The Japan/East Sea ecosystem reconstruction under recent climate change: productivity lowering *vs* efficiency enhancing

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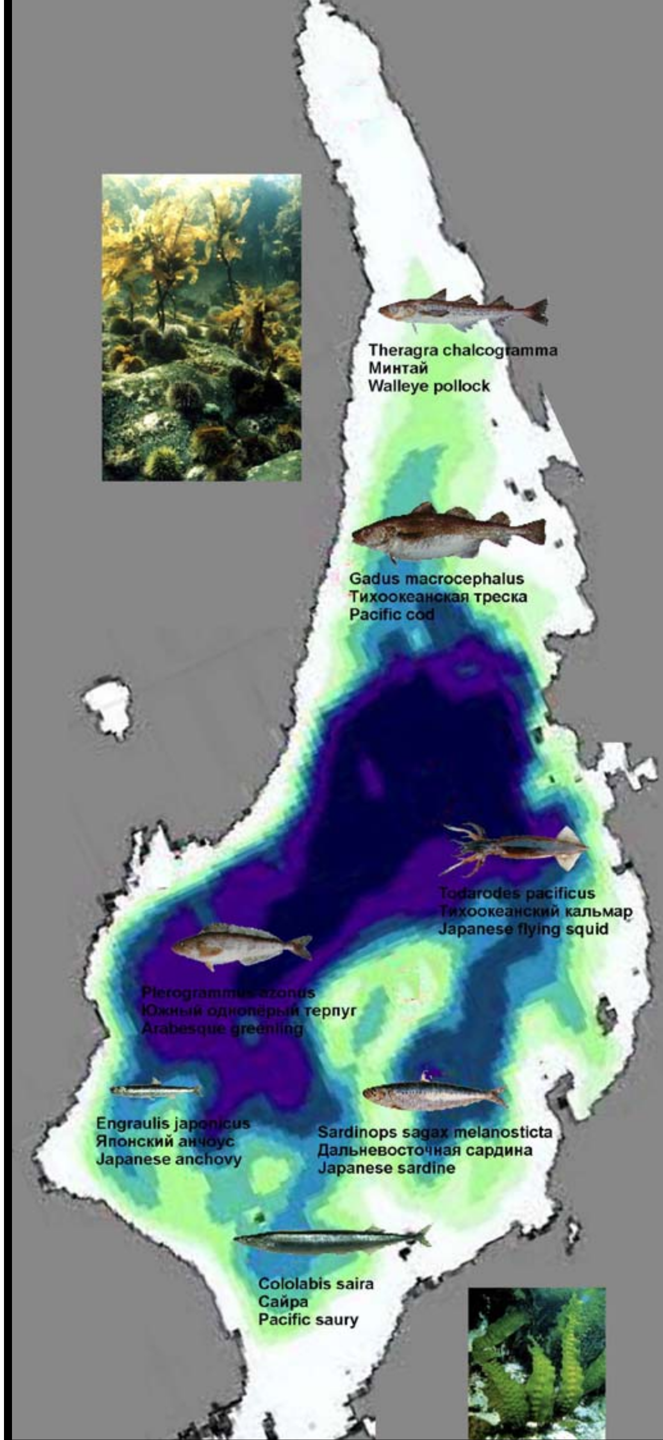
Outline:

- Changes in the Japan/East Sea ecosystem and their mechanisms
- *Pro- et contra-* of ecosystem models
- Role of reproduction processes
- Estimation of the ecosystem efficiency



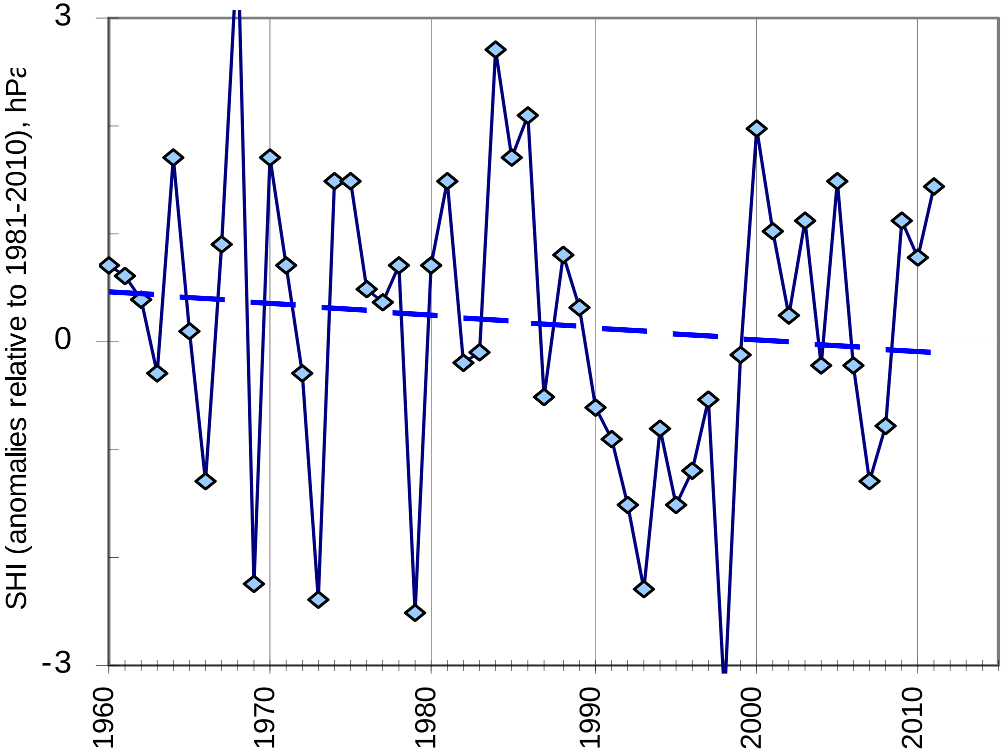
Atmosphere: winter monsoon weakening

Winter monsoon is driven by atmospheric pressure heightening over the continent in winter because of low air temperature. Its activity could be described by the Siberian High Index (SHI) – mean atmospheric pressure over northern Asia.

A significant negative trend of SHI is observed in the last three decades with the inclination –0.02 hPa per year. The tendency of the Siberian High weakening corresponds to winter warming on the continent and possibly is caused by enhancing of heat-insulating properties of the atmosphere (“greenhouse effect”).

This tendency is expected to continue.

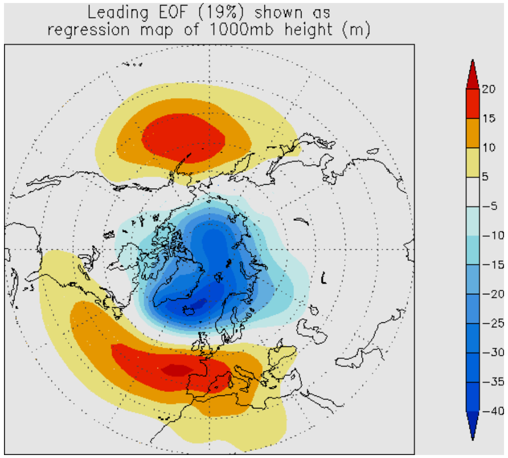
Scheme of winter monsoon



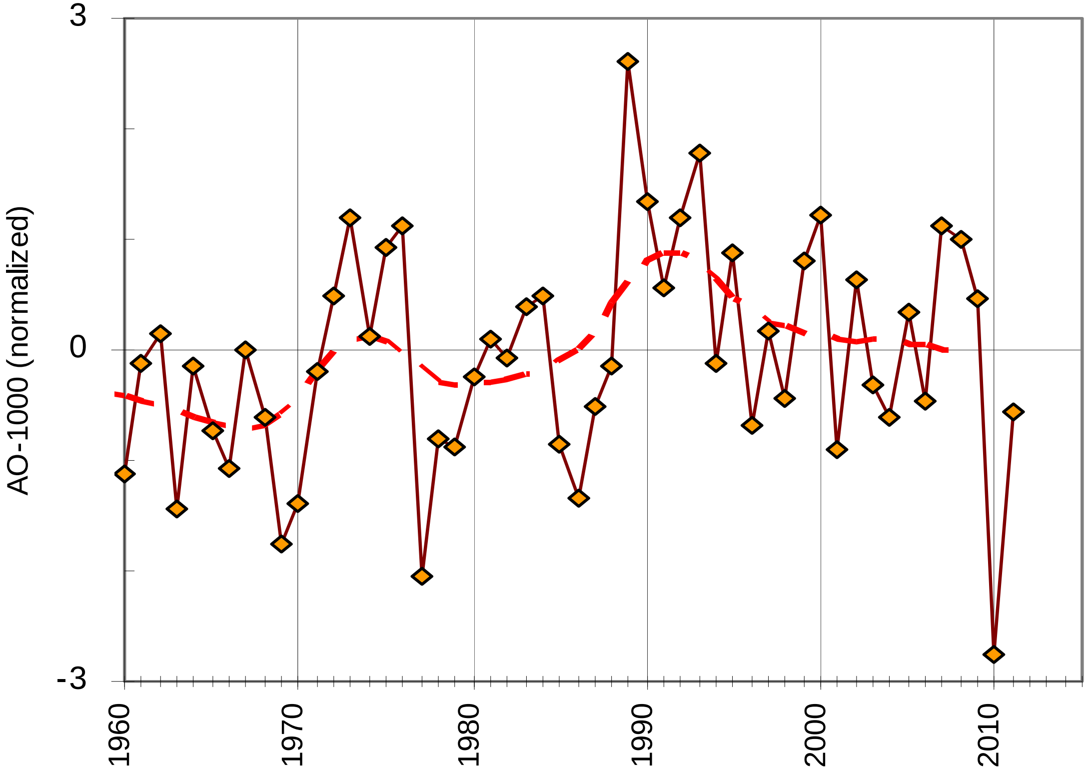
Siberian High Index changes.
Its lowering means the weakening of winter monsoon that prevents the sea surface cooling in the Japan Sea

Atmosphere: winter monsoon decadal variation driven by Arctic Oscillation

Siberian High changes in relation with Arctic Oscillation (AO) (r = –0.42 for the 60-year time series) – the process of periodic redistribution of air masses between polar and moderate latitudes. In positive AO phases (1970s, 1990s), zonal transfers across the continent become stronger that makes winters in Siberia warmer and Siberian High – weaker; and in negative phases (1980s, 2000s) the AO makes Siberian High stronger. These oscillations happen on the background of AO positive trend.



AO pattern

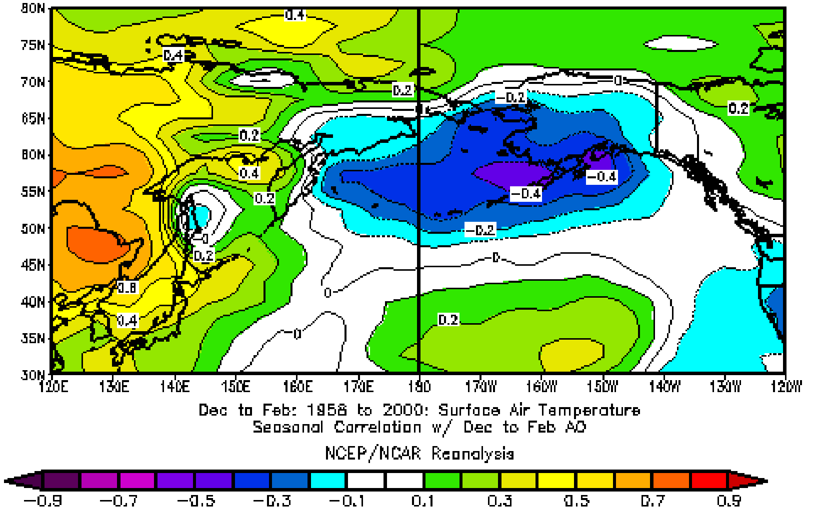


Arctic Oscillation Index changes.
Its heightening means the strengthening of zonal transfers which make warmer the winters in Siberia (from http://jisao.washington.edu/analyses0302/)

Water: SST heightening

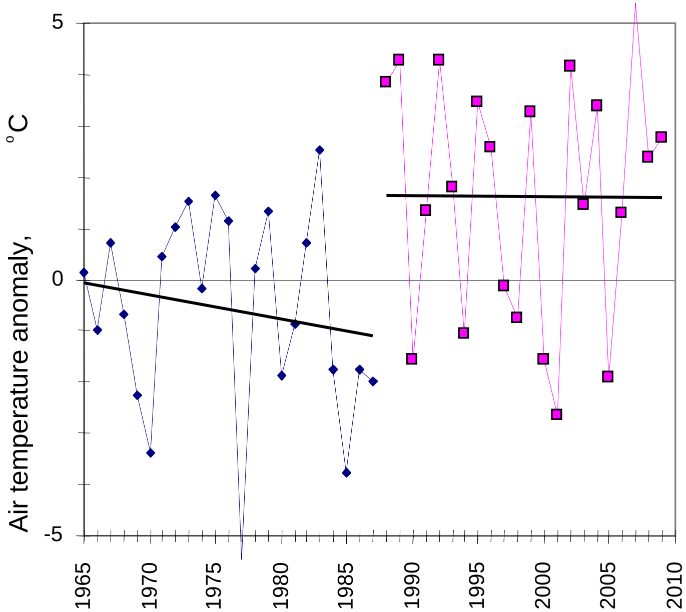
Winter air temperature in the Japan Sea correlates strongly both with winter AO index (r = +0.62 for January) and SHI (r = –0.57 for February). Following to the winter monsoon changes, the air temperature has a tendency to increase.

Winter SST had similar changes as the air temperature, but its fluctuations could be slightly distorted by occasional reasons because the range of wither SST changes is very narrow.

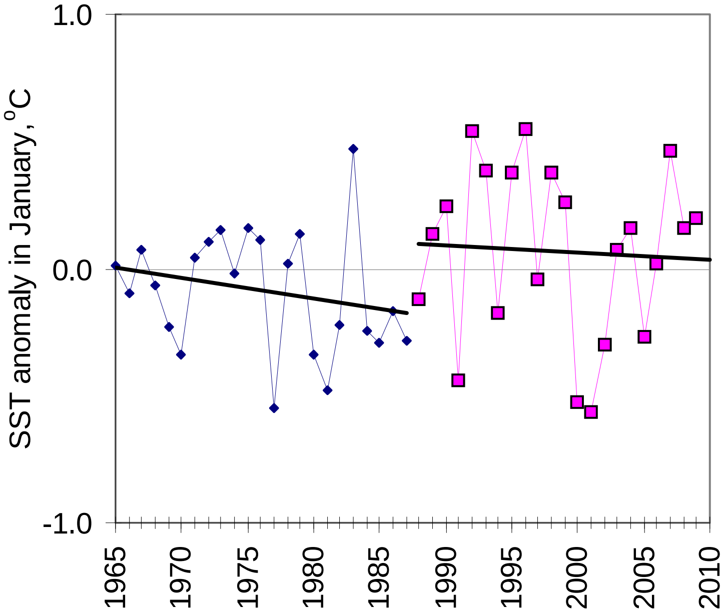


Correlations of air temperature with AO index. (from: Wu, Wang, 2002)

NOAA-CIRES/Climate Diagnostics Cent



Mean month air temperature anomalies in Vladivostok in January



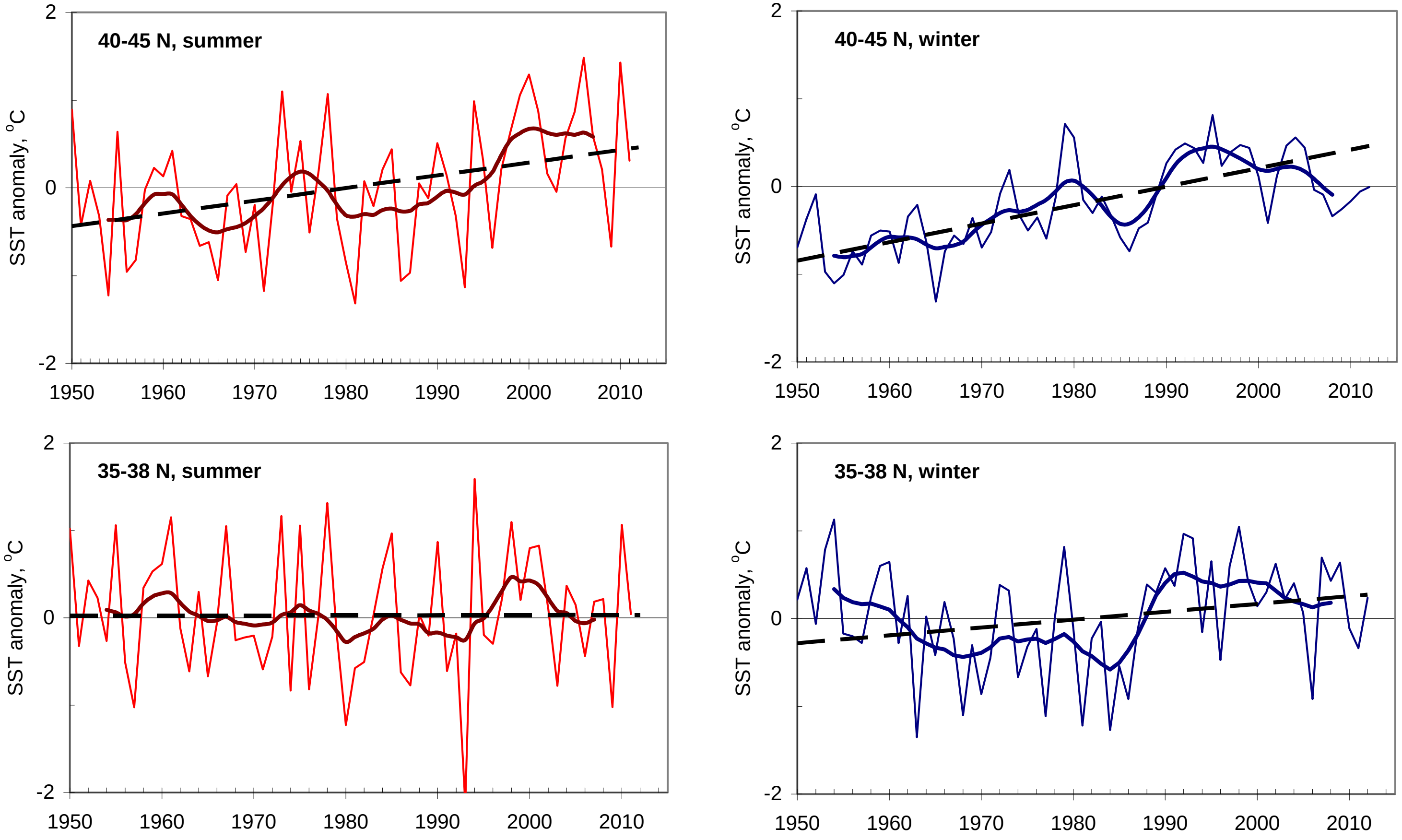
Mean month SST anomalies in Vladivostok in January

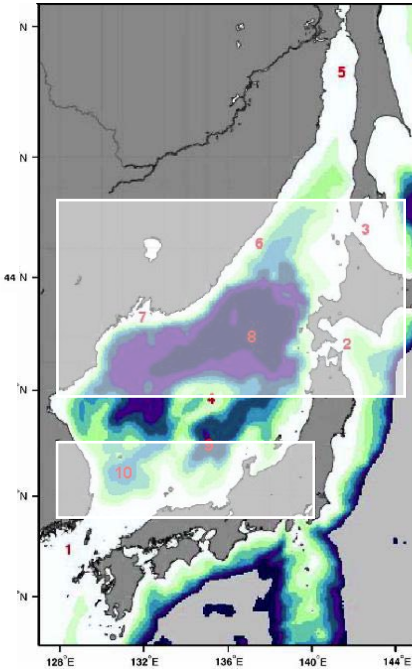
Water: SST heightening

Rates of the SST tendency to warming are different for certain areas and seasons, and in some cases the trend is statistically insignificant, but it is always positive.

Interdecadal oscillations of SST are stronger than year-to-year fluctuations: SST grew until late 1990s and was lower in the 2000s.

Trend to warming is stronger in the northern part of the Sea. Obviously, it is caused by the winter monsoon weakening





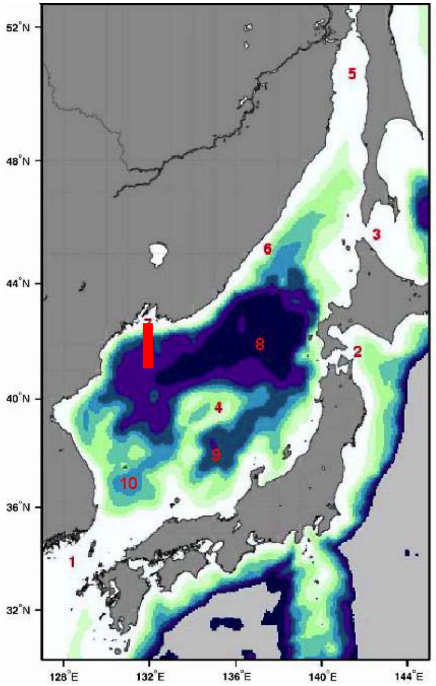
SST anomalies for certain areas and seasons (JMA data)

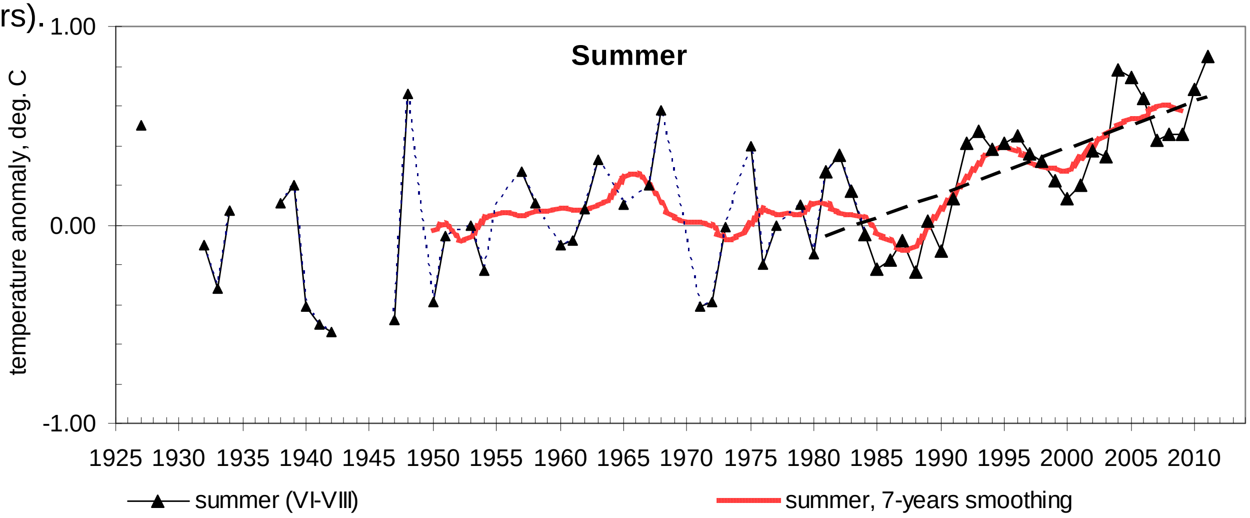
Water: Intermediate layer warming

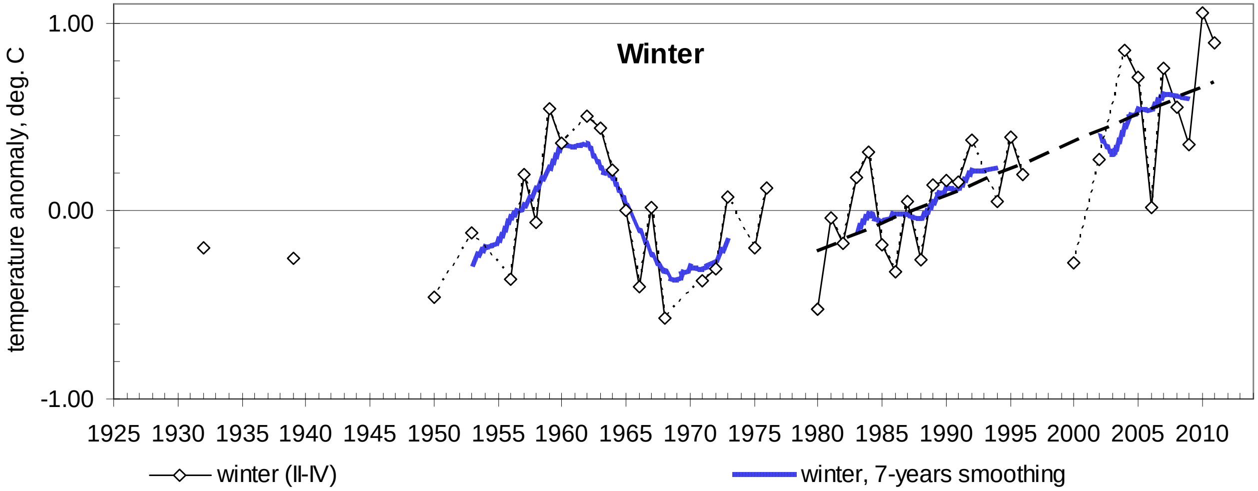
Temperature of the Intermediate Water has positive trend in the last 3 decades.

It has also the interdecadal oscillations around the trend line with warming in the 1990s and cooling in the 1980s and 2000s.

The main reason of both changes is change of winter SST southward from the Polar Front, where IW forms, but temperature in the intermediate layer changes with a prominent lag (up to 3 years).





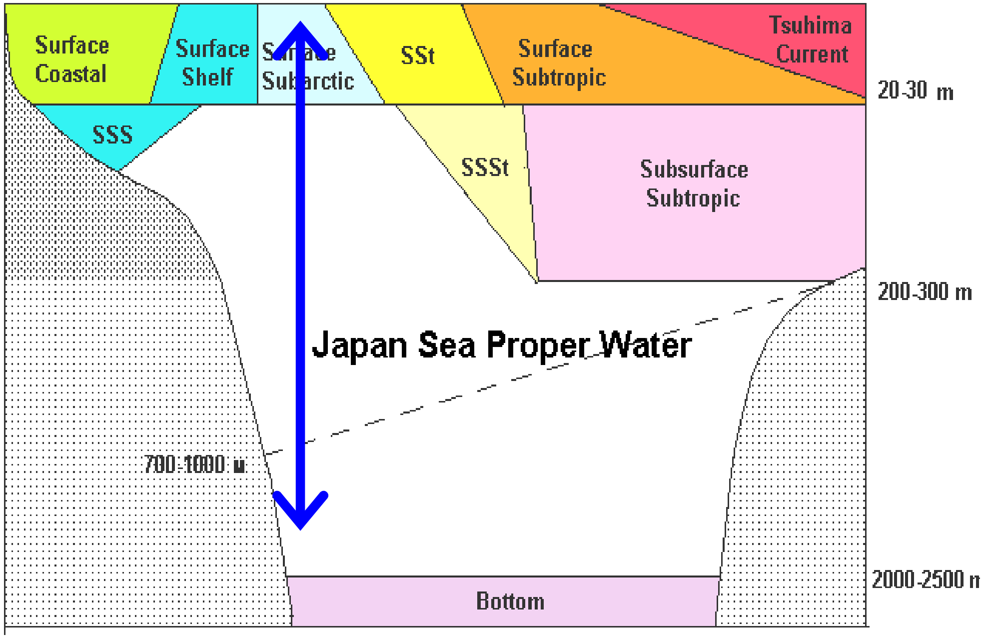


Temperature anomalies in the layer from thermocline to 200 m at the standard section along 132º E for summer (Jun.-Aug.) and winter (Feb.-Apr.).
Linear trends for the last 3 decades are shown

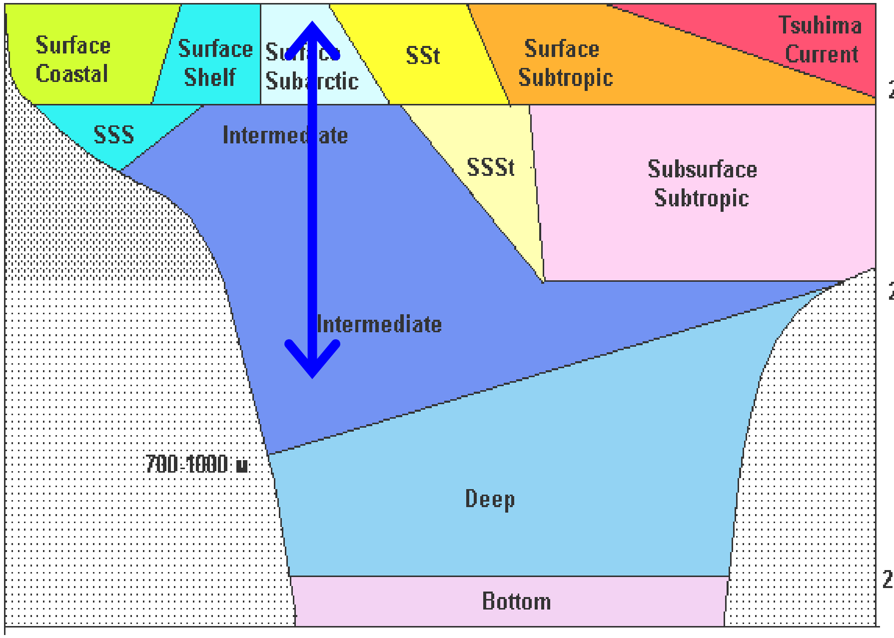
Water: reconstruction of water structure with separation of the Intermediate Water

Warmer winter conditions cause the convection weakening, so now it ventilates the 400 m layer instead of 1500-2000 m layer in the 1980s.

As a result, the Deep and Intermediate Water are well-separated now, in opposite to the times before the 1990s when they were united in a common Japan Sea Proper Water mass.



Before 1990

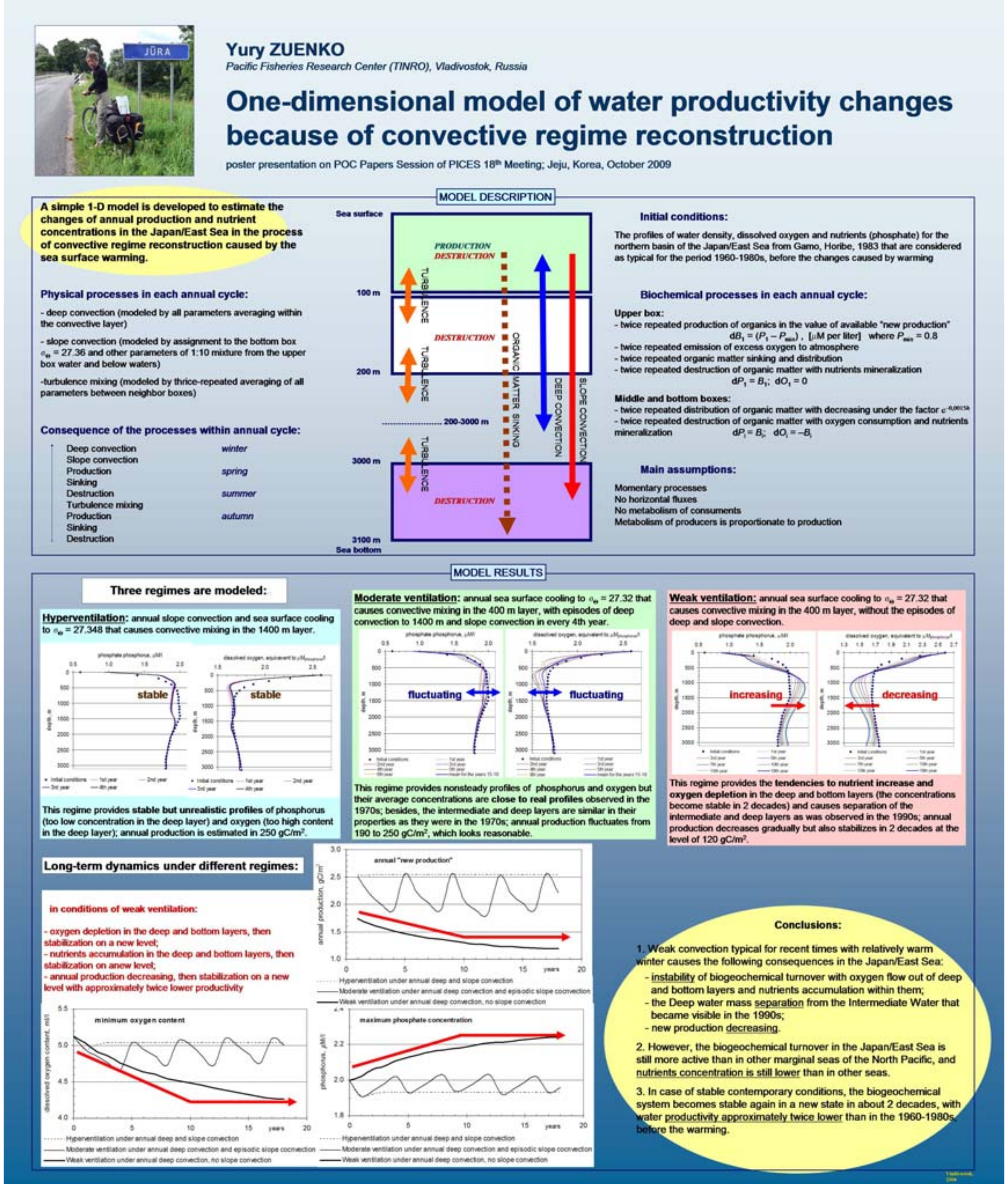


After 1990

Nutrients: burial in the deep layer and lack in the active layer

After the separation between the Deep and Intermediate water masses, nutrients become to bury in the deep layer, and their concentration in the convective layer theoretically becomes lower.

The process is modeled in 1-D model presented at PICES in 2009 (Zuenko, 2009)



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One-dimensional model of water productivity changes because of convective regime reconstruction

poster presentation on POC Papers Session of PICES 18th Meeting; Jeju, Korea, October 2009

MODEL DESCRIPTION

A simple 1-D model is developed to estimate the changes of annual production and nutrient concentrations in the Japan/East Sea in the process of convective regime reconstruction caused by the sea surface warming.

Physical processes in each annual cycle:

- deep convection (modeled by all parameters averaging within the convective layer)
- slope convection (modeled by assignment to the bottom box $\sigma_\theta = 27.36$ and other parameters of 1:10 mixture from the upper box water and below waters)
- turbulence mixing (modeled by thrice-repeated averaging of all parameters between neighbor boxes)

Consequence of the processes within annual cycle:

Deep convection	*winter*
Slope convection	
Production	*spring*
Sinking	
Destruction	*summer*
Turbulence mixing	
Production	*autumn*
Sinking	
Destruction	

Initial conditions:

The profiles of water density, dissolved oxygen and nutrients (phosphate) for the northern basin of the Japan/East Sea from Gamo, Horibe, 1983 that are considered as typical for the period 1960-1980s, before the changes caused by warming

Biochemical processes in each annual cycle:

Upper box:
- twice repeated production of organics in the value of available "new production"
$dB_1 = (P_1 - P_{min})$, [µM per liter] where $P_{min} = 0.8$
- twice repeated emission of excess oxygen to atmosphere
- twice repeated organic matter sinking and distribution
- twice repeated destruction of organic matter with nutrients mineralization
$dP_1 = B_1$; $dO_1 = 0$

Middle and bottom boxes:
- twice repeated distribution of organic matter with decreasing under the factor $e^{-0.0015h}$
- twice repeated destruction of organic matter with oxygen consumption and nutrients mineralization $dP_i = B_i$; $dO_i = -B_i$

Main assumptions:

Momentary processes
No horizontal fluxes
No metabolism of consuments
Metabolism of producers is proportionate to production

MODEL RESULTS

Three regimes are modeled:

Hyperventilation: annual slope convection and sea surface cooling to $\sigma_\theta = 27.348$ that causes convective mixing in the 1400 m layer.

This regime provides **stable but unrealistic profiles** of phosphorus (too low concentration in the deep layer) and oxygen (too high content in the deep layer); annual production is estimated in 250 gC/m².

Moderate ventilation: annual sea surface cooling to $\sigma_\theta = 27.32$ that causes convective mixing in the 400 m layer, with episodes of deep convection to 1400 m and slope convection in every 4th year.

This regime provides nonsteady profiles of phosphorus and oxygen but their average concentrations are **close to real profiles** observed in the 1970s; besides, the intermediate and deep layers are similar in their properties as they were in the 1970s; annual production fluctuates from 190 to 250 gC/m², which looks reasonable.

Weak ventilation: annual sea surface cooling to $\sigma_\theta = 27.32$ that causes convective mixing in the 400 m layer, without the episodes of deep and slope convection.

This regime provides the **tendencies to nutrient increase and oxygen depletion** in the deep and bottom layers (the concentrations become stable in 2 decades) and causes separation of the intermediate and deep layers as was observed in the 1990s; annual production decreases gradually but also stabilizes in 2 decades at the level of 120 gC/m².

Long-term dynamics under different regimes:

in conditions of weak ventilation:

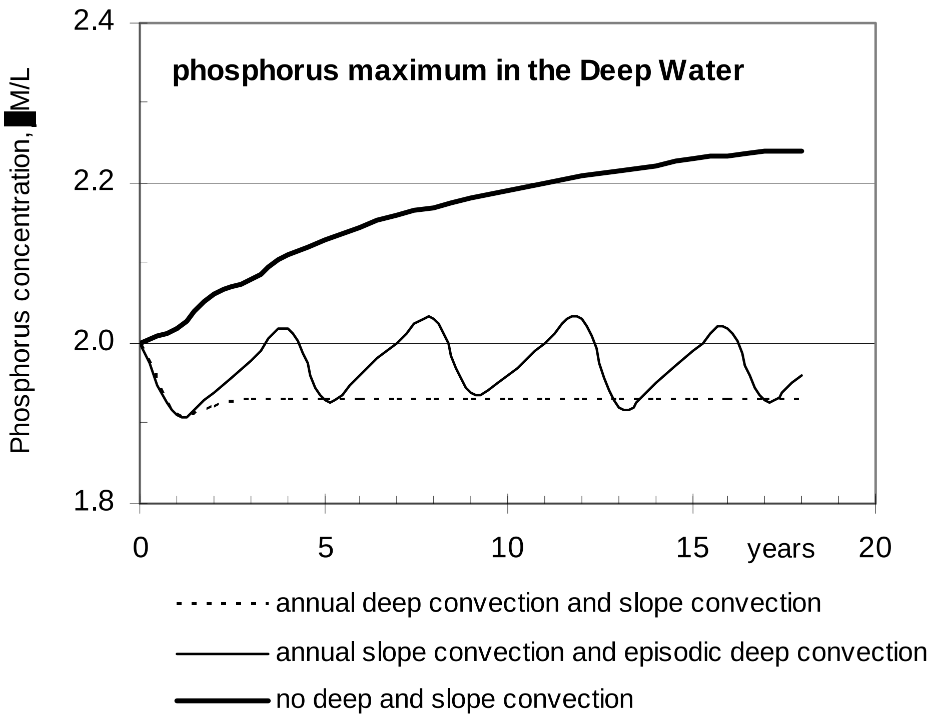
- oxygen depletion in the deep and bottom layers, then stabilization on a new level;
- nutrients accumulation in the deep and bottom layers, then stabilization on anew level;
- annual production decreasing, then stabilization on a new level with approximately twice lower productivity

Conclusions:

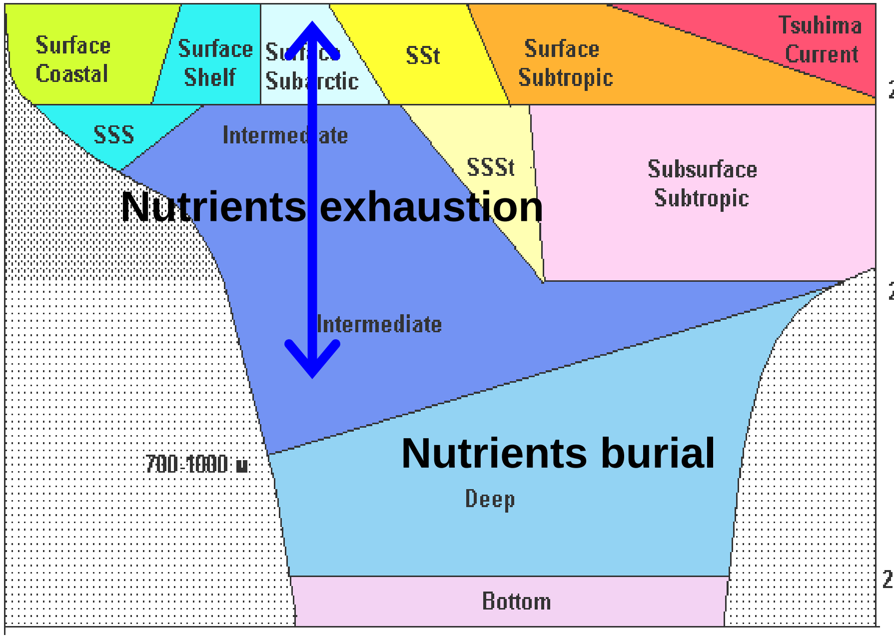
1. Weak convection typical for recent times with relatively warm winter causes the following consequences in the Japan/East Sea:
   - instability of biogeochemical turnover with oxygen flow out of deep and bottom layers and nutrients accumulation within them;
   - the Deep water mass separation from the Intermediate Water that became visible in the 1990s;
   - new production decreasing.
2. However, the biogeochemical turnover in the Japan/East Sea is still more active than in other marginal seas of the North Pacific, and nutrients concentration is still lower than in other seas.
3. In case of stable contemporary conditions, the biogeochemical system becomes stable again in a new state in about 2 decades, with water productivity approximately twice lower than in the 1960-1980s, before the warming.

Nutrients: burial in the deep layer

After the separation between the Deep and Intermediate water masses, nutrients become to bury in the deep layer, and their concentration in the convective layer theoretically becomes lower.



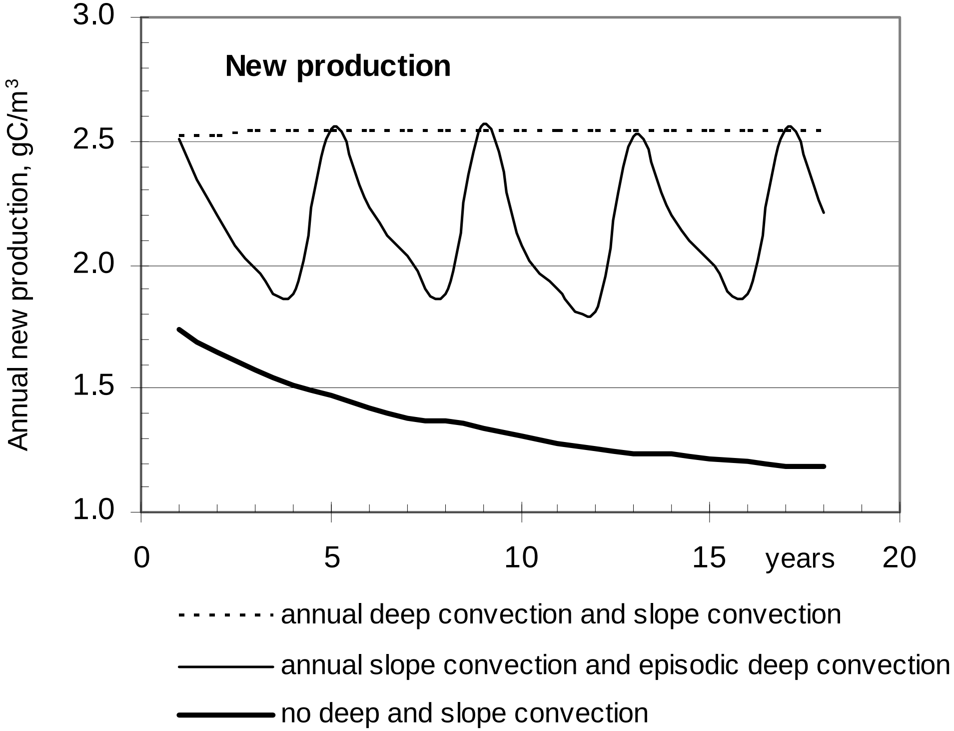
Model results on the phosphorus concentration growth in the deep layer after winter convection limiting by 400 m depth (thick line)



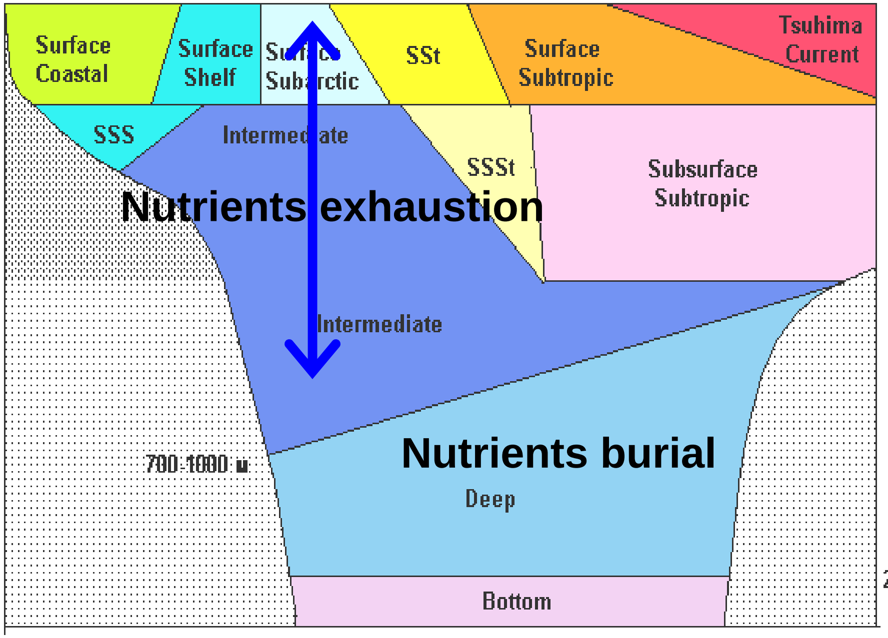
Nutrients: lack in the active layer – lower the nutrients, lower the production

Lowering the nutrients concentration in the euphotic layer causes the lowering of new primary production (produced mainly in spring).

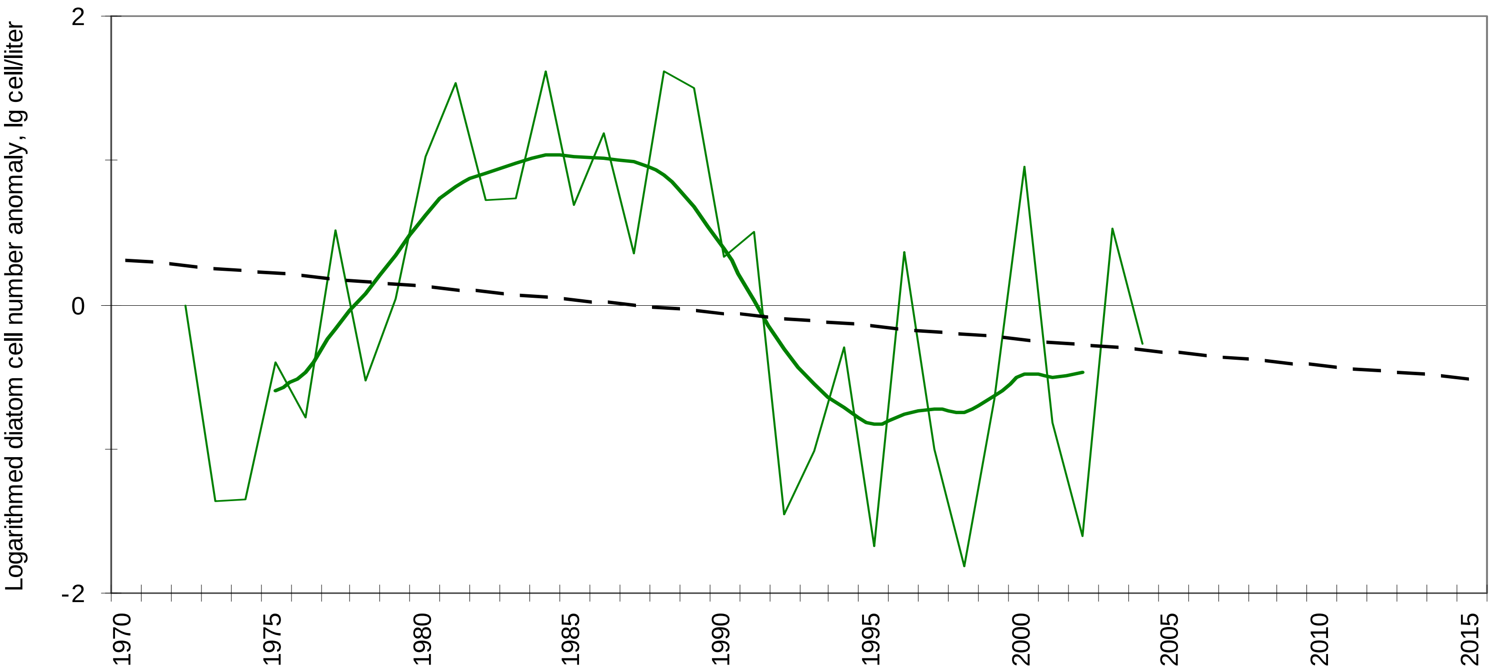
After convection weakening, the new production decrease gradually during two decades and finally becomes twice lower.



Model results on the new production decrease after winter convection limiting by 400 m depth (thick line)

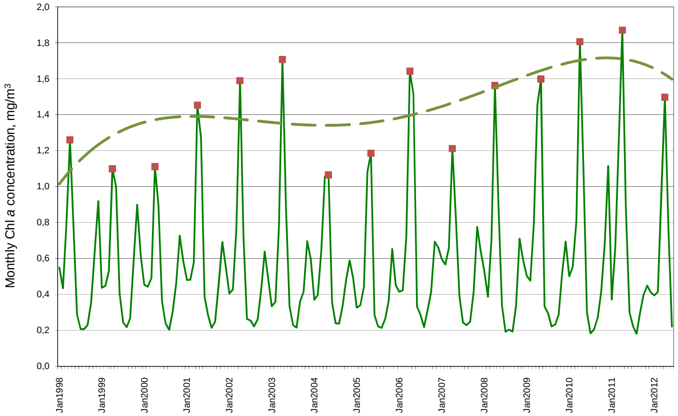


Phytoplankton: decadal oscillations, trend unclear



Phytoplankton abundance in spring has definite decadal oscillations coinciding with temperature changes: it is high in “cold” decades (1980s), low in “warm” ones (1990s), and heightened again in the 2000s. Long-term tendency of the phytoplankton abundance is not clear.

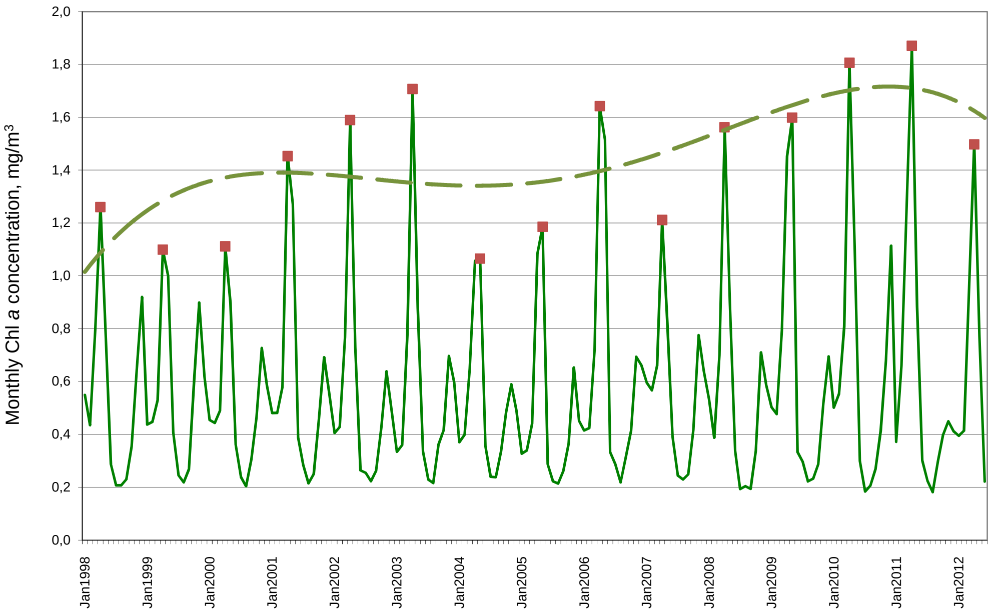
*Year-to years changes of diatom abundance at PM-line (SE Japan/East Sea) in spring (from: **Tian et al., 2008**). Results of 5-years smoothing and linear trend for 1973-2004 are shown, as well*



Monthly values of Ch a concentration at the sea surface in the deep-water part of the Japan/East Sea in 1997-2012 (from the data of satellite SeaWiFS and MODIS color scanners: http://oceancolor.gsfc.nasa.gov/)

Phytoplankton: decadal oscillations, trend unclear

Although the spring bloom became stronger in the last decade (in conditions of stopped warming), the fall bloom became weaker, and the mean annual concentration of Chl *a* does not show any significant tendency.



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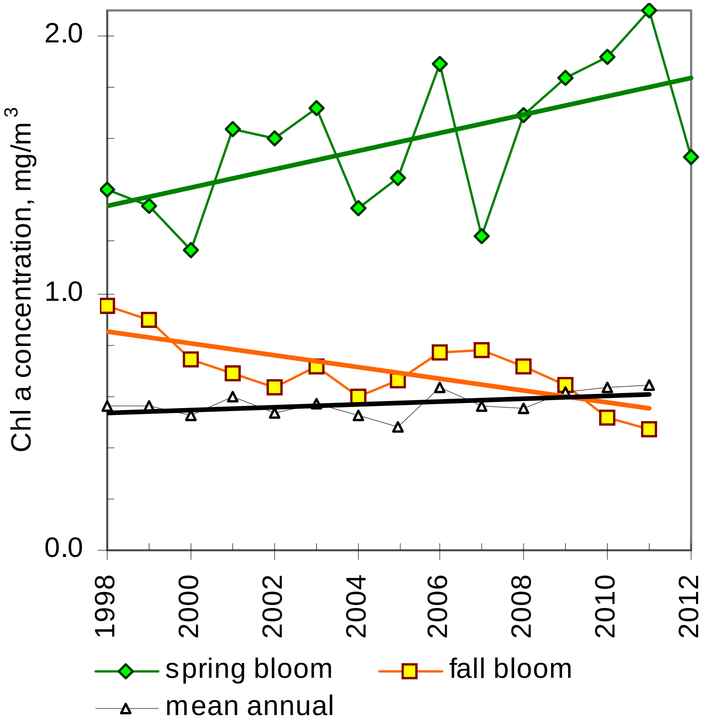
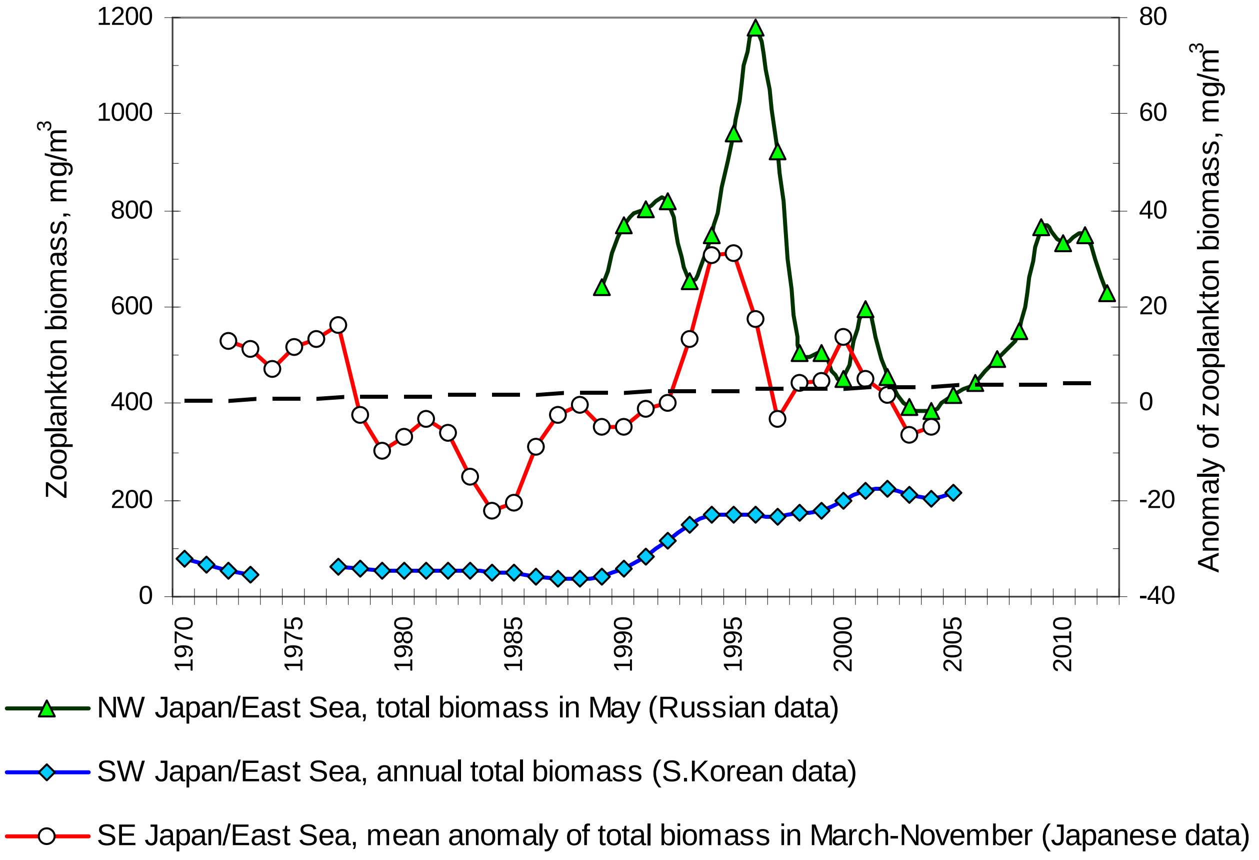


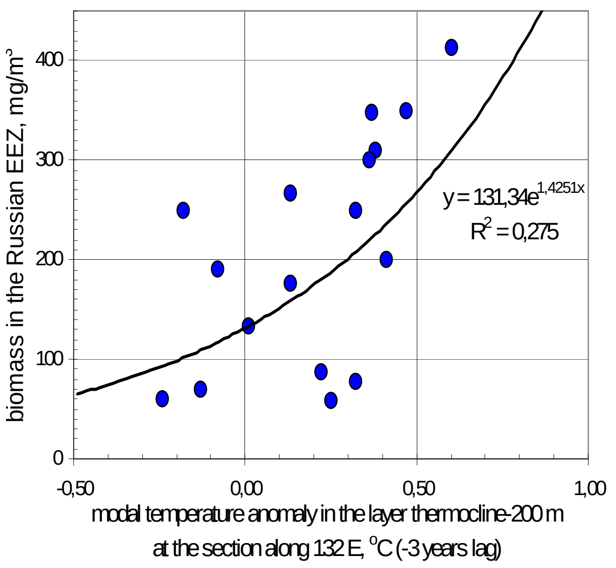
Mean annual Ch a concentration at the sea surface and its concentration in the months of spring and fall blooms, averaged for the whole deep-water part of the Japan/East Sea (from the data of satellite-mounted SeaWiFS and MODIS color scanners: http://oceancolor.gsfc.nasa.gov/)

Zooplankton: no trend, decadal oscillations

Zooplankton biomass changes in accordance with both SST (the colder, the better) and the Intermediate Water temperature (the warmer, the better). Recently, the zooplankton abundance is high because of warming the Intermediate Water and cooling at the sea surface. The zooplankton dynamics has no any significant trend.



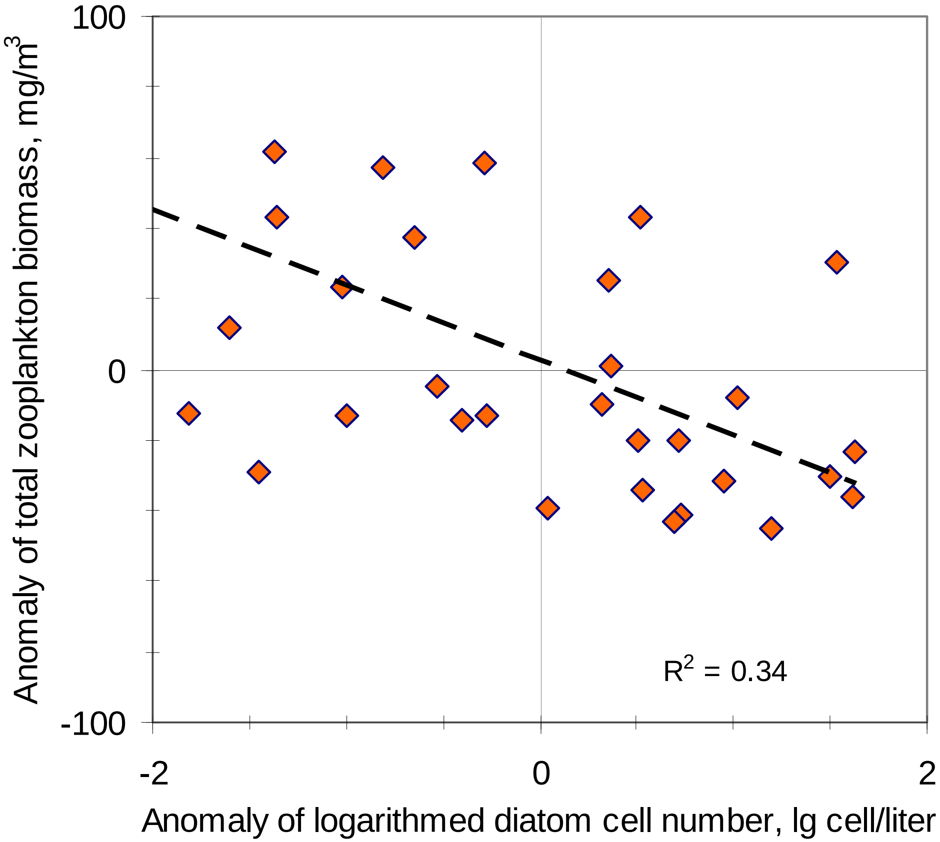
*Zooplankton abundance changes (smoothed) in the SE (red, from **Tian et al., 2008**); SW (blue, from **Kang et al., 2011**), and NW (green: from the data base collected by **Natalia Dolganova**) of the Japan/East Sea. Trend for the SE sector is shown.*



Zooplankton biomass (NW part) dependence on the Intermediate Water temperature (positive, 3 yr lag)

Zooplankton vs Phytoplankton: negative correlation!

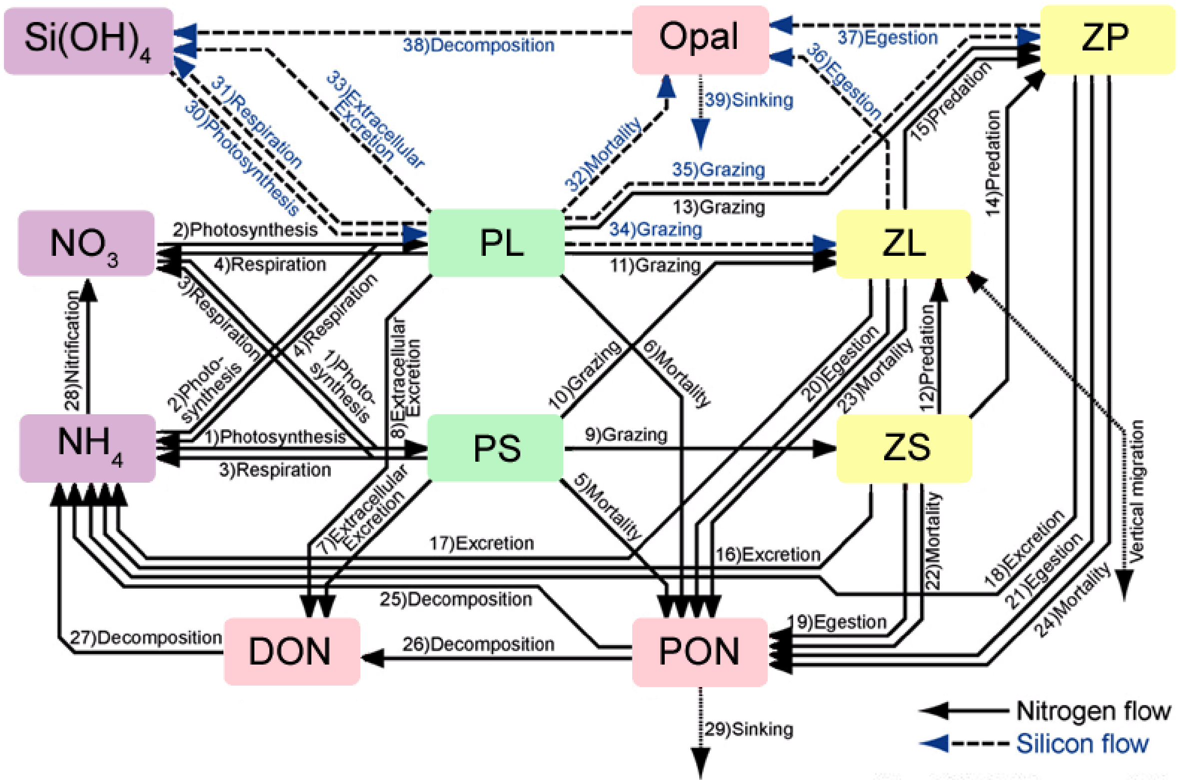
Decadal oscillation of zooplankton biomass are opposite to the changes of spring phytoplankton abundance. Of course, that does not mean that zooplankton “likes” lack of food, but the reason is favorable conditions for zooplankton reproduction in the years unfavorable for phytoplankton bloom.



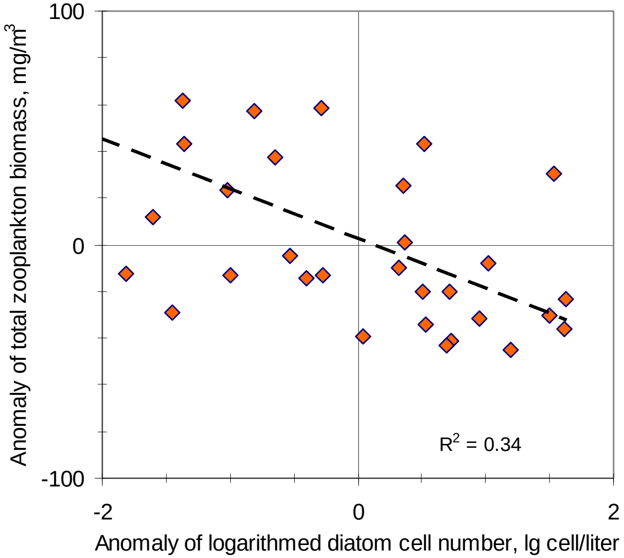
Correlation between zooplankton biomass and phytoplankton abundance in the SE Japan/East Sea (PM-line) in spring (all data from: ***Tian et al., 2008****)*

Zooplankton vs phytoplankton: grazing does not depend on the bloom

Ivlev approach is used usually in ecosystem modeling for grazing. Under this approach, the grazing value depends on abundance of prey only in cases with low concentration of the prey, in other cases it depends on abundance of predators only. Obviously, this approach is quite realistic in conditions of the Japan/East Sea – that's why zooplankton does not depend on phytoplankton abundance during its blooms.



*NEMURO prototype low-trophic model (from: **Kishi et al., 2006**)*



*Correlation between zooplankton biomass and phytoplankton abundance in the SE Japan/East Sea (PM-line) in spring (all data from: **Tian et al., 2008**)*

$$\mathrm{GraPL2ZLn} = \mathrm{Max}[0, \mathrm{GR_{max}}L_{\mathrm{pl}} \exp(k_{\mathrm{GraL}}\mathrm{TMP})$$

$$\times \{ 1 - \exp(\lambda_{\mathrm{L}}(\mathrm{PL2ZL^*} - \mathrm{PLn})) \}\mathrm{ZLn}]$$

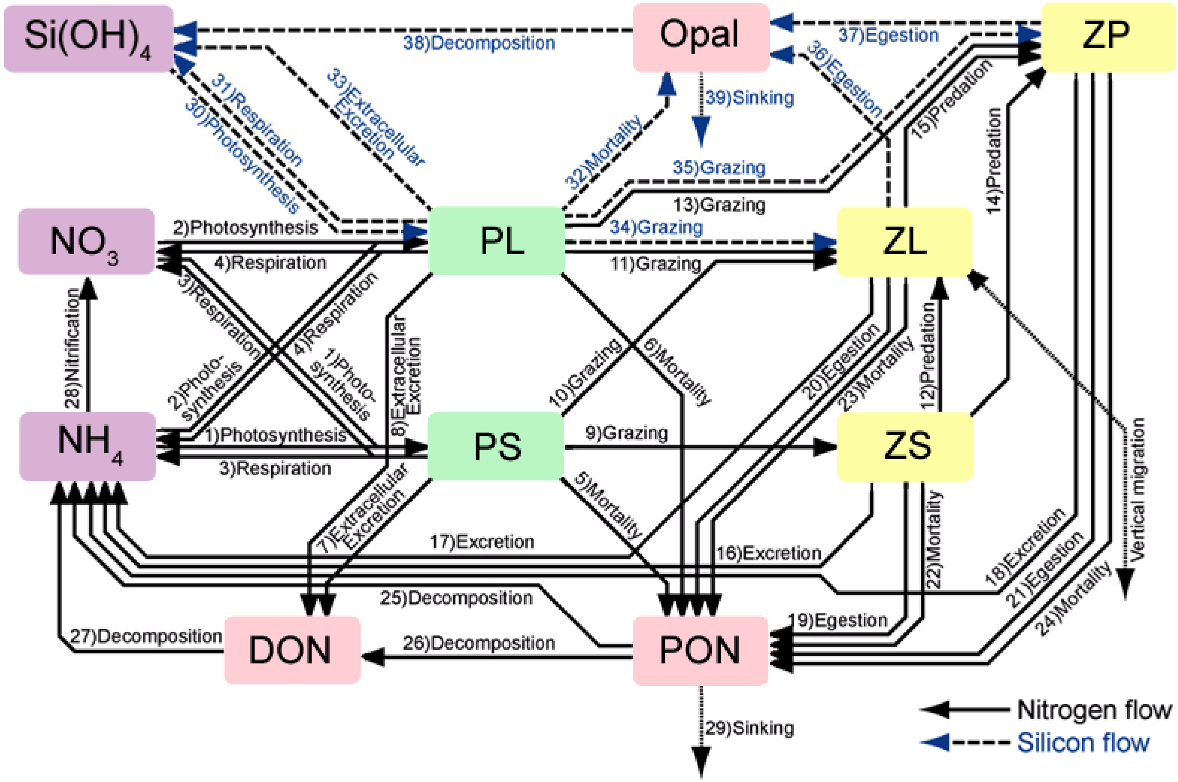
$\mathrm{GR_{max}L_{pl}}$ = 0.4 $\mathrm{day^{-1}}$ (Large zooplankton maximum grazing rate on PL at 0 deg C)
k_{GraL} = 0.0693 deg C-1 (Large zooplankton temperature coefficient for grazing)
λ_L = 1.4 (micro mol N l-1)-1 (Ivlev constant for ZL)
PL2ZL* = 0.04 micro mol N l-1 (Large zooplankton threshold value for grazing on PL)
PLn = large phytoplankton concentration, diatoms (micro mol N l-1)

ZL = **Grazing – Predation – Egestion – Excretion – Mortality**

Zooplankton: reproduction component is absent in ecosystem models

NPZD ecosystem models usually have not any certain flux that describes reproduction. The reproduction process is considered together with growth, so it is included into the Grazing flux. And the grazing depends mainly on zooplankton abundance, with only slight relation to environments.

In real, the reproduction success have more complicated dependence on fecundity, development rate, larvae survival, and other factors, and most of them depend strongly on environmental conditions.



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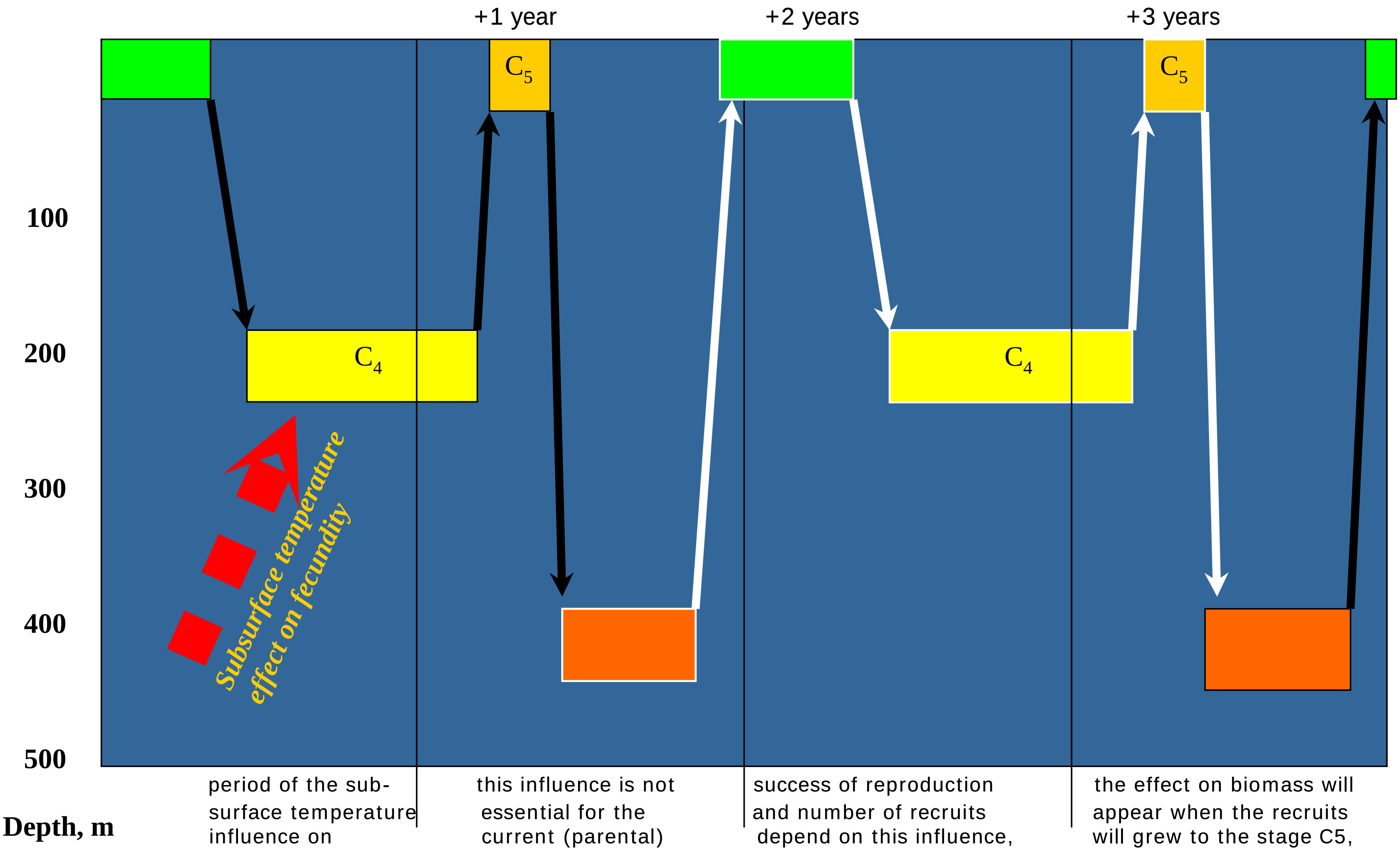
Zooplankton: possible mechanism of temperature influence on reproduction of large-sized Copepoda with 2-years life cycle



period of the sub-surface temperature influence on copepods maturing

this influence is not essential for the current (parental) generation abundance but affect the fecundity

success of reproduction and number of recruits depend on this influence, but the biomass of recruits is insignificant at first

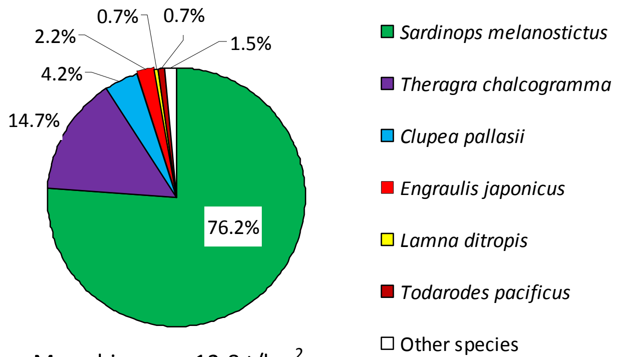
the effect on biomass will appear when the recruits will grew to the stage C5, i.e. in the 3rd year after the impact

Nekton: species structure reconstruction

Species composition of nekton changed fundamentally in the last several decades, with replacement of dominant species. Sardine dominated in 1980s, but common squid dominates since the middle 1990s.

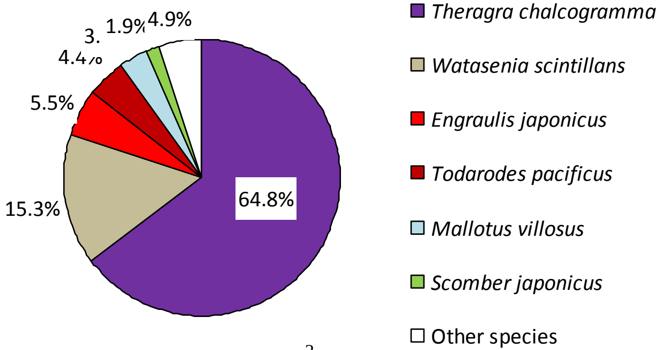
Generally, biomass of nekton is determined by trophic status of dominant species: it was very high in the period of planktivorous sardine, but rather low in the period of predatory common squid.

1981-1990



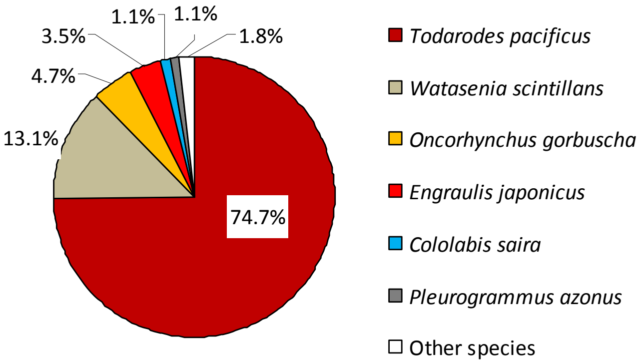
Mean biomass: 12.8 t/km^2

1991-1995



Mean biomass: 1.2 t/km^2

Since 1996

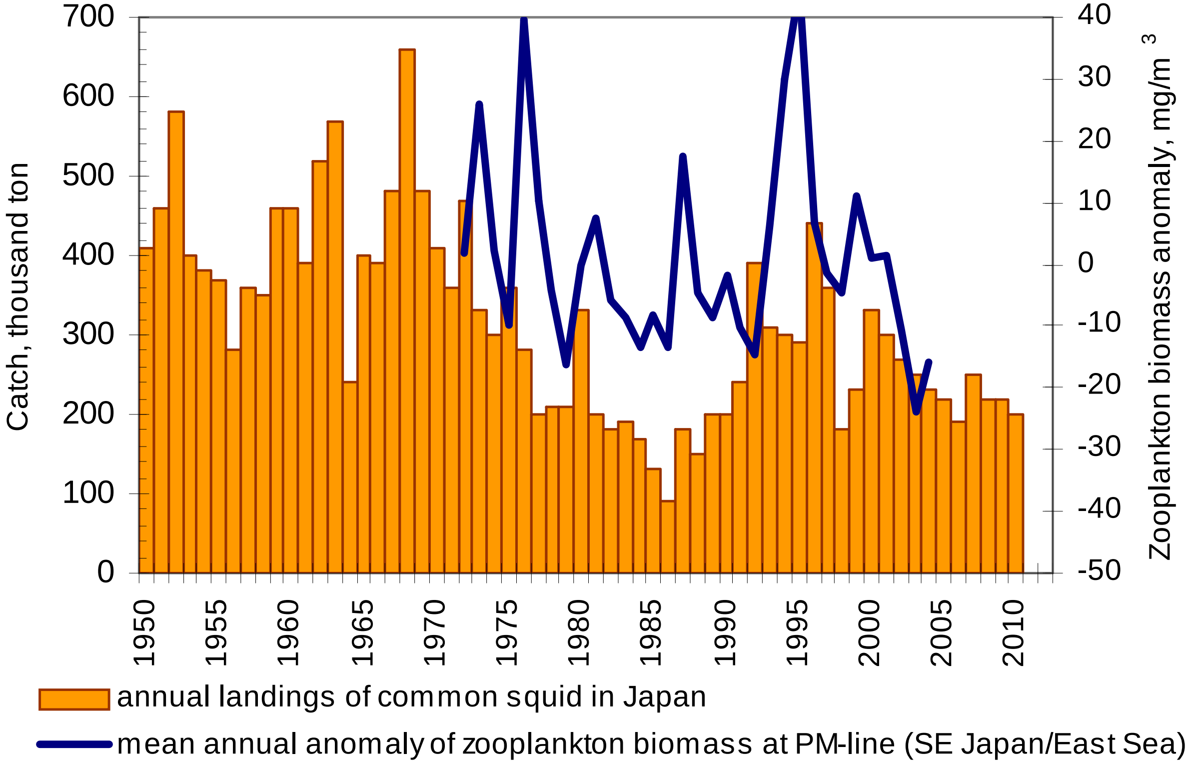


Mean biomass: 0.9 t/km^2

Ratio of pelagic nekton species biomass in the northwestern East Sea (from ***Sukhanov, Ivanov, 2009****)*

Nekton: common squid *Todarodes pacificus*

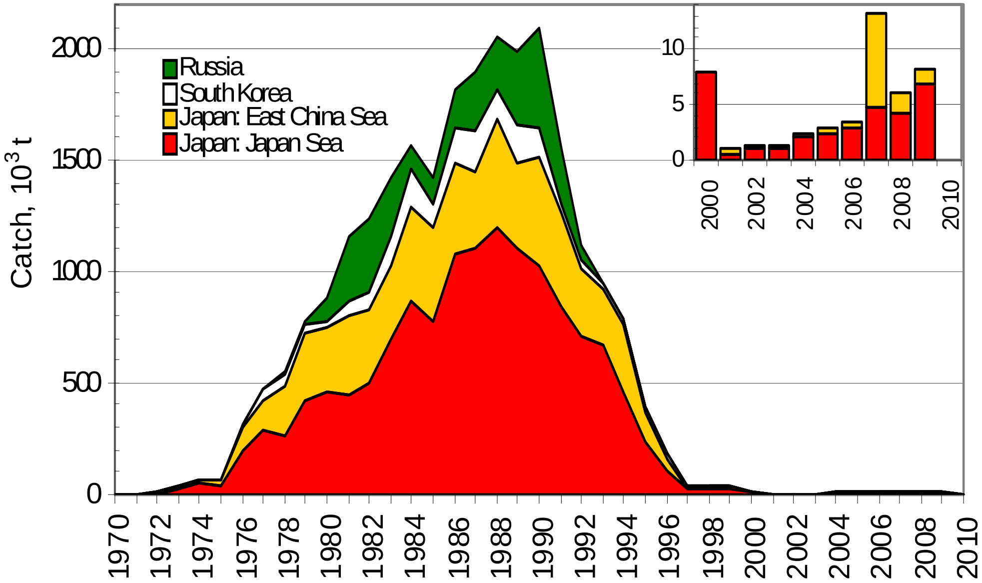
Abundance of common squid (as could be seen from its annual landings) is well-correlated with zooplankton abundance. Possibly, its reproduction depends on zooplankton abundance (bottom-up control) or on the same factors as the zooplankton abundance.



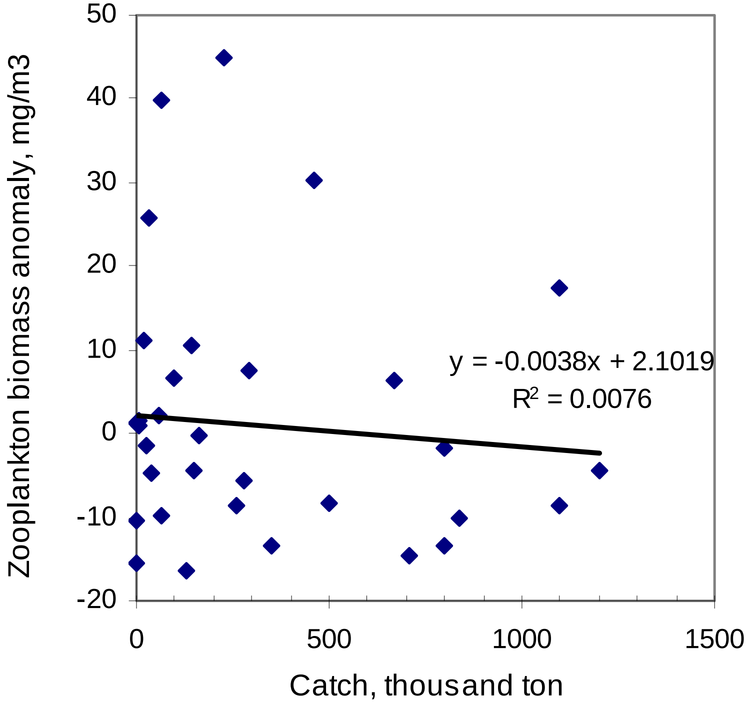
Year-to-year changes of total annual landings of common squid in the Japan/East Sea by Japan (from fishery statistics) and mean annual anomaly of zooplankton biomass at PM-line in the SE Japan/East Sea (from ***Tian et al., 2008****)*

Nekton: japanese sardine *Sardinops melanostictus*

Changes of the japanese sardine abundance (as could be seen from its total annual landings) are opposite to the decadal changes of zooplankton abundance. Possibly, the zooplankton abundance depends on the sardine grazing (top-down control) or reproduction of sardine and zooplankton are determined by opposite factors.



Year-to-year changes of total annual landings of japanese sardine in the Japan/East Sea by Japan, S.Korea, and Russia (from fishery statistics)



Relationship between annual landings of japanese sardine in the Japan/East Sea by Japan, S.Korea, and Russia and mean annual anomaly of zooplankton biomass at PM-line in the SE Japan/East Sea

Nekton: winners and losers

In the last three decades, the following key species of fish and invertebrates have a prominent increasing of their stocks in the Japan/East Sea:

- **common squid** (stabilized in the 2000s)
- **yellowtail**
- **spanish mackerel**
- **japanese anchovy** (retreated in the 2000s)
- **jack mackerel**
- **sailfin sandfish**
-.**pacific herring** (southern population only)

The following species have prominent decreasing of their stocks in the Japan/East Sea:

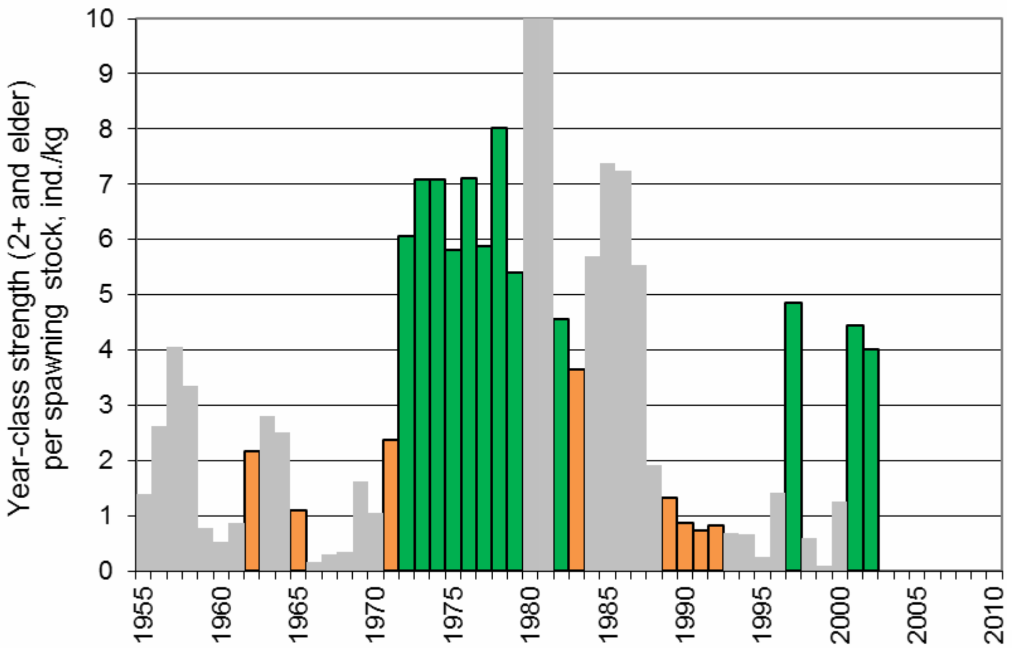
- **pacific cod** (partially restored in the 2000s)
- **saffron cod** (partially restored in the 2000s)
- **walleye pollock**
- **japanese sardine**

Nekton: a case of japanese sardine

Huge fluctuation of the sardine stock have decadal scale; its reproduction has not any significant relationship with the environmental changes of climate scale (warming).

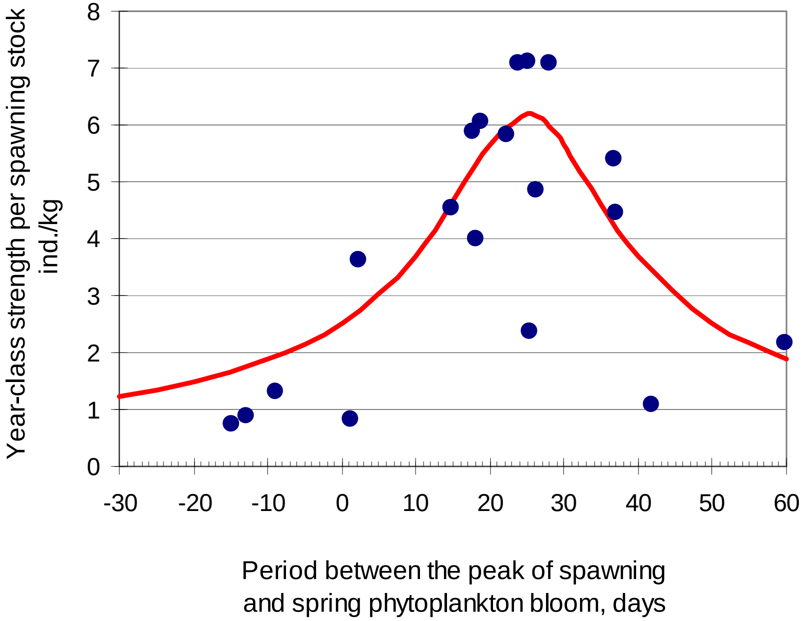
The sardine reproduction began to worse before the climate shift in the late 1980s, and some its strong generations appeared after the shift, in warm conditions of the late 1990s.

One of the most important conditions for successive reproduction of sardine is the match of its larvae hatching with the spring blooming: they match if the peak of spawning occurs in 15-36 lays before the peak of blooming.



*Year-to-year changes of the sardine reproduction efficiency index (year-class strength per spawning stock) for the Japan/East Sea (from: **Zuenko, submitted to Fisheries Oceanography**)*

Reliable values are shown as dark-colored bars, the values considered as unreliable because of extremely high or extremely low landings of young fish are shown in light-grey



Approximation of the sardine reproduction success dependence on match/mismatch of spawning with spring bloom by resonance function:

$$N_i = \frac{a}{\sqrt{1 + [Q \cdot (T_i - T_R)]^2}}$$

where T_R = 25 days; Q = 0.09; a = 6.2 ind./kg

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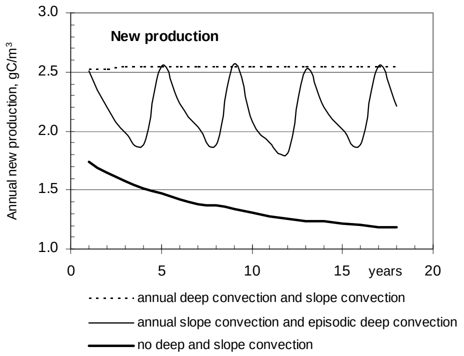
Ecosystem: winners and loosers

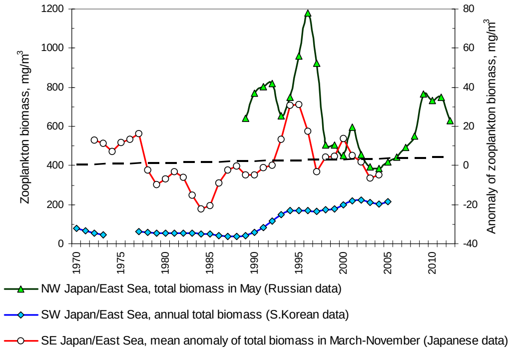
In the last three decades, the Japan/East Sea ecosystem had controversial changes caused by complicated influence from its environments:

- **Primary production decreasing** (in model):
  from 2.5 to 1.2 gC/m^3 in 2 decades

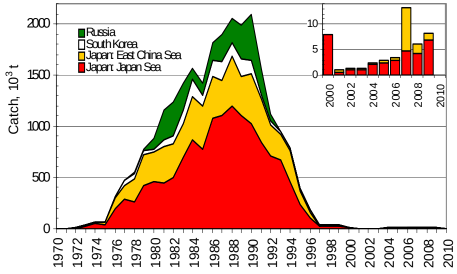


- **Phytoplankton abundance decreasing** (trend is not clear)

- **Zooplankton abundance stability or increasing** (trend is not significant):
  +1 mg/m^3 per decade for the SE part



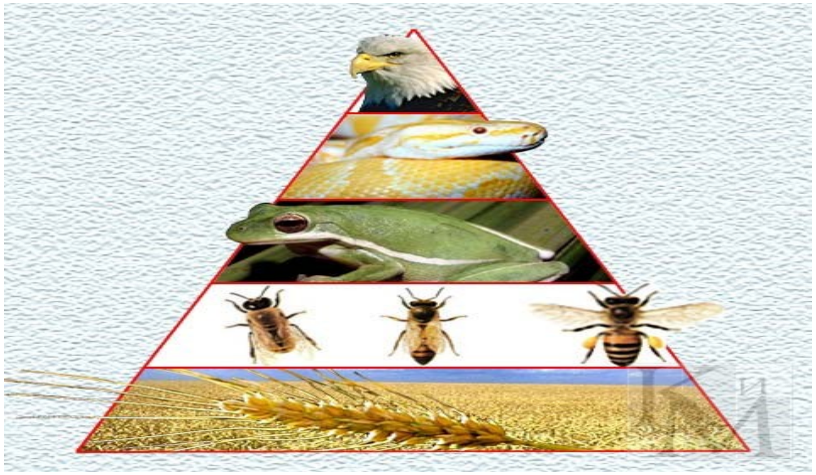
- **Nekton biomass decreasing** (because of sardine collapse, but the **biomass increasing** for many species):
  in 10 times after sardine collapse in the 1990s, but trophic status is changed



These changes cannot be simulate by the ecosystem models based on the growth/grazing balance, but reproduction should be taken into account.

Ecosystem: growth of effectiveness after regime shift in the late 1980s

Thus, huge amount of phytoplankton is produced in the Japan/East Sea in springs after cold winters, but it cannot be consumed by zooplankton – the ecosystem works inefficiently. And it is generally more effective in cases of warm winters, when spring bloom is weaker and new production is utilized more rationally, though these changes can affect negatively on some herbivorous species (as winter-spawning ones).

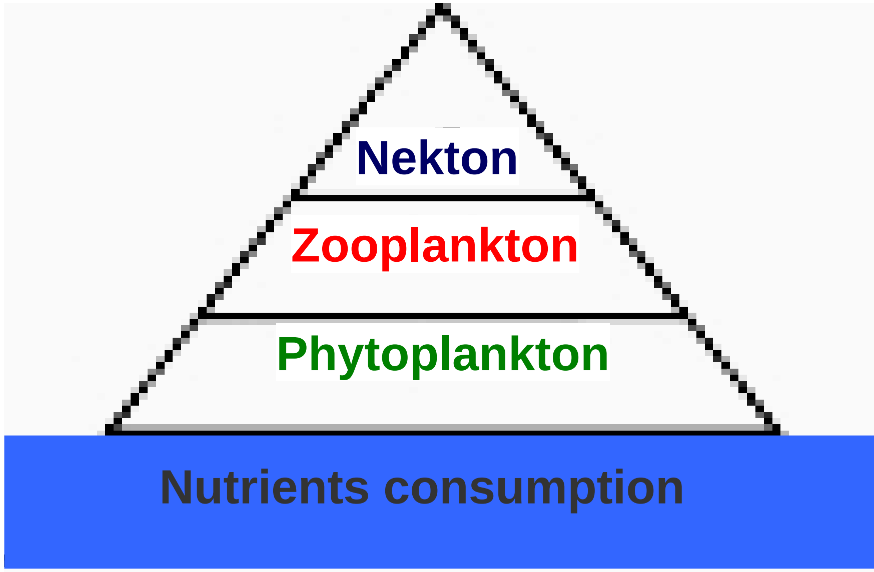


Recent tendencies in the Japan/East Sea ecosystem could be described as a transition from **high-productive low-effective** ecosystem of subpolar seas to **low-productive high-effective** one typical for subtropic waters.

The ecosystem efficiency can be measured quantitatively as a ratio between annual new primary production and annual production of herbivorous zooplankton.

Quantitative estimation of the ecosystem efficiency (for the deep-water northwestern Japan/East Sea):

	1980s	1990s	2000s
Annual new production (modeled; gC/m^{3}yr)	2.5	1.4	2.1
Mean annual biomass of zooplankton (with correction to Jeday net catchability; WW, mg/m^3)	832	850	644
Mean P/B-coefficient of zooplankton ($a_* GR_{max}$, day^{-1})	0.12	0.12	0.12
Annual production of zooplankton (WW, g/m^{3}yr)	36	37	28
Annual production of zooplankton (gC/m^{3}yr)	1.3	1.3	1.0
Ratio Zooplankton / New Primary production (**coefficient of efficiency**), %	**52**	**93**	**48**



Nekton

Zooplankton

Phytoplankton

Nutrients consumption

Conclusion

1. **Physics: warming.** Recent changes in the Japan/East Sea ecosystem are driven mainly by winter warming in conditions of weak winter monsoon, in particular in the late 1980s, with partial retreat to cooling in the 2000s.

2. **Chemistry: nutrients burial.** Warm winter conditions prevent from active convective mixing that impedes the overturn of nutrients and decreases the new production.

3. **Phytoplankton: slight lowering.** Loss of new production causes weakening of phytoplankton spring blooms, though this effect is visible in decadal scale **but is not clear in climate scale.**

4. **Zooplankton: trend is not significant.** Zooplankton abundance changes in opposite to phytoplankton changes in decadal scale that could be explained by *i*) excessive biomass of phytoplankton during its blooms, and *ii*) changes in the zooplankton reproduction. The latter factor is not considered in ecosystem models. In the period of high stock of sardine, the zooplankton abundance could be influenced by grazing from sardine (top-down effect).

5. **Nekton: warm-species increasing.** Nekton reaction to climate change **is controversial**: many species increase their abundance, but other ones decrease the stock (mainly cold-water ones). However, the total biomass of nekton became in 10 times lower since the 1980s because of collapse of japanese sardine (theoretically, its population could be recovered even in warm environments).

6. **Ecosystem efficiency: heightening in “warm” conditions.** Generally, the changes in the Japan/East Sea ecosystem after the regime shift to warming in the late 1980s could be described as a transition from **high-productive low-effective** ecosystem of subpolar seas to **low-productive high-effective** one typical for subtropic waters.