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SETTLEMENT AND ASSESSMENT OF THE POSSIBLE RANGE OF SNOW CRAB (CHIONOECETES OPILIO) IN THE BARENTS SEA

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Abstract: The paper describes the dynamics of settlement of the snow crab in the Barents Sea in 1996-2014, and also considers the factors influencing the processes of its acclimatization. Based on the modeling of the spatial distribution, it was found that the area of distribution of the crab has increased 10 times since the beginning of regular research and now its range covers 34% of the area of the Barents Sea. The main factor limiting the further distribution of the crab may be the warm bottom water temperature in the southwest of the sea. However, the potential for further dispersal of the crab in the Barents Sea remains very high. Predictive estimates show that the area can double due to the northwestern regions of the Barents Sea and coastal waters of arch. Spitsbergen.

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Introduction

At present, two species of invasive crabs of commercial importance play an important role in the ecosystem of the Barents Sea: the king crab (*Paralithodes camtschaticus*) and the snow crab or *opilio* snow crab (*Chionoecetes opilio*). The appearance of the first species is associated with a targeted introduction from areas of the native range, which took place in the second half of the 20th century. Long-term monitoring of the expansion of the red king crab made it possible to study and describe in great detail the features of its dispersal and adaptation in the Barents Sea region (Kamchatka crab…, 2003). On the basis of scientific recommendations, the successful commercial exploitation of this hydrobiont in the southeast of the Barents Sea was organized. The research results showed that at present, in the main habitats of the king crab, the processes of acclimatization are completed or are close to completion (Pinchukov, 2011; Pinchukov and Sundet, 2011).

The reasons for the invasion of the second species, the snow crab, are still unclear and can be associated with both the unintentional transfer of larvae with ballast water and the independent migration of adults under the influence of natural environmental factors (Kuzmin et al., 1998). The results of ten-year monitoring show that this crab has formed a self-reproducing population in the Barents Sea, which occupies a vast area. At the same time, the processes of acclimatization of this species have not yet been completed. The crab is actively exploring new areas, and is also increasing its numbers in already populated areas.

In this paper, for the first time, the dynamics of dispersal of snow crab in the Barents Sea is analyzed in detail, and also factors influencing the processes of acclimatization are considered. On the basis of modeling the spatial distribution of the species, a forecast is given for its further dispersal under different temperature conditions.

Materials

The work used PINRO data on snow crab catches in the Barents Sea, obtained during:

1) observations of the fishery of benthic fish species and scientific surveys of northern shrimp in 1996-2003;

2) a comprehensive Russian-Norwegian ecosystem survey in 2004-2014.

Crab by-catch in bottom fisheries was reported from vessels attended by scientific teams or fisheries inspectors. The messages indicated the date and coordinates of the capture, the parameters of the fishing gear, the number of crabs caught and their main biological characteristics (sex, carapace width, state of the covers). The total number of crabs caught was 164 specimens. (tab. 1)

Table 1. Amount of material on snow crab obtained during observations of the fishery of benthic fish species and research surveys of northern shrimp in 1996-2003.

Year	Number of messages	Number of crabs, specimen
1996	5	5
1997	one	one
1998	2	2
1999	7	8
2000	12	8
2001	nine	5
2002	21	28
2003	79	107

Research into the distribution of snow crab on a regular basis became possible with the start (2004) of Russian-Norwegian integrated ecosystem surveys. Annual survey conducted by a standard technique in summer-autumn period and covered most of the Barents Sea, the area of which the average is about 1500 thousand. Km ^{2} (Eriksen, 2012). Each survey was carried out simultaneously on 4-5 vessels. The collection of material was carried out with a Campelen bottom trawl with a horizontal opening of 25 m, vertical - 5 m and an insert in the core part from a Delhi with a mesh of 22 mm. The number of bottom trawls performed per survey varied from 650 to 1123. The total number of crabs caught was 77854 individuals. (Table 2).

Table 2. Amount of material on snow crab obtained during ecosystem surveys in the Barents Sea in 2004-2014.

Year	Number of trawls	Number of trawls with crab	Number of crabs, specimen
2004	1123	5	6
2005	1008	ten	14
2006	999	29	61
2007	1007	56	134
2008	776	77	670
2009	754	66	284
2010	710	58	400
2011	775	84	6657
2012	835	121	37737
2013	859	132	19020
2014	650	87	12871

Methods

To calculate the probability of snow crab occurrence, the water area of the Barents Sea was divided into polygons by a regular grid with a step of 0.25 ° north latitude and 1 ° east longitude. The polygon attributes included the following indicators: number, coordinates, depth (m), bottom temperature (° C), distance (km) from the geometric center of the crab distribution area, crab capture (1 - there is a crab; 0 - no crab; NA - there is no observation). The distance from the geometric center of the crab distribution area was calculated annually for each survey and served as a factor in the distance from the core of the initial crab dispersal. To construct the distributions of the probability of occurrence of the crab by years and to predict its further distribution, a generalized linear model (GLM) was chosen, implemented in the package biomod2 of the statistical platform R. its diagnostics, as well as the assessment of the influence of variables on the simulation results, were carried out using the built-in functions of the biomod2 3.1 package (https://cran.r-project.org/web/packages/biomod2/). The factors that determine the likelihood of the occurrence of a crab in each polygon during the survey period were: depth, temperature, and distance from the center of settlement. When predicting the potential range of the crab in the Barents Sea, only depth and temperature were taken into account, and the distance from the center of settlement was excluded. At the same time, three variants of calculations were performed at different temperatures: the long-term average for 2010-2014, 1 ° C lower than the long-term average, and 1 ° C higher than the long-term average. The area of distribution of the crab was calculated in the water area with the probability of occurrence of the crab over 50%, i.e. in cases when the species can be considered constant (Ioganzen, Faizova, 1978). The construction of cartograms of the simulation results was also carried out in R using the PBSmapping package (https://cran.r-project.org/web/packages/PBSmapping/).

To calculate the density of distribution and indices of crab abundance by years, an area with a high occurrence of animals was identified, which was divided into regions and sub-regions (strata with a depth range of 0-100, 100-200, 200-300 and more than 300 m). The abundance index in the stratum (*N*) was calculated by the areal method: $N = C * (S / T)$, where *C* is the average catch of the crab per trawling, in the water area of the subarea with area *S* , and the trawling area (*T*) was taken equal to 0.022224 km ^{2} ... The swept area is calculated taking into account a standard 15-minute trawl with a horizontal trawl opening of 15 m and a speed of 3.2 knots.

results

Snow crab *Chionoecetes opilio* (Fabricius, 1788) (Brachyura, Majidae) is a common and widespread representative of benthic communities on the shelf and continental slope of the northwestern Atlantic and northern Pacific. (Kobyakova, 1958; Slizkin, 1982; Galkin, 1985; Davidson et al., 1985). In 1996, the crab was first recorded in the Barents Sea on the northern slope of the Goose Bank during a survey of northern shrimp stocks (Kuzmin et al., 1998). Since that time, there has been a gradual increase in the annual number of reports of crab by-catches on the slopes of the Gusina and Demidovskaya banks (Kuzmin, 2000; Pavlov, 2006) (Fig. 1).

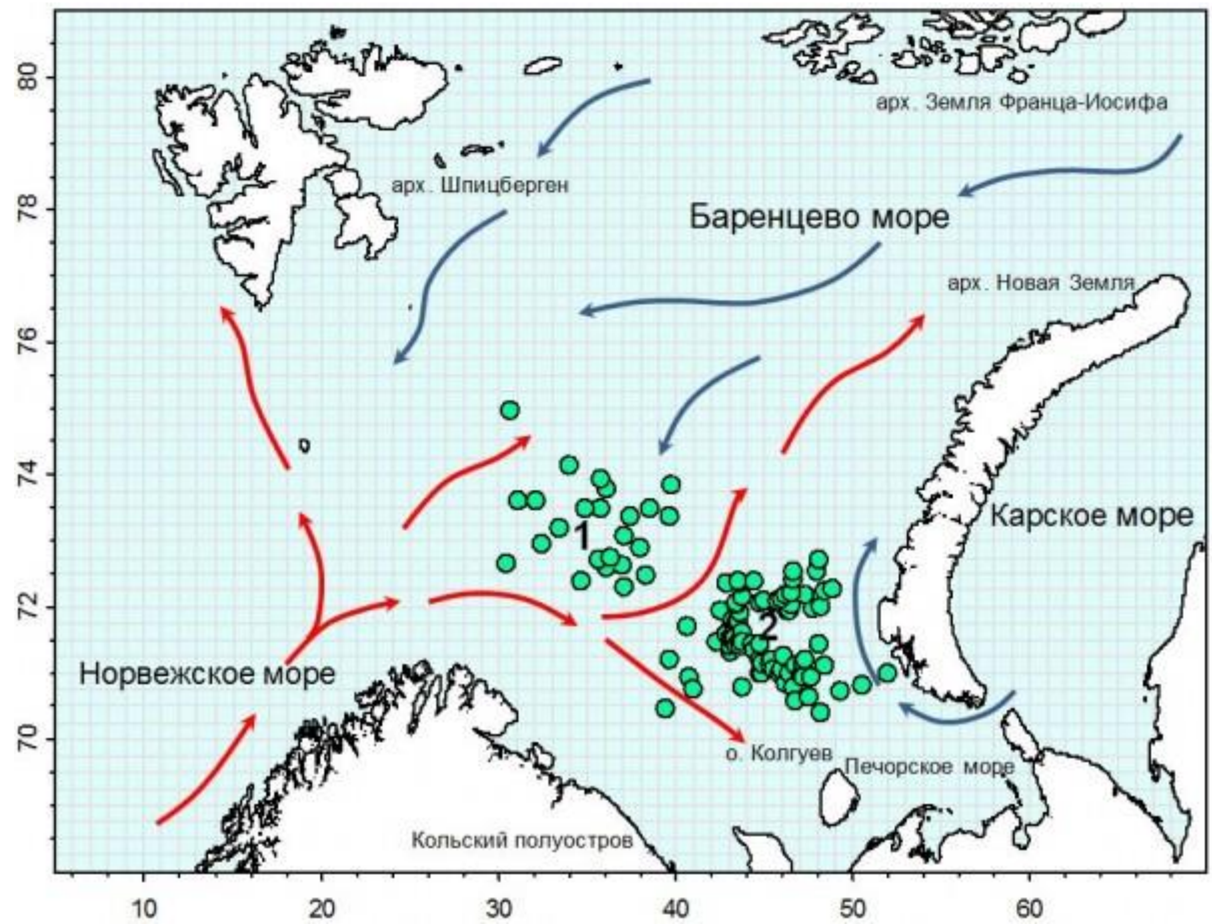

Fig. 1. Locations of Snow Crab Catch in 1996-2003 in the Barents Sea (1 - Demidov Bank, 2 - Goose Bank) and the main directions of warm (red arrows) and cold (blue arrows) currents

Figure 1. Places of catches of snow crab opilio in the Barents Sea (1 - Demidovskaya Bank, 2 - Gusinaya bank) in 1996-2003 and the main directions of warm (red arrows) and cold (blue arrows) currents.

During the research period from 1996 to 2003. snow crab in the Barents Sea was recorded at depths of 100-330 m, mainly on silty and sandy-silty soils, less often on silty-clayey and sandy-clayey. The water temperature within the limits of its habitat in the bottom layer varied from -1.5 to +4.3 ° C, salinity - from 34.5 to 35.1 ‰. In the temperature range from -1.1 to +1.3 ° C, crab catches reached their maximum values.

Since 2002, reports of crab by-catch have increased (see Table 1). Animals were noted not only in the areas of their first registration, but also far beyond the slopes of the Goose Bank. The presence of functionally mature individuals of the species, as well as the finding of females with eggs, confirmed the successful breeding of snow crabs in the new habitat. In accordance with the main directions of the bottom currents, the most probable northeastern vector of the expansion of the crab at the larval plankton stage was determined. However, the lack of systematic research and fishing did not allow to reliably assess the presence of crabs in the northeastern regions of the Barents Sea until 2004.

Since 2004, in the course of ecosystem surveys, studies have shown an increase in the range, density and abundance of snow crab in the new region (Table 3). The water area of occurrence of the crab in 2005 increased threefold, and in 2006 it even doubled in comparison with the previous observations. During the first 4 years of research, the area of distribution increased 10 times. Since 2007, this area has increased on average by 10%

annually. The reduction in the area of distribution in 2014 most likely indicates not real processes in the dynamics of the population caused by natural causes of mortality and recruitment, but about the technical features of the survey, which entailed changes in the catchability of the trawl for benthic organisms (oral reports of D.V. Prozorkevich and Lyubina P.A.).

Table 3. Area of distribution, average distribution density and index of snow crab abundance in the Barents Sea in 2004-2014.

Year	Distribution area, thousand km	Average distribution density, ind./km ^{2}	Population index, mln.
2004	44	one	0.63
2005	130	3	2.21
2006	262	7	5.24
2007	336	19	14.31
2008	447	116	86.38
2009	514	36	26.91
2010	557	76	56.25
2011	605	1144	849.63
2012	569	5854	4346.32
2013	662	3071	2280.25
2014	452	2234	1658.43

Along with an increase in the area of distribution of the crab, the relative density of its distribution also increased (Table 3). Until 2007, crabs were only found in catches. Average crab catches per trawling have increased significantly since 2011.Since that time, immature juveniles have predominated in the size composition of catches, which now constitute the bulk of the population. Over the entire period of research, the population index increased by three orders of magnitude; such an explosive nature of the number is often observed in acclimatized animals at the beginning of the acclimatization period. However, in the last two years there has been a decrease in the average catches of crab in surveys. The nature of this decline has not yet been precisely established and requires further research.

Mapping the results of modeling the distribution of snow crab based on the results of ecosystem surveys in 2004-2014. showed that the expansion of the area took place in the northern, southern and western directions (Fig. 2). In 2005, the eastern boundary of occurrence came close to the shores of arch. New Earth. In 2008, the southern and southeastern distribution boundaries also approached their geographical limit - the coastal regions of the Pechora Sea (Kolguev and Vaigach Islands, Kanin Peninsula, Kara Vorota Strait). During this period, the formation of the modern southwestern boundaries of the distribution of the crab took place. The limiting factor for further spread was the high bottom temperature (5-7 ° C) of the coastal areas of the Kola Peninsula, at which the probability of occurrence of the crab was less than 20%.

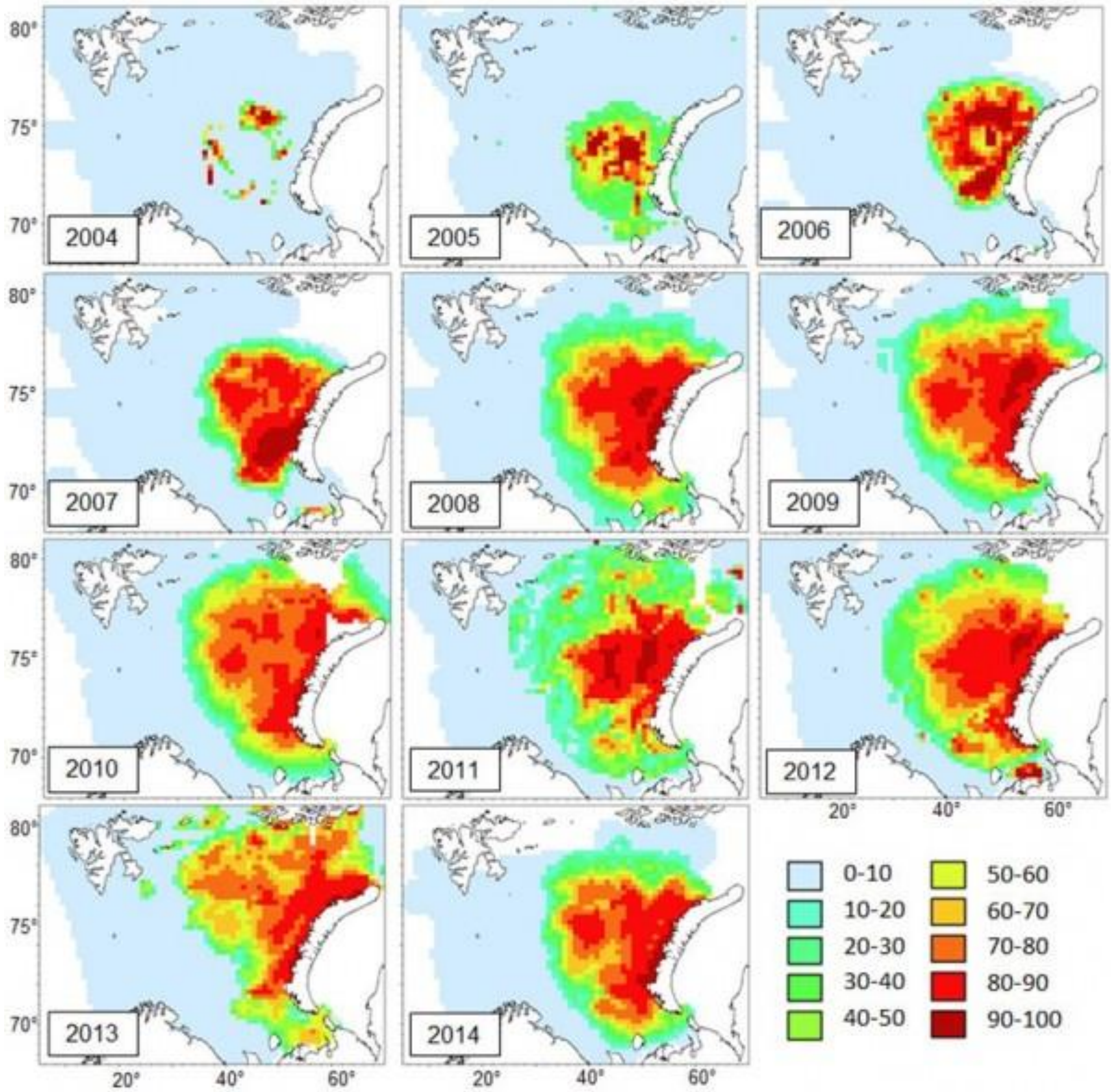

Figure: 2 Probability of occurrence (%) of snow crab in the Barents Sea in 2004-2014
Figure 2. Occurrence probability (%) of snow crab opilio in the Barents Sea in 2004-2014.

The dispersal of snow crab in the northern, northwestern and northeastern directions was observed during the entire observation period. In 2009, the crab was recorded in the coastal areas of arch. Franz Josef Land (FZI). Since 2010, the crab has been regularly encountered not only in the FFI areas, but also in other areas of the northeastern Barents Sea, reaching the boundaries of the ecosystem survey. In this regard, monitoring the settlement of the crab in the northern direction is currently difficult due to the lack of observations. In 2010-2011. the expansion of the crab in the northwestern direction slowed down, without reaching the eastern shores of arch. Spitsbergen. Single catches of crabs west of 34-35 ° E. during the research period were of a random nature and cannot reliably indicate the mass settlement of the crab in the western regions of the Barents Sea.

Analysis of the factor of distance from the center of settlement showed that the most active expansion of the crab was noted in the northeastern direction. The rate of settlement in this direction averaged 105 km / year. The settlement of the crab both in the southern and northern directions took place at an average speed of 69 km / year. The advance to the west was not so active and averaged 39 km / year.

Analysis of the distribution of crab catches by depths for the entire observation period showed that most often the crab was observed at depths of 150-250 m.At the same time, the crab was periodically found in shallow waters (up to 100 m) and deep-water depressions (more than 250 m). With the dispersal of the crab in the eastern and southeastern directions, its catches increased in shallow water areas (up to 50 m) adjacent to arch. New Earth. In 2012-2013. crab began to occur in the shallow waters of the Pechora Sea with depths of 17-20 m. At present, this is the lowest depth at which crab catches have been recorded in the Barents Sea. The maximum depth of detection of the crab was noted in 2011 and amounted to 551 m. During this period, the dispersal of the crab in the northeastern direction reached the boundaries of the St. Anna Trench at the border of the Barents and Kara Seas.

Ecosystem surveys have shown that snow crab distribution ranges vary from year to year. However, since 2010, the area of the crab distribution area has not changed significantly, and the boundaries of high densities remain practically unchanged. With this in mind, below are the features of the current state of the snow crab population in the Barents Sea, estimated based on the combined data of research surveys in 2010-2014.

Currently, the snow crab range covers 34% of the Barents Sea area. The area of distribution of the crab is 618 thousand km ^{2}. The crab has become a common representative of the benthic fauna in the eastern part of the Barents Sea from about. Kolguev in the south up to arch. Franz Joseph in the north. The densest accumulations of juveniles are found in the southeastern area (Pechora Sea) and northeastern waters off the coast of arch. New Earth. Aggregations of mature individuals are noted in the central (Central Upland) and central-eastern (Novaya Zemlya Bank) regions. The range of the crab has reached its geographical boundaries in the east, approaching the coastline of arch. New Earth. The active settlement of the crab was also completed in the southeast; the boundaries of its range coincide with the southern boundary of the Pechora Sea (Fig. 3A).

The forecast of further dispersal can be demonstrated by modeling the distribution without taking into account the factors of time and distance from the geometric center of the water area of distribution of the crab, using only the factor of temperature and depth. In this case, long-term temperature changes can significantly affect the distribution of the crab (Fig. 3). At the temperature that was observed in 2010-2014, the water area of the occurrence of the crab can increase 2 times, while the area of distribution of the crab with a probability of occurrence of more than 50% will increase to 1237 thousand km ^{2}... The expansion of the area will take place at the expense of the northern and northwestern regions of the Barents Sea (Fig. 3B). With a cooling of the bottom layers by 1 ° C, the water area will increase by 3 times in comparison with the modern distribution (Fig. 3B). The area of distribution of the species can be 1421 thousand km ^{2} . The cold snap will facilitate further westward expansion of the crab. With an increase in the average bottom temperature by 1 ° C, the expansion will slow down, and the area of distribution of the crab with its full acclimatization in the Barents Sea may amount to 1019 thousand km ^{2} , i.e. 20% more area of modern distribution.

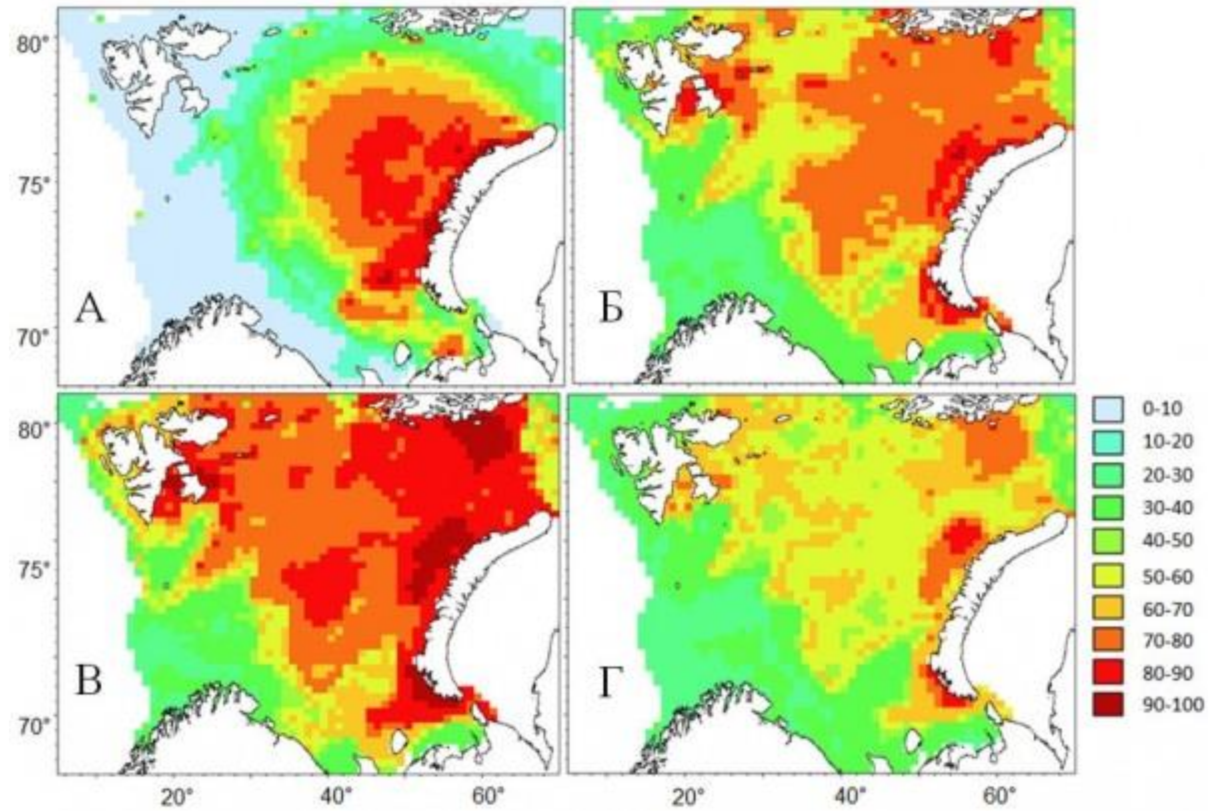

Figure: 3 Probability of occurrence (%) snow crab in the Barents Sea in 2010-2014 (A), as well as the forecast of the distribution at the mean long-term temperature (B), lower than the mean long-term temperature by 1 ° C (C), higher than the mean long-term temperature by 1 ° C (D).

Figure 3. Occurrence probability (%) of snow crab opilio in the Barents Sea in 2010-2014 (A), and the forecast of its distribution at the temperature equal to the long-term average annual temperature (B), 1 ° C lower than the long-term average annual temperature (B), 1 ° C higher than the long-term average annual temperature (G).

As mentioned above, this settlement forecast is based on the influence of two environmental factors: depth and bottom temperature. Analysis of the distribution of depths in the Barents Sea and the distribution of crab by depth showed that the depth factor is not significantly limiting for the further dispersal of the crab (Fig. 4A). The crab is currently found in almost the entire depth range from 20 to 550 m. This range covers 98% of the Barents Sea. Simulation data show that the contribution of the depth factor to the model is 28%. Analysis of the probability of the presence of a crab by depth showed that the optimal range of depths for snow crab is in the range from 0 to 300 m (Fig. 4B). This depth range covers 83% of the Barents Sea area.

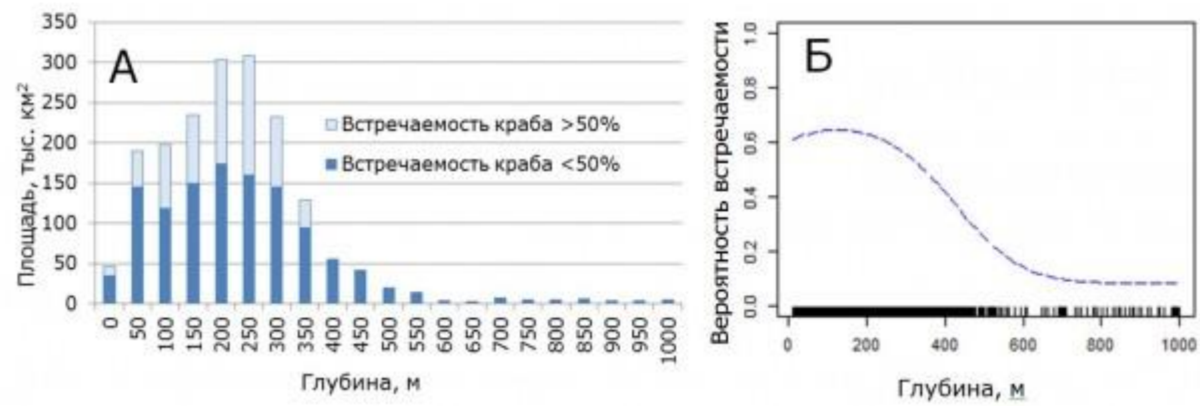

Figure: 4. Areal distribution of the depths of the Barents Sea, taking into account the occurrence of snow crab in 2010-2014. (A) and the curve of the influence of depths on the probability of its occurrence (B).

Figure 4. Areal distribution of Barents Sea depths taking into account the occurrence of snow crab opilio in 2010-2014 (A) and the curve of the depth influence on the occurrence probability (B).

Analysis of the distribution of the bottom temperature in the Barents Sea and the distribution of the crab showed that the temperature factor is to a large extent limiting for the further dispersal of the crab in areas with increased heat content of waters (Fig. 5A). The crab is currently found in the bottom temperature range of -1.5 ° C to 6.5 ° C. However, the highest occurrence was noted at bottom temperatures from -1.5 ° C to 3.0 ° C. This range covers 82% of the area of account in the Barents Sea. Simulation data show that the contribution of the temperature factor to the model is 72%. Analysis of the likelihood of the presence of a crab showed that the most optimal temperature range for snow crab is between -1.5 ° C and 2.0 ° C. This depth range covers 70% of the Barents Sea area.

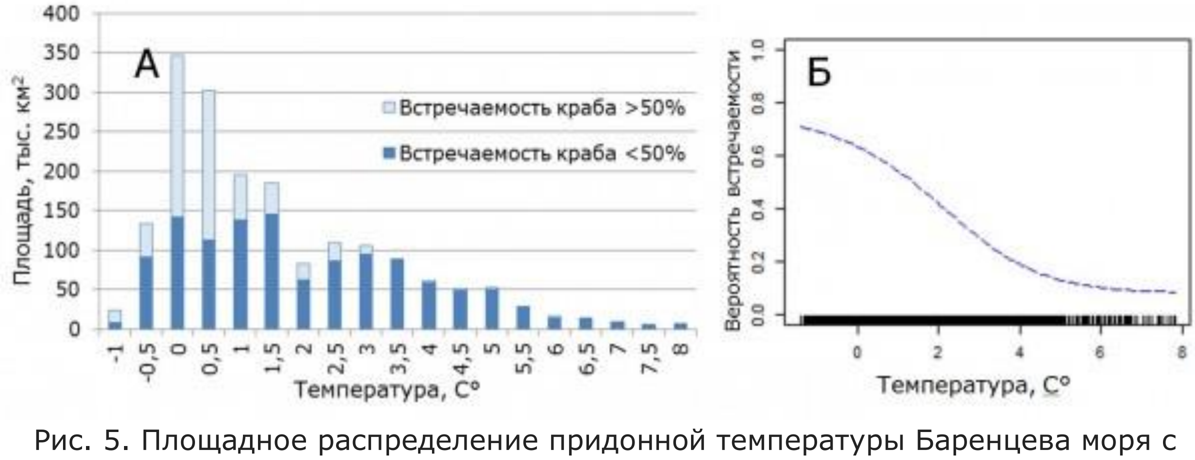

Рис. 5. Площадное распределение придонной температуры Баренцева моря с учетом встречаемости краба-стригуна в 2010-2014 гг. (А) и кривая влияния температуры на вероятность его встречаемости (Б).

Figure 5. Areal distribution of the Barents Sea bottom temperature taking into account the occurrence of snow crab opilio in 2010-2014 (A) and the curve of the temperature influence on the occurrence probability (Б).

Обсуждение

В литературе отмечается, что основными факторами, влияющими на распределение и формирование промысловых скоплений краба, являются температура, глубина и тип грунта (Слизкин, 1982; Михайлов и др., 2003). Предпочитаемый диапазон глубин и температур краба-стригуна в Баренцевом море весьма сходен с условиями обитания популяций краба в традиционных районах его обитания от Северо-Восточной Атлантики до Японского моря. Наиболее холодноводные и глубоководные скопления этого вида, имеющие промысловое значение, были отмечены у берегов Гренландии. В этом районе краб часто живет в области отрицательных температур и глубин более 300-400 м. Максимальная глубина, на которой были обнаружены крабы – 1400 м. Основные глубины обитания промысловых крабов 150-250 м характерны для популяций, обитающих в водах американского побережья Берингова моря, канадской зоны и дальневосточного региона России. Промысловые скопления на глубинах менее 100 м краб образует у восточного побережья Канады. Верхний предел температур для краба ограничивается 9-10 °С. Однако с увеличением среднегодовой придонной температуры до 6 °С плотность поселений краба заметно снижается, а промысловые скопления практически не встречаются. Южная граница обитания краба в Тихом океане проходит у берегов Японии в префектуре Киото. Поверхностные воды в этом районе теплые, поэтому краб обитает в основном на глубинах более 200 м с придонными температурами не выше 5 °С.

Таким образом, учитывая тепловой режим и батиметрическое распределение краба в нативном ареале и Баренцевом море, лимитирующим фактором дальнейшего расселения краба может стать высокая придонная температура. Такие придонные температуры (>6°С) характерны для юго-западной части Баренцева моря.

При оценке распределения и дальнейшего расселения необходимо учитывать направление и скорость течений, тип грунта, соленость и наличие кормового бентоса. В нативном ареале краб предпочитает илистые и песчано-илистые грунты. Однако молодь, которая в большей степени встречается на мелководье, чаще отмечается на песчаных и илисто-гравийных грунтах (Иванов, Соколов, 1997, Слизкин, 1982; Dufour, 1988). Большая часть дна Баренцева моря покрыта песчаным илом. Прибрежные районы, склоны и возвышенности банок покрыты илистым песком. В некоторых районах имеется песок. Юго-восточную часть моря занимают илистые отложения (Добровольский, Залогин, 1982). Таким образом, тип грунта оптимален для жизнедеятельности и не будет препятствовать дальнейшему расселению краба в Баренцевом море.

Одним из основных абиотических факторов, способствующих широкому расселению краба в Дальневосточном регионе, указывается направление течений, переносящих личинок (Слизкин, 1982). В Баренцевом море существует сложная система поверхностных и глубинных течений, самым общим свойством которых является движение вод против часовой стрелки (Новицкий, 1961). Это свойство благоприятно сказалось на успешной акклиматизации вида, направив основной вектор расселения в северо-восточном направлении в район с наиболее оптимальным температурным режимом (менее 3°С) для развития молоди. Дальнейшему расселению краба в северо-западном направлении будут способствовать холодные течения из Арктического бассейна, направленные к югу от Земли Франца-Иосифа и вдоль восточного берега Шпицбергена.

Одним из возможных факторов, влияющих на распространение краба в прибрежных районах, может стать соленость придонных вод, которые часто подвержены значительному опреснению (Anger, 2003). В то же время известно, что краб достаточно часто образует плотные скопления при пониженной солености вплоть до 32 ‰ (Слизкин, 1982). Учитывая, что 2/3 акватории Баренцева моря находятся под влиянием атлантических вод и даже на поверхности моря соленость воды превышает 34‰, а на остальной акватории моря соленость колеблется в пределах 32-34 ‰ (Добровольский, Залогин, 1982), фактор солености не будет играть значимую роль в дальнейшем расселении краба.

Таким образом, основные абиотические факторы среды в Баренцевом море, влияющие на распределение краба-стригуна, не препятствуют акклиматизации вида, колонизации акваторий и формированию скоплений в северном и северо-западном районах Баренцева моря. Многие авторы в числе факторов, влияющих на распределение краба-стригуна, справедливо указывают следующие биотические особенности: наличие кормового бентоса и хищников (Кобякова, 1958; Слизкин, 1982; Галкин, 1985). Бесспорно, что для формирования плотных скоплений краба, на основе которых можно организовать успешный промысел, необходимы существенные пищевые ресурсы. Весьма важно при этом отсутствие каннибализма и массовых хищников, которые могли бы подорвать численность популяции на ранних стадиях развития. Однако большинство авторов отмечают важность наличия кормовой базы в контексте формирования промысловых скоплений. К сожалению, недостаток данных о распределении кормового бентоса в северо-западных районах Баренцева моря не позволяет количественно доказать эту гипотезу. Однако наличие пищевых ресурсов для краба-стригуна можно подтвердить косвенно через присутствие видов, имеющих схожие пищевые предпочтения, в районах, перспективных для расселения краба-стригуна.

Анализ питания краба-стригуна в Баренцевом море показал, что наиболее близкими пищевыми конкурентами для него являются два вида краба-аборигена *Hyas araneus* и *Lithodes maja*, которые весьма часто отмечаются в северо-западных районах моря (Павлов, 2007). Кроме того, постоянное присутствие в этих районах рыб-бентофагов также свидетельствует о наличии удовлетворительной кормовой базы в этих районах для дальнейшего расселения краба-стригуна. В то же время оценка достаточности этих пищевых ресурсов для формирования промысловых скоплений требует дальнейших исследований.

Заключение

Динамика расселения краба-стригуна в Баренцевом море с 2004 г. соответствует процессу акклиматизации и формирования новой популяции. За период исследований площадь распространения этого вида увеличилась в 10 раз, а численность возросла на три порядка.

Основным фактором, лимитирующим дальнейшее распространение краба, может стать придонная температура на юго-западе моря. Однако потенциал дальнейшего расселения краба в Баренцевом море остается весьма высоким. Прогностические оценки показывают, что его ареал может увеличиться в два раза за счет северо-западных районов Баренцева моря и прибрежных акваторий арх. Шпицберген.

Похолодание будет способствовать дальнейшей экспансии краба в западном направлении и увеличению его численности в традиционных районах обитания. При потеплении придонных слоев экспансия замедлится.

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