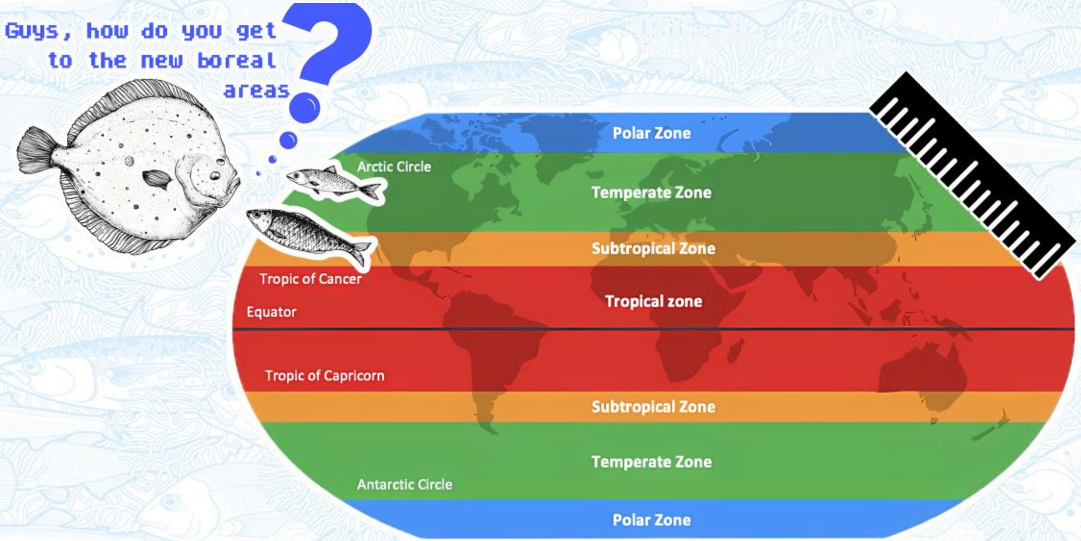
An overview of Pacific Arctic marine fauna borealization and the novel approach for process quantification



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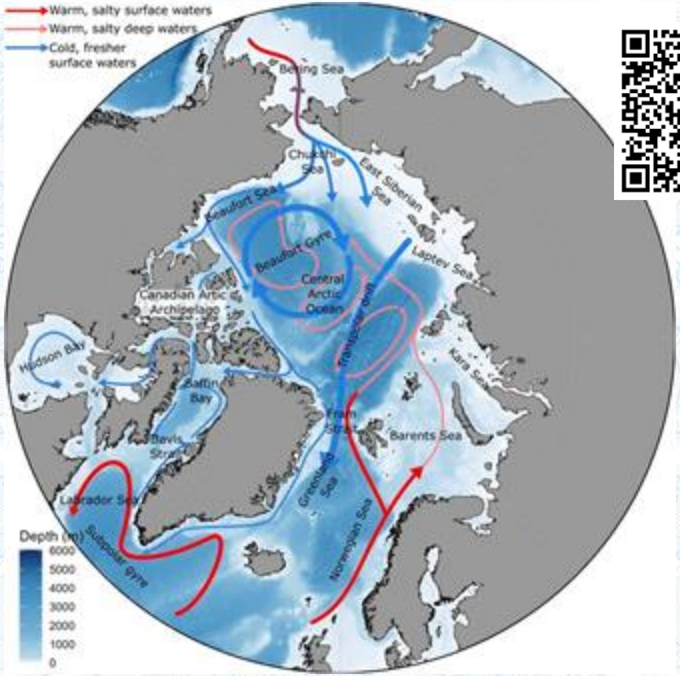
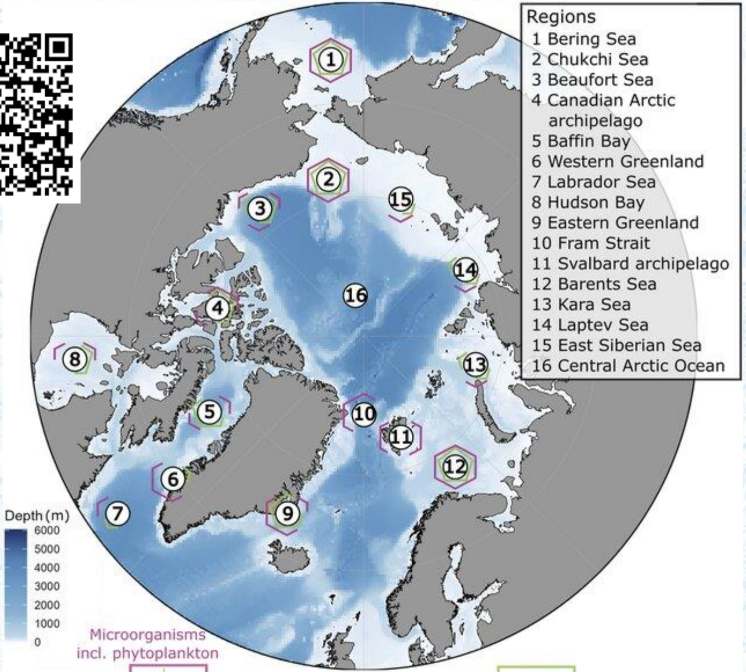
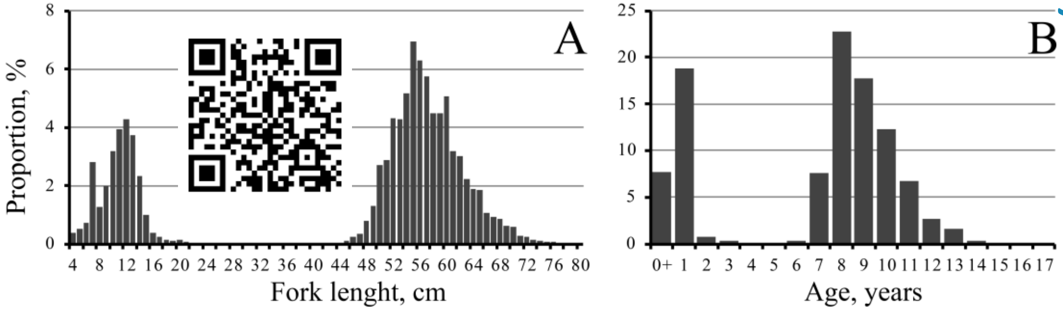




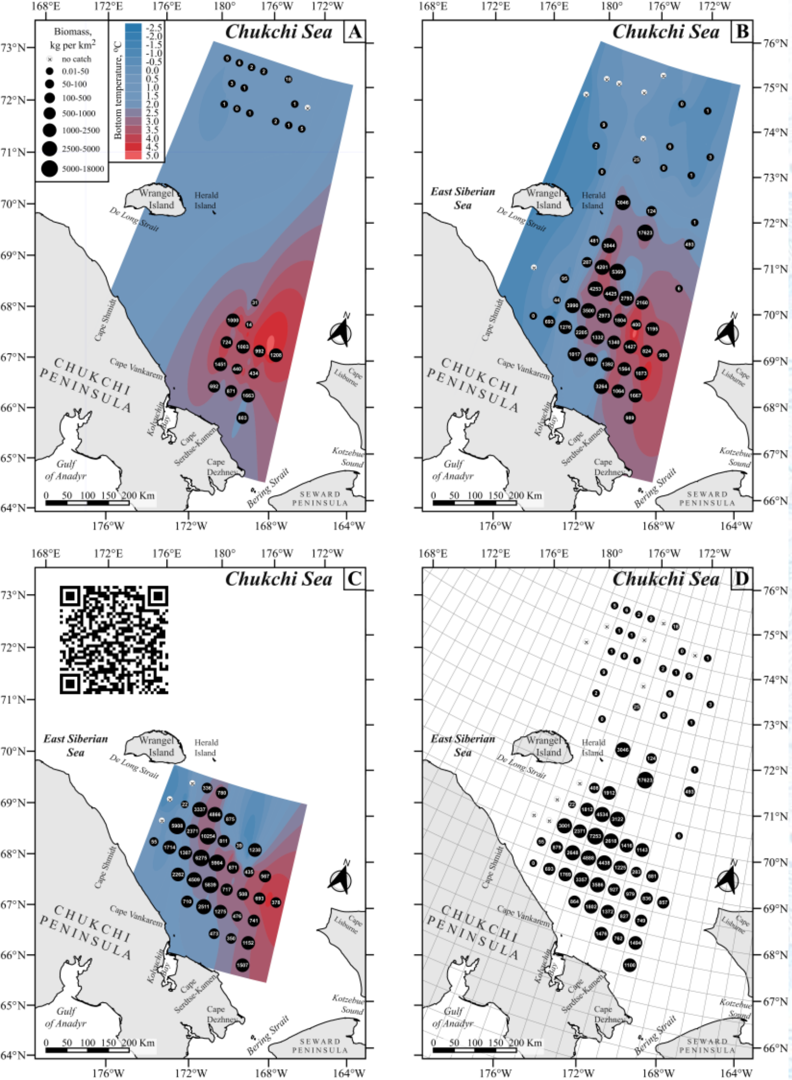
Source:

Husson B, Bluhm BA, Cyr F, Danielson SL, Eriksen E, Fossheim M, Geoffroy M, Hopcroft RR, Ingvaldsen RB, Jørgensen LL, Lovejoy C, Meire L, Mueter F, Primicerio R and Winding M (2024)
Borealization impacts shelf ecosystems across the Arctic.
Front. Environ. Sci. 12:1481420.
doi: 10.3389/fenvs.2024.1481420

In general, **borealization** can be defined as a process of Arctic and sub-Arctic ecosystem modification with acquiring features typical of boreal ecosystems (in abiotic and biotic components). Boreal species of many functional groups shown northward shifts into the Arctic, driven by local habitat modifications and advection of warm water and associated species from lower latitudes.



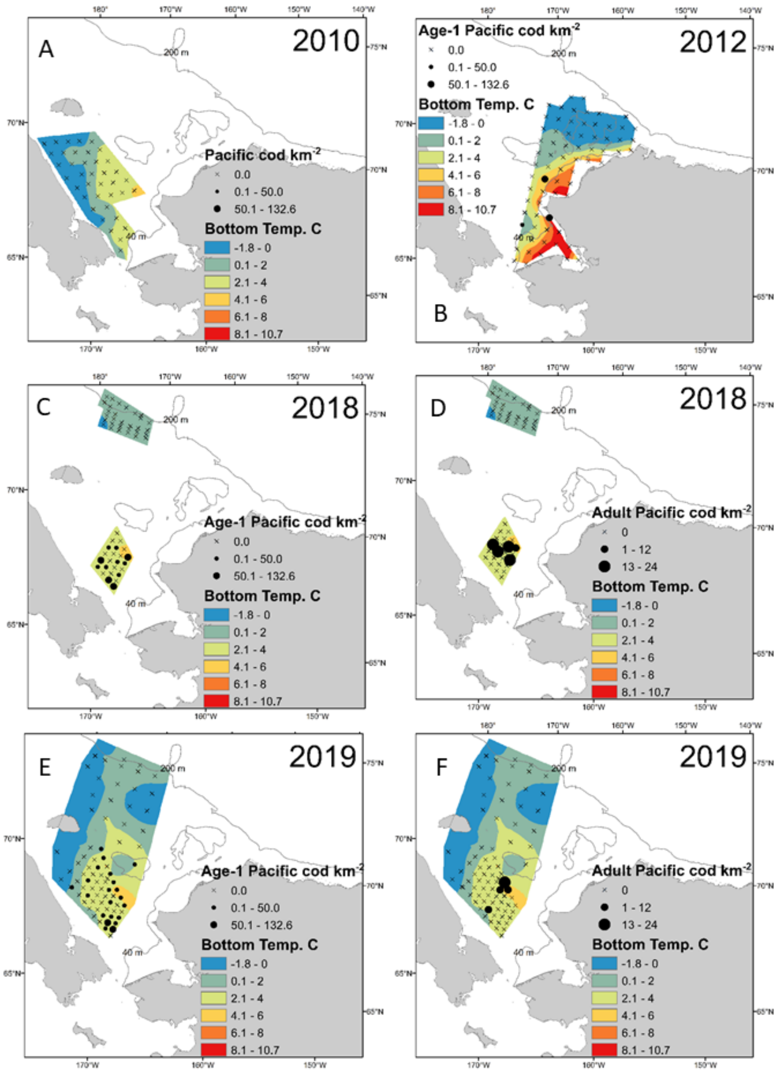
The average multi-annual size (A) and age (B) compositions of **walleye pollock** in bottom trawl catches in the western Chukchi Sea, 2018–2020



Spatial distribution of bottom temperatures and relative abundance of walleye pollock (kg/km²) in the western Chukchi Sea in 2018 (A), 2019 (B), 2020 (C), and averaged data for 2018–2020 (D).

Source:

- Maznikova O.A., Emelin P.O., Sheibak A.Yu., Nosov A.M., Orlov A.M. 2022. Can an invader support commercial fishing? A case study of walleye pollock *Gadus chalcogrammus* in the western Chukchi Sea // Deep Sea Research Part II: Topical Studies in Oceanography. Vol. 207. 105222. DOI: 10.1016/j.dsr2.2022.105222
- Emelin P.O., Maznikova O.A., Benzik A.N., Sheibak A.Yu., Trofimova A.O., Orlov A.M. Invader's portrait: Biological characteristics of walleye pollock Gadus chalcogrammus in the western Chukchi Sea // Deep Sea Research Part II: Topical Studies in Oceanography (2022). Vol. 206. 105211. DOI: 10.1016/j.dsr2.2022.105211



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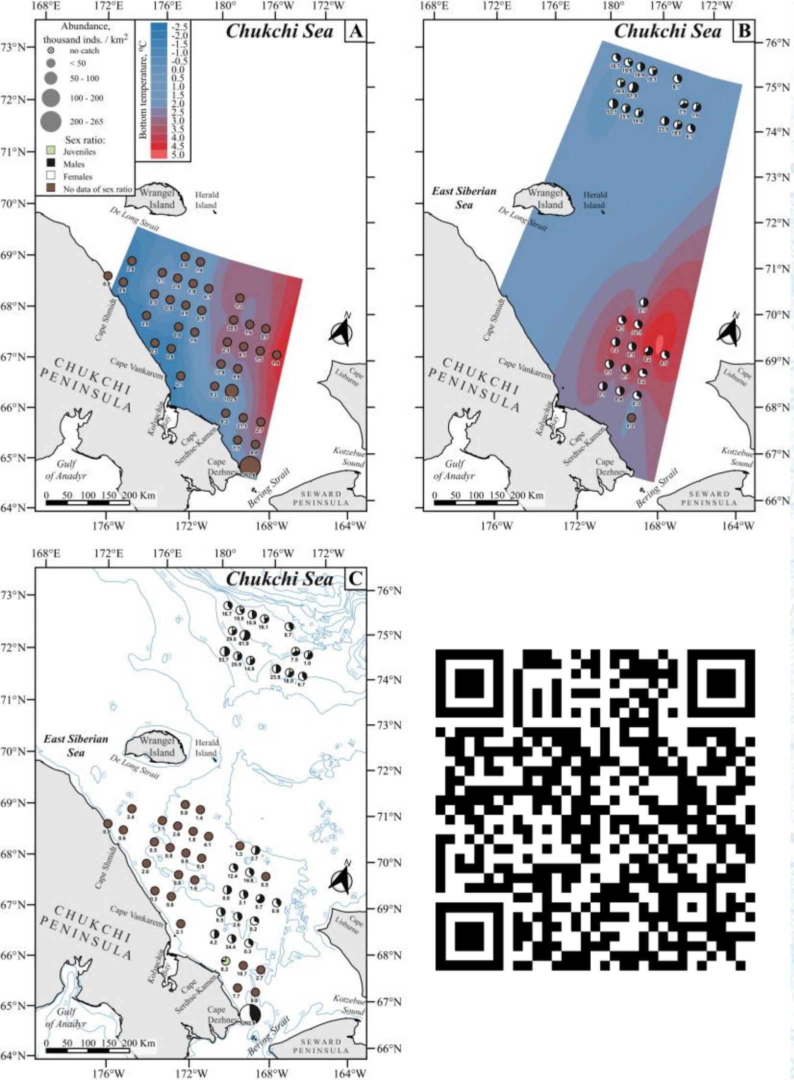
Distribution and catch per unit effort of juvenile (age-1) and adult **Pacific cod** in large-mesh benthic trawl in the Chukchi Sea: (A) Age-1s and adults in 2010; (B) Age-1s in 2012; (C) Age-1s in 2018; (D) Adults in 2018; (E) Age-1s in 2019; (F) Adults in 2019.

Source:

Cooper D.W., Cieciel K., Copeman L., Emelin P.O., [et.al.]. 2023. Pacific cod or tikhookeanskaya treska (*Gadus macrocephalus*) in the Chukchi Sea during recent warm years: Distribution by life stage and age-0 diet and condition // Deep Sea Research Part II: Topical Studies in Oceanography. Vol. 208. 105241.
DOI: 10.1016/j.dsr2.2022.105241



Spatial distribution of bottom temperatures and relative abundance of **polar cod** in the Chukchi Sea (thousand inds./km²) based on results of bottom trawl surveys: (A) – 2010; (B) – 2018; (C) – averaged data.

Source:

Maznikova O.A., Emelin P.O., Baitalyuk A.A., Vedishcheva E.V., Trofimova A.O., Orlov A.M. Polar cod (*Boreogadus saida*) of the Siberian Arctic: Distribution and biology // Deep Sea Research Part II: Topical Studies in Oceanography. 2023. Vol. 208. 105242.

DOI: 10.1016/j.dsr2.2022.105242

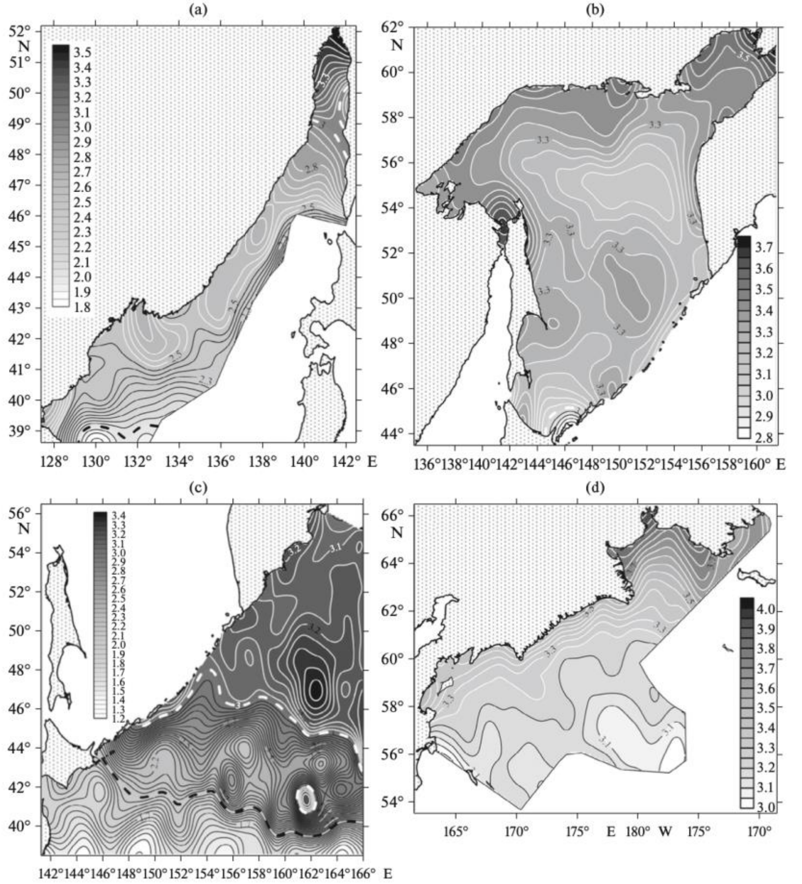


Fig. 2. Latitudinal zoning of epipelagic region: (a) northwestern Sea of Japan; (b) Sea of Okhotsk; (c) Pacific waters of Kamchatka and Kuril Islands; (d) western Bering Sea. Vertical scale is gradation of changes in index of latitudinal zoning (ILZ), isolines are boundaries between areas with identicql ILZs. White dashed line is boundary between high- and low-boreal subzones, and black dashed line is boundary between boreal and tropical latitudinal zones.

Index of latitudinal zoning (ILZ)

Source:

Ivanov, O.A., Sukhanov, V.V. Biogeographic Zoning of Russia's Far Eastern Seas and Adjacent Waters Based on Nekton Trawling Samples.
Oceanology 57, 817–827 (2017).
https://doi.org/10.1134/S0001437017050083

Biogeographical index, implemented by Oleg A. Ivanov and Vitaliy V. Sukhanov shown prospective results for biogeographic zoning of Russia's Far Eastern Seas and adjacent waters.

Other papers in English:

Sukhanov V.V., Ivanov O.A.A New Approach to Biogeographical Subdivision // Russian J. Mar. Biology. 2009. Vol. 35, № 1.P. 79–86.
Ivanov O.A. Zoogeographic Subdivision of the North-Western Sea of Japan Based on Species Areas of Pelagic Nekton // Russian J. Mar. Biology. 2009. Vol. 35, № 1. P. 87–96.
Ivanov O.A. Zoogeographical Subdivision of the Pelagic Zone of the Sea of Okhotsk Based on Nekton Species Areas // Russian J. Mar. Biology. 2011. Vol. 37, № 4. P. 243–254.
Ivanov O.A. Zoogeographical Subdivision of the Pelagic Zone of the Western Bering Sea Based on Nekton Species Ranges // Russian J. Mar. Biology. 2013. Vol. 39, № 6. P. 392–402.

Index of latitudinal zoning (ILZ)

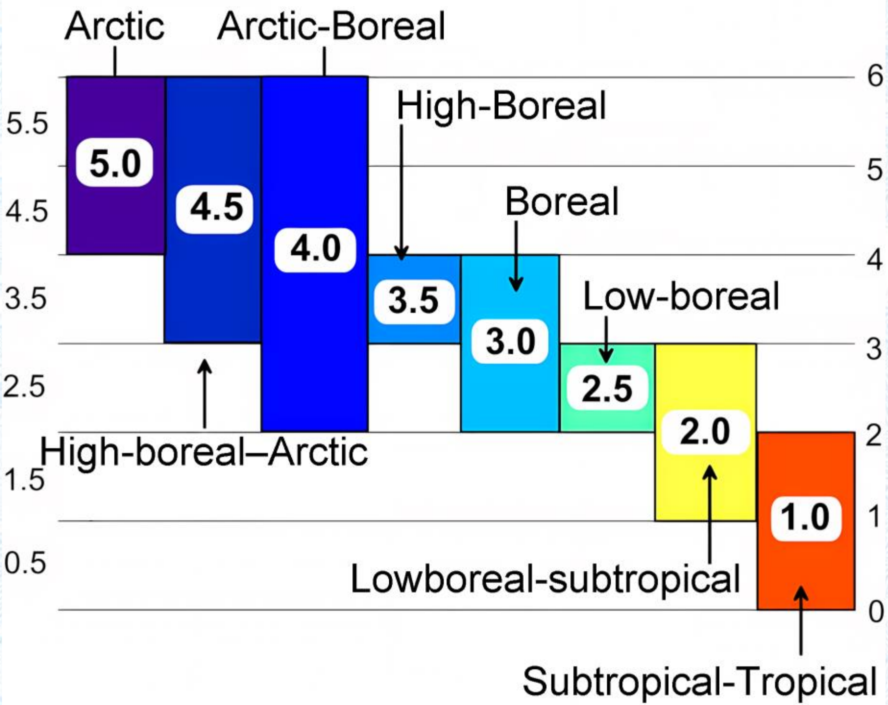
Authors conclusions (Ivanov, O.A., Sukhanov V.V):

Features of the latitudinal zoning method:

1. The spatial distribution pattern of biogeographic areas is based on a continual approach, which represents biogeographic parameters as continuous fields. This agrees with the widely accepted viewpoint of G. Leibnitz that nature does not take leaps (*natura non facit saltus*) and corresponds to the fundamental principle of biospheric organization: continuality of natural boundaries.
2. Use of software to create maps for continuous biogeographic fields makes it easy to vary the scale and level of detail in zoning maps. As a result, the internal structure of a biogeographic element can be studied. Variations in the distribution pattern of biogeographic areas (dynamic biogeography) can be easily revealed for different time periods (daily, seasonal, and annual processes) and different spaces (within a chosen natural complex).
3. Determination of the boundaries between biogeographic areas is not subjective, which can often be seen with conventional zoning approaches. The boundaries are constructed by computer programs as a result of statistical and cartographical analysis of biogeographic data.

The Sea of Okhotsk and the western Bering Sea have been assigned to the same high-boreal latitudinal subzone. The epipelagic region of the northwestern Sea of Japan and Russia's Pacific waters is assigned to the low-boreal subzone. With respect to the chorological structure of fauna, the mesopelagic region of all areas corresponds to the low-boreal latitudinal sub-zone. The distribution and direction of ILZ isolines correspond to real relatively stable elements of biotopes (water masses, currents, frontal zones, eddies, and rings).

Calculation method for the Index of latitudinal zoning (ILZ)



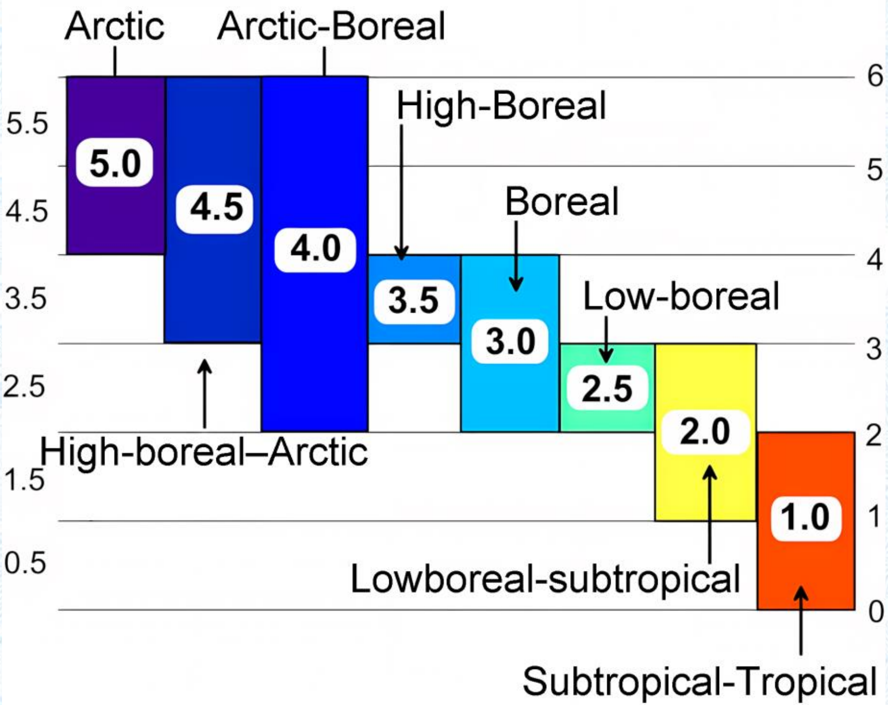
Range scale of indexes of latitudinal zoning (ILZ). Mean ranges of subzones are given on left, and boundaries between subzones are given on right in units of ranges

Three planetary latitudinal zones are usually specified in the Northern Hemisphere: Arctic Zone, Boreal zone, and tropical zone. Each of them includes two subzones: Arctic and Sub-Arctic, Boreal and Low-boreal, and subtropical and tropical (or equatorial).

The procedure of converting area descriptions into a numerical scale was as follows:

- The subzone was chosen as an indivisible minimal area.
- The boundaries between subzones were allocated ranges from 0 to 6. They increased from tropical (the range of the equator is 0) to northern latitudes (the range of the North Pole is 6).

Calculation method for the Index of latitudinal zoning (ILZ)



Range scale of indexes of latitudinal zoning (ILZ). Mean ranges of subzones are given on left, and boundaries between subzones are given on right in units of ranges

If a species' range is restricted to one of the latitudinal subzones, its latitudinal zonality index corresponds to the rank of a particular subzone.
For example, for a species with a high-boreal type of range this index is 3.5, and for a low-boreal species it is 2.5.
If the range of a species covers several latitudinal subzones or zones, in this case the index of its latitudinal zonality is determined as the arithmetic mean of all ranks of the subzones where the species was observed. For example, for species with an arcto-boreal type of range the latitudinal zonality index was (2.5 + 3.5 + 4.5 + 5.5 + 5.5)/4 = 4.0, and for species with a low-boreal-subtropical type of range - (1.5 + 2.5)/2 = 2.0.

For each geographical point, ILZ of the sample is an arithmetic mean of the zone code values for each species:

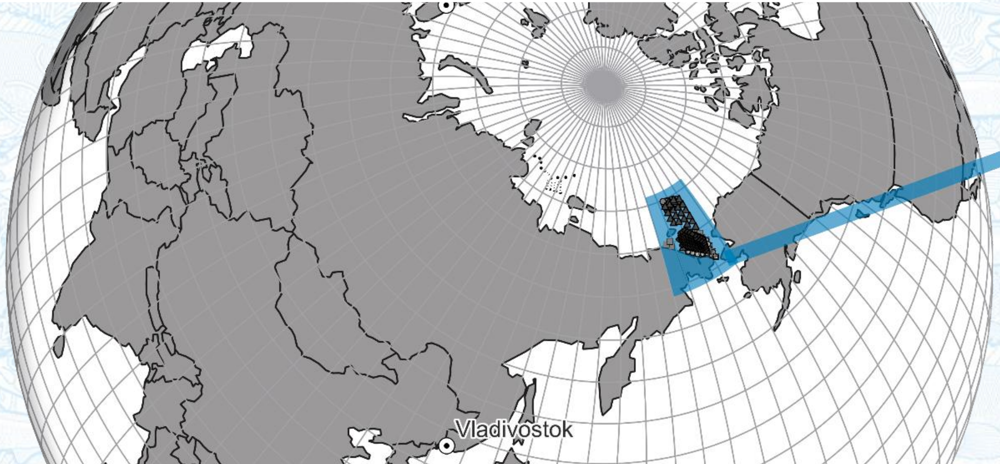
$$ILZ = \frac{\sum(S_1 + S_2 + \cdots + S_n)}{n}$$

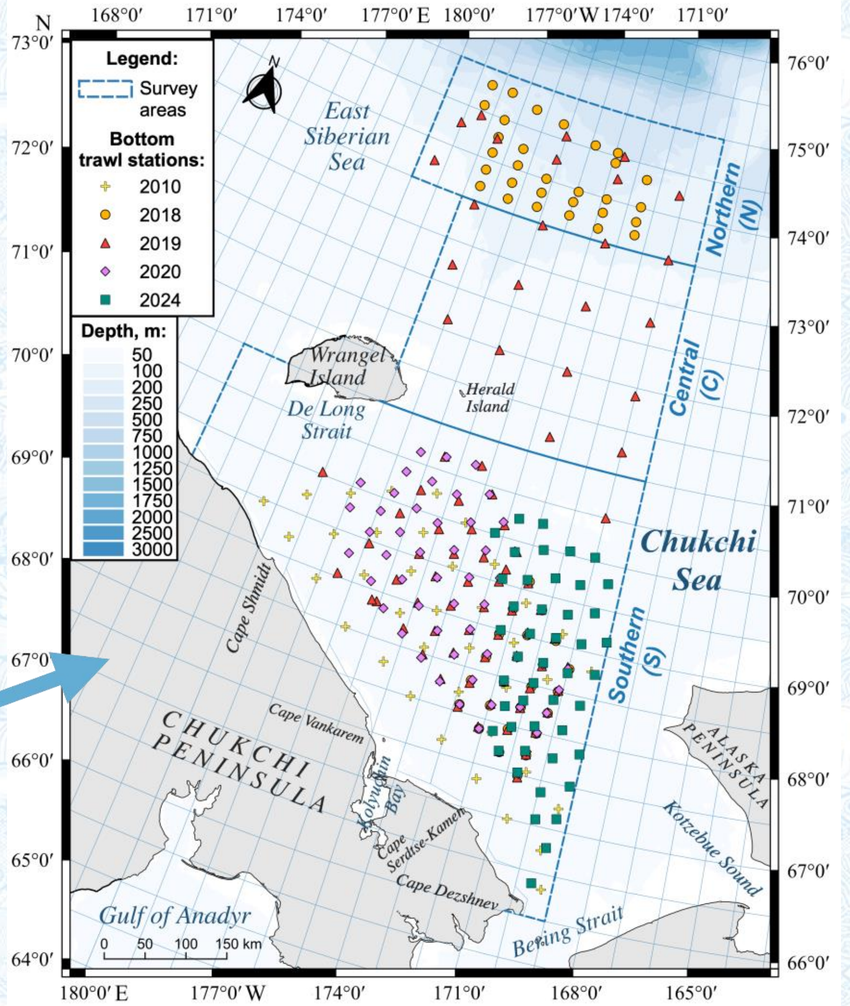
Where S_1 – *Zone code for species 1*, S_2 – *Zone code for species 2, etc., n – species richness of sample*

Year	Number of hauls	Gear	Depth range, m	Area surveyed, thousand km²
2010	38	*Bottom trawl (BT) "DT 27.1/24.4"*	45–57	80,8
2018	54		43–270	56,82
2019	80		27–267	119,16
2020	62		43–68	85,37
2018-2020	*196*		*27–270*	*153,6*
2024	46		*35-53*	*49,1*

Survey area subdivision

Southern area (S): data of 2010, 2018-2020, 2024 for trawl hauls <71°N;
Central area (C): data of 2019 for trawl hauls located between 71° and 73°30′N;
Northern area (N): data of 2018 and 2019 for trawl hauls > 73°30′N.





Step 1. Proof-check of the species' list records. Searching for range information for all nekton species and determining ranks for the Index of latitudinal zoning (ILZ)

Rank for ILZ	Latitude zone	Zoogeographic pattern	Short description of pattern
	Source: Ivanov, Sukhanov, 2017	Source: Marine Fishes of the Arctic Region (Mecklenburg et al. 2018*)	
5	Arctic	Arctic	continuously distributed and reproducing in Arctic waters
4.5	High-boreal - Arctic	Mainly Arctic	commonly distributed in Arctic waters but also occurring in adjacent boreal waters
4	Arctic-Boreal	Arctic-Boreal	distributed and reproducing in both Arctic and boreal waters
3.5	High-boreal	Mainly Boreal	characteristic of boreal waters and common also in the border areas of the Arctic Region
3	Boreal	Boreal	distributed and reproducing in boreal waters and rare in the Arctic Region

*Mecklenburg, C.W., A. Lynghammar, E. Johannesen, I. Byrkjedal. J.S. Christiansen, A.V. Dolgov, O.V. Karamushko, T.A. Mecklenburg, P.R. Møller, D. Steinke, and R.M. Wienerroither. 2018. Marine Fishes of the Arctic Region. Conservation of Arctic Flora and Fauna, Akureyri, Iceland. ISBN 978-9935-431-69-1.

Results: Species composition & richness

Familia	Number of species	First records for the WCS	% of new records
Agonidae	6	3	50%
Ammodytidae	1		
Clupeidae	1		
Cottidae	17	5	29%
Gadidae	4		
Hemitripteridae	2		
Liparidae	5	2	40%
Myctophidae	1	1	100%
Octopodidae	2		
Osmeridae	2		
Pleuronectidae	8	1	13%
Psychrolutidae	2	2	100%
Rajidae	1	1	100%
Stichaeidae	5	1	20%
Zoarcidae	9	4	44%
Total	**66**	**20**	**30%**

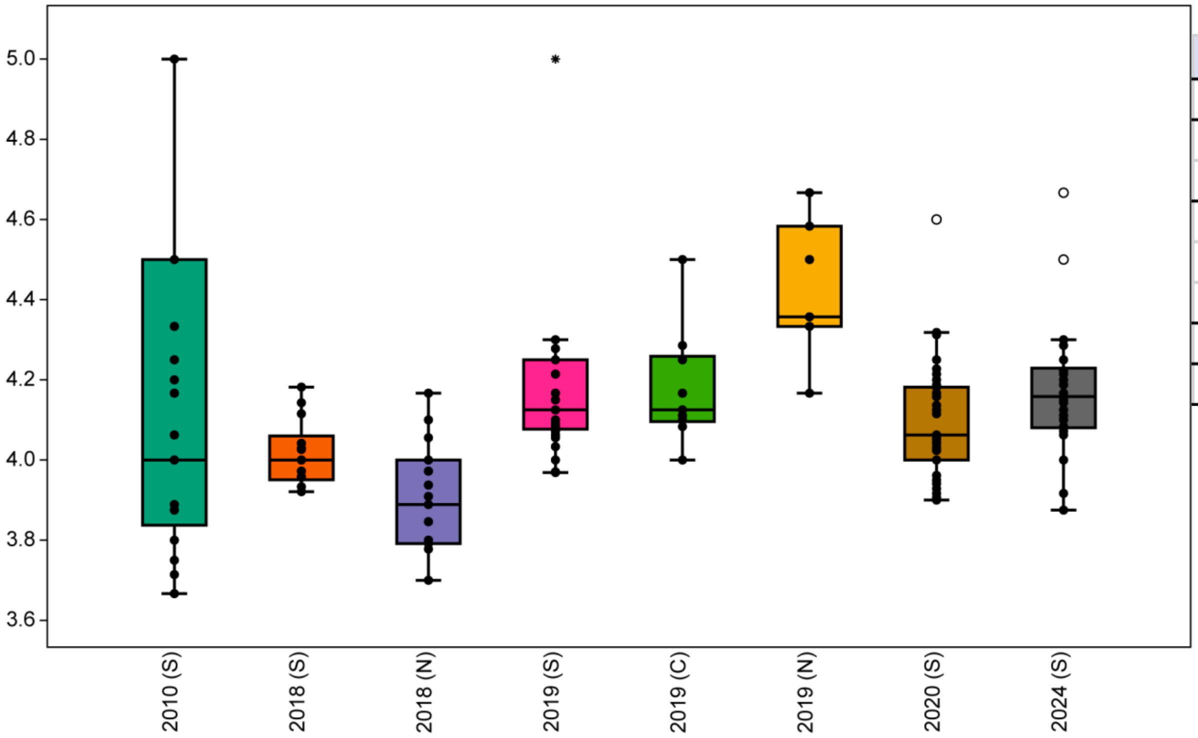
Taxonomical structure of nekton in the WCS:

3 classes, 15 families, containing

- 63 species of ray-finned fishes (Actinopterygii);
- 1 species of skates (Chondrichthyes)
- 2 species of squids and octopuses (Cephalopoda)

Rank for ILZ	Zoogeographic pattern	Number of species recorded for the first time
5	Arctic	3
4.5	Mainly Arctic	1
4	Arctic-Boreal	2
3.5	Mainly Boreal	3
3	Boreal	11

Step 2. Calculation of the Index (ILZ) % basic statistics

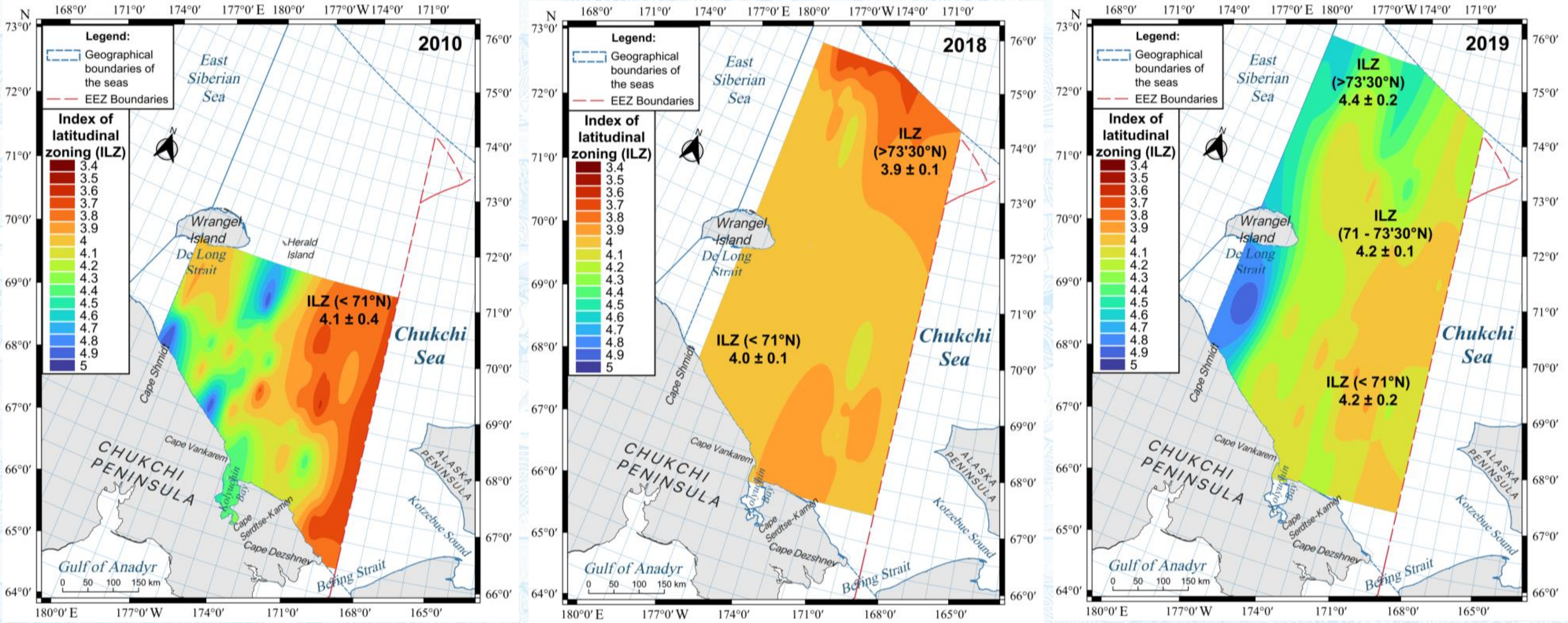


Year (Area)	min	max	avg	SD
2010 (<71°N)	3.7	5.0	**4.1**	0.4
2018 (<71°N)	3.9	4.2	**4.0**	0.1
2018 (> 73°30'N)	3.7	4.2	**3.9**	0.1
2019 (<71°N)	4.0	5.0	**4.2**	0.2
2019 (71°-73°30'N)	4.0	4.5	**4.2**	0.1
2019 (> 73°30'N)	4.2	4.7	**4.4**	0.2
2020 (<71°N)	3.9	4.6	**4.1**	0.1
2024 (<71°N)	3.9	4.7	**4.2**	0.2

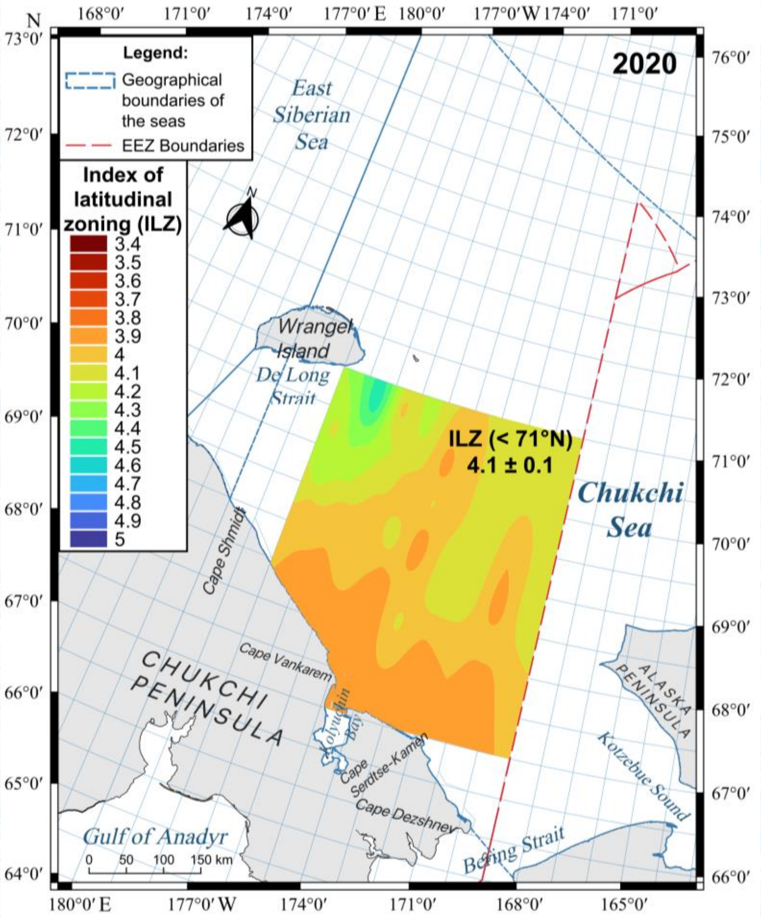
Results:

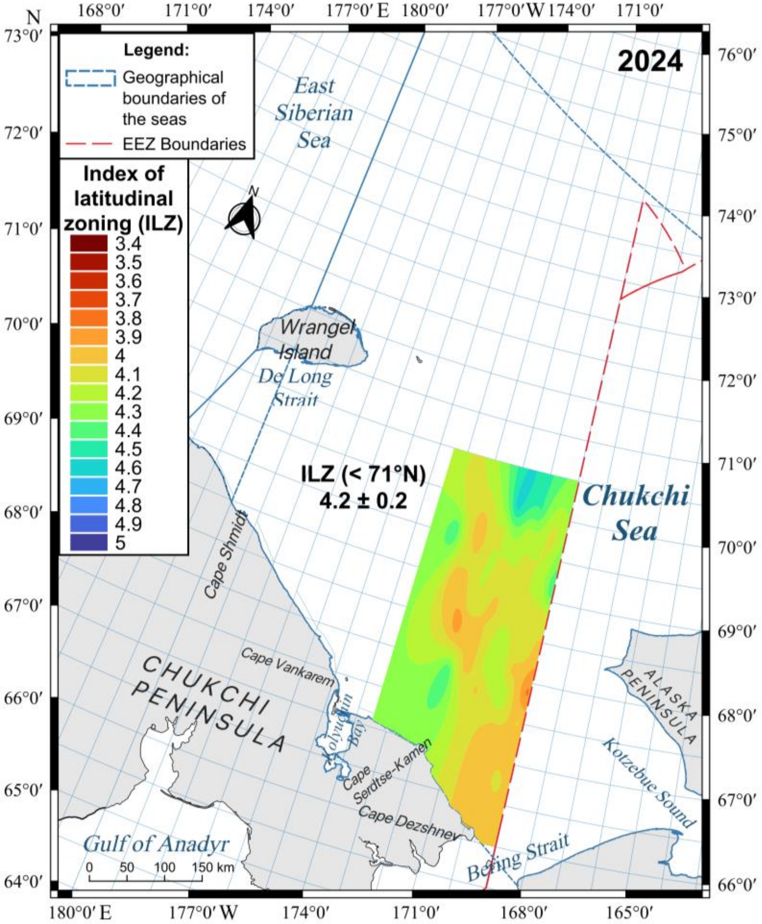
- For the southern part of the Chukchi Sea, **no** significant **differences** between the values of the **ILZ** were observed.
- Strong effects of outliers!

Step 3. Mapping the distribution of ILZ (Kriging interpolation)



Step 3. Mapping the distribution of ILZ

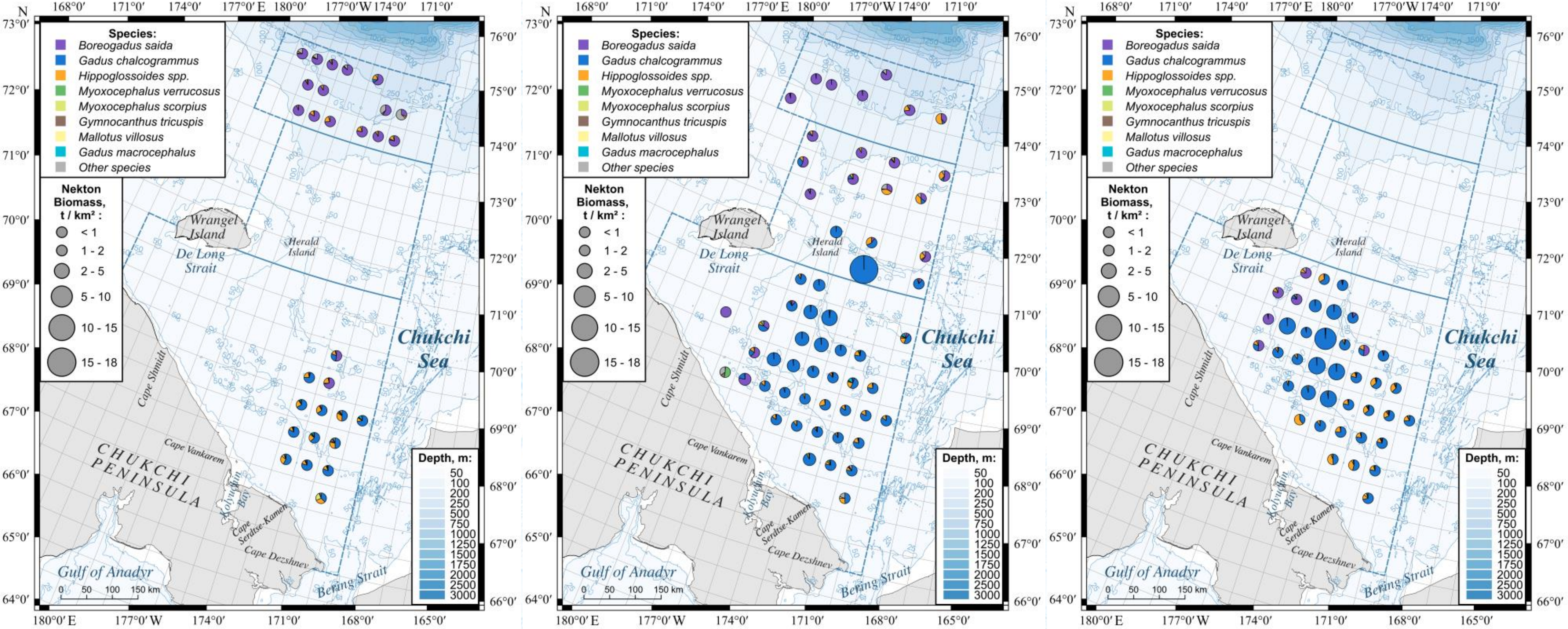




???

The results are meaningless

Nekton biomass composition during 2018-2020



2018 2019 2020

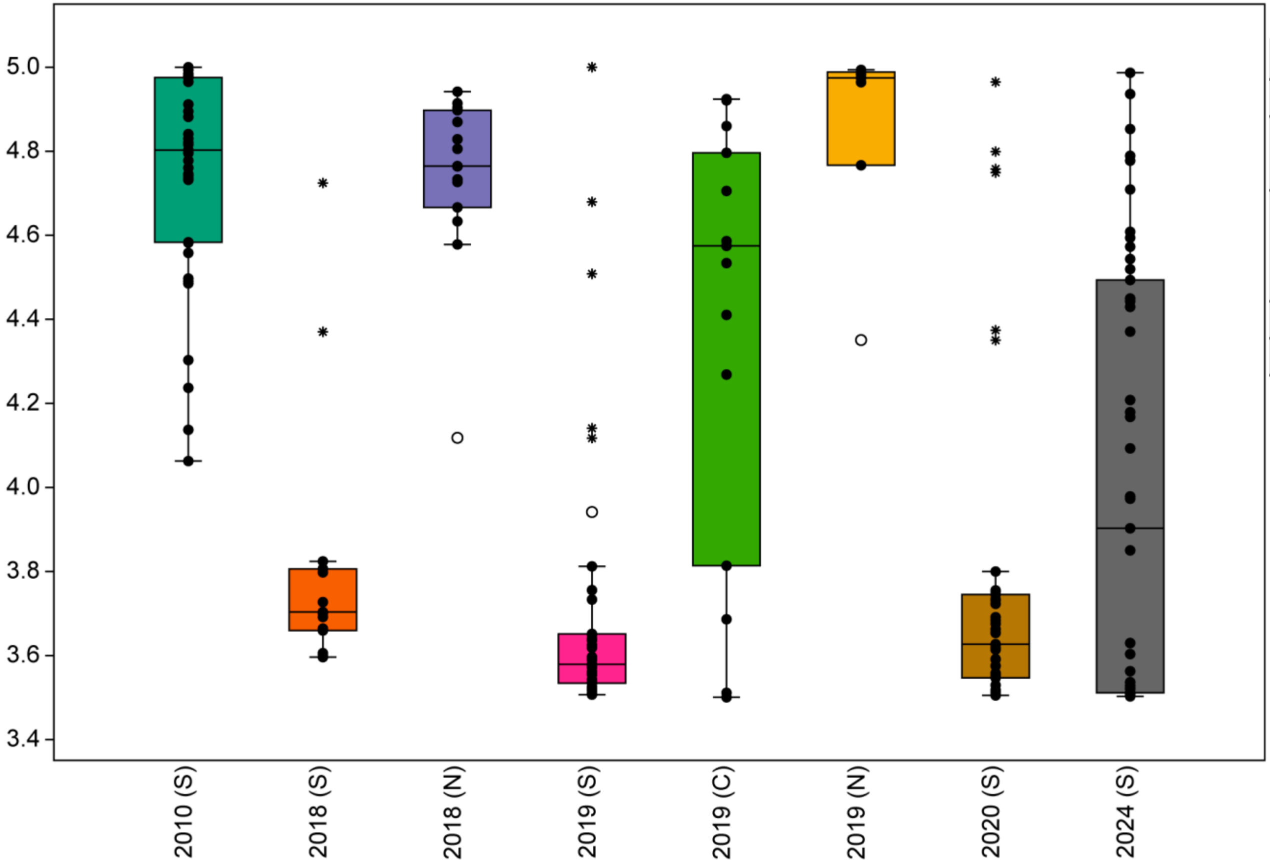
New step (1). Don't worry about the previous results!
We had to implement the new version of index with an added statistical weight parameter – Weighted Index of Latitudinal Zoning (WILZ).

For each geographical point, **W**ILZ of the sample is an *weighted* (by biomass density, kg/km²) *arithmetic mean* of the zone code values for each species:

$$WILZ = \frac{\sum(S_1 \cdot B_1 + S_2 \cdot B_2 + \cdots + S_n \cdot B_n)}{\sum B}$$

Where S_1 – *Zone code for species 1*, S_2 – *Zone code for species 2, etc.*,
B_1 – *biomass density for species 1*, B_2 – *biomass density for species 2, etc.*
$\sum B$ – *Total density of sample biomass.*

New step (2). Calculation of the weighted Index (WILZ) % basic statistics

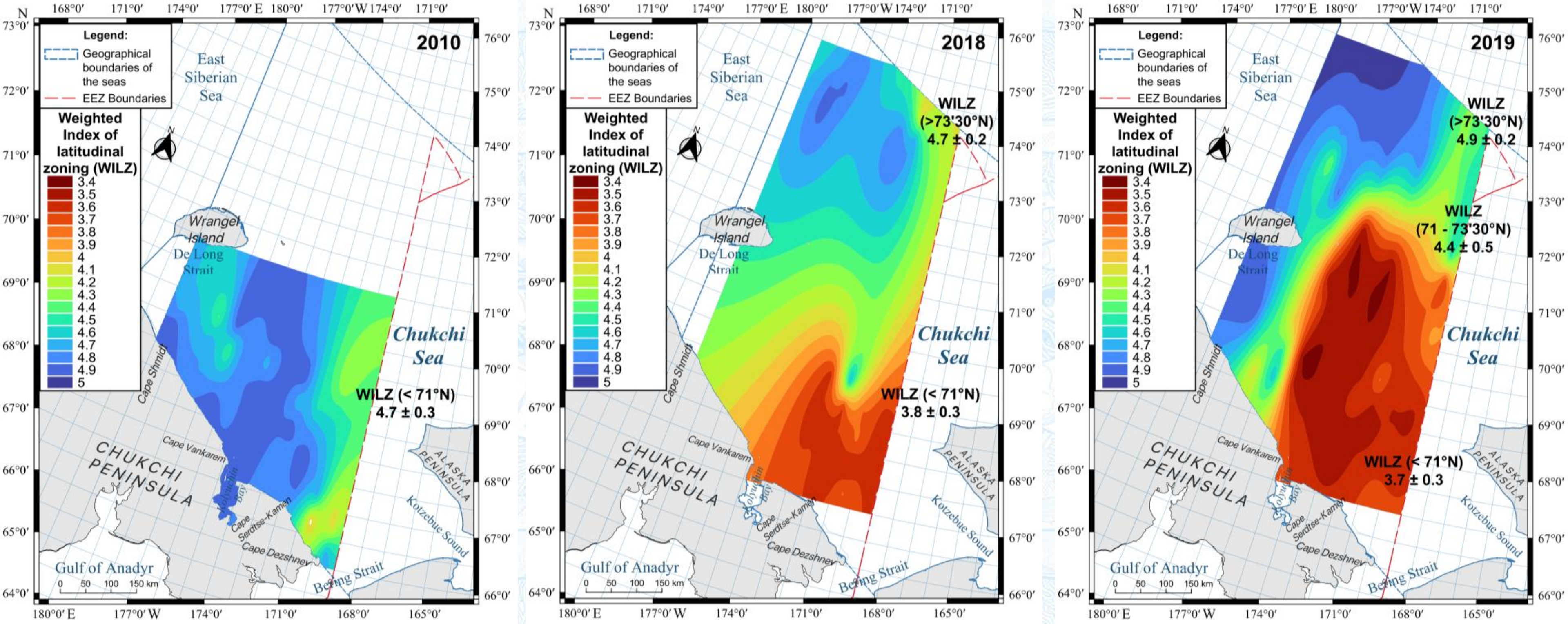


Year (Area)	min	max	avg	SD
2010 (<71°N)	4.1	5.0	**4.7**	0.3
2018 (<71°N)	3.6	4.7	**3.8**	0.3
2018 (> 73°30'N)	4.1	4.9	**4.7**	0.2
2019 (<71°N)	3.5	5.0	**3.7**	0.3
2019 (71°-73°30'N)	3.5	4.9	**4.4**	0.5
2019 (> 73°30'N)	4.4	5.0	**4.9**	0.2
2020 (<71°N)	3.5	5.0	**3.8**	0.4
2024 (<71°N)	3.5	5.0	**4.0**	0.5

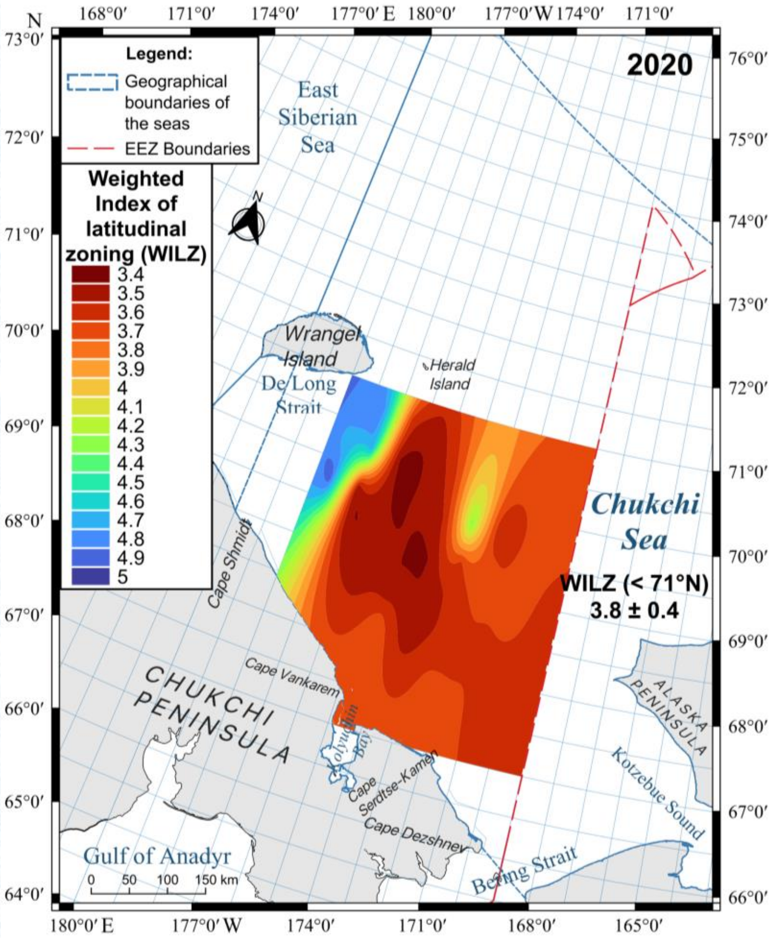
Correct results:

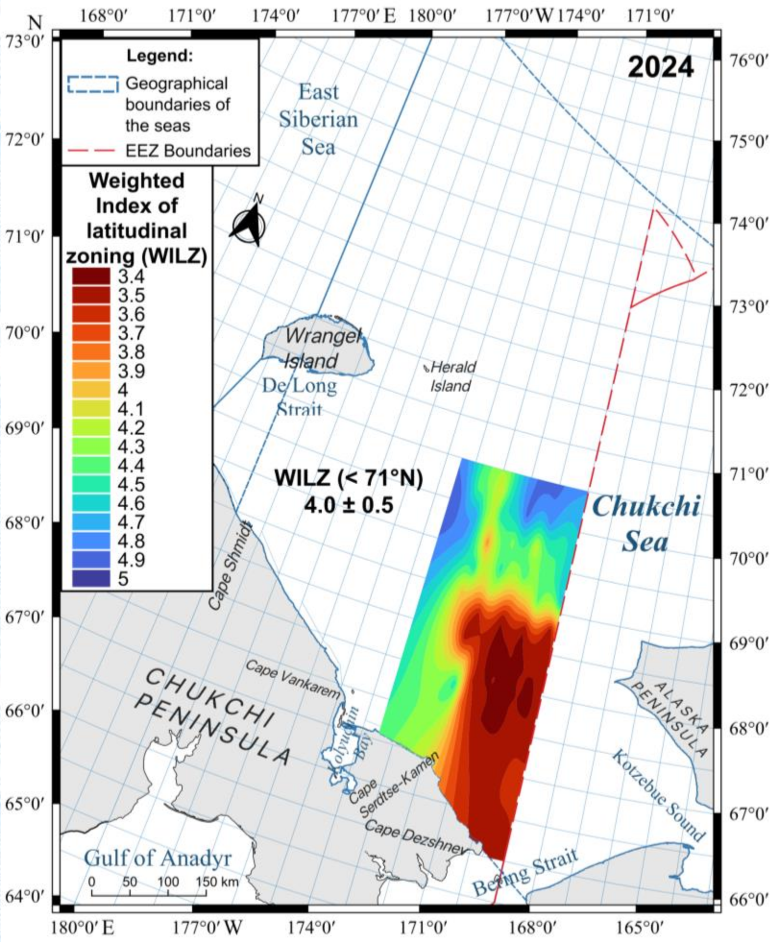
- For the southern part of the Western Chukchi Sea, **there was** significant **decrease** of WILZ from 2010 to 2018-2020 and 2024.
- Significant differences among the geographic parts

New step (3). Mapping the distribution of WILZ (Kriging interpolation)



Mapping the distribution of WILZ





Some preliminary thoughts:

1. **W**eighted **I**ndex of **L**atitudinal **Z**oning could be used as "*quantitative measure" of faunal shifts* regarding to ***borealization***.
2. **New index is *reflects the energy processes*** in the biological community better, since the statistical weight is the species *biomass density* and it is less sensitive to low species richness
3. A robust index requires clear criteria for determining whether each species belongs to a ***specific zoogreographical pattern***.

What we are currently working on and where we can cooperate?

- We are currently processing data from bottom trawl surveys of the western part of the Bering Sea (2003-2024).
- We intend to compare the results with data from pelagic trawl surveys of the same areas (i.e. the Chukchi and Bering Seas).
- A search for statistical relationships between the index and environmental parameters will be conducted, and modelling will be performed.

We can collaborate on using this index to assess borealization using nekton or plankton data for other adjacent areas of the North Pacific or the similar area in the northern Atlantic.

Thank you for your attention!

If you have any questions, I will be glad to answer via e-mail:

emelin@vniro.ru

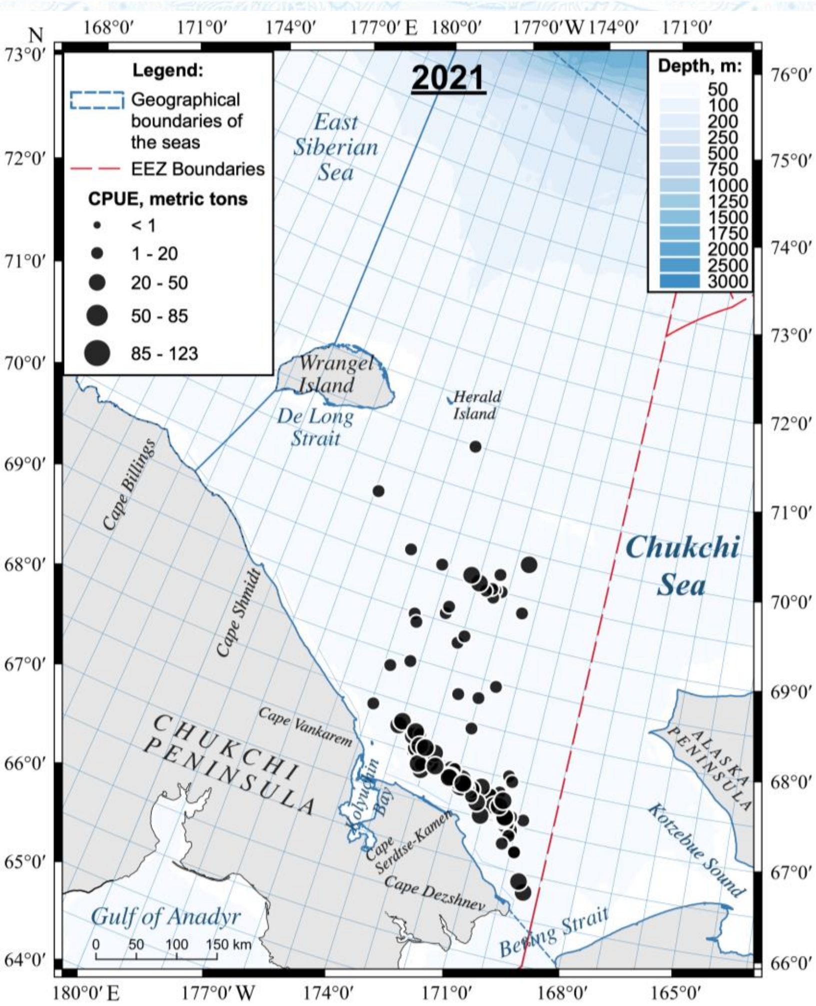
Link to my ResearchGate profile:
https://www.researchgate.net/profile/Pavel-Emelin

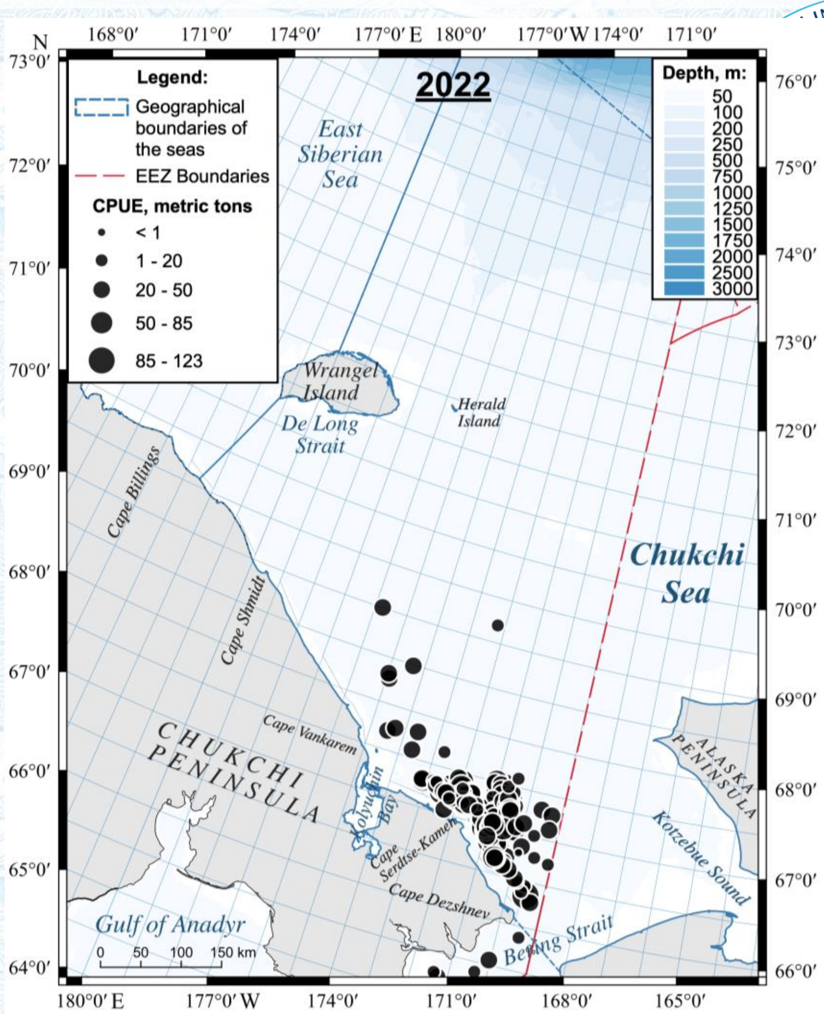
Acknowledgments

The author would like to express sincere gratitude to the colleagues from the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO, Moscow, Russia) and its Pacific branch (TINRO, Vladivostok, Russia) for their invaluable assistance with biological samplings. The author would also like to extend the deepest appreciation to the crews of RV "TINRO" and RV "Professor Levanidov" for their commendable support during the research cruises.

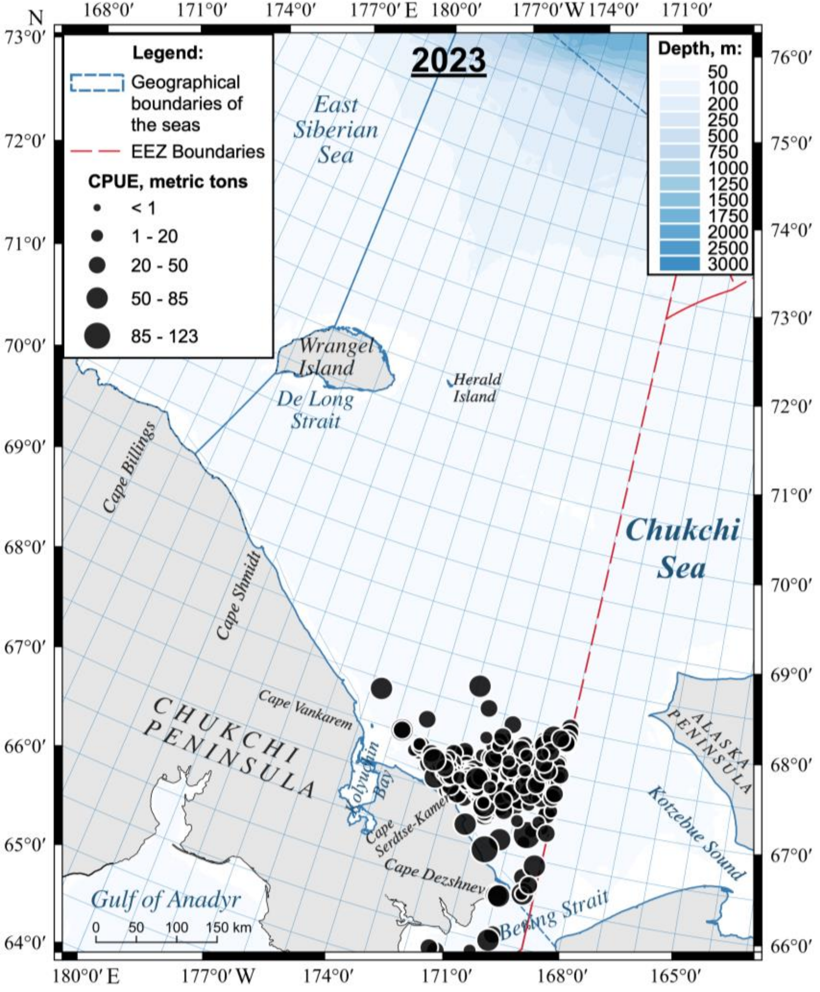
Supplementary slides for Q&A

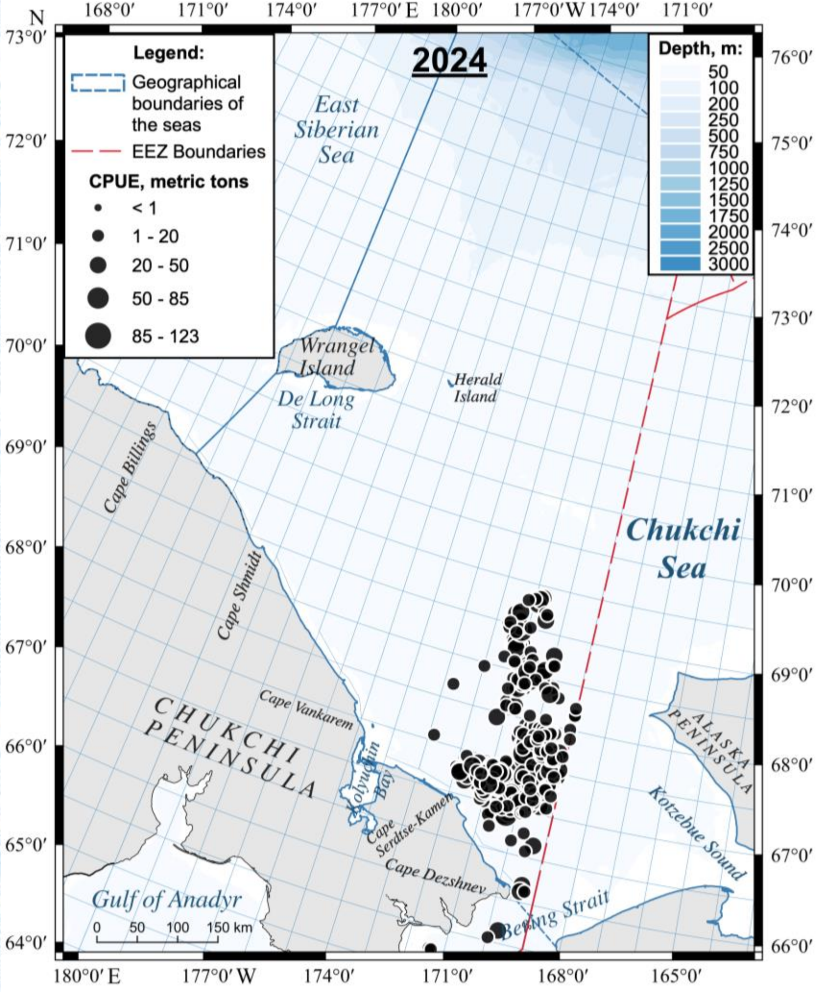
S1





Spatial distribution of catch per unit effort of the Chukchi Sea walleye pollock commercial fishery in 2021 and 2022





Spatial distribution of catch per unit effort of the Chukchi Sea walleye pollock commercial fishery in 2023 and 2024