Toxic "bloom" and Pacific Salmon (Catch, Spawning Migrations, Production) in the Far Eastern Seas of Russia—Are There New Risks?

Ekaterina Lepskaya[1], **Kseniya Efimova**[2,3], **Sergei Shubkin**[1], and **Vladimir Kolomeitsev**[1]

[1]*KamchatNIRO (Kamchatka Institute of Fishery and Oceanography), Petropavlovsk-Kamchatsky, Naberezhnaya street, 18, 683000, Russia*

[2]*Zhirmunsky Institute of Marine Biology, National Scientific Center of Marine Biology, Far Eastern Branch, Russian Academy of Sciences, Pal'chevskystr.,17, Vladivostok, 690041, Russia*

[3]*Far Eastern Federal University, Sukhanova street, 8, Vladivostok 690950, Russia*

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"Red tide" was again observed in Olyutorsky Gulf in July 2017. This specific phenomenon was successfully studied in detail for the first time due to the concern and consequent interest of commercial fishermen whose trade nets appeared to be in the "bloom" zone. Having carried out species definition of the microalgae on the basis of morphology we stated that the "bloom" was caused by dinoflagellates from *Alexandriumtamarense*-species-complex. The taxonomic position of *Alexandrium* was more exactly defined by molecular-genetic analysis, ascertaining that the sample contained essentially a monoculture of *A. fundyense* (Balech) (Group I ribotype, previously known as the North American ribotype) from the above-mentioned complex. The number of dinoflagellates in the sample was estimated. On the basis of the satellite data, the "bloom" development dynamics were reconstructed using the chlorophyll-*a* accumulation. The presence of saxitoxin was revealed in the water sample that containined the suspension of *Alexandrium* cells. We collected information on unusual behavior of pink salmon which entered the zone of the "bloom", on peculiarities of the seabirds' behavior, on the air quality in the near-shore area; on weather conditions prior to and during the "bloom"; and the contents of the biogenic elements in the coastal water at the beginning of the "bloom". Also, on the basis of the satellite data the dynamics of surface water temperature in the coastal zone of Olyutorsky Gulf were reconstructed. The population rate of spawning areas in main rivers of reproduction of pink salmon and chum salmon in the basin of Olyutorsky Gulf–Pakhachi and Apuka–and terminal neighboring rivers was estimated by air search (Lepskaya et. al. 2017, 2018).

The analysis of the data obtained revealed the following set of questions:

- How close to each other are the areas of reproduction and catch of the Pacific salmon and the zones of "bloom" including toxic ones? Do they overlap?
- Do the toxins produced by harmful microorganisms directly impact fish of the genus *Oncorhynchus*?
- How does the quality of raw material change in the case of the influence of harmful microalgae on salmon?
- Can coastal "blooms" of harmful microalgae cause a sudden and thus unpredictable decrease of productivity of the areas of reproduction of Pacific salmon?
- What are the conditions of formation of the "toxic blooms";
- Is it possible to forecast the "toxic blooms"? What might be their expected frequency in conditions of retention of a warming trend in the North-western Pacific?

How close to each other are the areas of reproduction and catch of the Pacific salmon and the zones of "bloom" including toxic ones? Do they overlap?

"Red tides" are not rare in the Far Eastern seas (Konovalova 1993, 1999a). Studies in the 1980–2000s showed that "red tides" at the Pacific coasts of Russia were often caused by dinoflagellates of the genus *Alexandrium*, their concentration being maximal exactly at the eastern coasts of Kamchatka (Fig. 1). *Alexandrium* can be preserved for a long time in bottom sediments in the form of viable cysts (Fig. 2). In favorable conditions, the cysts are activated and through the process of vegetative reproduction form local or spacious aggregations of vegetative cells, quite often in huge concentrations (Konovalova 1999b).

Some species of this genus are able to produce saxitoxin (SXT)—a poison with neuroparalytic effects, which cause paralytic intoxication by mollusca (PSP). The species of *Alexandrium* are also well-known producers of ichthyotoxins (Emura et al. 2004) and allelochemical substances with high inhibition or stimulation effects (Arzul et al. 1999; Tillmann et al. 2008). Harmful/potentially toxic species of *Alexandrium* periodically have mass reproduction at the coasts of Kamchatka (Fig. 3), overlapping with the areas of fish number formation during key stages of ontogenesis and also catches of large portions of producers of populations of pink salmon, red salmon,

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All correspondence should be addressed to E. Lepskaya.
email: lepskaya@list.ru

silver salmon and king salmon in the Russian Far East. The portion of the total Far Eastern catches which come from for these species is 80%, 93%, 77% and 99% respectively, according to 2017 data (Shuntov and Temnykh 2017).

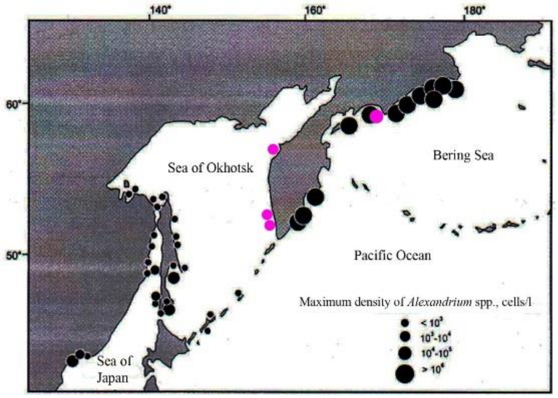

Fig. 1. Distribution of *Alexandrium*near Pacific shore of Russia (Selina et al., 2006 with additions by Lepskaya–pink circles).

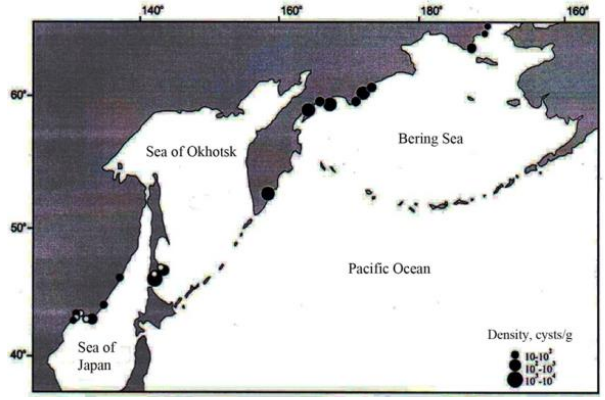

Fig. 2. *Alexandrium*cyst concentration in surface bottom sediments near Pacific shore of Russia (Selina et al., 2006).

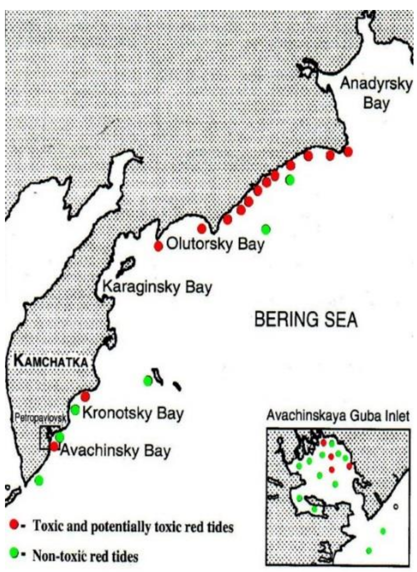

Fig. 3. Distribution of toxic, potentially toxic (red circles) and non-toxic (green circles) red tides (Konovalova, 1993).

Fig. 4. Areas of reproduction and catching of some Oncorhynchus species in Kamchatka.

Information on the influence of toxic "blooms" on aquatic bioresources and coastal biota of the Peninsula is limited and fragmentary because of sparsely populated sea coasts. For instance, Lobkov (1991) proposed that the increase in the number of dead seabirds on the coast of Kronotsky Gulf in odd years was caused by their eating of macrozooplankton which in turn accumulated toxins by feeding on toxic microalgae. Konovalova (1993, 1999b) pointed out that in July 1986 a "bloom" of *Alexandriumtamarense* in Olyutorsky Gulf was accompanied by the death of pinnipeds, fish, and birds.

Toxicity of *Alexandrium* was acknowledged only for the population of this microalga from the Avachinskaya Bay at the beginning of the 1980s when the presence of 11-hydroxysaxitoxin in mussels from this water basin was confirmed (Orlova et al. 2007).

The ability of *Alexandrium* to produce toxins in cultures derived from cysts taken from the bottom sediments of the Kamchatka shelf was confirmed by the works of Orlova and co-authors in 2005 (Fig. 5 and 6) (Orlova, 2005, 2007).

We managed to extract saxitoxin in concentration of 330 mkg/l only in 2017 (Lepskaya et al. 2017) from the water sample containing the suspension of *Alexandrium* cells, which was taken by fishermen at the coasts of Olyutorsky Gulf during the July water "bloom". It should be noted that in the paper by Lepskaya et al. (2018) there was a technical error, and a concentration of saxitoxin of 0.33mkg/l was published incorrectly.

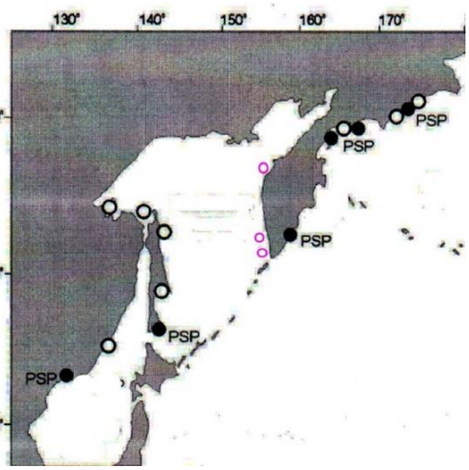

Fig. 5. Distribution of *Alexandrium*sp. with confirmed toxicity in cultures (black circles), and non-confirmed (empty circles) (Orlova, 2005 with additions by Lepskaya– pink circles).

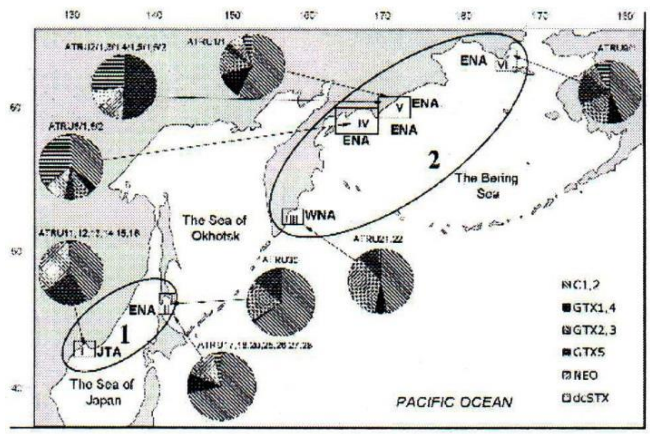

Fig. 6. Toxin composition of *Alexandriumtamarense* from the Russian Pacific shore (Orlova et al., 2007).

Thus, such areas of migration and catch of Pacific salmon as Avachinskaya Guba Inlet, Olyutorsky and Karaginsky Gulfs get into the zone of potential toxic impact of microalgal "blooms". The beginning and dynamics of the fishery, as well as the total catch of Pacific salmon are unknown for the Olyutorsky and Karaginsky Gulfs. As for Avachinskaya Bay, there is large-scale poaching of Pacific salmon and invertebrates, the volume of which is very difficult to figure out.

The microalgal "blooms" are not marked in the remaining regions of the Eastern Kamchatka, for example, in the Kamchatsky Gulf.

Despite the fact that concentration of *Alexandrium* in some parts of Kamchatka portion of the Sea of Okhotsk coastal water areas reach concentrations of 1000 cells/l or more, it does not form vast aggregations (Lepskaya et al. 2009). This is due to the high dynamic activity of the waters in this area, which prevents stagnant effects from forming (Anon 1993).

Olyutorsky Gulf and possibly its adjacent water areas are the most significant basins of reproduction and catch of Pacific salmon that get into the risk zone. To the west of Olyutorsky Gulf, it is the Korf Gulf, to the East it is the water areas of the Bering and Chukchi Seas, where *A. fundyense* is able to produce saxitoxin, neosaxitoxin, gonyautoxins 1 and 3, and C2 toxin, in cultures, and perhaps *in vitro* (Natsuike et al. 2017).

Do the toxins produced by harmful microalgae directly impact fish of the genus Oncorhynchus?

The unusual behavior of pink salmon was observed in 2017 in the coastal zone of Olyutorsky Gulf where trade nets were located in the belt of "bloom" of *Alexandrium.* According to fishermen, fish that bumped into aggregations of the microalgae were trying to dive under these aggregations or move along their borders in clean water. Also, according to fishermen, the fish that moved through aggregations of *Alexandrium* were "flabby and exhausted" and died soon after. Fish quickly became lethargic in the trade nets. During transport, from nets to the coast in special boats with slots on the bottom, the fish were already dead, "inelastic".

Such behavior and the state of fish when caught testify to the fact that saxitoxin in the water impacted the nervous system of fish leading to an abnormal state similar to paralysis.

It is known that the motor activity of fish changes under the influence of saxitoxin. These changes can include anomalous (convulsive) swimming, loss of balance (disorientation), full immobility—lethargy with lethal termination (Saito et al. 1985; Turner 1997; Zaccaroni and Scaravelli 2008). Interesting data on the cases and the reason for the mass death of fish, including salmon, caused by HAB, and PSP are presented in the review by Costa (2016).

Besides that, the dwellers of the Pakhachi settlement noted a strong unpleasant smell of “decaying grass” from the seaside and the deserted seashore which is usually full of seabirds.

How does the quality of raw material change in the case of influence of harmful microalgae on salmon?

Passing through the “bloom” zone, fish have complete contact with the toxin released by algae into the water, they have to “breathe in toxic water” and suspended algae, which can also get into their stomachs.

It is shown that Pacific salmon with a long-term period in the marine nursery can accumulate some quantity of saxitoxin in their internal organs, which, in such case passes in food chains from algae via macrozooplankton to fish. For instance, saxitoxin was found in the viscera of spawning chum salmon (Sato et al. 1998).

It was experimentally shown with Atlantic salmon that the concentration of saxitoxin coming from the blood into muscles is less than in other organs and tissues because it is intensively excreted from Atlantic salmon by the liver and kidneys (Bakke and Horsberg 2010).

In the case of the direct impact of saxitoxin on the pink salmon observed in Olyutorsky Gulf in July 2017, the fish probably died before accumulating any significant amount of saxitoxin in the muscles and gonads.

Can coastal “blooms” of harmful microalgae cause a sudden and thus unpredictable decrease of productivity in the areas of reproduction of Pacific salmon?

It seems to us to be quite possible. Let us discuss the situation observed in Olyutorsky Gulf in July 2017, when the estuaries of spawning rivers were closed by the belt of the “bloom” of *Alexandrium*. According to the fishermen, the majority of the fish moved along the borders between the clean and “blooming” water. With these observations, it is possible to suppose that it was impossible for the pink salmon to reach its native river, forcing part of the pink salmon stock to move to terminal rivers that were not closed by the “bloom”. In other words, there was a redistribution of migration streams. As a result, a much smaller number of spawning fish came to the rivers of Olyutorsky Gulf than was expected.

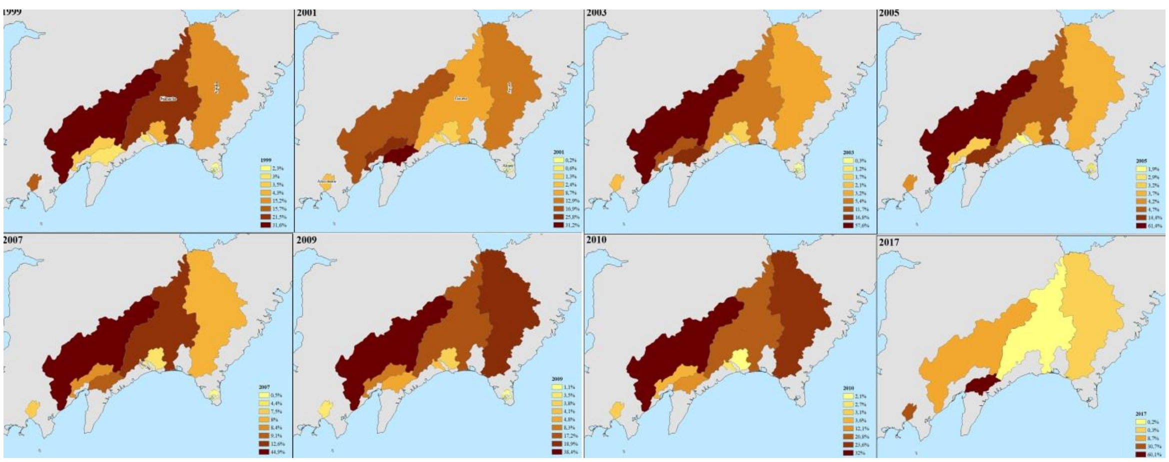

Fig. 7. Filling of the spawning rivers of Olyutorsky Gulf and Korf Gulf by humpback salmon (% of the total filling rate).

This conclusion confirms the retrospective analysis of the data of research of pink salmon on the spawning areas of the Korf-Olyutorsky basin (Fig. 7). Filling of the spawning rivers of Olyutorsky Gulf in 2017 by pink salmon was unexpectedly low in the series of odd years, and compared with the last registration year, 2010.

The “bloom” of *Alexandrium* also influenced the pink salmon fishery in Olyutorsky-Karaginsky zone during the peak phase of the runs. Thus, in spite of “the third in number and the second in catch result in the history of Karaginskypink salmon fishery”, field conditions in the Olyutorsky Gulf were the worst in the region. And the beginning of the fishery shifted from the Olyutorsky Gulf to the central part of Karaginsky Gulf in contrast to the last years (Shevlyakov et al. 2017).

The Olyutorsky Gulf portion of the total catch of pink salmon in Olyutorsky-Karaginsky region since 2005 was 20% (min 9%, max 54%), in 2017 this portion decreased to 5%.

In the last 12 years, catches of pink salmon in the Olyutorsky Gulf have correlated with the total catch of this species in Olyutorsky-Karaginsky region, but in 2017 this correlation was broken (Fig. 8).

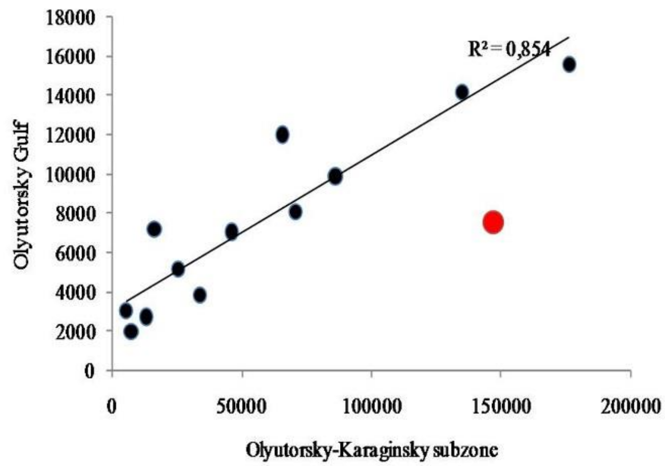

Fig. 8. Correlation of pink salmon catch in Olyutorsky Gulf and Olyutorsky-Karaginsky region in 2005–2017. Red circle—2017.

Conditions of the formation of "toxic blooms"

There were heavy showers in Olyutorsky Gulf and riverheads of the Pakhacha and the Apuka in early July 2017 that caused a mudflow in the Pakhacha River. A huge quantity of biogenic elements was carried out to the seashore (Table 1). Concentrations of biogenic elements (mean for July) in Avachinskaya Bay, which is exposed to long-term chronic anthropogenic impact, are presented in the Table for comparison.

Table. 1. Biogenic elements in the water in Olyutorsky Gulf and Avachinskaya Bay.

Biogenicelement	OlyutorskyGulf	AvachinskayaBay	Excess of concentration of biogenic elements in Olyutorsky Gulf as compared to AvachinskayaGuba Inlet
Mineralphosphorus, mgP/l	0.181	0.049	4
Ammoniumnitrogen, mgN/l	2.637	0.174	15
Nitritenitrogen, mgN/l	0.042	0.004	11
Nitratenitrogen, mgN/l	+	0.01	-
Mineralnitrogen, mgN/l	2.68	0.19	14
Iron, mgFe/l	0.40	0.10	4
Silicon, mgSi/l	3.0	4.4	1.5

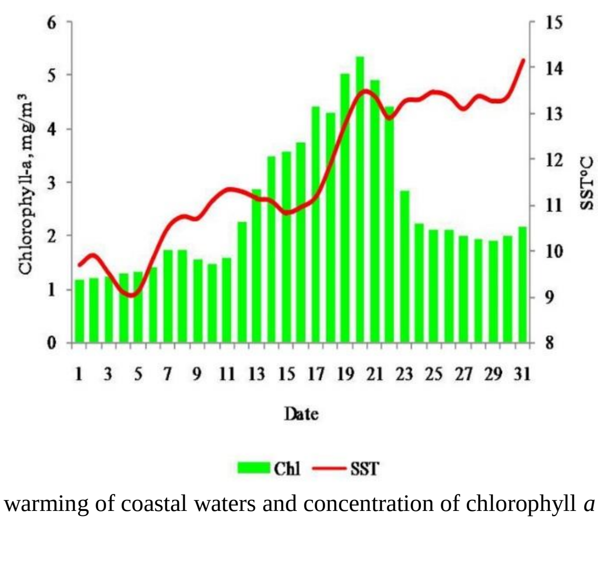

Fig. 9. The dynamics of warming of coastal waters and concentration of chlorophyll *a* at the coasts of Olyutorsky Gulf in July 2017.

Besides that, the flood became the probable cause of desalination in the coastal water area. Calm sunny weather set in the region after the cyclone. The coastal water area started warming (Fig. 9). Light south-western and south-eastern breeze shifted the belts of "blooming" to the shore in the zone of trade nets, which fused in the common field with enormous biomass judging by the amount of chlorophyll *a.* (Fig. 9). The first spots of colored water appeared before that, about 2 miles from the shore. Calm weather lasted during the entirety of July. Light offshore winds and tidal currents were unable to drive the dense surface layer of microalgae away. Perhaps, some limiting role was played by the trade nets.

Earlier, only two taxa of *Alexandrium*: *A. tamarense* and *A. ostenfeldii*were found in the Olytutorsky Gulf (Selina et al. 2006). Further studies showed that *A. tamarense* represented a complex of morphologically close species, including those that produce saxitoxin and the ones that do not produce this substance (John et al. 2014).

According to our data, species of *Alexandriumtamarense*-complex found on the Kamchatka coasts of the Sea of Okhotsk are considerably more abundant in the desalinated and warm water areas (Lepskaya et al. 2009). However, conditions for activating the "bloom" of toxic species are still unknown.

Is it possible to forecast "toxic blooms"? What might be their expected frequency in conditions of retention of a warming trend in the North-western Pacific?

According to the data of G.V. Konovalova (1999b), "red tide" caused by *Alexandriumtamarense*f. *excavata* was recorded in Olyutorsky Gulf in July 1986, and in mid-late July 1988, 1990. The toxic impact of the "bloom" was observed only in 1986 because it was accompanied by the death of pinnipeds, fish, and birds. In the time between 1986 and 2017, i.e., for 31 years, there was no information on the "blooms" and the simultaneous death of animals.

Thus, in spite of the commonness of such phenomenon as "red tides" in the eastern Kamchatka and the Bering Sea, toxic "blooms" are rare and local. It is impossible to predict them and in the opinion of V.V. Bogatov (Keynote at the United Plenary meeting of Scientific Council on hydrobiology and ichthyology RAS, Hydrobiological society of RAS, and Interdepartmental ichthyologic committee "Actual problems of hydrobiology and ichthyology", 27 March 2018, Moscow), such events may appear more frequently in the "period of climatic extremes". Their impact may cover larger areas and be longer in time.

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