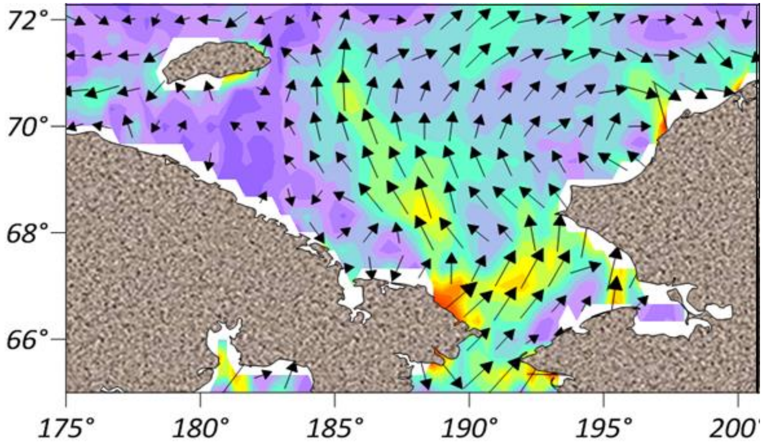
W3 HD/MEQ/FUTURE Workshop
Present and Future Pressures and Human Activities
in the Arctic Ocean and Pacific Gateways

Utilization of nutrients transported from the Bering Sea to the Chukchi Sea



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Goal: to determine paths and fate of the nutrients injected to the Chukchi Sea through Bering Strait and localization of concerned productivity

1. Introduction on water structure and circulation in the southern Chukchi Sea and the polar ecosystem bioproductivity

2. How to evaluate quantitatively fluxes of nutrients in an advective system

3. Dynamics of nutrient concentration in the flow of water from the Bering Sea after passing the Bering Strait (on example of phosphorus)

4. Localization of high-productive areas in the Chukchi Sea supported by imported nutrients in conditions of their strong and weak advection from the Bering Sea

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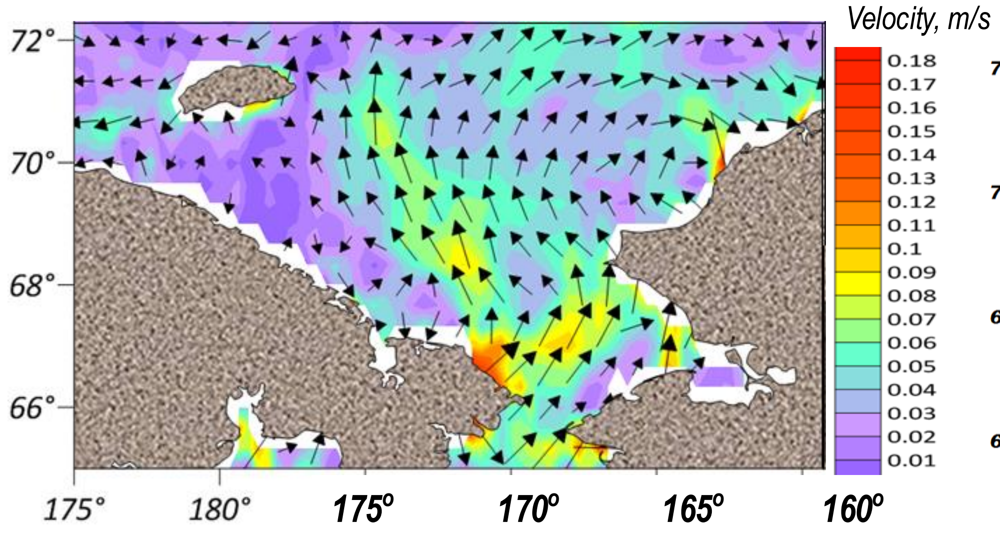
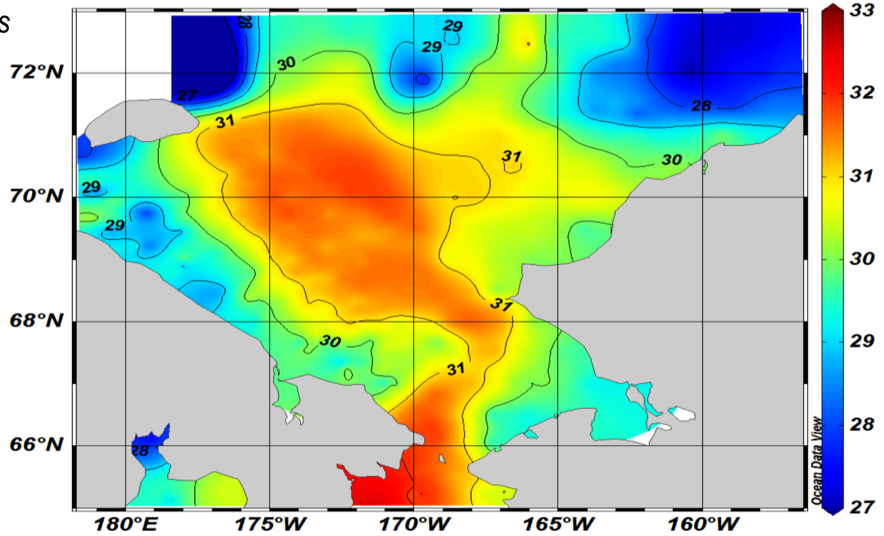
Water structure and circulation in the southern Chukchi Sea

Water flows in opposite directions are possible through the Bering Strait, but the northward ones prevail in summer. The flow along Alaska coast is stratified with rather warm and brackish water in the upper layer, whereas the flow through the middle and western parts of the strait is vertically mixed and therefore colder and saltier. Both flows are salted and reach with nutrients. After invasion into the Chukchi Sea, they propagate mostly in north-west direction; the warmer water – at the sea surface, and the colder water – in the subsurface layer that reaches bottom on shallows.

The opposite East-Siberian Current is weak in August-September though can reach the Bering Strait in cold seasons.



Mean climatic (1991-2020) scheme of water circulation at the surface of Chukchi Sea in September calculated by on-line model OSCAR (https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg)



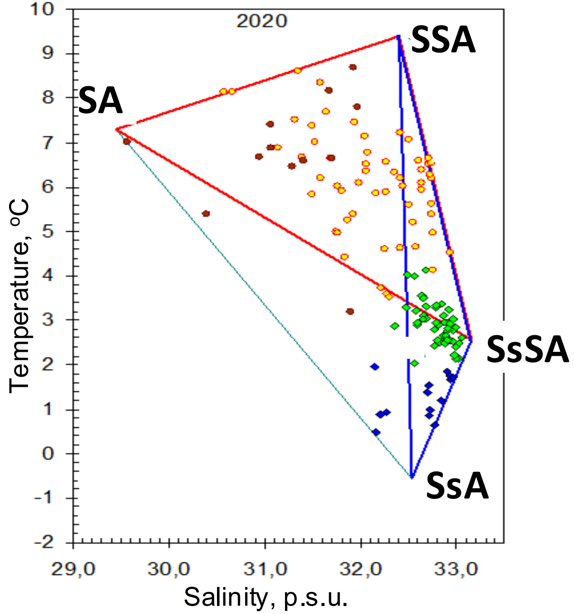
Sea surface salinity in the Chukchi Sea in August-September (averaged data of surveys conducted aboard TINRO research vessels in 2003-2020)

Water structure and circulation in the southern Chukchi Sea

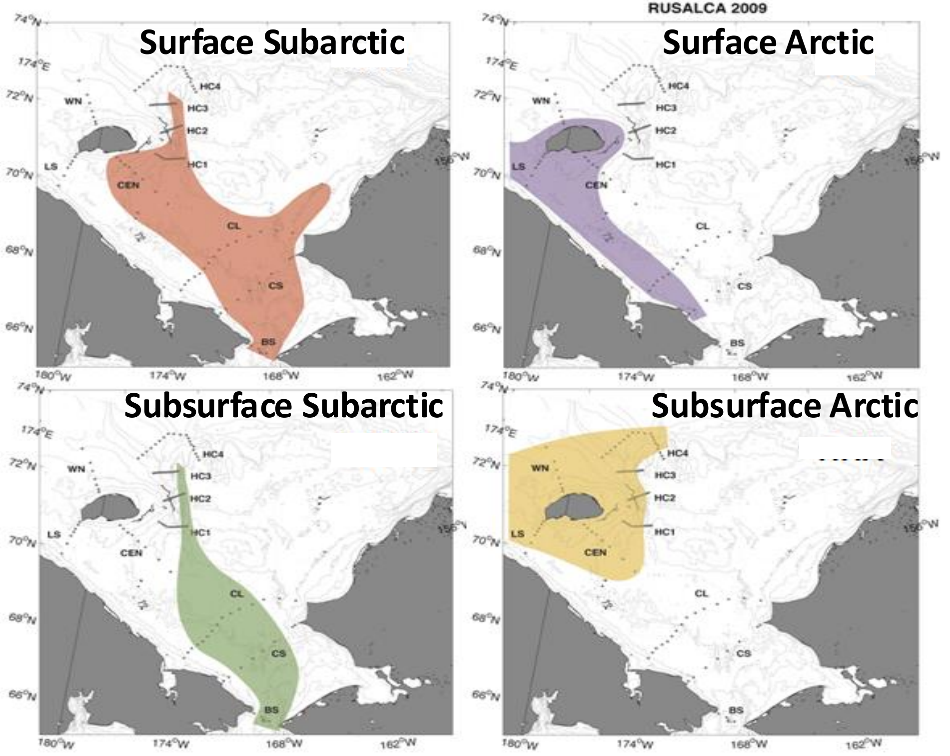
Recently the sea ice is absent in the southern Chukchi Sea in summer and relatively warm and brackish upper layer is formed, while the subsurface layer remains cold and relatively salt. So, 2 local water masses (Arctic waters) and 2 water masses originated from Bering Sea (Subarctic waters) are presented here in summer:

SA – Surface Arctic Water **SsA – Subsurface Arctic Water**

SSA – Surface Subarctic Water **SsSA – Subsurface Subarctic Water**



TS-diagram for temperature and salinity averaged by layers at each station of RV TINRO survey in the Chukchi Sea on August 26 – September 5, 2020

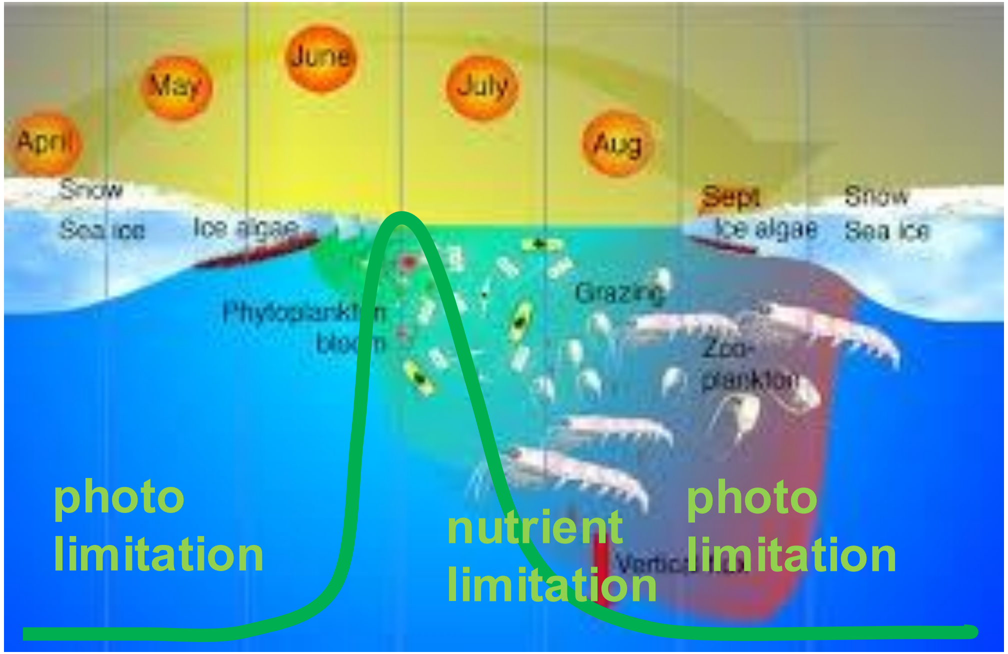


Cores of the main water masses in the southern Chukchi Sea by the data of RUSALCA survey in August 2009 [Pisareva et al., 2018]

Primary productivity in polar waters

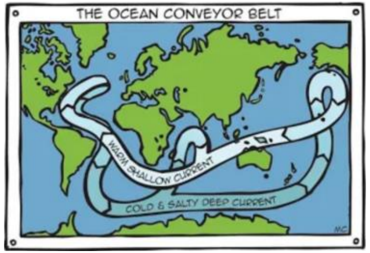
Sunlight, CO_2, H_2O and some other elements - nutrients are necessary for photosynthesis of new organic matter. The main nutrients are nitrogen, phosphorus, and iron (silicon and potassium for some species, as well). These nutrient elements are consumed for photosynthesis and growth of algae and return to mineral forms after destruction of organic matter.

Light availability is the main factor that limits bioproductivity in polar waters because of no density stratification. Only in a short polar summer, the stratification appears and keeps phytoplankton cells in the photic layer. Unfortunately, the upper layer is thin, its stock of nutrients is exhausted quickly, and the stratification prevents vertical exchange by nutrients. So, the summer bloom stops in several days because of nutrient limitation. That's why the polar seas are mostly low-productive, and even short prolongation of the summer bloom with additional delivery of nutrients can enhance significantly the productivity of marine ecosystem.



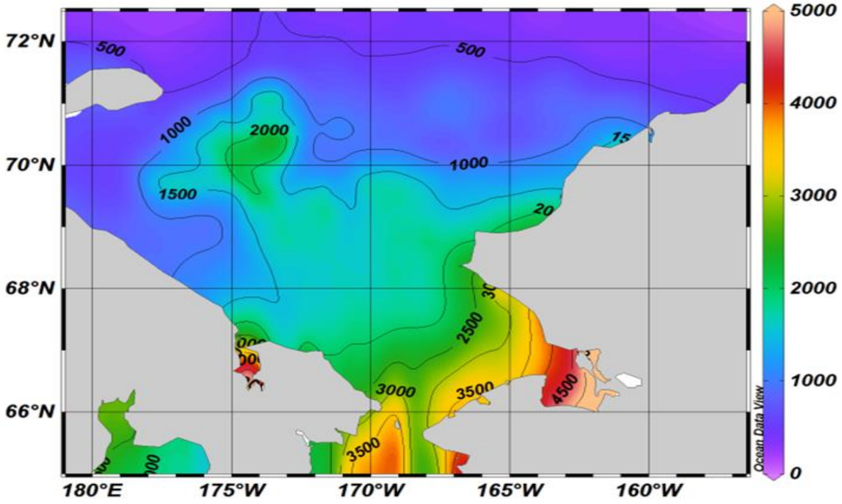
Scheme of summer bloom in polar waters followed by successive development of zooplankton community

Primary productivity in polar waters

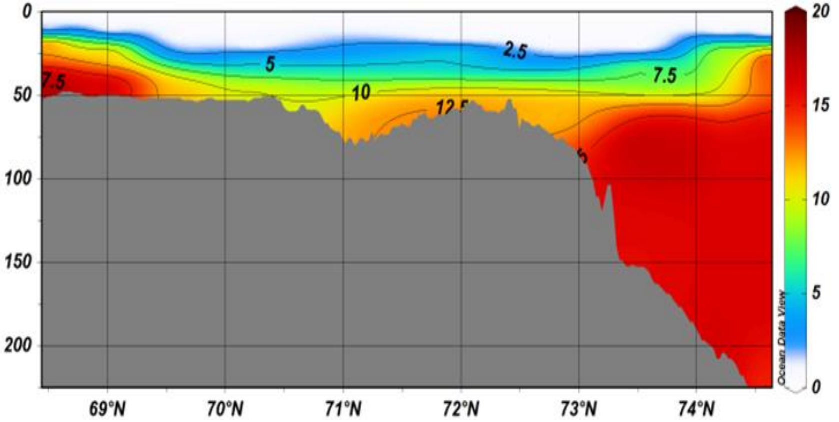


Such source of additional nutrients for Chukchi Sea is the Bering Strait. The nutrients are transported here from the most richest in the world area – Bering Sea located in the end of global Ocean Conveyor. Consequently, the southernmost area of the sea closest to the strait is distinguished by high concentration of phytoplankton, so high bioproductivity. However, other productive areas are located in a distance from the strait – what is their nature?

Possibly, the bloom in distant areas is supported by nutrients from Bering Sea transported there within subsurface layer. The flow of subarctic waters is less stratified and storm or tidal mixing is able to induce here an upward flux of nutrients, whereas the nutrients in the subsurface layer of Arctic waters remain at the depth .



Primary production in the Chukchi Sea on August 22-29, 2018, mgC/m² per day (calculated from satellite data on Chl a)



DIP vertical distribution at the transect along 175º W across the flow from Bering Sea in late August 2019, mM

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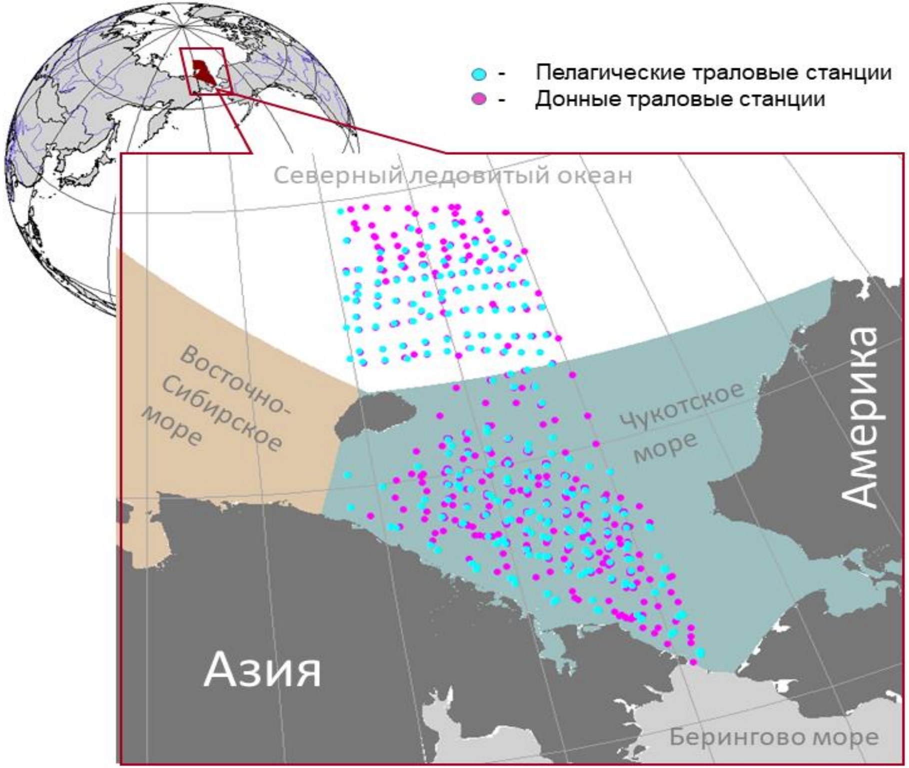
Quantitative evaluation of nutrient fluxes

Data of the Russian surveys in the western Chukchi Sea conducted by TINRO are analyzed. The widest chemical program was done in 2010 and 2020 when the surveys covered the southwestern part of the sea and observed well the northwestward flow from the Bering Strait.



Scheme of TINRO surveys in the Chukchi Sea (all stations of 11 surveys conducted from 1994 to 2020, colors show the type of trawl gear)

Quantitative evaluation of nutrient fluxes

There are two main reasons of change for dissolved nutrients concentration in water:

1) [physical] – the water mixing/dilution by water with different concentration of nutrients;
2) [biogeochemical] – nutrients consumption for photosynthesis or mineralization of organic matter.

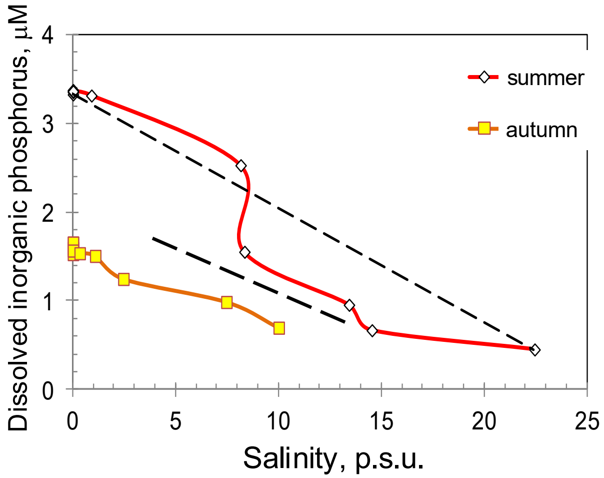
The mixing concerns other salts, too, so the changes by physical reason are proportional to the change of salinity. In marine chemistry these conservative changes of concentration are considered as 'potential' ones (dC_p) .

The biogeochemical loss or income (dP) can be calculated as difference between real and potential concentrations:

$$dP = dC_p - dC \text{ , where}$$

dP – change of nutrient concentration (DIP or DIN) after its consumption for production or regeneration from decomposition of organic matter;
dC – actual (observed) change of nutrient concentration;
dC_p – potential change of inorganic phosphorus concentration caused by water mixing only.

This methodical approach Is easy understandable for a simple 1-dimention estuarian system where the fresh and nutrient-rich water from river is diluted by salt and nutrient-poor marine water



DIP variations along the estuary of Suifen River near Vladivostok in summer and fall seasons relative to salinity. Potential concentration C_p is shown by dashed line. In summer, DIP is above C_p upstream and below C_p downstream that is interpreted as the inorganic phosphorus mineralizing (income) in the internal estuary and consumption (loss) in the external estuary. No DIP income is observed in autumn [from: Vazhova, Zuenko, 2015]

Quantitative evaluation of nutrient fluxes

The water structure in the southern Chukchi Sea is more complicated – the nutrient-rich stream has 2 layers and these layers mix between each other and with surrounding Arctic waters. Such mixing is described by triangles at the TS-diagram. Those diagrams were constructed for each pair of stations along the flow and potential DIP was calculated separately for the surface and subsurface layers:

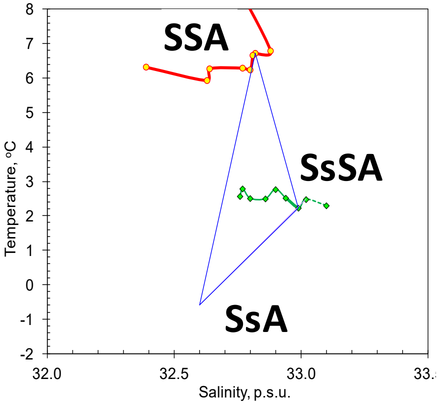
for the subsurface layer: $dC_{pSs} = dR_S\ (C_{pS} - C_{pSs}) + dR_{SsA}\ (C_{pSsA} - C_{pSs})$, *where*

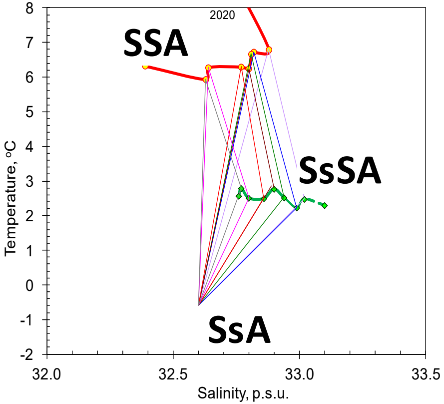
C_{pS} – potential concentration of inorganic phosphorus in the surface layer of the flow before passing between stations;
C_{pSs} – potential concentration of inorganic phosphorus in the subsurface layer of the flow before passing between stations;
C_{pSsA} – potential concentration of inorganic phosphorus in the core of the Subsurface Arctic Water;
R_S – admixture of the Surface Subarctic Water within the subsurface layer of the flow;
R_{SsA} – admixture of the Subsurface Arctic Water within the subsurface layer of the flow;

and similarly for the surface layer: $dC_{pS} = dR_{Ss}\ (C_{pSs} - C_{pS}) + dR_{SA}\ (C_{pSA} - C_{pS})$, *where*

R_{Ss} – admixture of the Subsurface Subarctic Water within the surface layer of the flow;
R_{SA} – admixture of the Surface Arctic Water within the surface layer of the flow.

The values of admixtures R_S, R_{SsA}, R_{Ss}, and R_{SA} were calculated from the triangles of mixing for each pair of stations.





Scheme of R_S and R_{SsA} calculation for subsurface layer of the flow from Bering Sea mixed with the surface layer (SSA) and Subsurface Arctic water (SsA)

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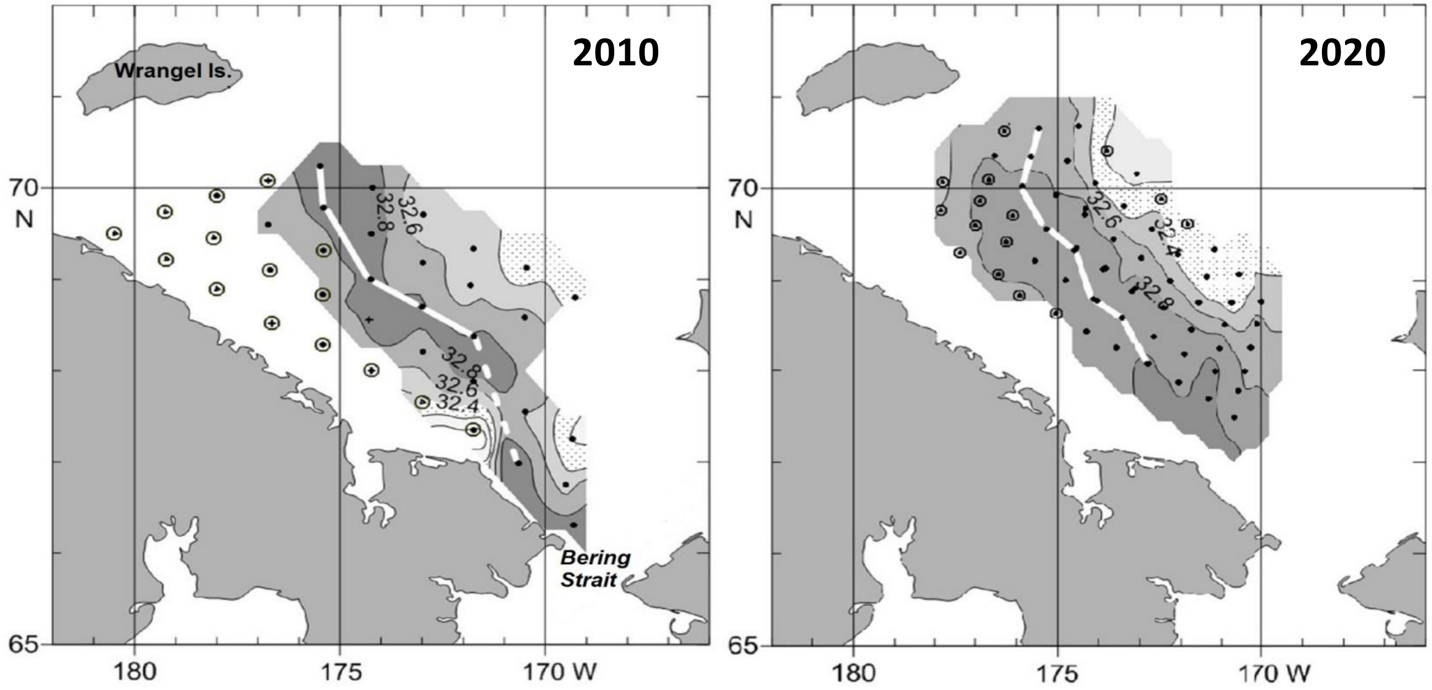
Dynamics of nutrients after passing the Bering Strait

The flow from the Bering Sea can be easy traced by heightened salinity in the subsurface layer.



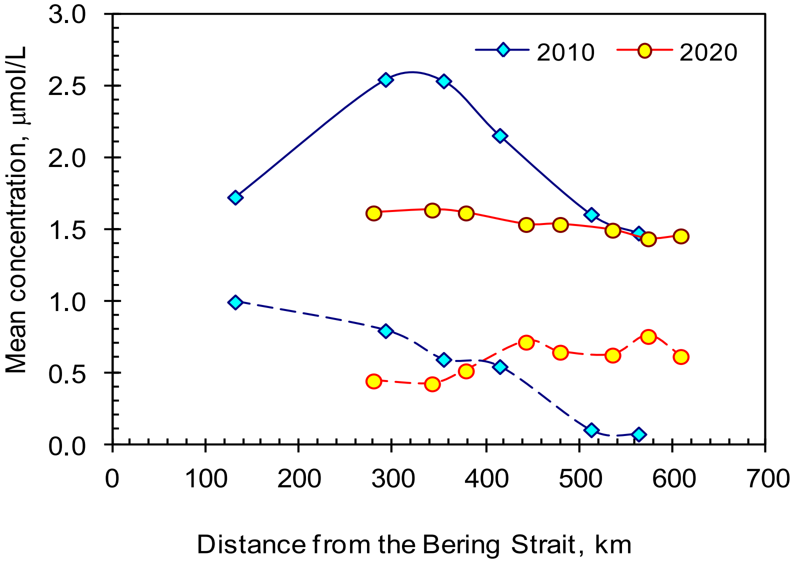
Average salinity in subsurface layer of the stream invaded from Bering Sea to Chukchi Sea on the data of R/V TINRO surveys on September 7–16, 2010, and August 26–September 5, 2020.

Dots, all oceanographic stations; circles, stations with Arctic Subsurface water in subsurface layer; white lines, transects along the stream

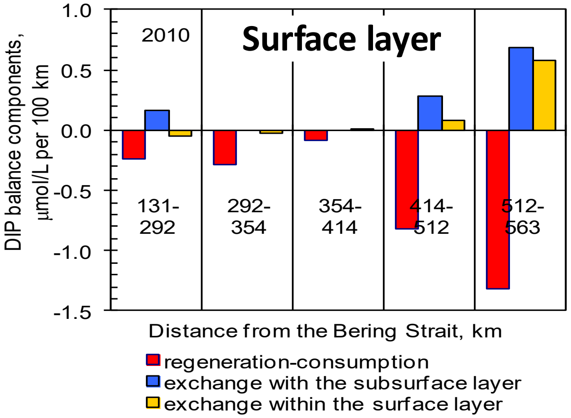
Dynamics of nutrients after passing the Bering Strait

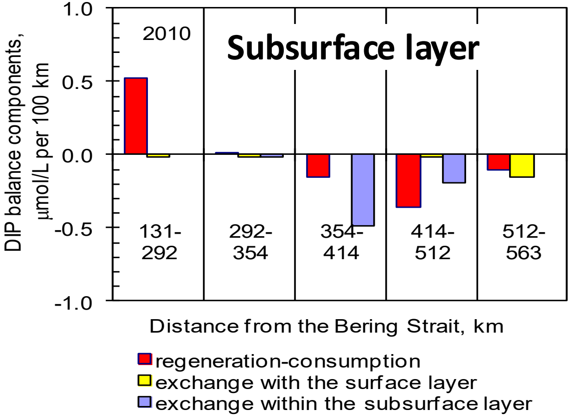
Along the flow, the phosphorus concentration had a complicated dynamics that explains the balance of physical and biogeochemical processes.

In 2010, the phosphorus consumed in the surface layer, firstly its own stock, than the upward flux from the depth. The subsurface layer firstly received mineralized DIP, then lose DIP to mixing and consumption. This scenario looks as “normal”.



Variations of average DIP concentration in the subsurface (solid lines) and surface (dotted lines) layers of the stream invaded from Bering Sea to Chukchi Sea



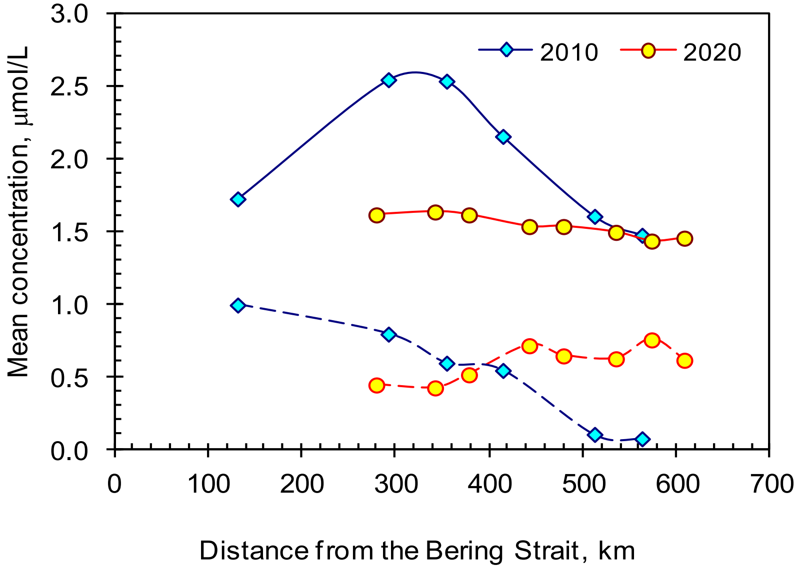


Components of DIP balance in the surface and subsurface layers of the stream invaded from Bering Sea to Chukchi Sea in 2010

Dynamics of nutrients after passing the Bering Strait

Along the flow, the phosphorus concentration had a complicated dynamics that explains the balance of physical and biogeochemical processes.

In 2020, the phosphorus didn't consumed but regenerated in both layers. The consumption at the sea surface layer began in ≈ 600 km from the strait. This scenario is considered as typical for case of strong flow through Bering Strait.



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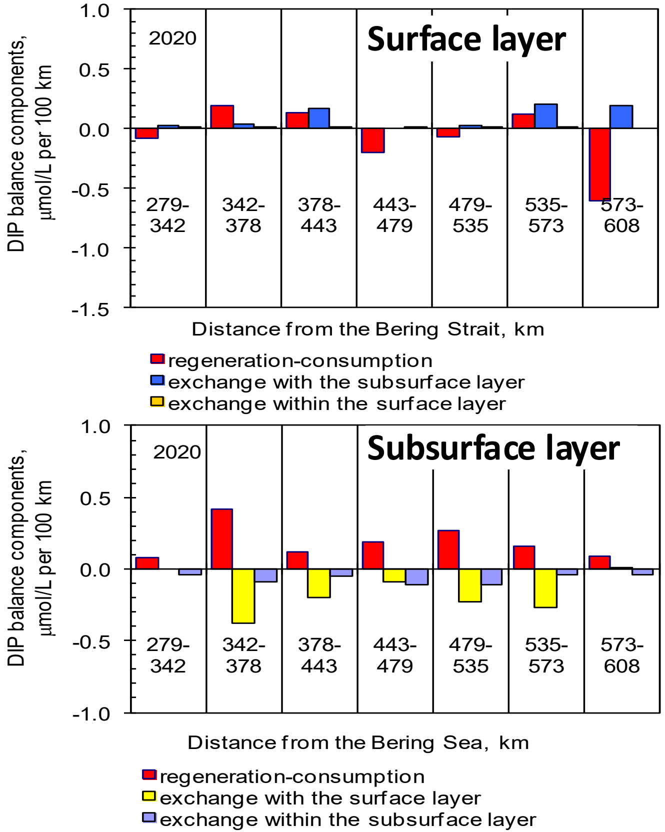
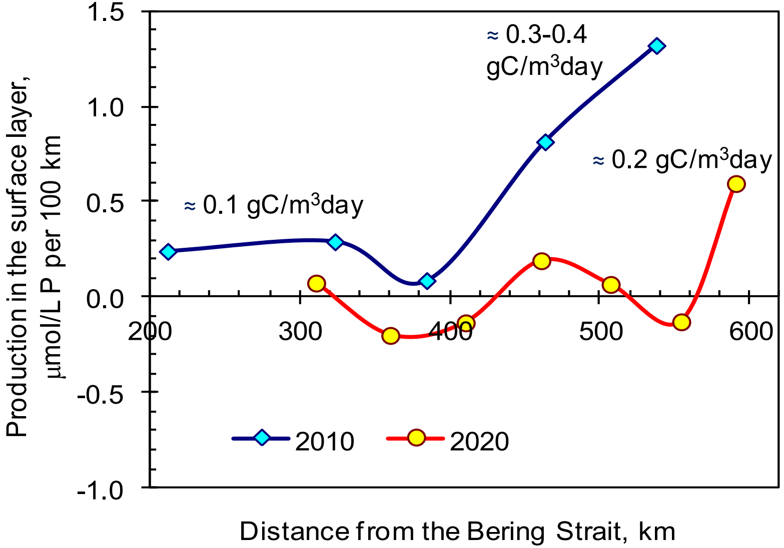


Components of DIP balance in the surface and subsurface layers of the stream invaded from Bering Sea to Chukchi Sea in 2020

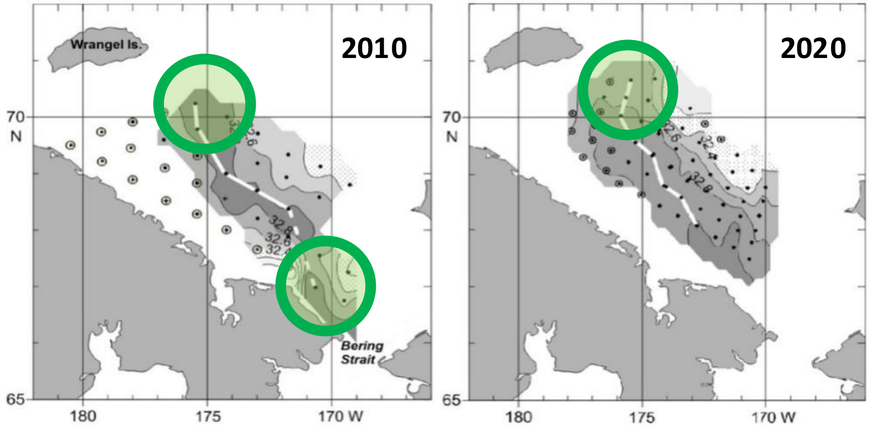
Dynamics of nutrients after passing the Bering Strait

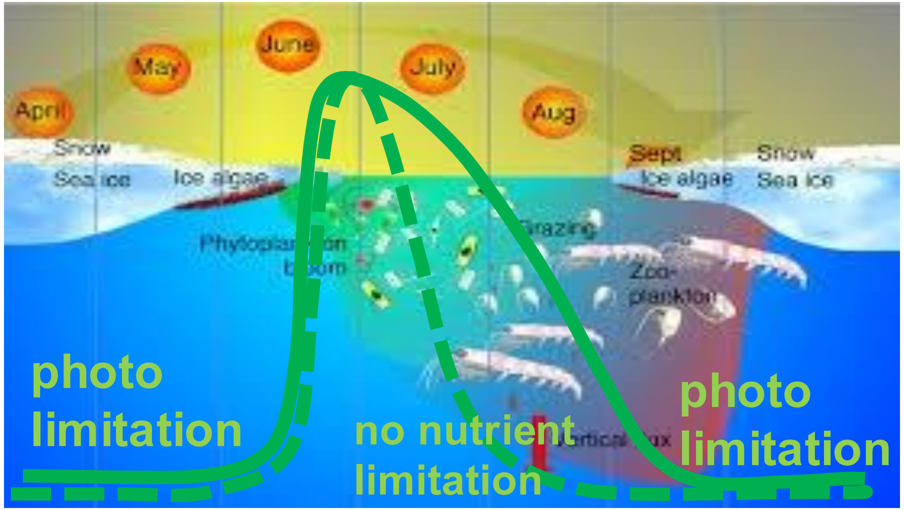
Along the flow, there were 2 productive zones in 2010 and 1 such zone in 2020.



Consumption of inorganic phosphorus in the surface layer of stream from Bering Sea to Chukchi Sea

Generally, the flow was less productive in 2020 when the main stock of nutrients was transported further to the north.





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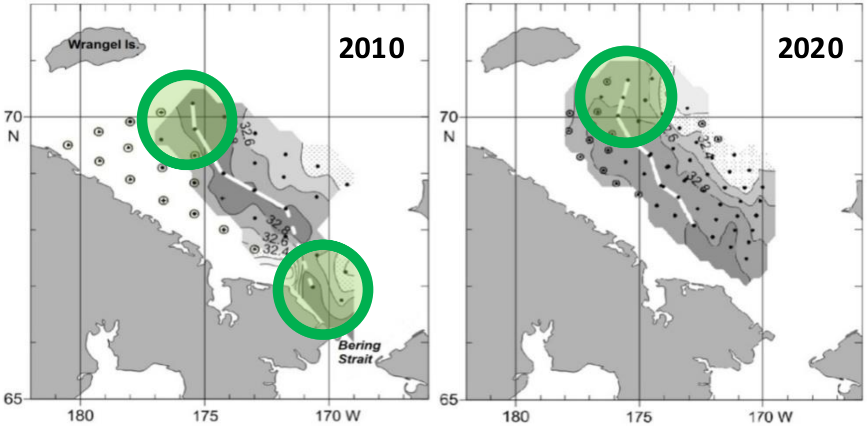
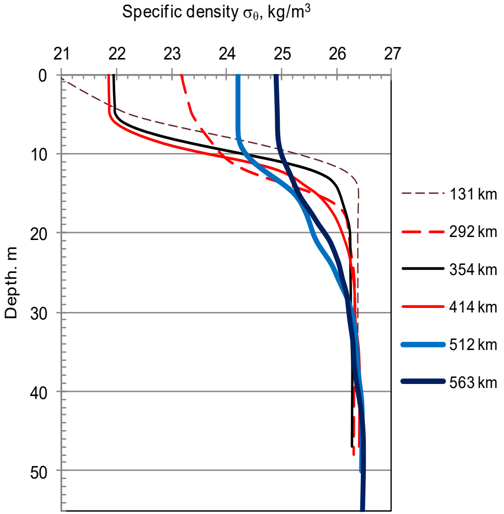
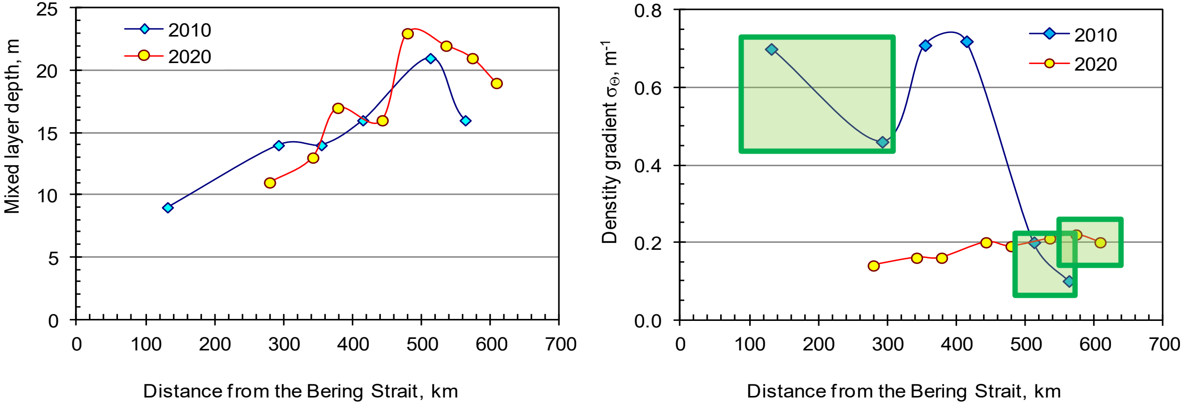
Localization of productive zones in the flow from Bering Strait

Conditions favorable for the nutrients consumption are determined – the "upstream" productive zone develops when grad $\sigma_\Theta > 0.2\ m^{-1}$ in pycnocline and the "downstream" zone when the mixed layer depth increases > 20 m with simultaneous weakening of pycnocline. The former factor allows phytoplankton cells to retain in the photic layer; the latter one provides water exchange between layers with upward flux of nutrients deposited in the subsurface layer.





Evolution of vertical profiles for water density along the stream from Bering Sea to Chukchi Sea, on the data of RV TINRO survey in summer 2010

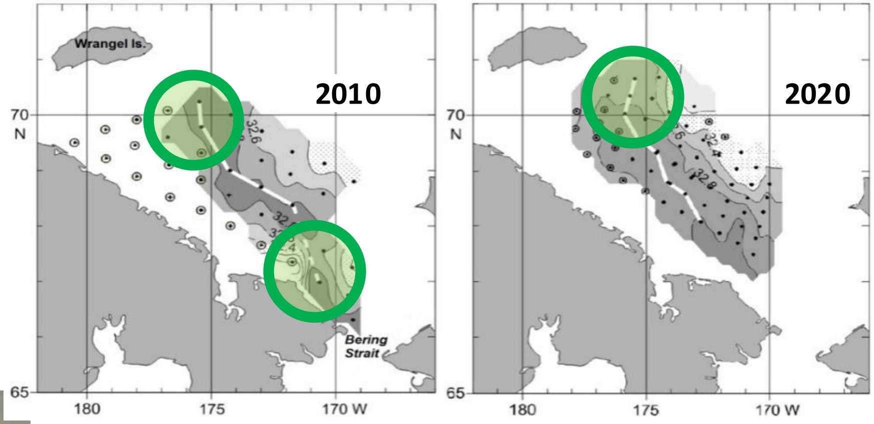


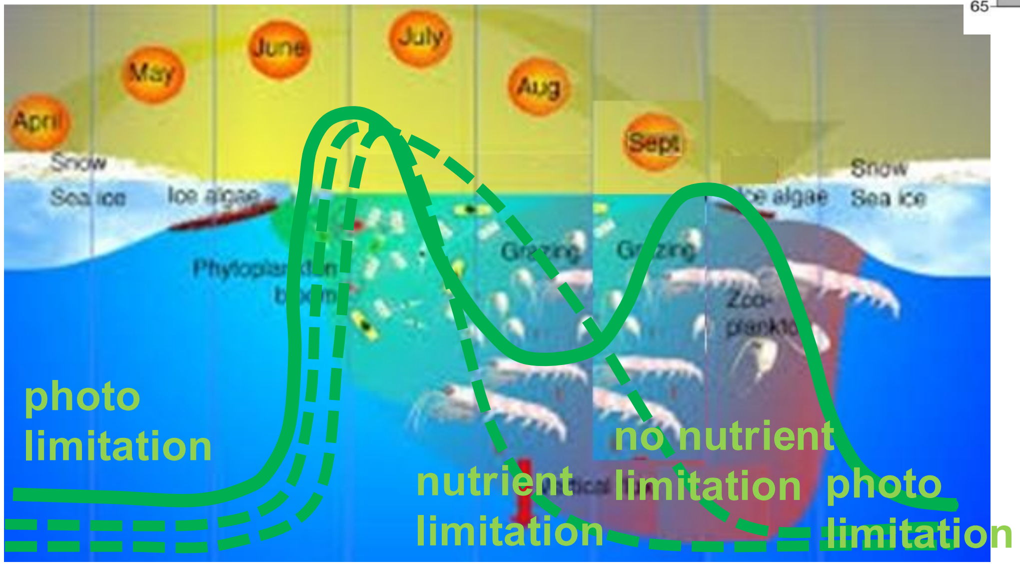
Mixed layer depth and maximum gradient in seasonal pycnocline along the stream from Bering Sea to Chukchi Sea, on the data of RV TINRO surveys in summer of 2010 and 2020

Conditions of strong and weak advection from the Bering Sea

In spite of enhanced delivery of nutrients to the Chukchi Sea by stronger advection (as in 2020), productivity in the flow decreases, so far as these nutrients remain unclaimed by consumers. Does it mean that bioproductivity of the southwestern Chukchi Sea will decrease with climate warming?

– No!





Summer season becomes less productive – as is typical for the subpolar seas. But in conditions of stronger stratification, the “polar” annual cycle of production with 1 peak changes to “subpolar” cycle with 2 peaks, so the total annual production will increase.

Conclusions:

1. **Uptake from the surface layer *vs* Stratification** – The nutrients entered to the Chukchi Sea with the flow through Bering Strait are utilized in dependence on stratification. If the stream is well stratified (grad $\sigma_\Theta > 0.2$ m^{-1}), the nutrients from the upper layer are rapidly consumed near the Bering Strait. If the sufficient vertical stability develops in a distance from the strait, the nutrients from the surface layer of stream are consumed at this distance (even near Wrangel Island).

2. **Uptake from the subsurface layer *vs* Stratification** – Most nutrients of Pacific origin enter the Chukchi Sea in the subsurface layer of the stream and are transported over long distance (hundreds of kilometers from the Bering Strait) until turbulent mixing weakens its stratification to grad $\sigma_\Theta < 0.2$ m^{-1} and the upward flux of these salts develops.

3. **Two productive zones** – The sequential uptake of nutrients from the surface and subsurface layers of the stream from the Bering Sea causes development of two zones of high productivity in the Chukchi Sea, separated by low productive zone several hundred kilometers wide. Localization of these productive zones is determined by the flow intensity: the greater the water transport through the Bering Strait, the further away from the strait are both zones.

4. **PP values** – Upstream, within the southwestern Chukchi Sea, the nutrients from the upper layer of the stream provide primary production of 0.1–0.2 gC m^{-3} day^{-1}. Downstream (near Wrangel Is. or in the northern Chukchi Sea, or even beyond the sea), the main stock of nutrients from subsurface layer provides production of 0.3–0.4 gC m^{-3} day^{-1}.

5. **Climate change effects** – The modern trend to increasing advection through the Bering Strait causes shifting the zones where nutrients of Pacific origin are utilized outside the southwestern Chukchi Sea with lowering bioproductivity of this area in summer. At the same time, restructuring of the seasonal succession of productivity processes can increase the annual production and promote more productive subarctic ecosystem in the southern Chukchi Sea.