yalta and Chernomorskoe during the period of 1951–2019. The time series from Feodosya was removed from analysis by uncertainty reason. Average SST excluding Feodosya correspondence showed no significant biases: absolute annual average deviation equaled 0.22 °C, correlation coefficient r_{avg} = 0.92, determination - R^2_{avg} = 0.85. Average SST in the future assessment was calculated from Yalta and Chernomorskoe, excluding Feodosya data. The final validation for averaged annual data is shown in figure 2.

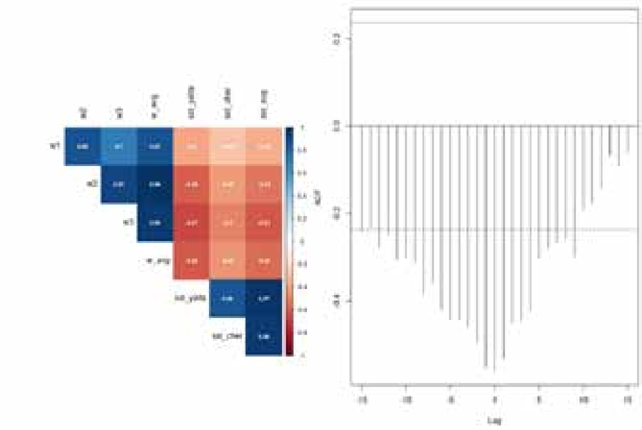

Figure 4. Raw data correlation test:
a) factor VS factor cross-table test;
b) cross-correlation test factors: w_avg VS sst_avg with -15 … +15 lag

Рисунок 4. Тест на корреляцию исходных данных:
а) кросс-табличный тест фактора против фактора;
б) кросс-корреляционный тест w_avg против sst_avg со смещением на -15 … +15 лет

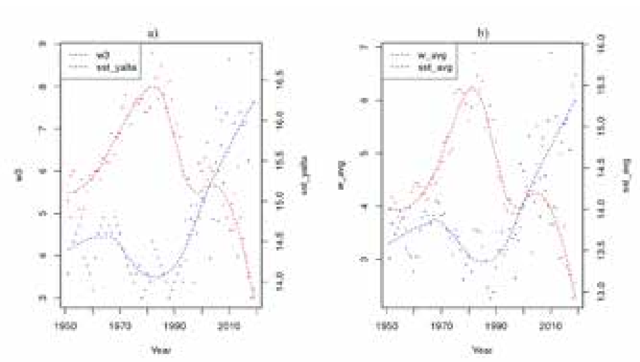

Figure 5. Local polynomial regression smoothing results for: a) SST in Yalta port and mean weight 3+ age group; b) average SST and average mean weight

Рисунок 5. Результаты сглаживания локальной полиномиальной регрессии для: а) SST в порту Ялты и средней навески возрастной группы 3+; б) усредненной SST и усредненной навески

For the raw data observation features, anomaly diagnostics was performed (*fig. 3*).

Preliminary raw data correlation test results with p-value significance test, cross-correlation test for average series (*w_avg* vs *sst_avg*) are presented in fig. 4. All raw factors have significant correlation (p-value < 0.05). Most highly correlated were mean weight 3+ age group (*w3*) and sea surface temperature in Yalta station, r = -0.67, p-value = 3.65 * 10-10. Cross-correlation test with time series lag indicate continuous SST effect on the sprat mean weight.

In order to to reduce the influence of inter-annual uncertainty, raw data were smoothed, fig. 5. Local regression approximation shows significant fitting diagnostics (RSE in range 0.36–0.54, best smooth fitting - *w_avg* and *sst_avg*). Local polynomial regression residual standard error (RSE) and Shapiro-Wilk residuals normality test are presented in table 1.

According to fit diagnostics, table 1, smoothed data series *w3* shows some over-fitting features. Finally, the smoothed data correlation test is shown in fig. 6. New results based on the smoothed data evidence improvement in the data series correlation: now Pearson correlation coefficient is more powerful (*r* = -0.86) between best SST/weight factors against r = -0.67 prior to smoothing.

In order to fit prediction model, smoothing diagnostics and smoothed data correlation test were investigated. The obtained sesults indicate that *w3* data seria can be over-fitted. Predictive model, based on the over-fitted results, may introduce a significant bias in predictions. Considering this, a linear model was fitted for *sst_avg* and *w_avg* factors, grouped by *sst_avg* vector (*fig. 7*).

Linear model, fig. 7, successfully passed all fitting diagnostics: fit has no bias for *a* = 0.05 level, no evidence of non-normality of residuals distribution have been found (Shapiro-Wilk test W = 0.91, df = 10, p-value = 0.26).

DISCUSSION

The results of this study confirm a significant impact of the temperature factor on the Black Sea sprat quality characteristics. Closer examination of the results, fig. 4 and fig. 6, indicate a significant negative correlation between the temperature factor and sprat mean weight-at-age. Performed data smoothing allows to achieve a more significant relationship confirmation, which evidences that inter-annual influence exists.

All temperature monitoring points were highly correlated between each other, like weight-at-age series did, before and after smoothing. This is not surprising due to the fact that spatial heterogeneity shouldnot make significant impact on

Table 1. Local regression raw data smoothing diagnostics /
Таблица 1. Диагностика сглаживания необработанных данных локальной регрессии

LOESS target data series	RSE	Shapiro-Wilk test p-value
w1	**0.37**	0.13
w2	0.47	0.61
w3	0.54	0.03
w_avg	0.36	0.97
sst_yalta	0.40	0.79
sst_cher	0.39	0.75
sst_avg	0.36	0.60

averaged values. This recommendation may lead to the statement that there is no significant difference existing in the environmental conditions in the sprat habitat areas. In another way, this can lead to a conclusion about a lack of spatial coverage of this study.

In addition to proving a correlation between temperature and sprat quality characteristics, another result should be focused on. As it can be seen from fig. 6, the correlation between temperature factor (*sst_**) and different weight-at-age groups (*w1, w2, w3*) has different power: *sst_avg* VS *w1* gave r = -0,52, *sst_avg* VS *w2* gave r = -0.73 and *sst_avg* VS *w3* gave r = -0.82. In a biological way, it means that younger age groups are less negatively exposed to the temperature factor than the older ones. It should be noted that this conclusion does not apply recruits: sprat in age group 1+ are fully mature fish. This temperature effect can be explained by higher resilience in food chains and widest eurythermal features of youngest fish groups. The other studies indirectly approve the assumption about sprat fat content, temperature factor and food chains [24, 25].

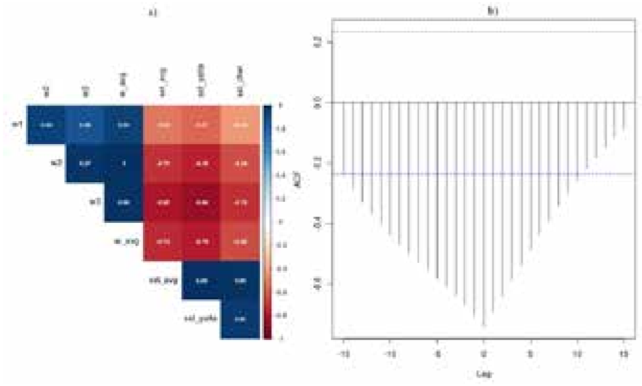

Figure 6. Smoothed data correlation test:
a) factor VS factor cross-table test;
b) cross-correlation test factors: w_avg VS sst_avg with -15 … +15 lag

Рисунок 6. Корреляционный тест сглаженных данных:
а) крос-табличный тест фактор напротив фактора;
б) кросс-корреляционный тест w_avg напротив sst_avg со смещением на -15 … +15 лет

Table 2. Black Sea sprat fishery catch proportion by age groups in the Crimean-Caucasian shelf in 1994-2019 / **Таблица 2.** Доля уловов черноморского шпрота по возрастным группам на Крымско-Кавказском шельфе в период 1994-2019 годы

Year	Age groups in catch, %		
	1-3	4-5	5+
1994	99.89	0.11	0.00
1995	99.85	0.15	0.00
1996	99.71	0.29	0.00
1997	99.78	0.22	0.00
1998	99.77	0.23	0.00
1999	99.99	0.01	0.00
2000	98.62	1.38	0.00
2001	99.36	0.64	0.00
2002	98.89	1.11	0.00
2003	94.84	5.16	0.00
2004	97.82	2.18	0.00
2005	96.64	3.36	0.00
2006	99.09	0.91	0.00
2007	99.03	0.97	0.00
2008	99.19	0.81	0.00
2009	99.87	0.13	0.00
2010	99.94	0.06	0.01
2011	99.97	0.03	0.00
2012	99.11	0.89	0.00
2013	99.85	0.15	0.00
2014	99.60	0.40	0.00
2015	96.39	3.61	0.42
2016	97.17	2.83	0.13
2017	99.42	0.58	0.00
2018	94.08	5.92	0.56
2019	98.31	1.69	0.52

Simple linear model fitting for the temperature factor and mean sprat weight in the fishery catches came as a surprise for authors, who expected to see a more complex relationship and a less obvious impact. However, linear model fitting, fig. 7, diagnostics shows a convincing result with high significance (R^2 = 0.87, RSE = 0.34). Moreover, the cross correlation test (*fig. 6b*) shows a continuous effect of the temperature factor even with a 10-year lag.

Obviously, the temperature factor is not the only one that impacts the sprat population. Actually, a number of ecosystem factors influence the sprat population, which is demonstrated by many scientists in their studies [23, 8]. The authors of this paper realize that and are not trying to emphasize a single factor, but want to focus on the long-term effect of global warming. A "bifurcation point" should have been stressed in the 1990s. As one can see from the long-term dynamics plots, fig. 3, fig. 5, since the 1990s a long-term trend has shifted. Starting from the 1990s a global temperature trend has shown a continuous increase, whereas all the sprat weight indicators – a continuous decrease with some uncertain fluctuations. This "bifurcation point", may be a global regime-shift point for the whole Black Sea area and should be closer investigated in the integrated ecosystem assessment. An accelerating effect of global warming should be taken into account in further complex ecosystem studies.

There is another hypothesis, which can be considered as a reason for such a drastic decrease in a mean weight of the sprat stock in the period of 1990–2019. This can be explained by a strong overfishing impact, which is not discussed in this paper. However, the first and most important signal of an overfishing impact is collapse of the population age structure: reduction of older age groups and increase of younger age groups in catch and, in general, in population. As it can be seen from table 2 (sprat catch age structure from fisheries data), there is no evidence that older age group (4–5 ages) catch structure collapse exists. On the contrary, since 2012 the share of older age groups has significantly increased. Moreover, recent reports of Scientific, Technical and Economic Committee for Fisheries [4, 9, 16] for the period of 1950–2016 do not indicate any presence of a prolonged overfishing period. Based on the STECF results, significant overfishing (over F_{MSY} = 0.64) was observed only in 1990, 1992–1994 and 2011. In accordance with these arguments, the hypothesis about the overfishing impact on the reduction of the sprat mean weights does not seem plausible.

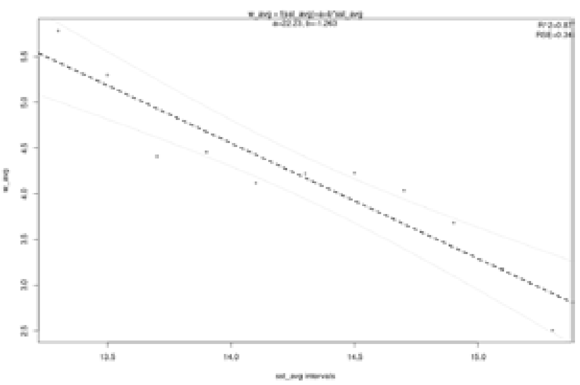

Figure 7. Linear model w_avg by SST grouped for Crimean-Caucasian Black Sea sprat fishery unit. R^2 - R-squared value, RSE - residual standard error value, a & b - fitted coefficient of linear model. Dashed line - regression model, dotted gray lines - model confidence interval at p = 0.95

Рисунок 7. Линейная модель зависимости w_avg от сгруппированного ряда SST для Крымско-Кавказской единицы запаса шпрота. R ^ 2 - значение R-квадрат, RSE - стандартная квадратичная ошибка, a & b - подобранные параметры линейной модели. Пунктирная линия - регрессионная модель, пунктирные (точка) серые линии - доверительный интервал модели при уровне значимости p = 0,95

Previous studies [3, 23] by co-authors of this paper show significance of the temperature factor for the purposes of sprat trawl fisheries and spatial distribution. The investigation of the seasonal spatial sea surface temperature and CPUE variability shows that effective fishing can be carried out only in a certain range of temperature conditions. Studies in the other seas [11, 15] also affirm importance of the temperature factor for sprat population conditions and fisheries.

However, it should be kept in mind that conclusions of this study can be accepted only in terms of two basic assumptions: temperature monitoring in discrete spatial points indicates global temperature dynamics in the Black Sea; the Black Sea sprat mean fishery weight represents a quality characteristic of its population.

CONCLUSION

The completed study confirms the impact of temperature factor on the sprat population. Global warming can be the main driver of the ecosystem variability in the Crimea-Caucasian shelf area of the Black Sea.

HIGHLIGHTS

1. The negative long-term linear relationship between temperature factor and sprat quality characteristics has been found and confirmed at significance level (p = 0.95).
2. Linear nature of the long-term relationship between temperature factor and sprat fishery mean weights was unexpected for the authors.
3. Younger age groups of sprat are less negatively exposed to temperature factor than the older ones.
4. Since the 1990's a long-term trend of the temperature factor has been shifted.

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