Изучение морей Арктики в условиях глобальных изменений :

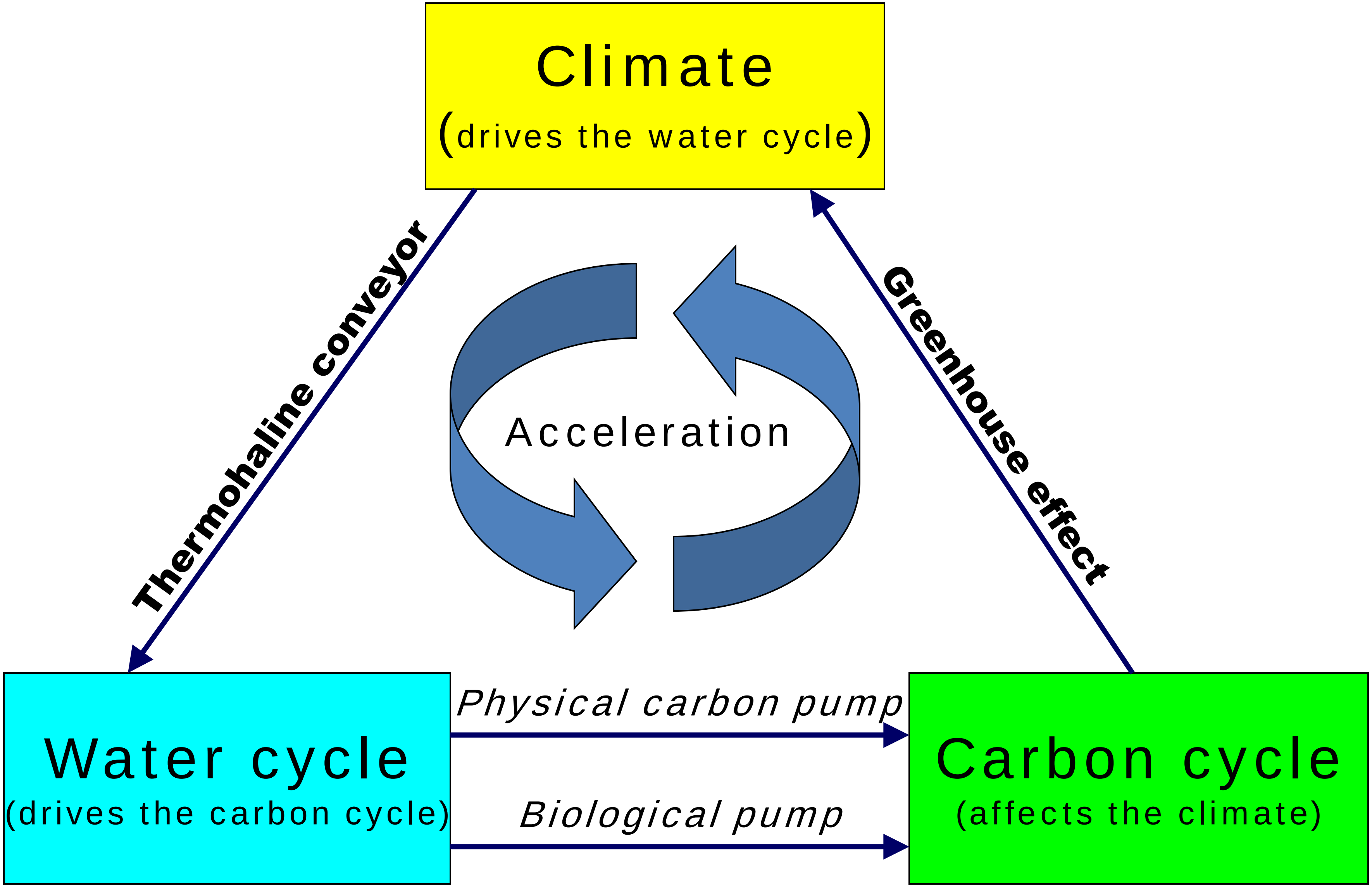
избранные результаты анализа 20 лет подспутниковых наблюдений

Игорь П Семилетов

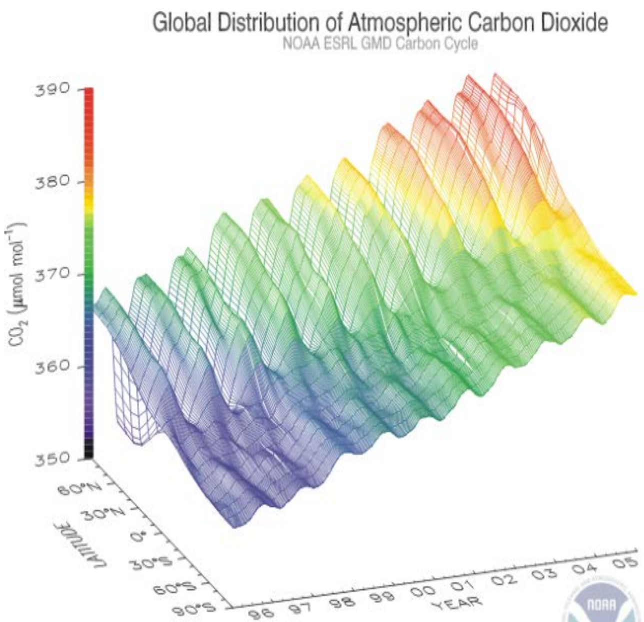
…and >70 colleagues from the Laboratory of Arctic Research POI FEBRAS, International Siberian Shelf Study (ISSS) and SWE-RUS-US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions (SWERUS-C3) programs (Stockholm university , IE HSE, TPU/TGU, MSU/Chemical Dpt, and others)

ИКИ РАН

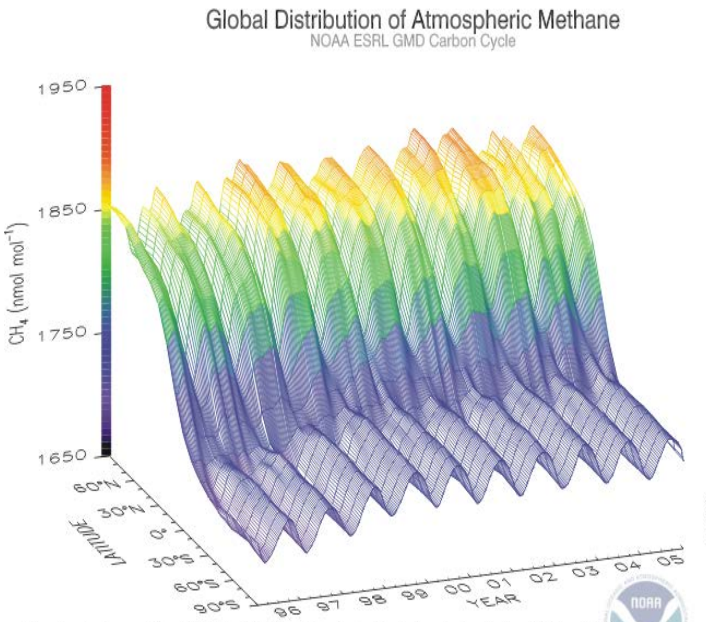
2021


Climate
(drives the water cycle)
Thermohaline conveyor
Greenhouse effect
Acceleration
Water cycle
(drives the carbon cycle)
Physical carbon pump
Biological pump
Carbon cycle
(affects the climate)

Global distribution of atmospheric concentration of main greenhouse Gases (GG) : CH4 and CO2, exhibits existence of their maximums above the Arctic where GG anthropogenic emission is negligible



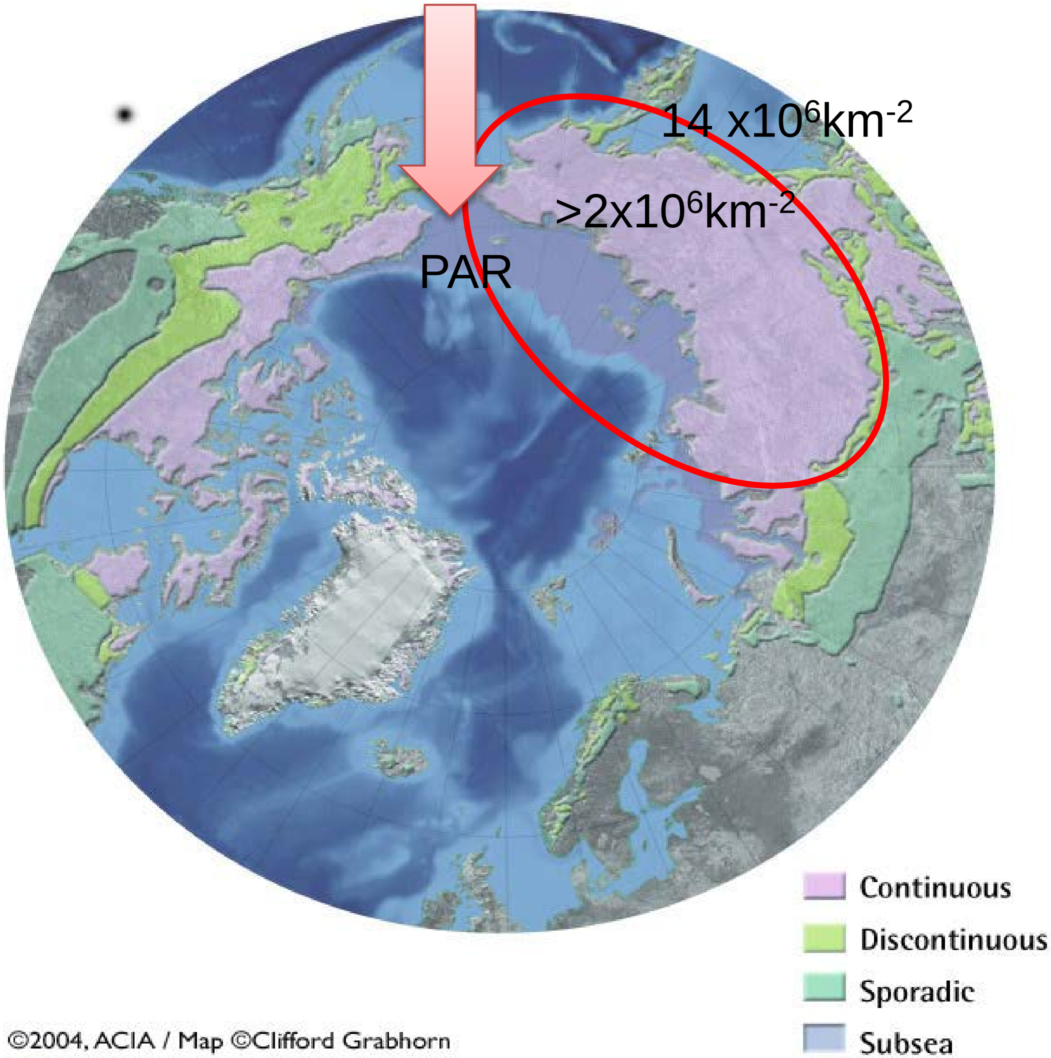
Three dimensional representation of the latitudinal distribution of atmospheric carbon dioxide in the marine boundary layer. Data from the GMD cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Pieter Tans and Thomas Conway, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).



Three dimensional representation of the latitudinal distribution of atmospheric methane in the marine boundary layer. Data from the GMD cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Ed Dlugokencky, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6228 (ed.dlugokencky@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

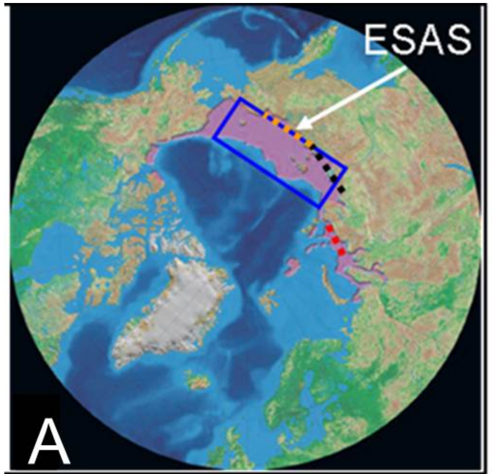
Our driving hypothesis: In climate time scale, planetary maximum of main greenhouses gases (GG), CO2 и CH4, is driven by permafrost (PF) thawing involving huge pools of carbon in the Arctic PF-related pools

Specific feature of the Arctic Ocean is cryosphere (permafrost and sea ice) - the most sensitive to warming

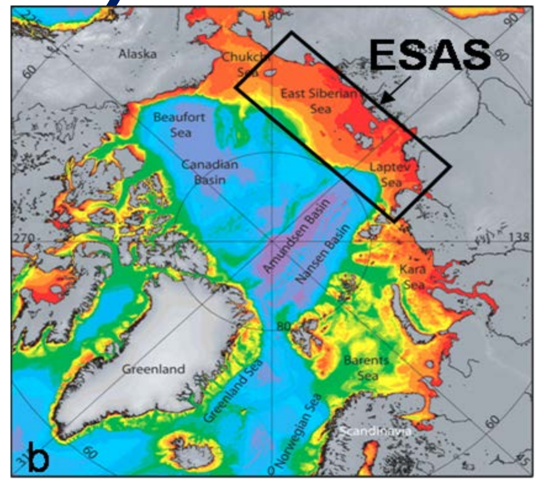


- **Arctic Ocean (AO) is surrounded underlain by permafrost; >90% of the predicted subsea permafrost is located on the ESAS/PAR shelf; the total area of permafrost is ≈ 14×10^6 km^2;**
- **50% of the world's carbon stock is in the Arctic region;**
- **Artic is warming twice as fast as the rest of the world.**

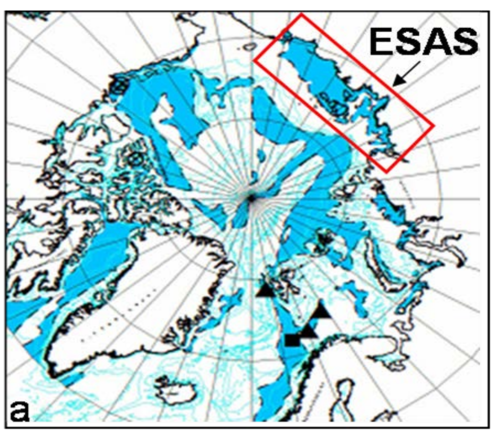
Why the Pacific Arctic Region / East Siberian Arctic Shelf (ESAS)?



>80% of predicted global sub-sea permafrost in the ESAS



~50% of AO is shelf seas; >80% of ESAS is shallower than 50 m

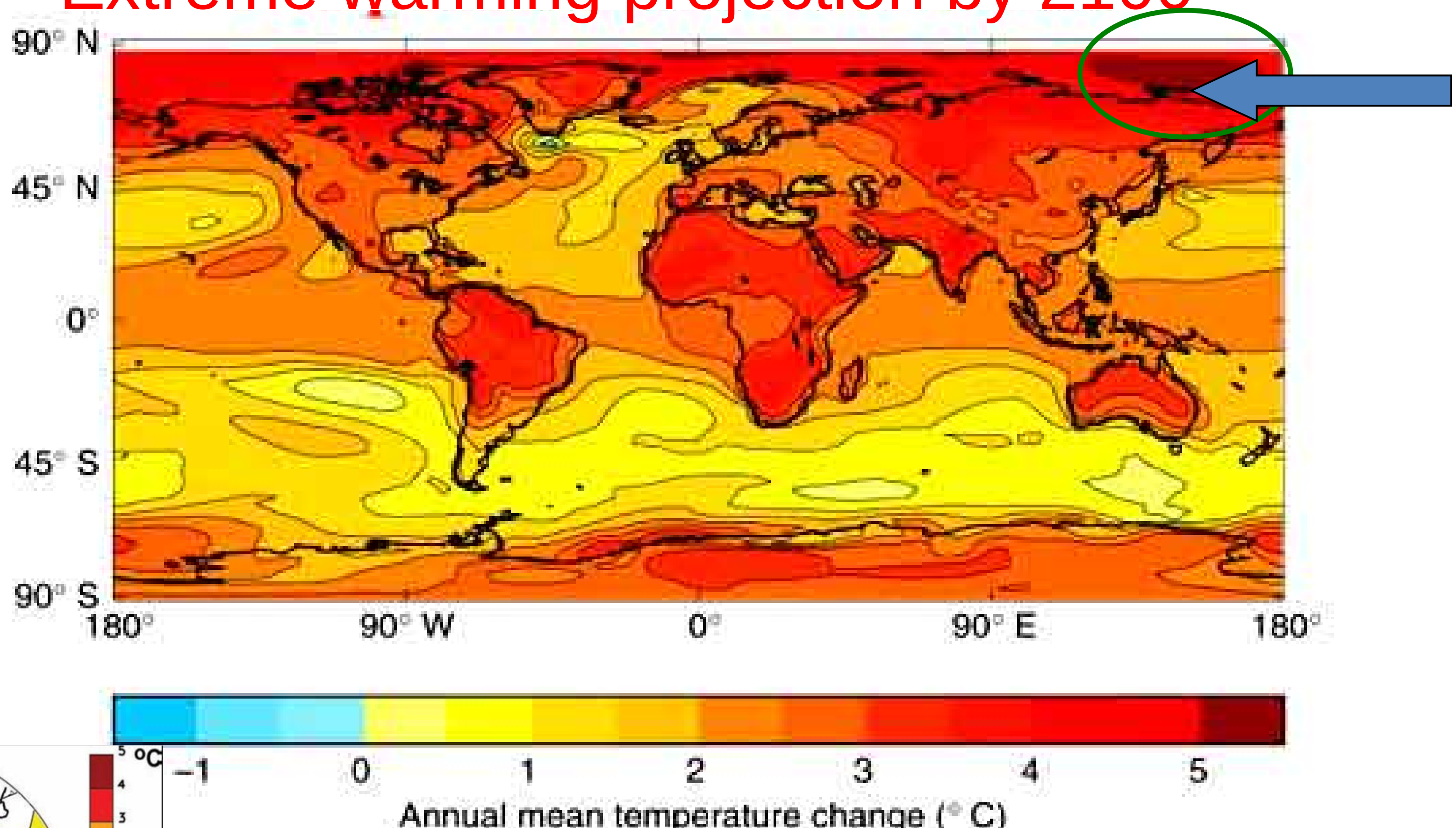


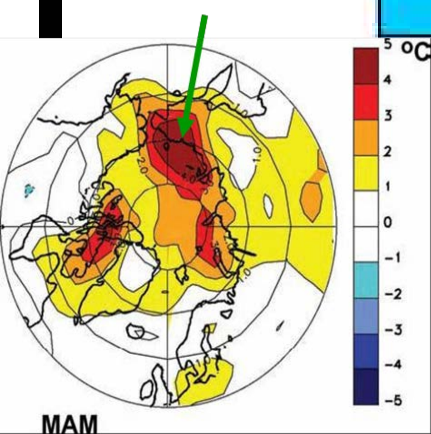
>80% of predicted shallow Arctic hydrate deposits underlies the ESAS

Strong Terr-C input: erosion of ESAS coastal Yedoma and discharge of major rivers

Arctic is warming twice faster than a rest of a world

Extreme warming projection by 2100





BUT <u>PAR/ESAS is already there</u>. See MAM air temperatures in the Pacific Arctic Region (NOAA custody)

The ESAS accumulates fresh water from 6 Arctic Siberian Rivers and it is the major ice factory of the Arctic Ocean

- 6 Siberian Rivers – Khatanga, Olenek, **Lena**, Yana, Indigirka and Kolyma bring their waters to the ESAS ≈ 700 km^3, which is similar value with the Transdrift ice export

- Total area of watershed of the Lena River alone is comparable with that of the ESAS ($2.5x10^6$) km^2

Carbon stocks most sensitive to warming are all in the Arctic

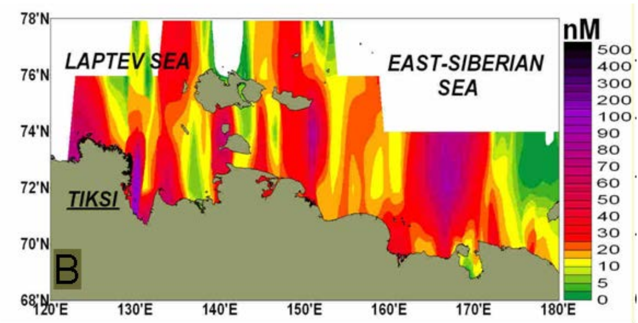
Tundra/taiga permafrost (still cold, T~-10ºC)

- Pool size (0-3m): ~**1400 Pg-C**
- thaw/erosion-release of OC, CO_2 and CH_4
- Echoed in rivers (Arctic boundless C cycle)

Photo: P. Kuhry (PPP, 2009)

Subsea permafrost on Siberian shelf (in transition, T~ -1ºC)

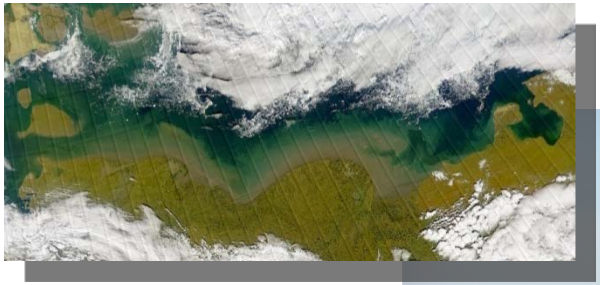
- Pool size: **~1000-1400 Pg-C (incl deep pools)**
- IPCC/ACIA: "permafrost lid" holds CH_4 in place
- but, elevated CH_4 levels in shallow bottom waters



Data: Shakhova et al. (Science, 2010)

Coastal Permafrost Complex / Yedoma

- Pool size: **~ 400 Pg-C**
- Pleistocene Ice Complex Deposit (ICD)
- thermal collapse, incr wave erosion
- thaw-release of OC and degr to CO_2



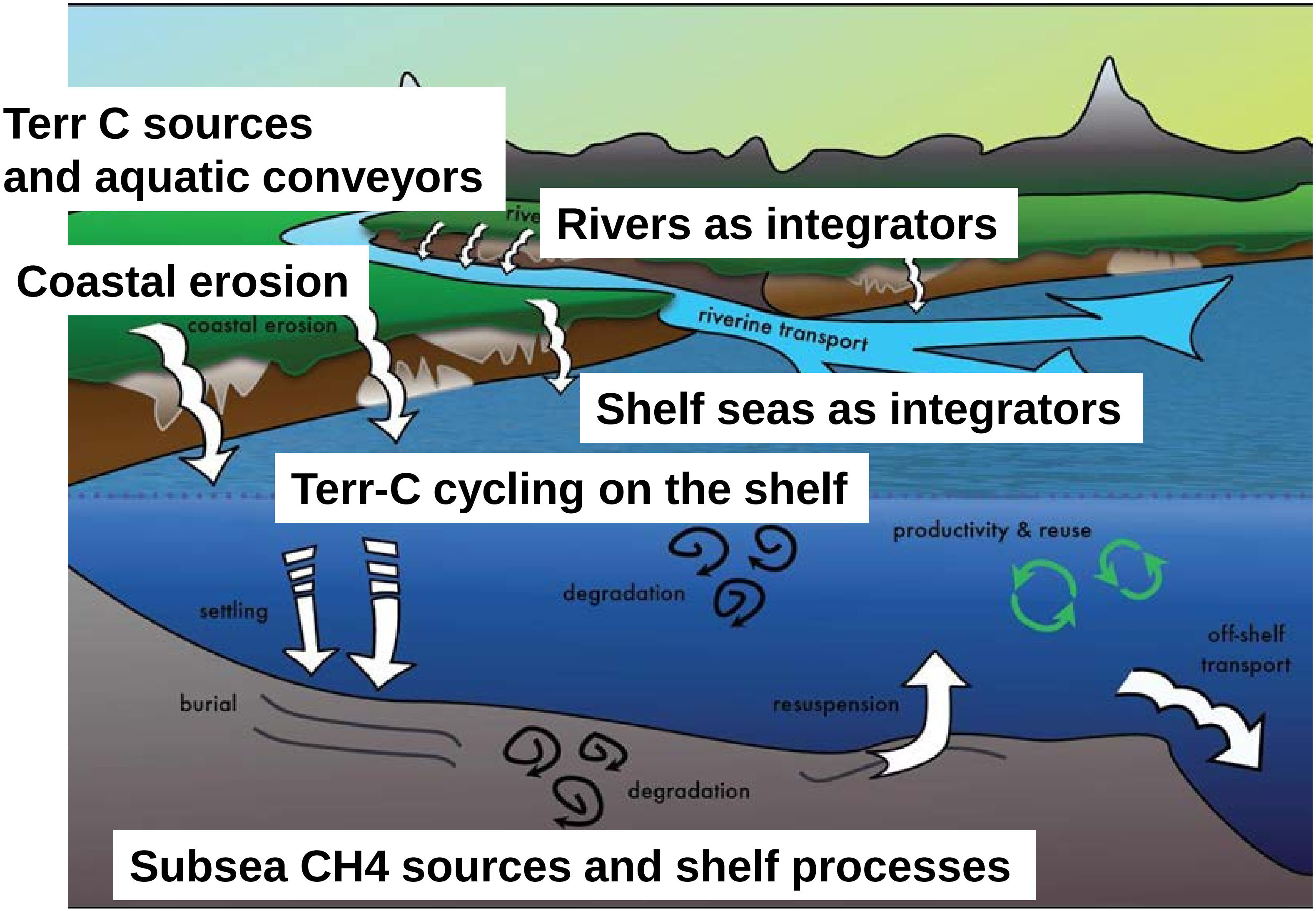
4000 km of East Siberian Arctic Coast

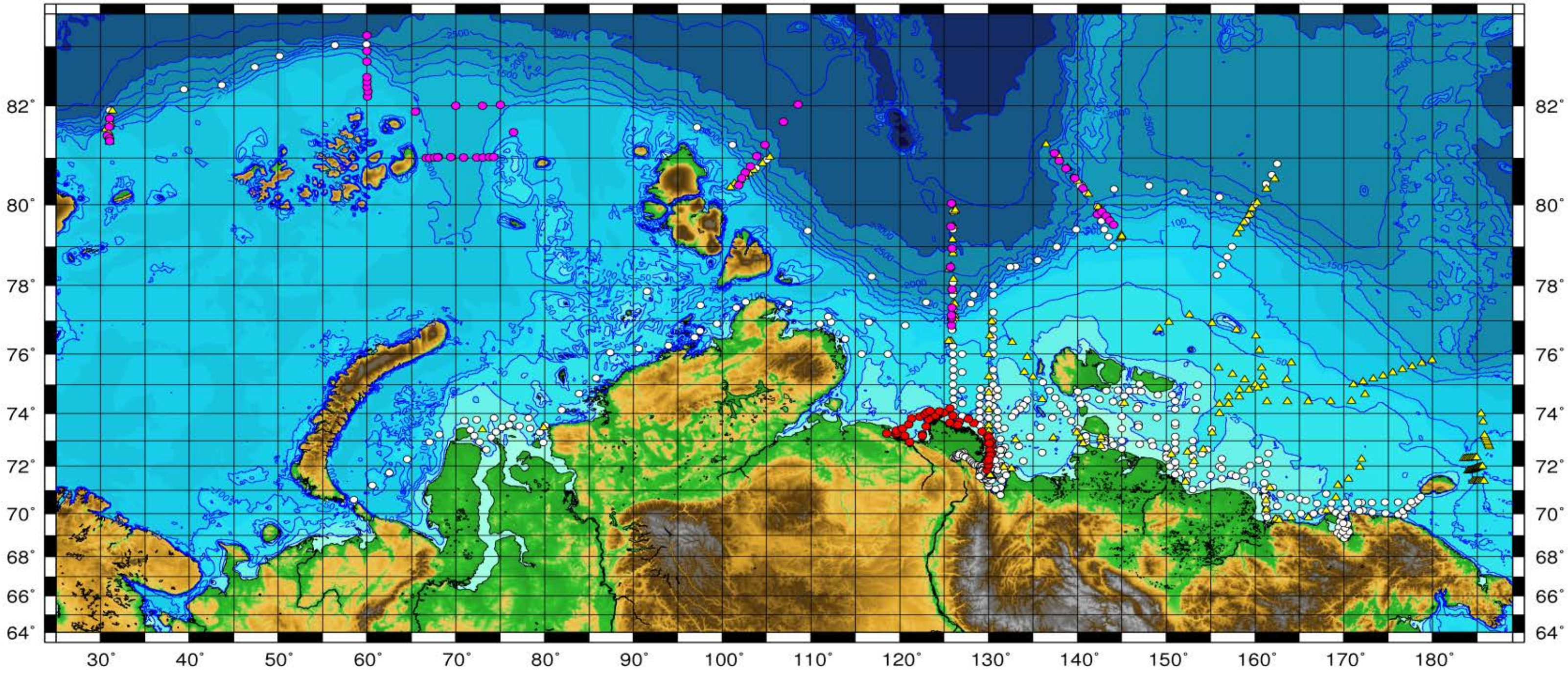
Photo: A. Charkin

Atmospheric pool, for comparison
CO_2: 760 Pg and CH_4: 5 Pg

1 Pg = 1 billion ton

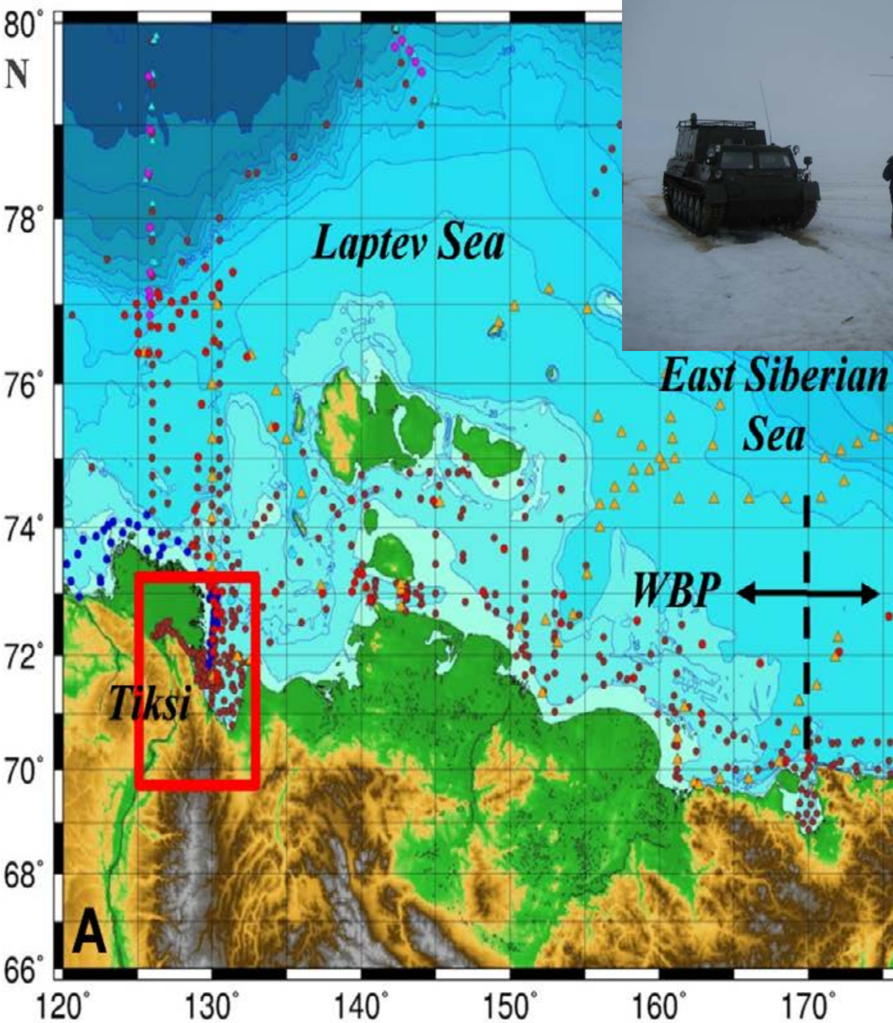
Terrestrial carbon sources and processing in the PAR/ESAS land-sea-slope system



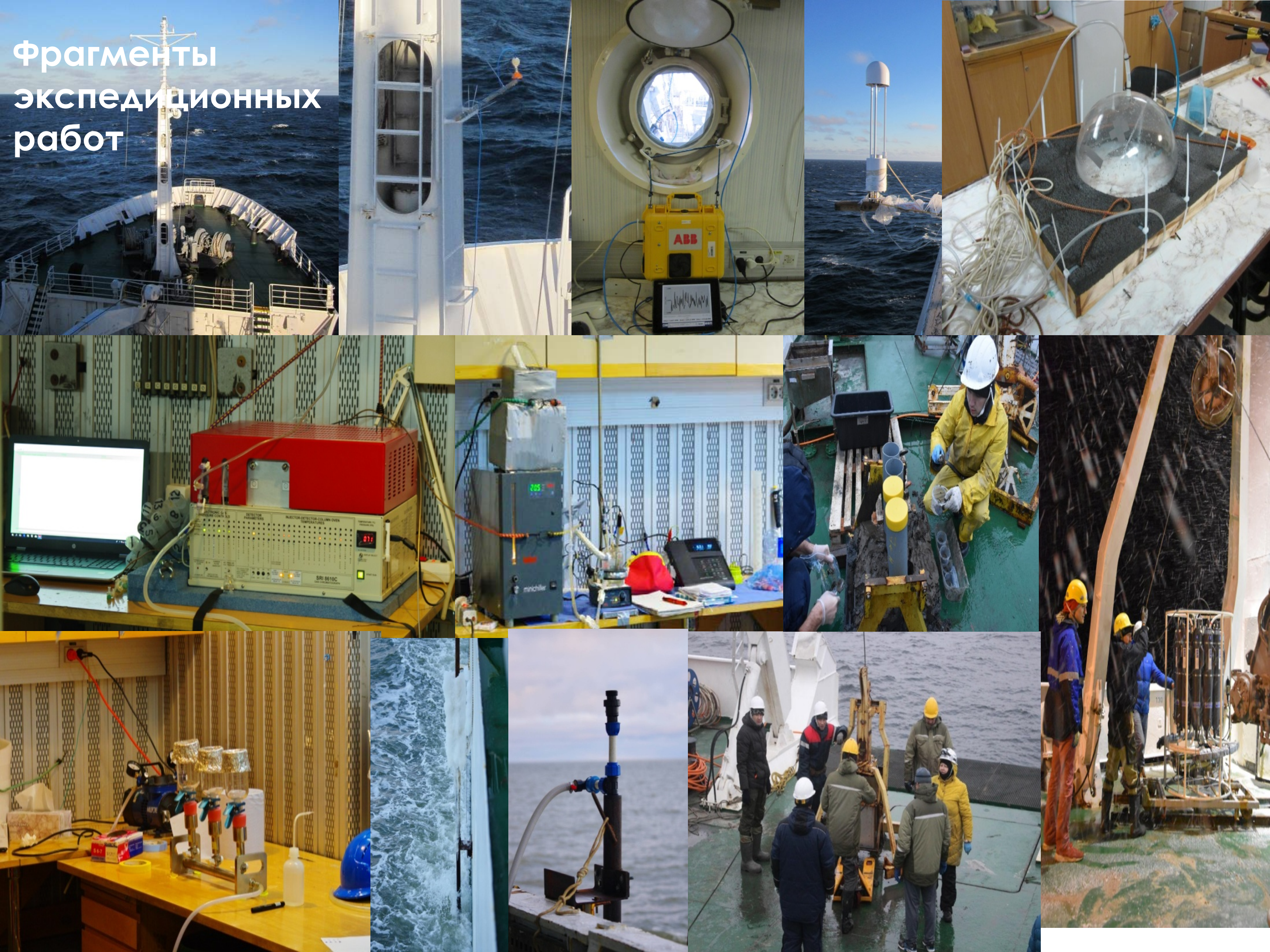


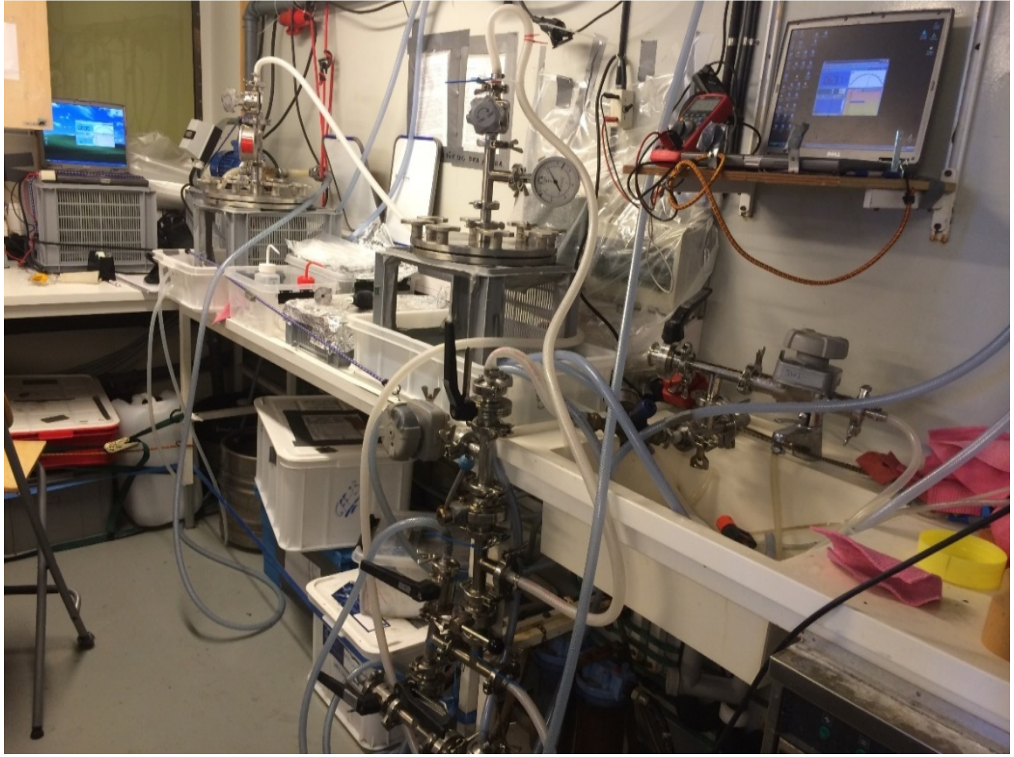
The overall *goal* of this study is to provide a quantitative, observationally-based assessment of the dynamics of different components of the East Siberian Arctic Shelf (ESAS) carbon cycle under conditions of changing climatic and environmental conditions

From 1999 to 2021 accomplished 49 all-seasonal expeditions, >3,500 oceanographic stations, >70,000 n. miles of geophysical survey, 17 boreholes drilled



Фрагменты экспедиционных работ





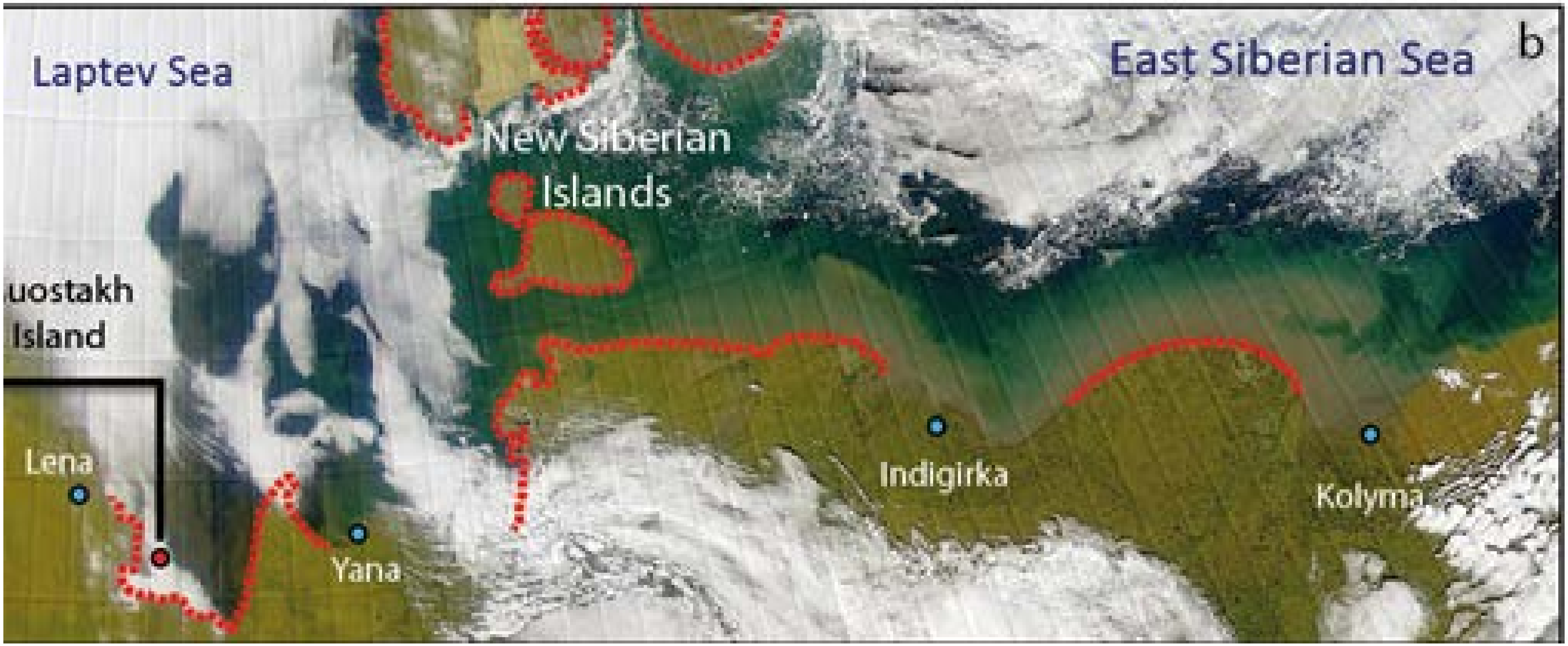
Фрагменты экспедиционных работ

Фильтрационная система для получения достаточно больших образцов взвешенного вещкства (ВВ) для проведения комплекса необходимых геохимических (биомаркеры, минералогия, химический состав) и изотопных анализов включая радиоуглеродный возраст органического вещества ВВ.

Использование экстракционной системы для извлечения метана из герметичных сосудов с пробами воды (пивные кеги) с последующей адсорбцией в холодной ловушке и измерения полного изотопного состава метана (C13, D, C14)

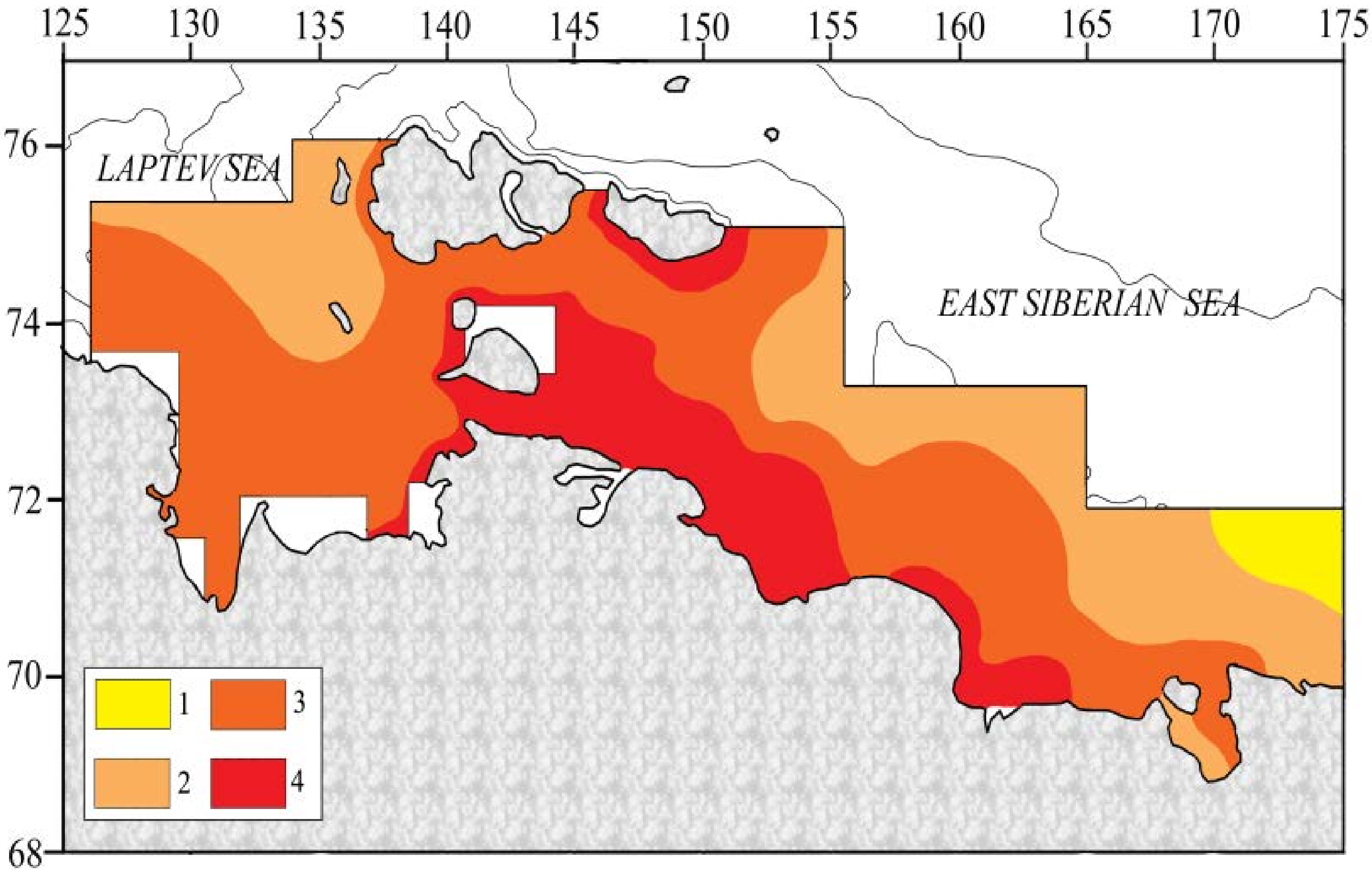
Фрагменты экспедиционных работ

Erosion of C-rich Ice Complex Deposits (ICD)along the Arctic coasts



Satelite image of shelf water turbidity caused by coastal erosion

Pleistocene ICD-OC dominates in surface sed. OC on World's largest shelf



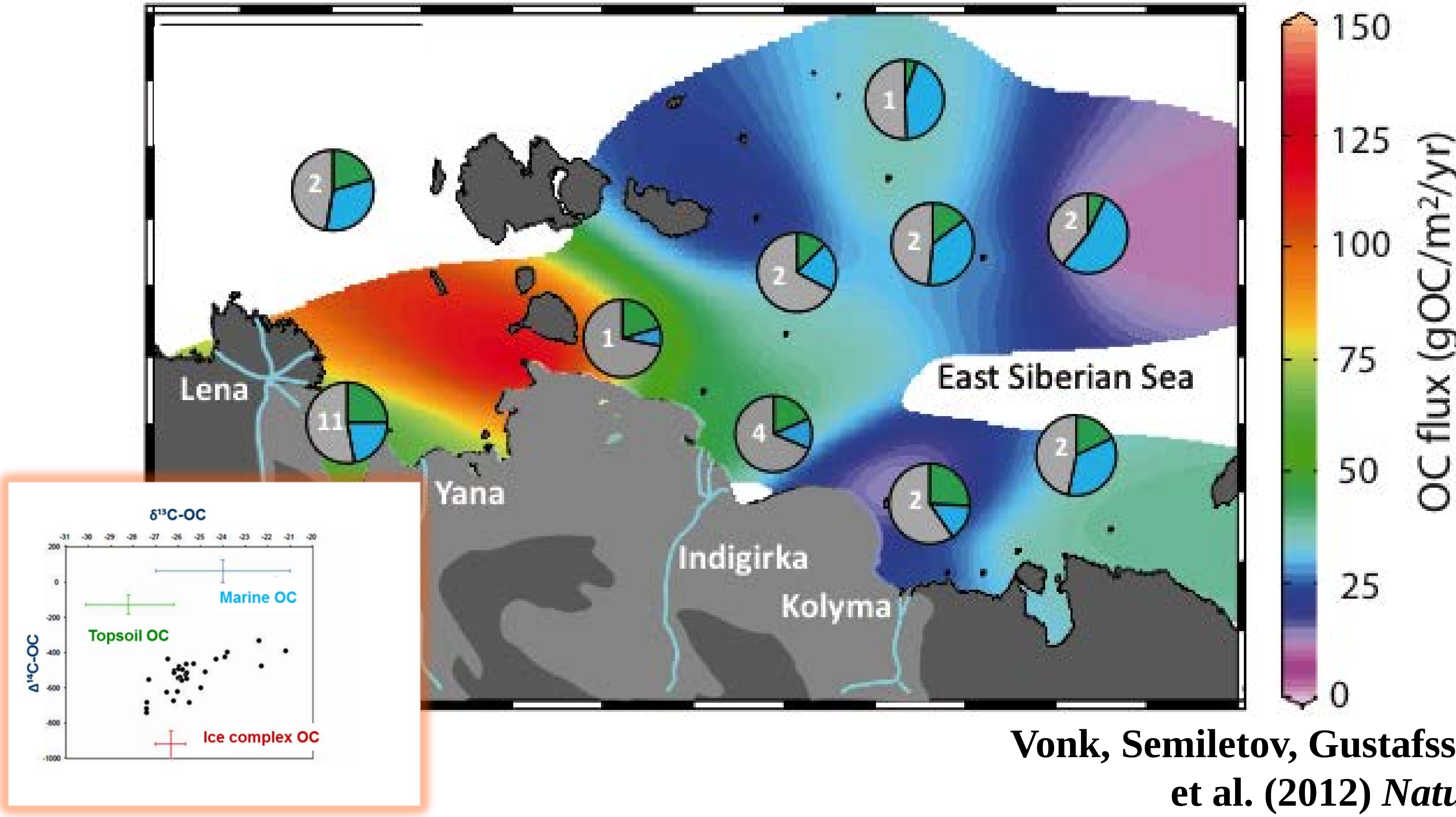
OM ccontribution of terrestrial organic carbon (CTOM, %)) in the surface ESAS sediments 1) <40%, 2) 40-69%, 3) 69-98%, 4) 98-100%

Semiletov et al., *Biogeosciences* (2011); Semiletov et al., *Environment. Res. Letters*(2012)

In present Pleistocene ICD-OC dominates surface sed. OC on World's largest shelf

- **Topsoil OC** **30 - 35 %**
- **Marine OC** **7 - 54 %**
- **Ice complex OC** **36 - 76 %**

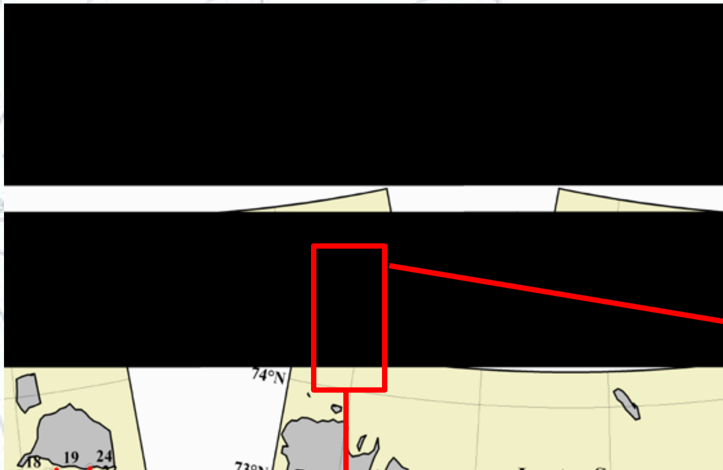
burial → **20±8 TgC/yr**

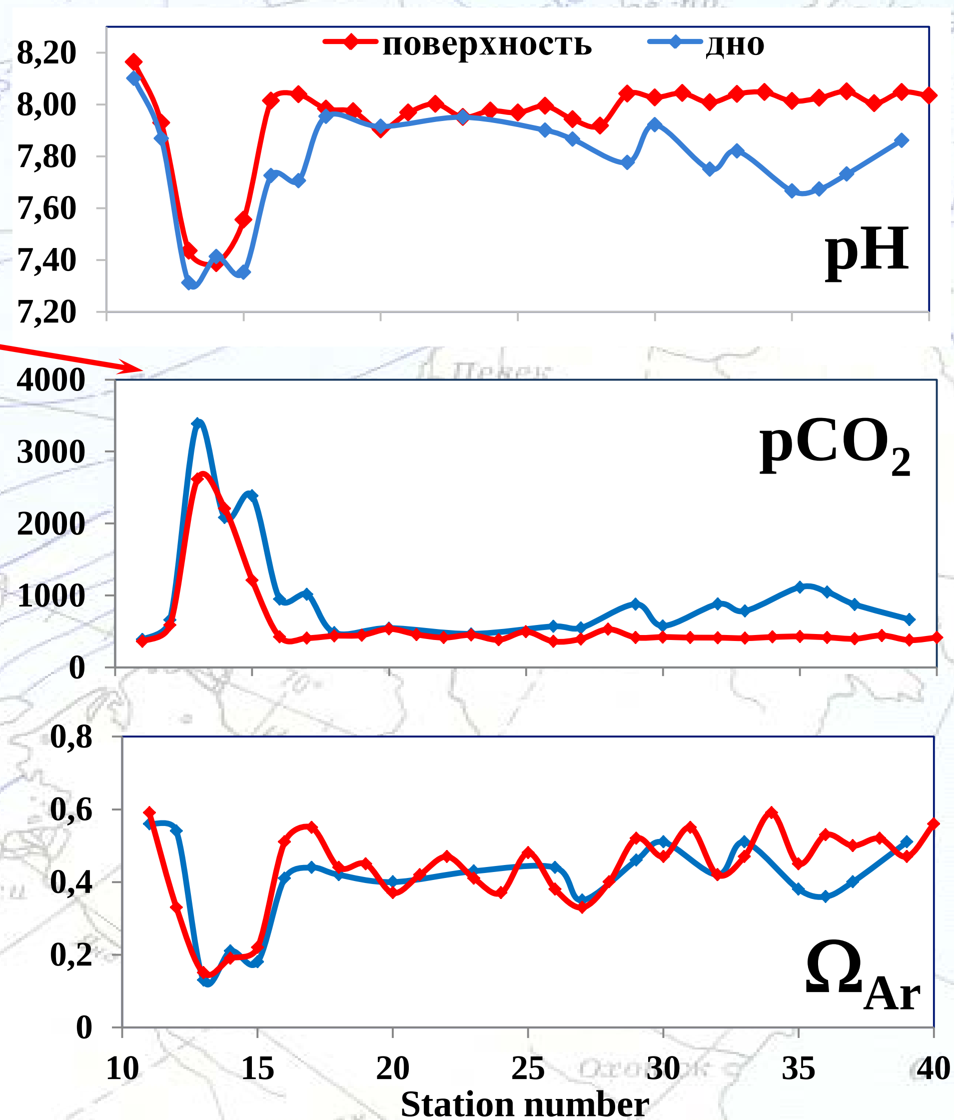


Vonk, Semiletov, Gustafsson et al. (2012) *Nature*

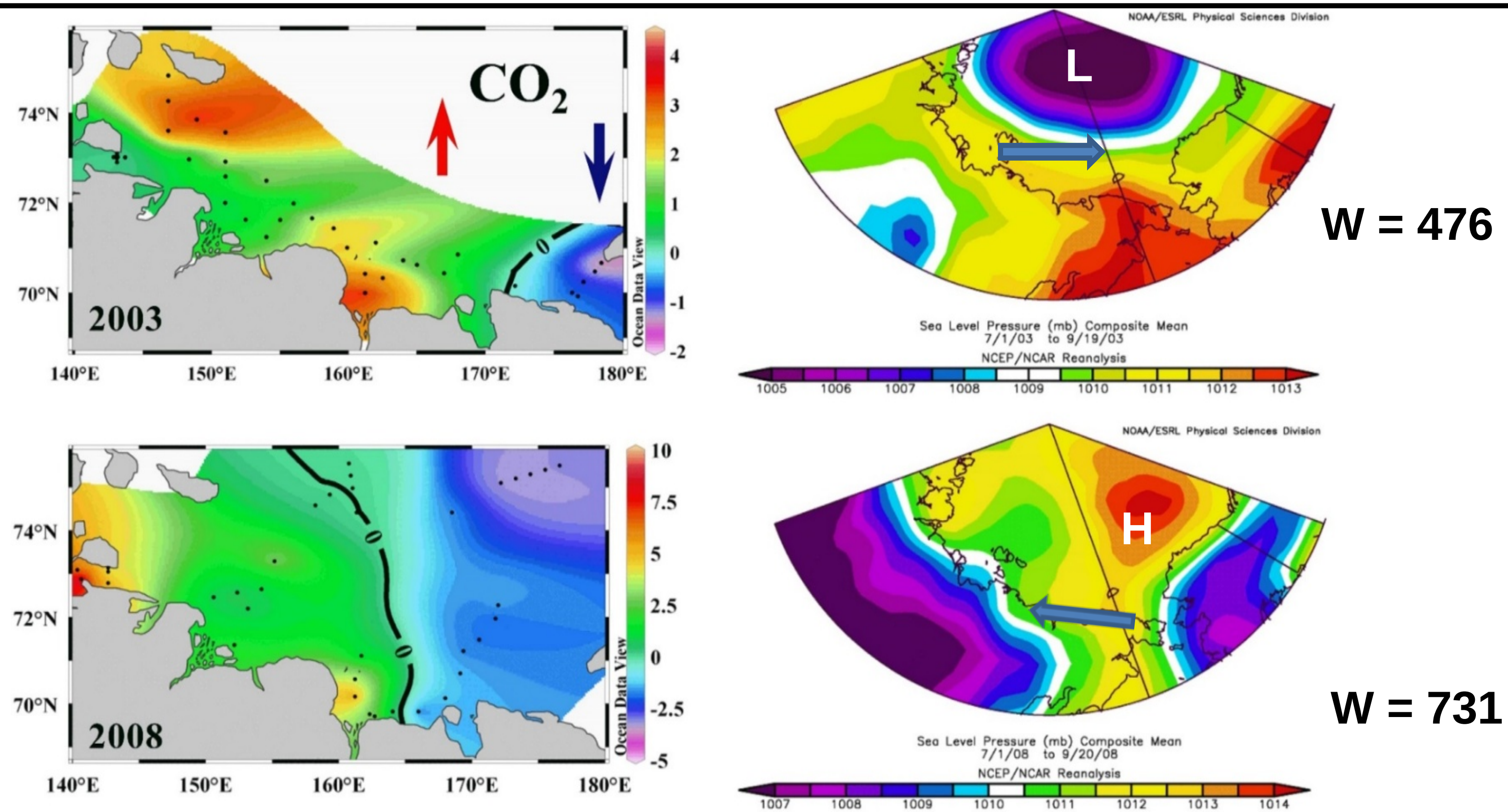
Biogeochemical consequences:

Oxidation of eroded C to CO2 drives the carbonate system – phys-chem. conditions in the Arctic seas





CO2 fluxes between air and sea are indicators of imbalance in the carbon cycling in the ESAS (its western biogeochemical province is a source of atm CO2, while the eastern province- the CO2 sink)



Left: Fluxes of CO_2 (mM/m2/day) in the air-sea system. **Right**: Sea level pressure (mb) in summer season of 2003 and 2008; W= total annual river discharge (км^3)

Up to 10 Tg of CO2 is released from the w. ESAS into the atmosphere, but most of it is coming back in the eastern ESAS

Based on: ***Anderson…Semiletov et al., GRL, 2009; Pipko, Semiletov et al., Biogeosciences, 2011; Semiletov, J. Atm.Sciences, 1999; Semiletov et al., GRL, 2005 and J. Mar. Systems 2007***

nature geoscience
LETTERS
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Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon

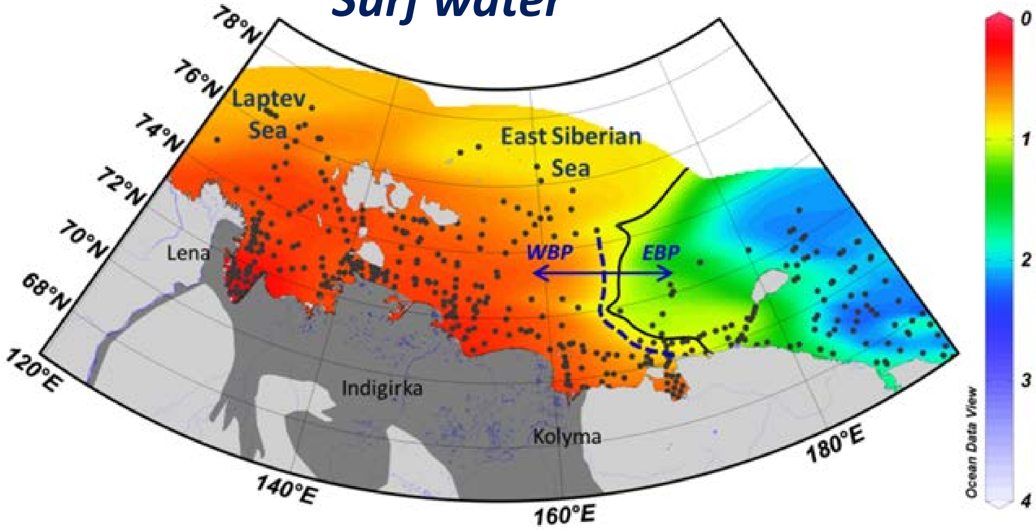
Igor Semiletov[1,2,3*], Irina Pipko[3], Örjan Gustafsson[4], Leif G. Anderson[5], Valentin Sergienko[6], Svetlana Pugach[3], Oleg Dudarev[3], Alexander Charkin[2,3], Alexander Gukov[7], Lisa Bröder[4], August Andersson[4], Eduard Spivak[3] and Natalia Shakhova[1,2]

Eroded C plays a key role in the PAR/ESAS biogeochemistry

Biogeochemical & ecological consequences:

Low Aragonite saturation state Ω_{Ar} from severe ocean acidification

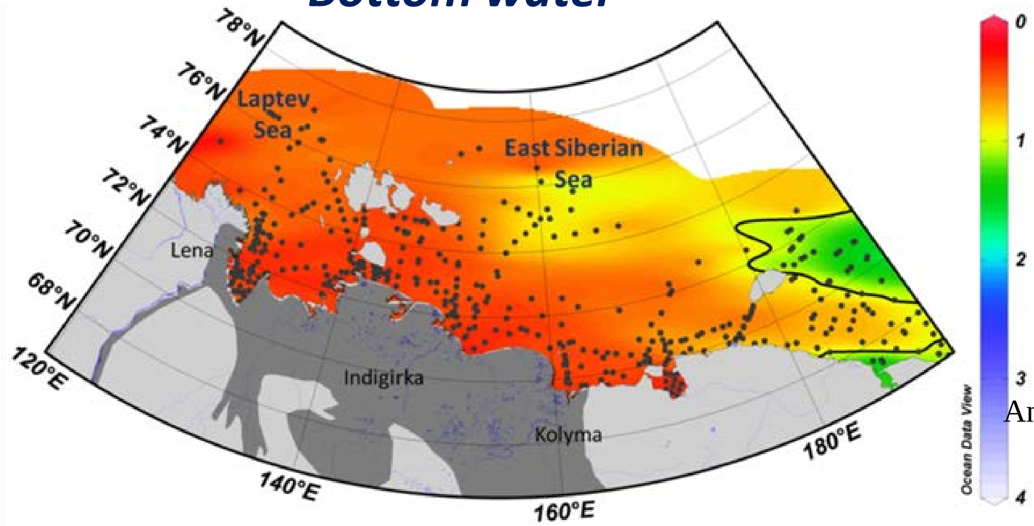
Surf water



Multi-year ocean data 1999-2013 on ESAS carbonate system:

- **pCO_2 oversat by 4x!**
- **pH down to 7.2-7.4*!**
- **Aragonite undersaturated!**

Bottom water



*** At several sites pH drops down to 6.9**

How acidification impact biodiversity: benthos ..., walruses, polar bears?

Igor Semiletov[1,2,3*], Irina Pipko[3], Örjan Gustafsson[4], Leif G. Anderson[5], Valentin Sergienko[6], Svetlana Pugach[3], Oleg Dudarev[3], Alexander Charkin[3], Alexander Gukov[7], Lisa Bröder[4], August Andersson[4], Natalia Shakhova[1,2]

***Nature Geoscience* (2016)**

Position of the boundary (Frontal zone, FZ) between the Pacific-derived and shelf water in 1932-2000 (marked in magenta) moved eastward in 2000-2012 (solid black line)

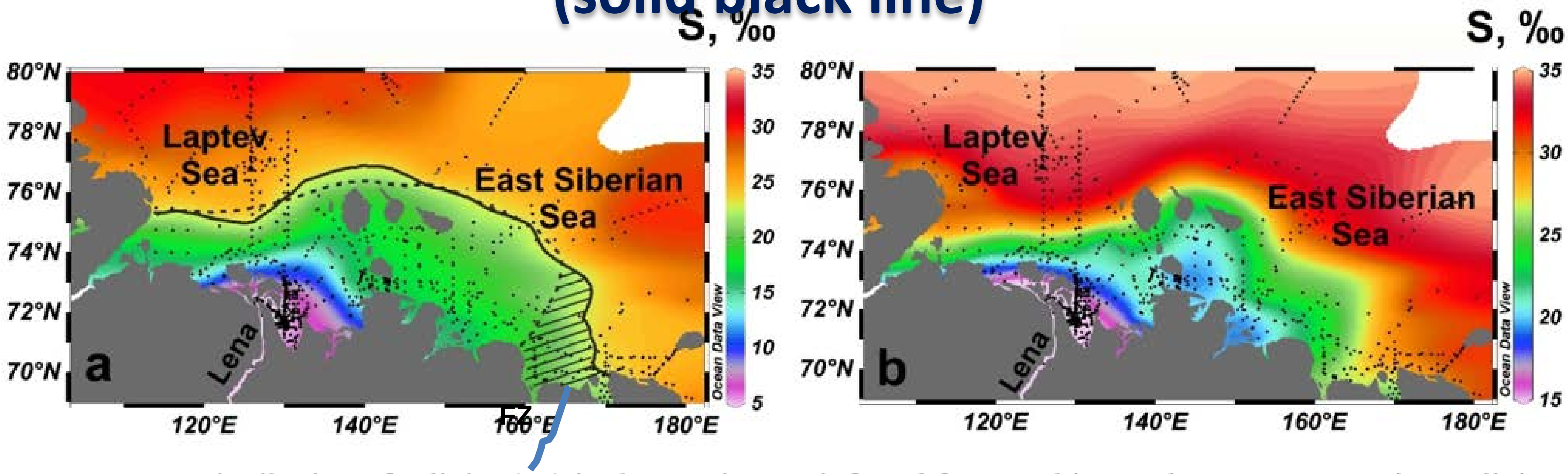
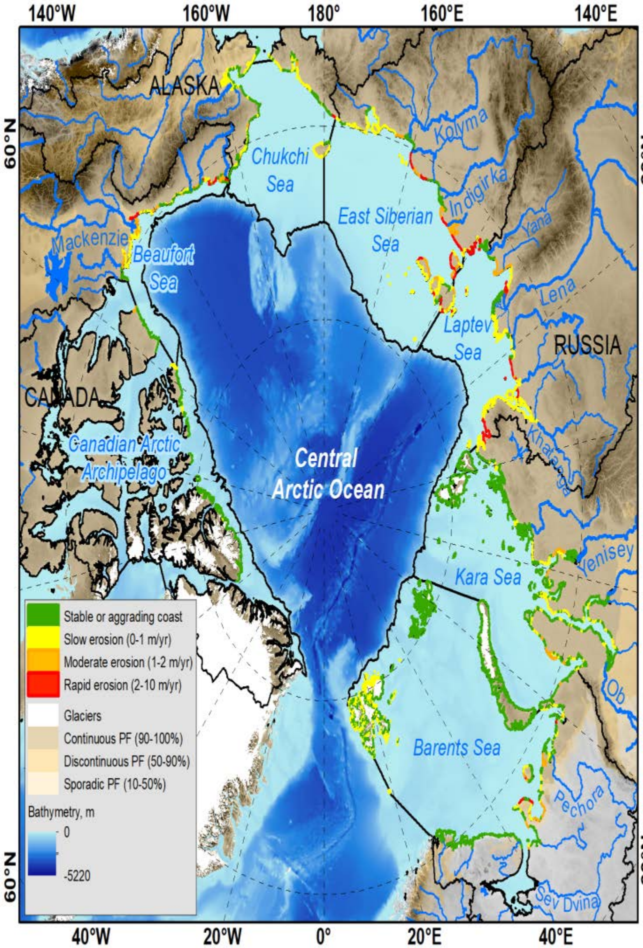
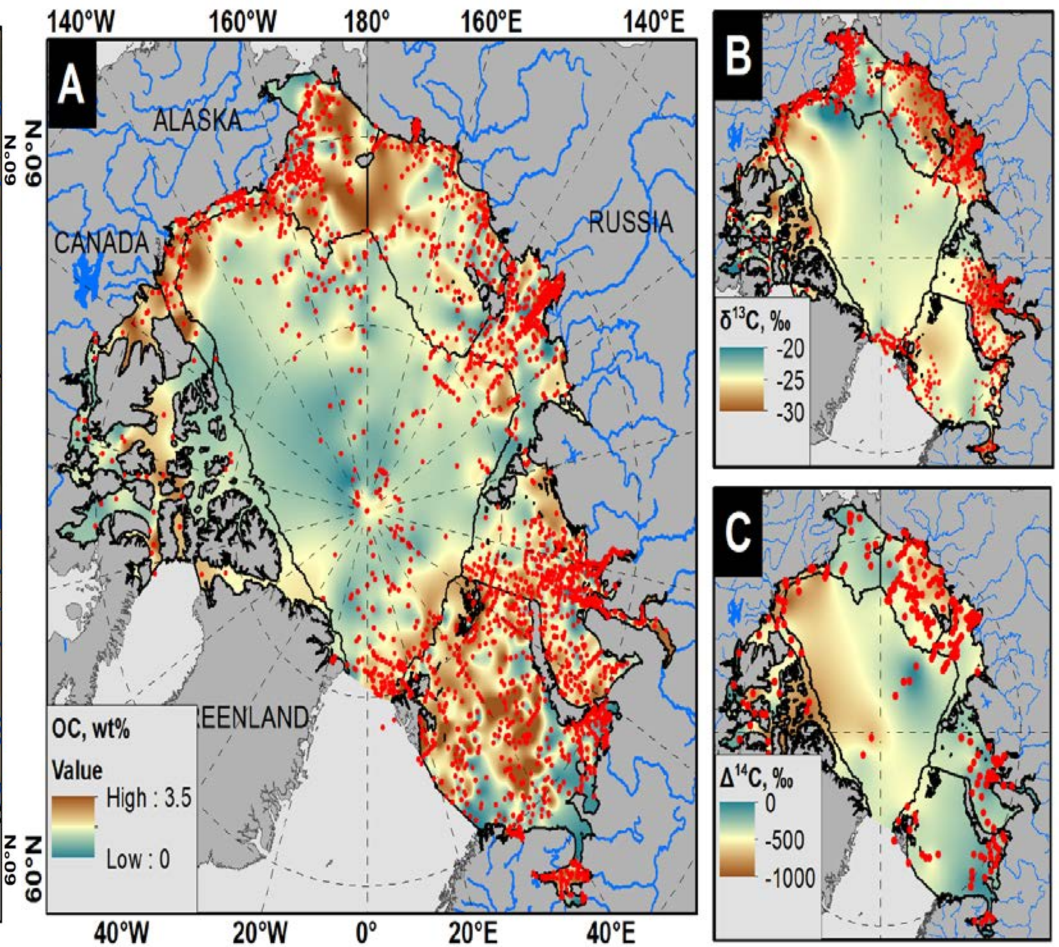


Figure 3. Distribution of salinity (‰) in the Arctic seas inferred from multi-year data. **a)** Summertime salinity observed in 2000-2012 vs that observed in 1932-2000 in the surface water **(a)** and in the bottom water **(b)**. Position of the isohaline = 23‰ observed in 2000-2012 is marked as a black solid line (2000-2012); its position in 1932-2000 is marked as a black dotted line; the area of its extension to the east during the last 12 years, equal to ~116,000 km^2, is shown as a shaded area in panel **(a)**; *(adopted from Semiletov et al., 2016).*

This S-shift could be an effect from increasing river runoff and changes in the atmospheric circulation from AZ to Zn mode which causes an extension of *heterotrophic* area (CO2 emission area)

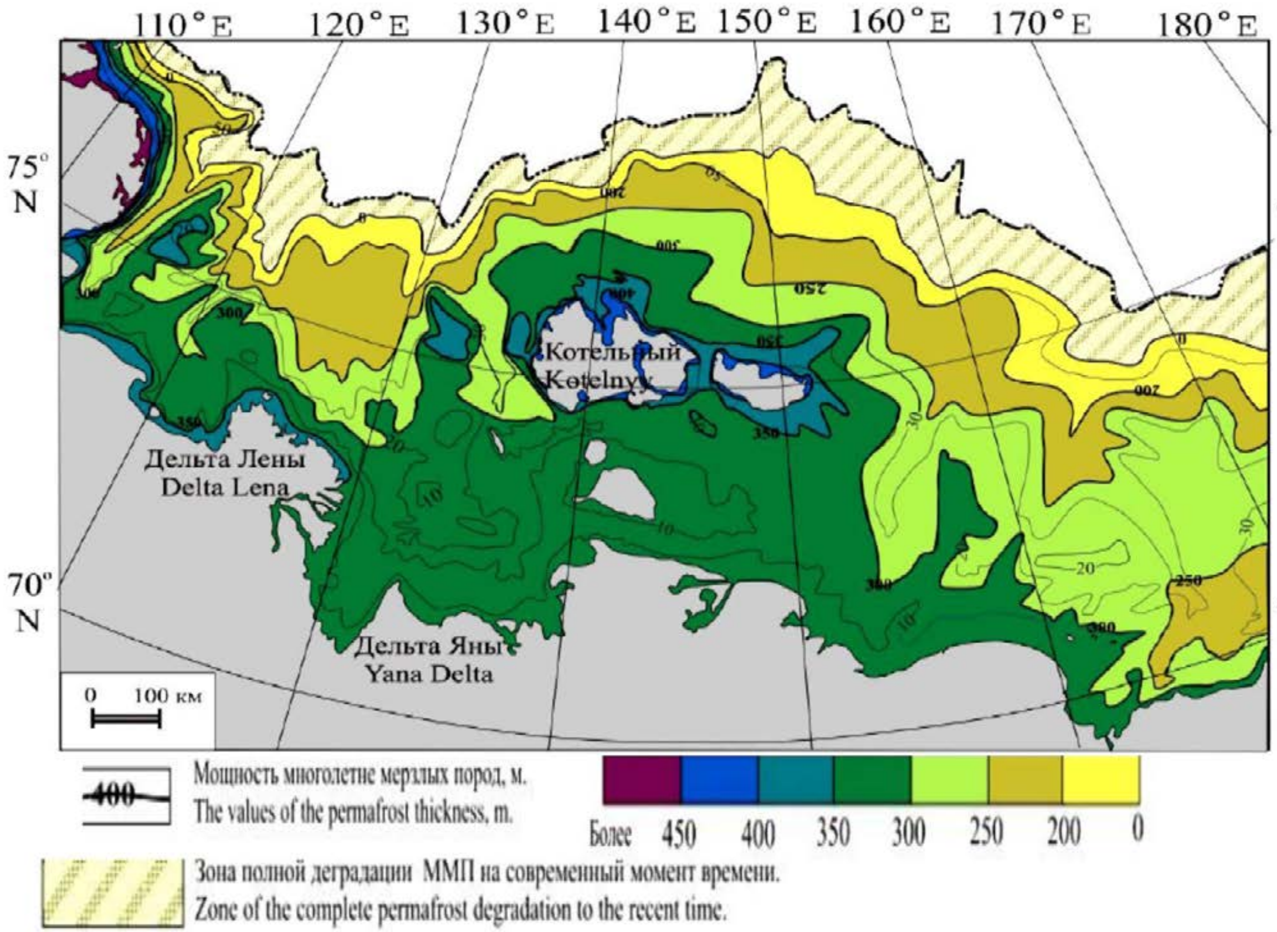
For surface sediments, **our data base** (ISSS/SWERUS CASSCADE scientific consortium) **includes 2919 different locations across the Arctic Ocean**, for which the OC concentration is known. The concentration of TN, thus also the OC/TN ratio, is known for 1181 locations. For carbon isotopes, the number of individual δ^{13}C-OC values is 1368 and for Δ^{14}C-OC it is 267





The CASSCADE also holds concentrations of terrigenous biomarkers at more than 250 locations, which are organized based on the compound groups. About half of these data are for HMW *n*-alkanes, either concentrations of HMW *n*-alkanes ($\sum C_{21}$-C_{31}) or of *n*-alkane chain lengths more specific for higher plants ($\sum C_{27}$, C_{29}, C_{31}).
The other half are concentrations of HMW *n*-alkanoic acids ($\sum C_{20}$-C_{30}) and the concentrations of lignin phenols.

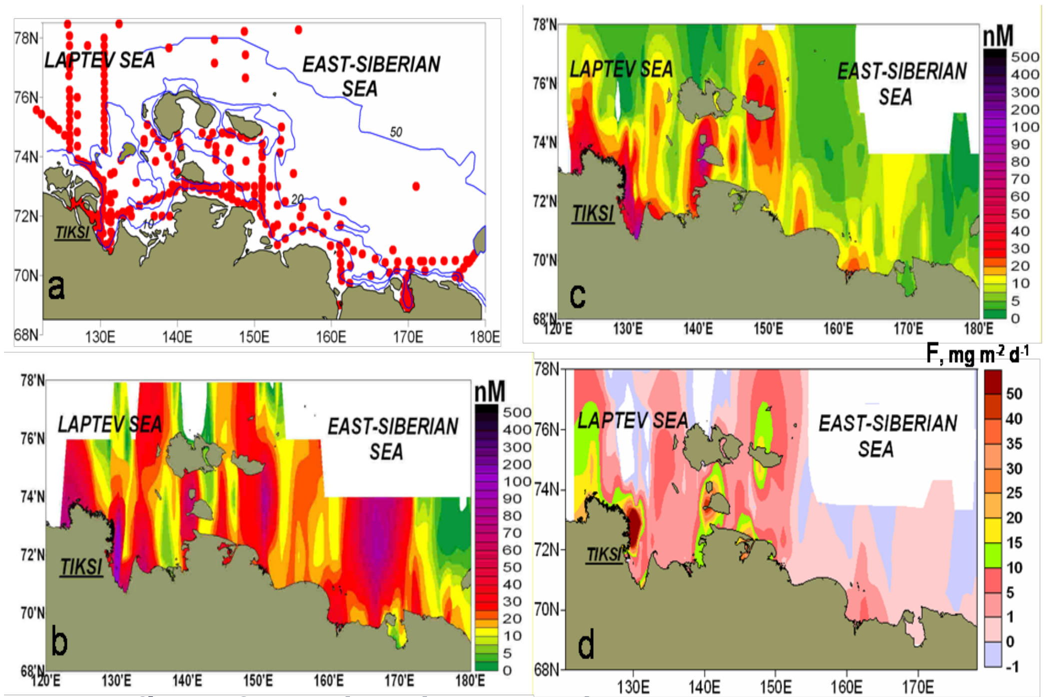
IPCC (2014) still claims that the subsea permafrost is stable and the Arctic ocean is near zero source of methane. That is based on modeling and speculations

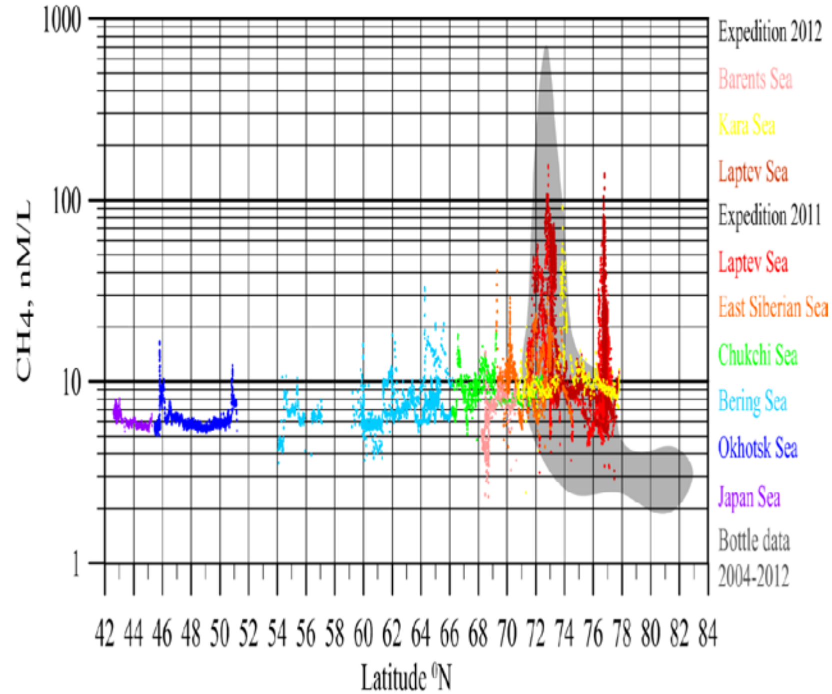


Результаты *моделирования* подводной мерзлоты (Романовский и др. , 2001) пересматриваются совместно с МГУ (группы Тумского и Кошурникова) и Сколково (гидратная группа Чувилина)

BUT : ESAS serves as a significant source of methane to the atmosphere

This contradicts with the old paradigm about the stable and continuous subsea permafrost in the ESAS.



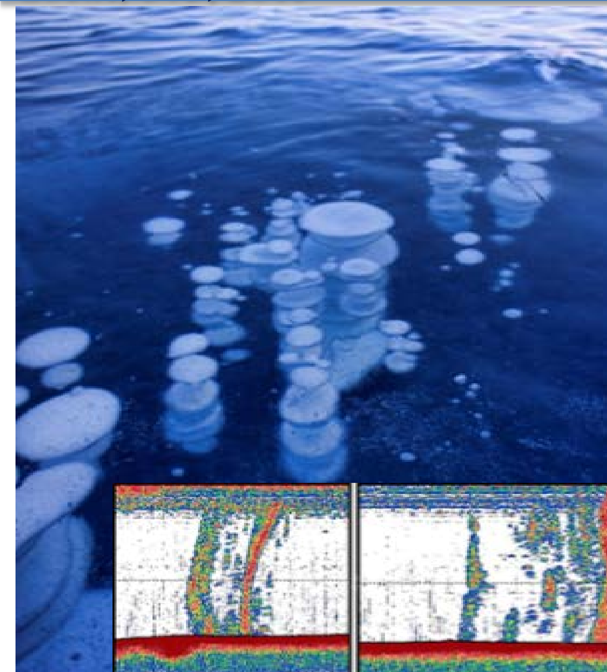


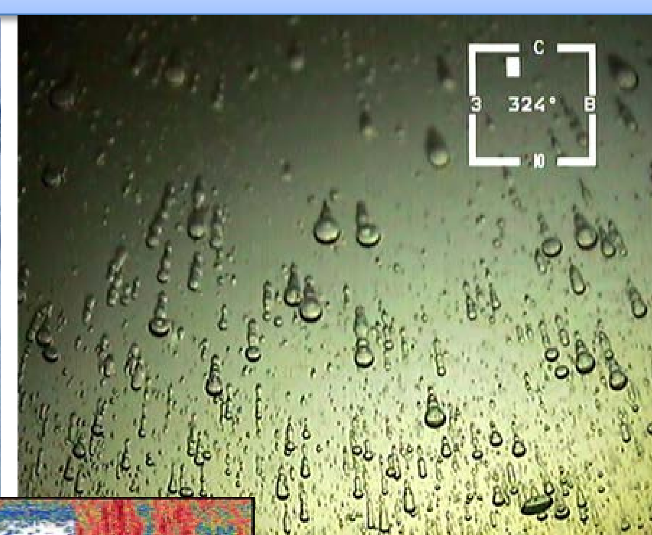
Mean flux: from background areas **3.67 mg/m²/d**, from hot spots – **11.8 mg/m²/d; annual flux 8 Tg-the 1st estimation (from Shakhova et al., Science, 2010)**

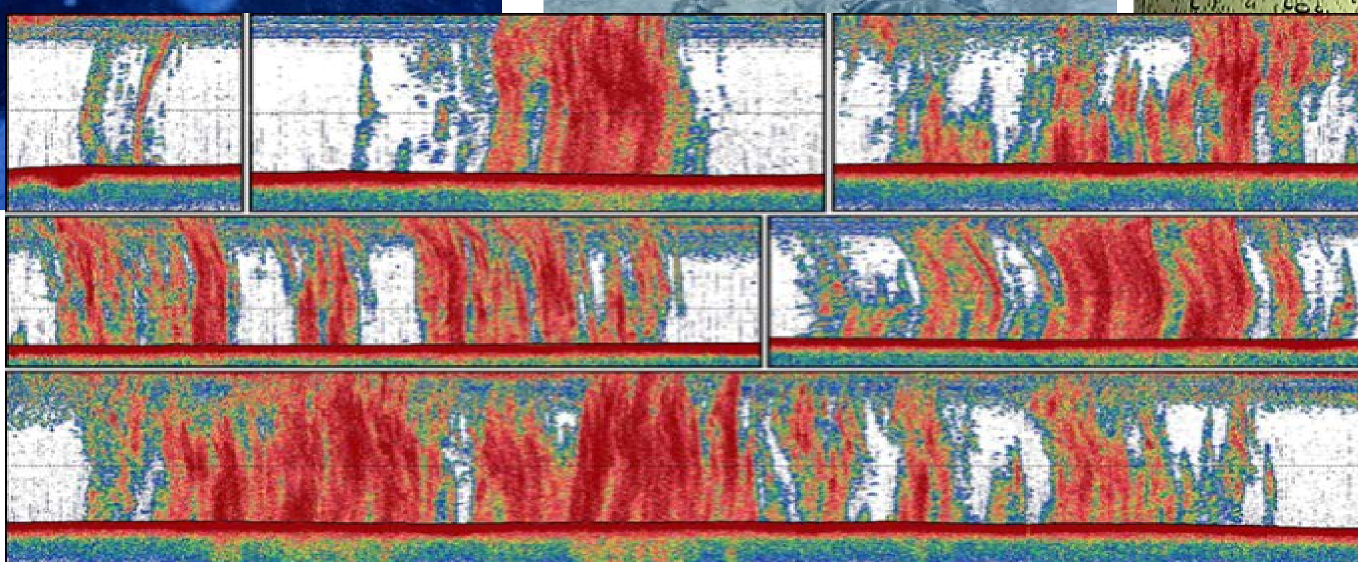
ESAS exhibits the highest surface concentrations of dissolved methane in the Eurasian marginal seas and the entire Northern Hemisphere

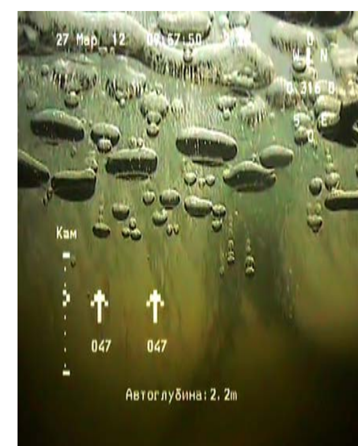
Пузырьковый перенос - основной механизм транспорта метана из донных отложений в водную толщу и атмосферу

Shakhova, Semiletov et al., *Nature Geoscience*, 7, 2014; Shakhova, Semiletov et al., *Phil. Trans. Royal Soc.A*, 373, 2015

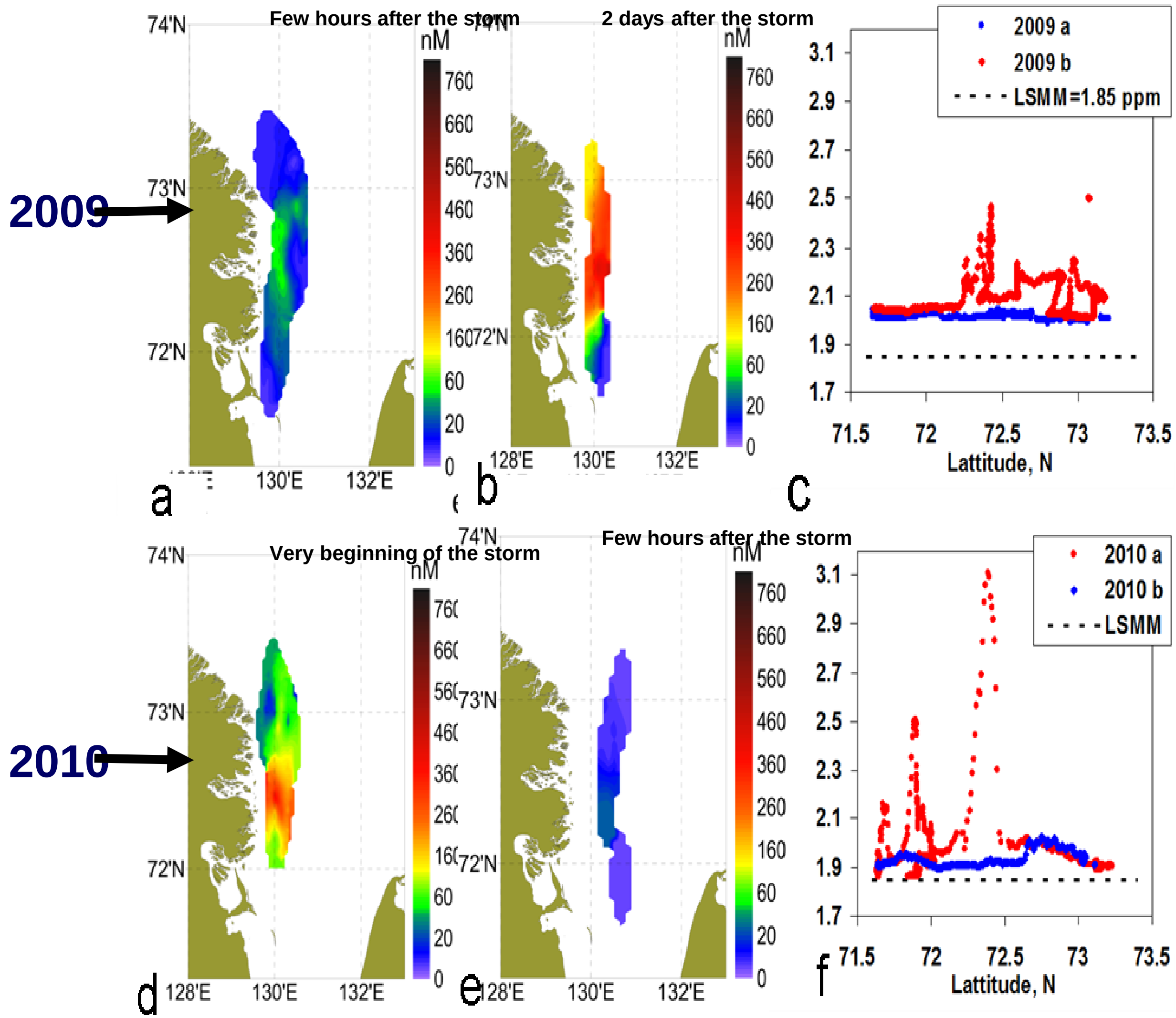






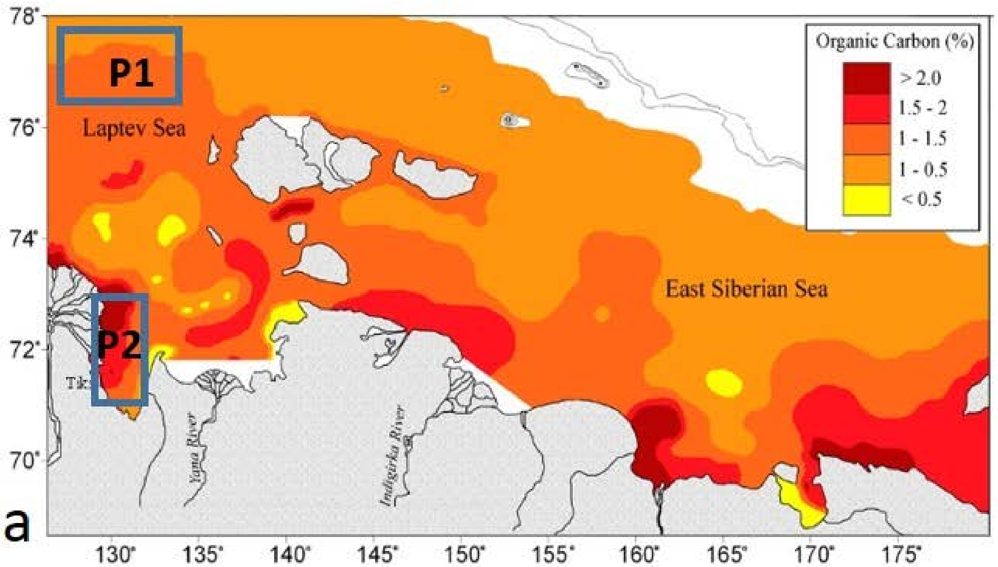


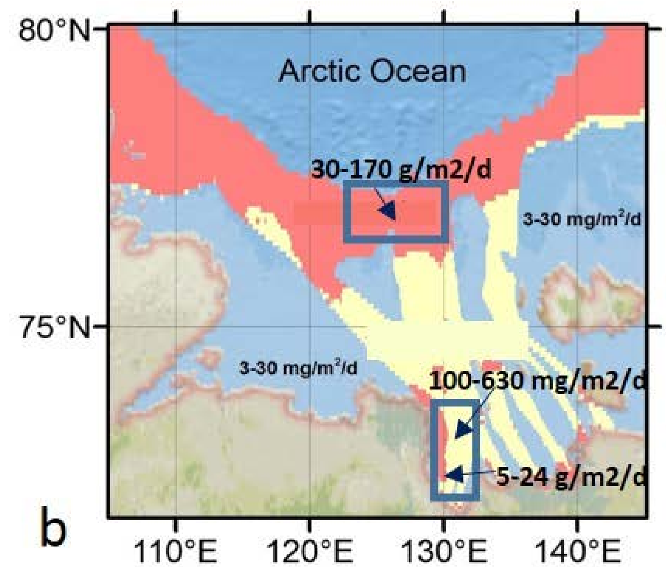
Atmospheric ratios of CH_4 reflect methane emissions from the sea surface

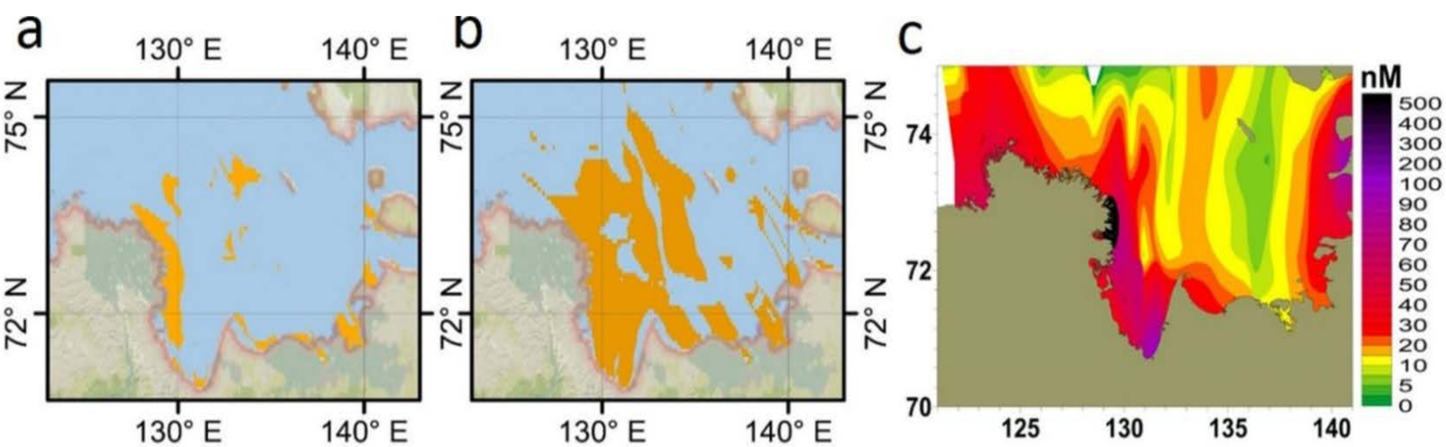


From Shakhova et al., Nature Geoscience2014

Annual CH_4 flux from the ESAS is determined by current state of subsea permafrost and areas of taliks, which will increase with time







from Shakhova, Semiletov et al., 2015

<u>Рабочая гипотеза</u> для объяснения механизма наблюдаемых массированных выбросов метана из донных отложений морей Восточной Арктики в водную толщу-атмосферу подразумевает значительную деградацию подводной мерзлоты и наличие сквозных таликов.

Запасы метанового гидрата в МВА оцениваются в **500 млрд тонн**, в атмосфере на 2 порядка меньше- в 5 млрд тонн

Это значит, что при условии выброса 10% от запасов гидратов в атмосферу, концентрация атмосферного метана может увеличиться в 10 раз, что может привести к потеплению соизмеримому с эффектом удвоения CO2

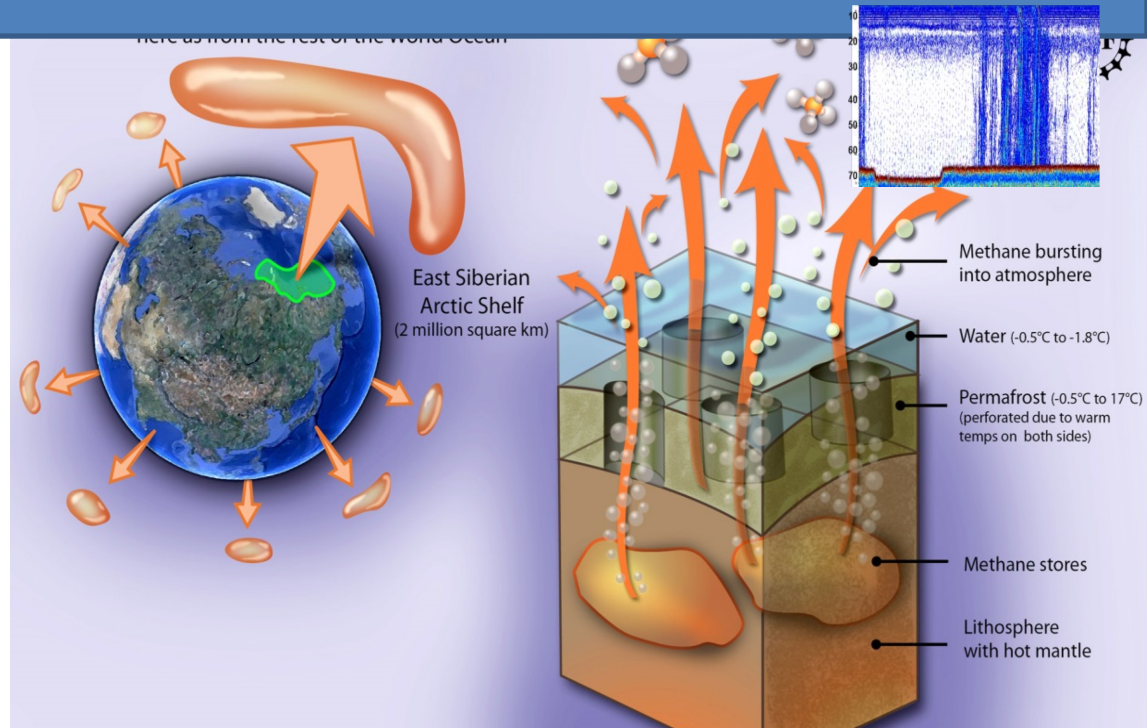
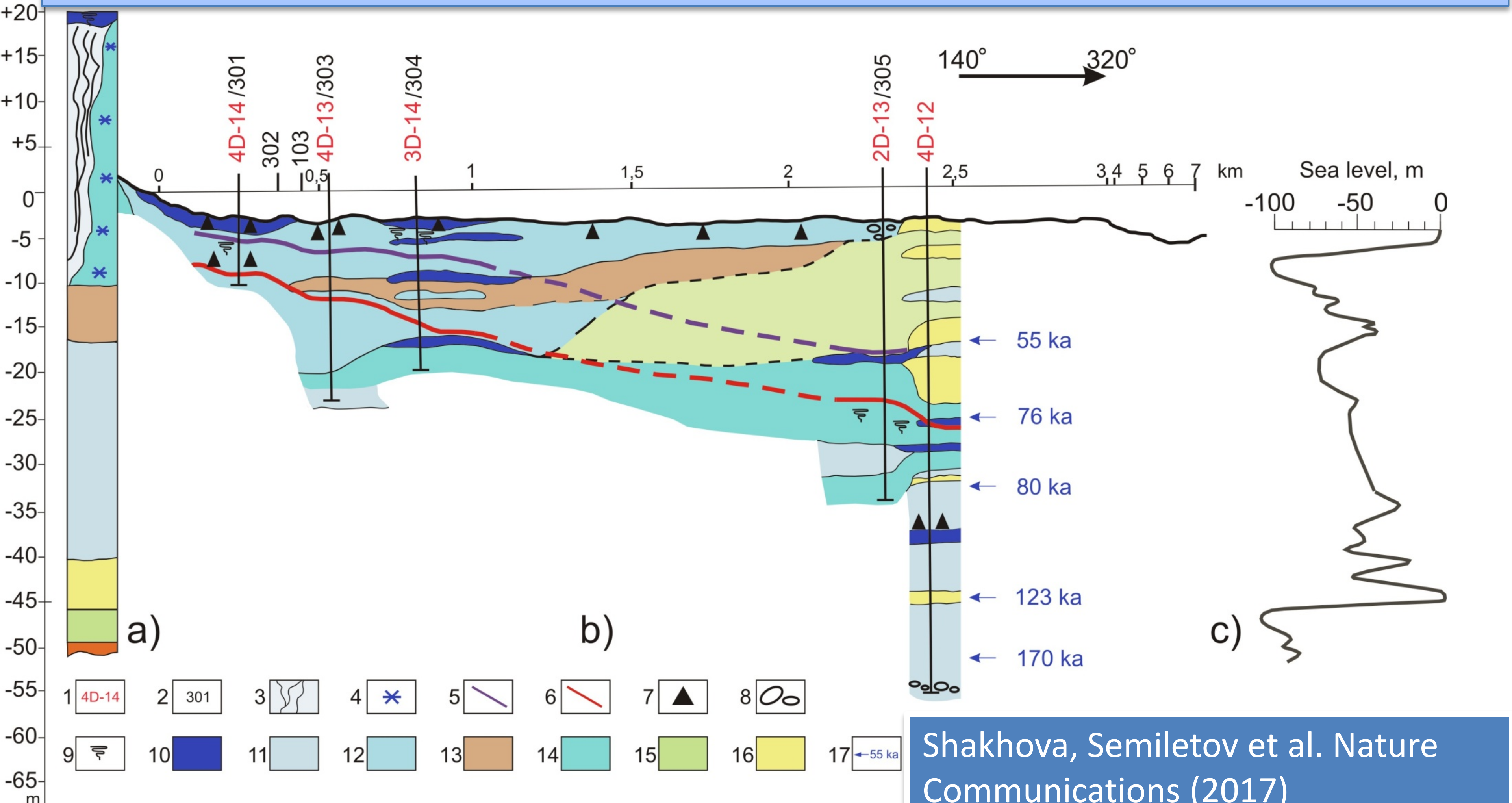


Схема миграции метана выполнена на основе публикаций *(Шахова, Семилетов и Сергиенко, Вестник РАН, 2009; Shakhova, Semiletov et al., Science, 2010*). Было показано, что **диффузионная эмиссия метана из МВА соизмерима с эмиссией метана из всего Мирового океана( ).** <u>**Добавление вклада пузырькового переноса увеличивает эту оценку как минимум в 2-3 раза**</u> *(Shakhova, Semiletov et al., Nature Geoscience, 2014).* <u>Выброс 3.65Тг из P1=6400км2 (0.3% МВА)....</u>

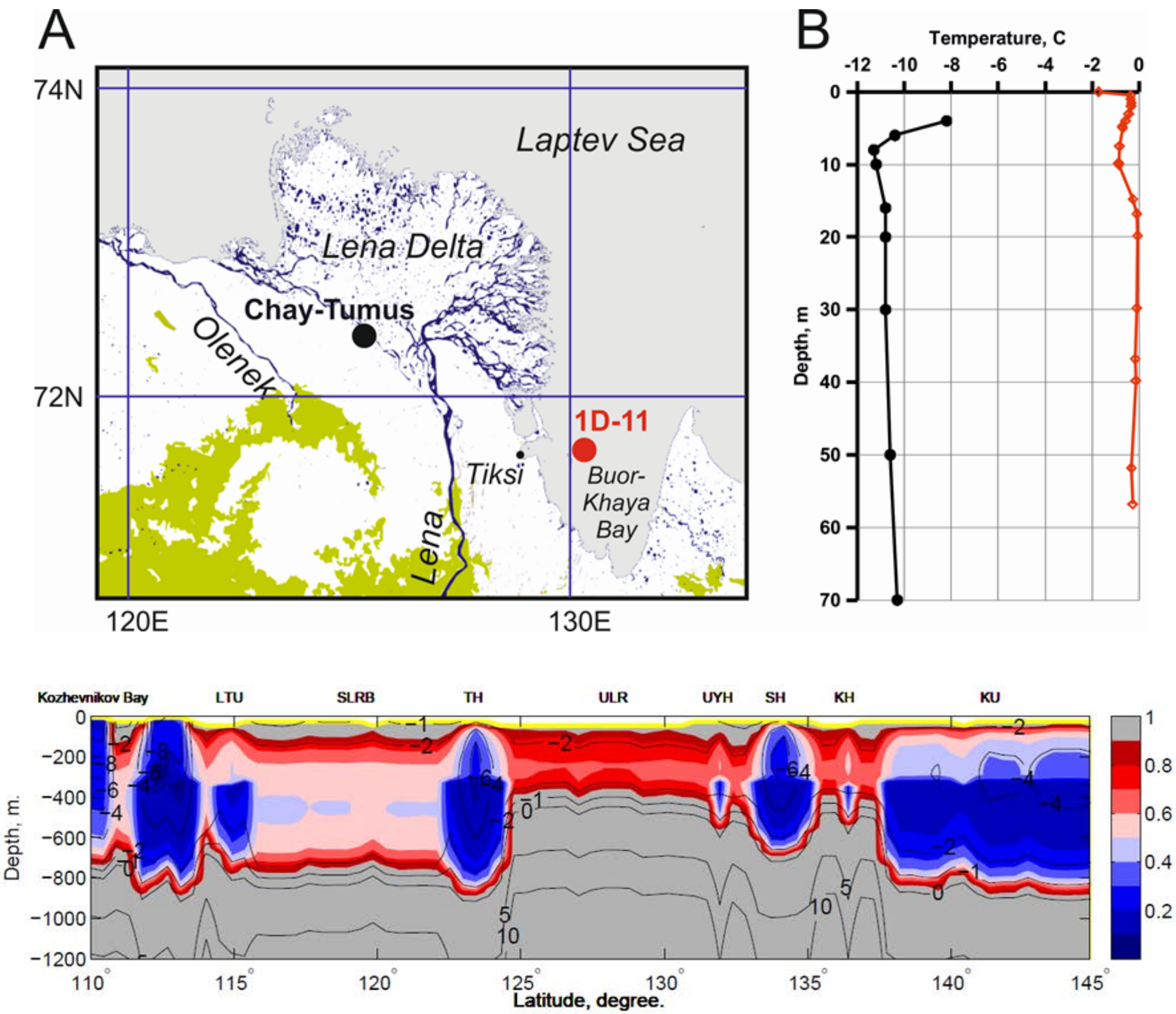
Vertical rates of the subsea permafrost degradation were determined by redrilling (2013-2014) of the transect accomplished by the Permafrost Inst –Yakutsk in 1982-83

Downward movement of the ice-bonded permafrost table of ~14 cm/year: almost one order higher than it was assumed before



Shakhova, Semiletov et al. Nature Communications (2017)

Disintegration of subsea permafrost is major factor driving methane emissions in the ESAS



- Thermal regime of subsea permafrost in the ESAS is up to 10°C warmer than thermal state of its terrestrial counterpart located just few miles away from the coast (A and B); this difference is determined by warming effect of seawater and other factors specific for the ESAS.
- Disintegration of subsea permafrost manifests as formation of taliks (layers or columns of thawed sediments throughout permafrost body, shown in blue on panel C). Taliks first form where subsea permafrost was submerged for longest (outer shelf, depth >50 m). In the shallow part (depth <50 m), taliks form in the areas underlain with fault zones, covered with submerged thaw lakes and influenced by warming effect of rivers.



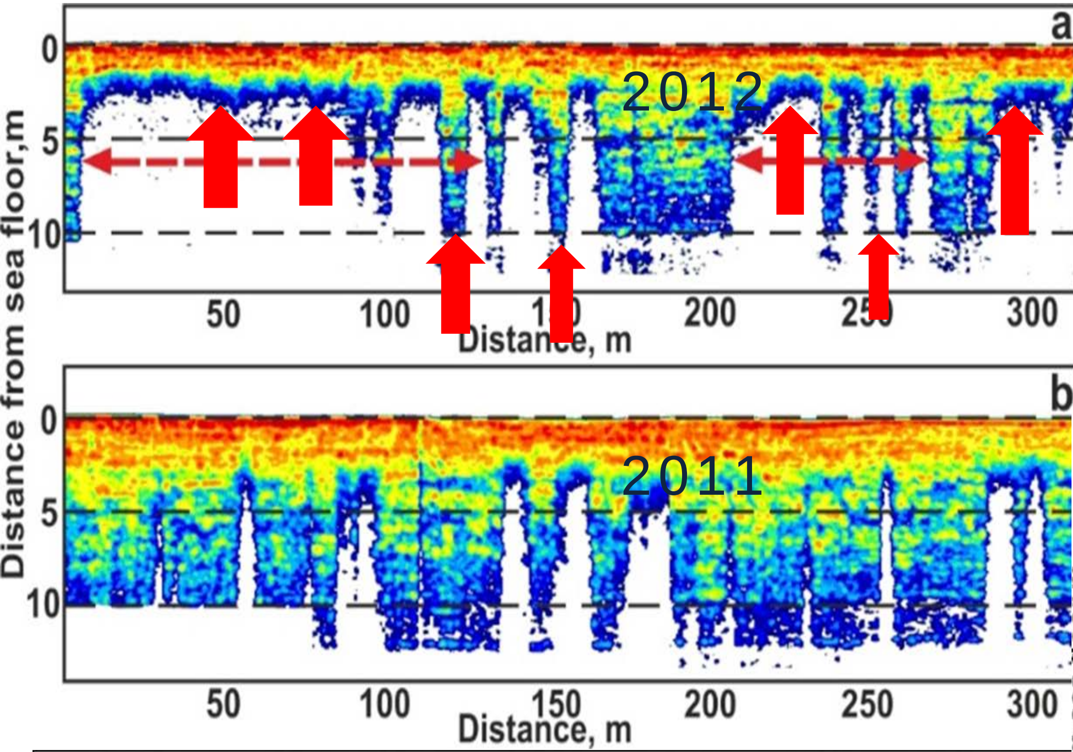

При глубине моря > 4 м подводная мерзлота не была обнаружена до глубины осадка 100 м, что указывает на наличие глубоких (возможно сквозных) таликов

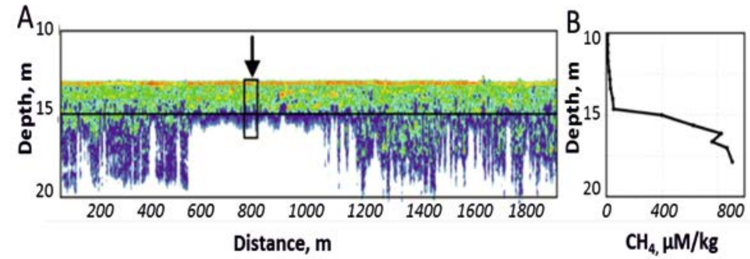


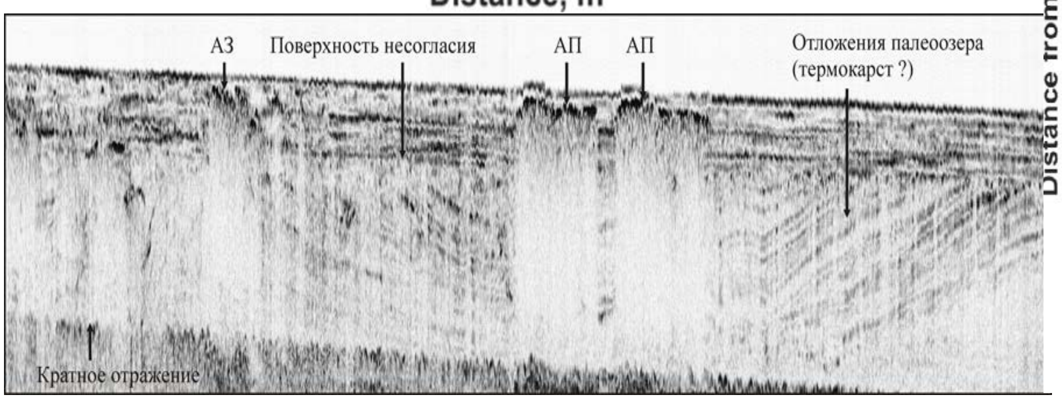


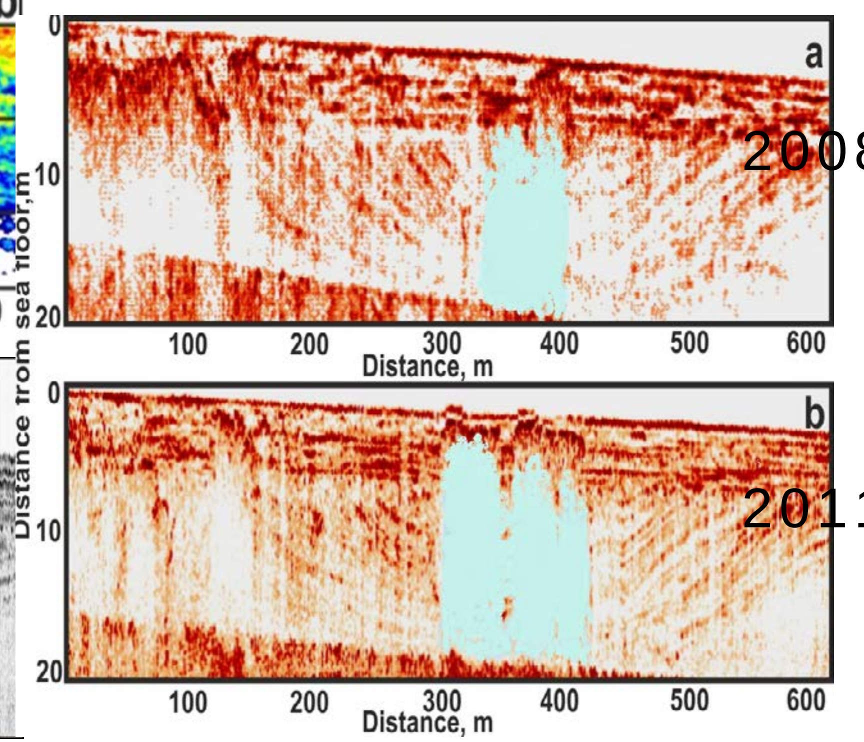
Это значит, что кровля подводной мерзлоты в исследуемом районе **уже близка или достигла** зоны стабильности газовых гидратов

Gas (methane) front moves through the sediments at speed up to 7-8 meters per year









(Shakhova, Semiletov, Lobkovsky et al., Nature Communications, 2017)

Борозды ледового выпахивания (*стамухи и айсберги*) являются эффективным механизмом для достижения газовым фронтом поверхности осадка и выброса метана (Shakhova, Semiletov, Sergienko et al., Nature Comm., 2017)

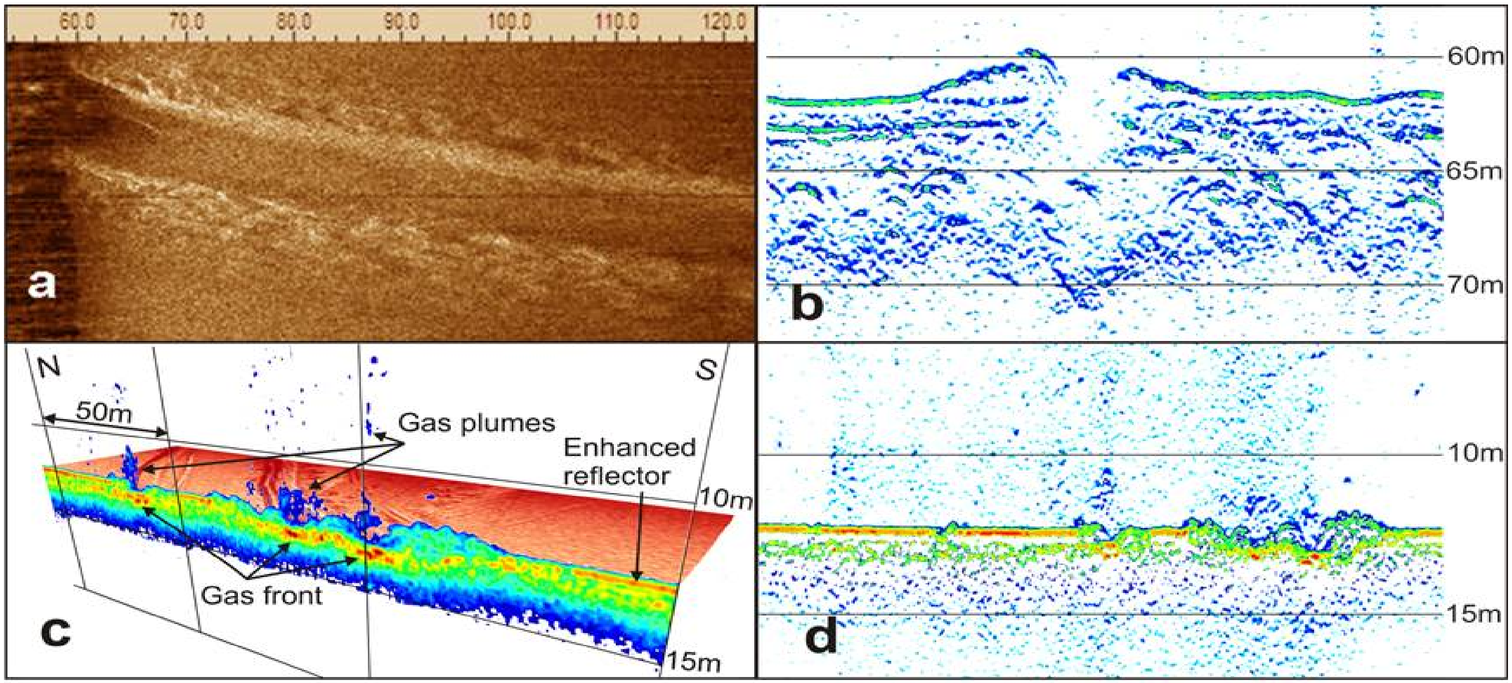
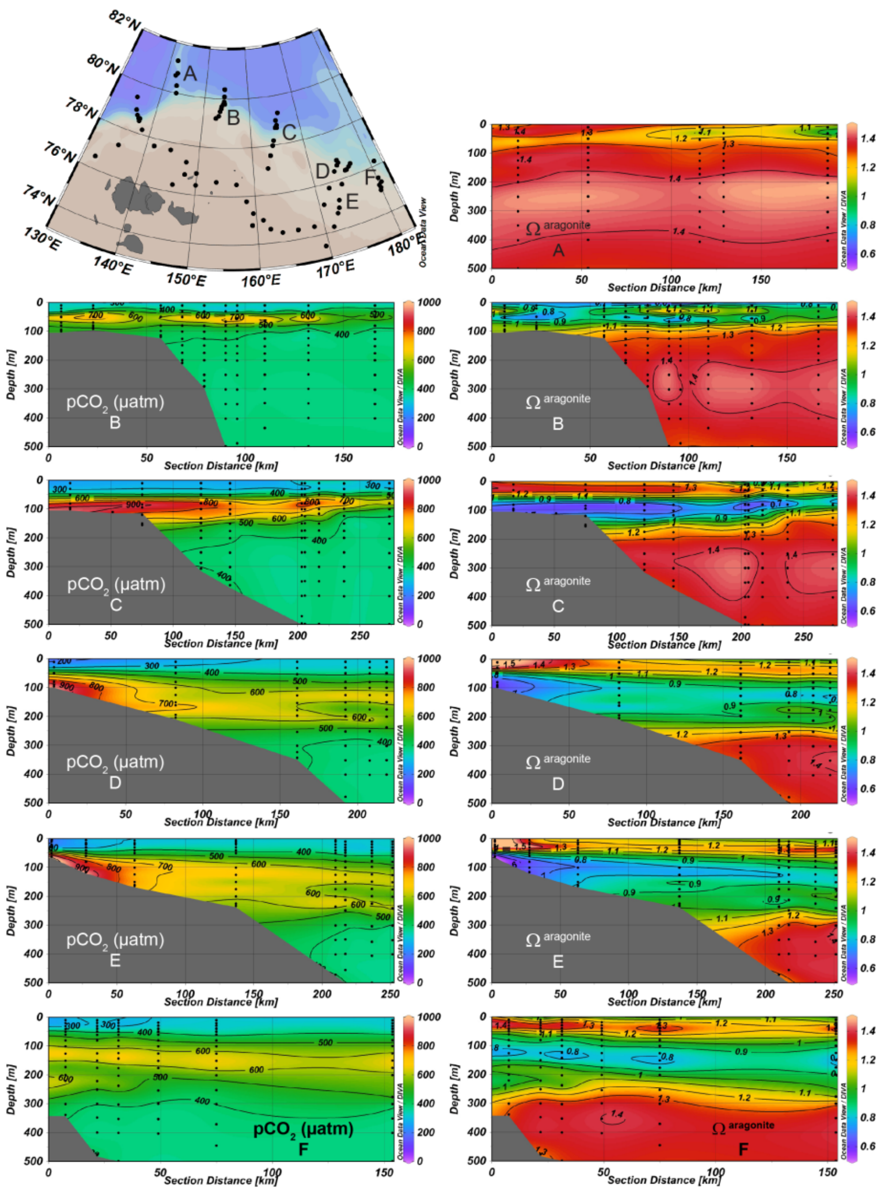
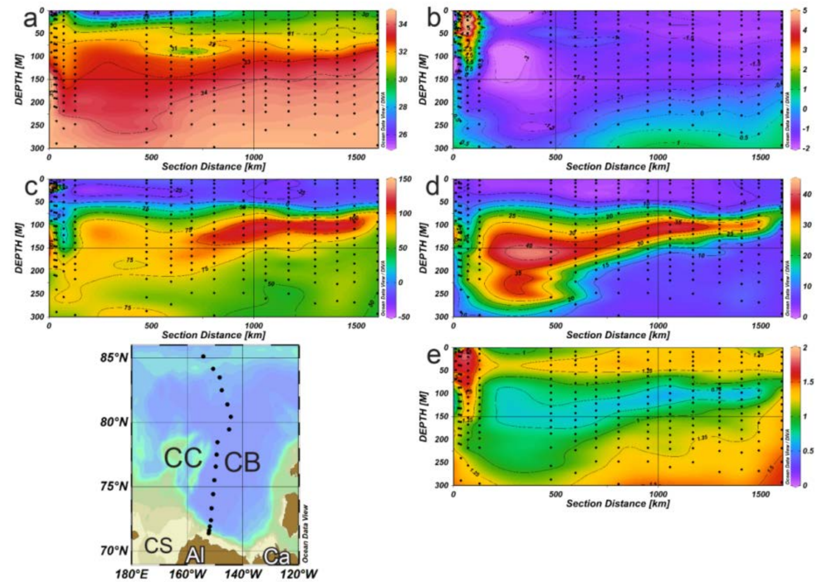


Figure 4 | Example of high-resolution seismic ice-scour images observed in the ESAS.
a) Backscatter image showing relative size of the ice scouring scar on the sea floor. **b)** vertical profile of the ice-scouring scar demonstrating penetration as much as 8 m into the sediment. **c)** 3D perspective view of ice scouring as a mechanism providing a gas migration pathway for shallow gas to escape to the water column. **d)** hydro-acoustical image of gas release due to ice scouring .

<u>Ecological remote impact</u>: Export of calcium carbonate corrosive waters from the shelf towards the deep-ocean

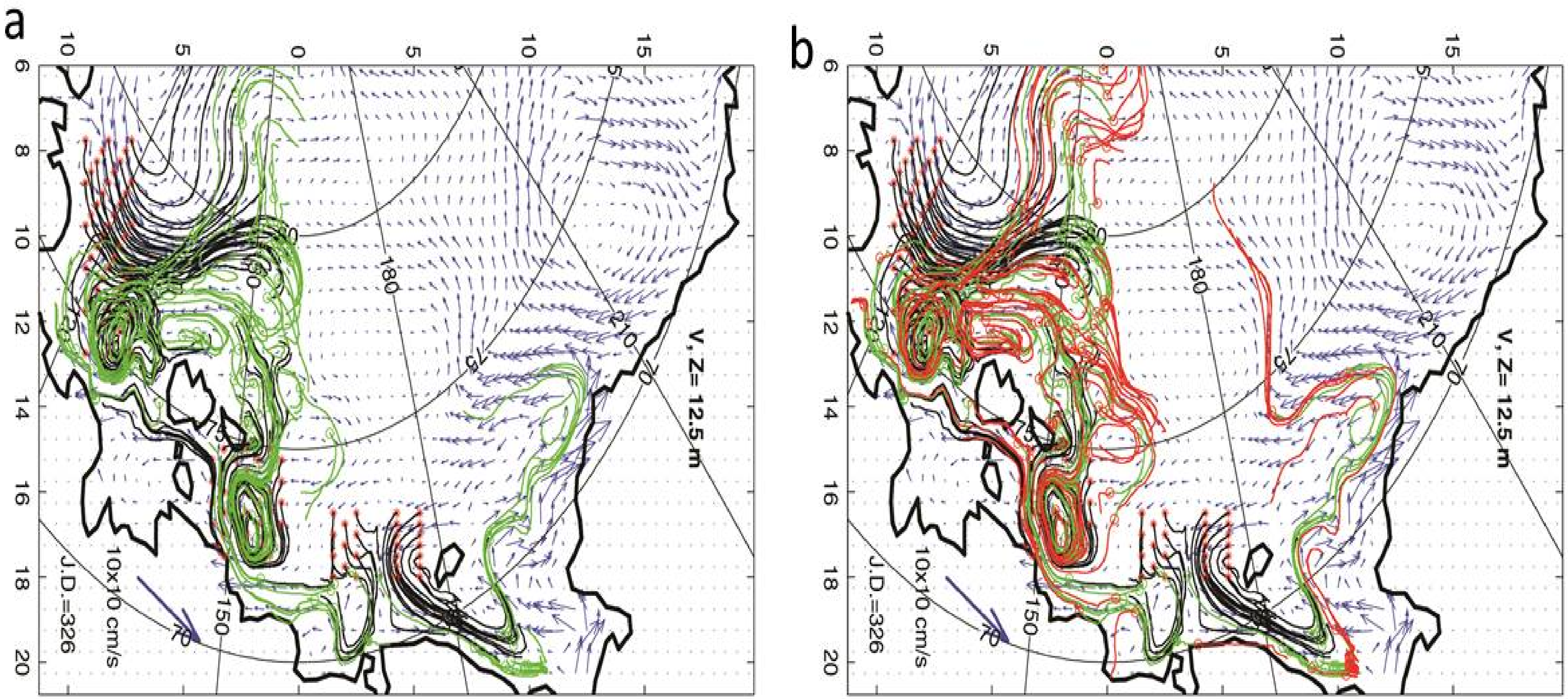




Sections of (a) salinity, (b) temperature, (c) AOU, (d) silicate, and (e) Ω^aragonite^ in the top 300 m across the Canada Basin as observed during the Beringia 2005 expedition. Station positions are noted on the map, with the abbreviations being; CB = Canadian Basin, CC = Chukchi Cape, CS = Chukchi Sea, Al = Alaska, and Ca = Canada.

from Anderson, Semiletov et al. Biogeosciences (2017)

Lateral transport allows any signal released from the shelf to be transported to the deep water in the Arctic Ocean



Modeling (4Dvar assimilation) results from Shakhova, Semiletov, Gustafsson, Panteleev et al., ***Royal Soc. Trans. (2015)***

<u>Challenge</u>: Recent PP OVERestimates are based on sat color data and different models which don't consider the effect of PM and CDOM

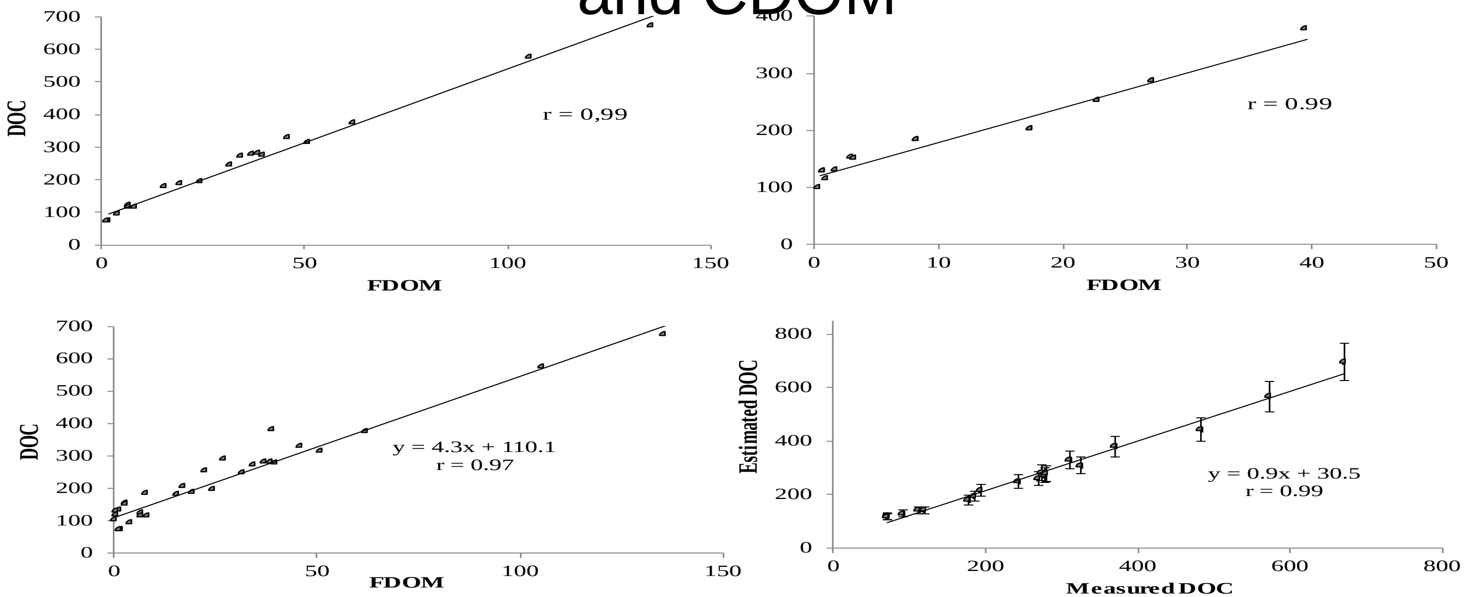


Fig.1 DOC concentration (µM) versus CDOM (QSU) in the ESAS surface water, September 2004 (a), 2008 (b) and combined for two years (c), (d) estimated DOC concentration against measured DOC concentration with 10% error bars.

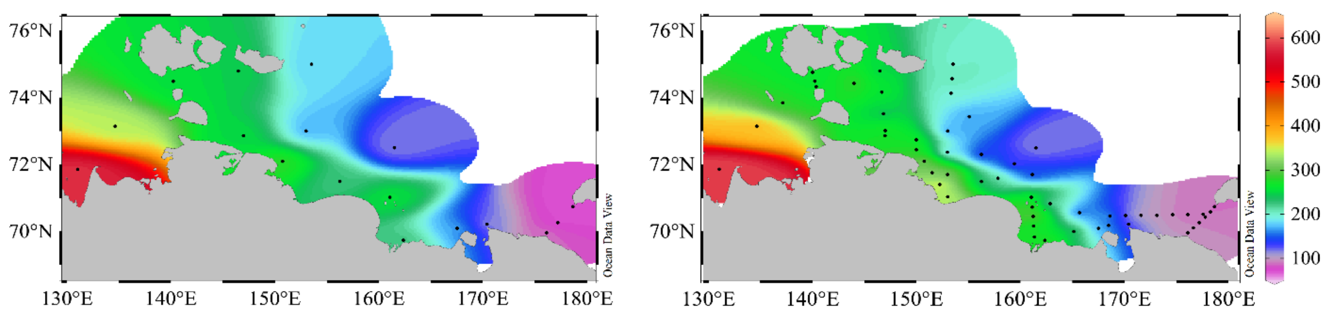
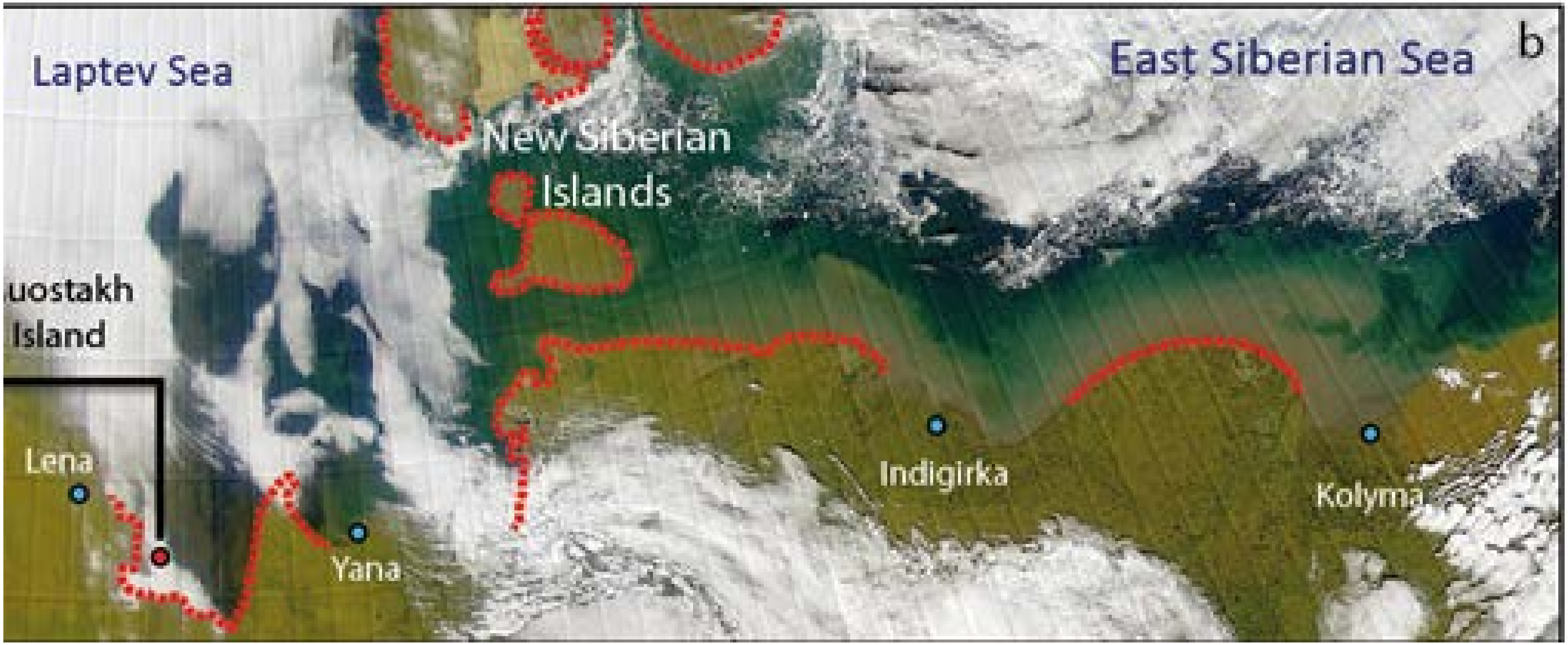


Fig 2. DOC distribution (µM) in the ESAS surface waters in September 2004: **(a)** measured DOC concentrations, **(b)** concentrations DOC, estimated from CDOM.

Pugach, Semiletov et al., Ocean Sciences, 2017)

Erosion of C-rich Ice Complex Deposits (ICD) plays key role in biogeochemistry and sedimentation along the Arctic coasts



Satelite image of shelf water turbidity caused by coastal erosion

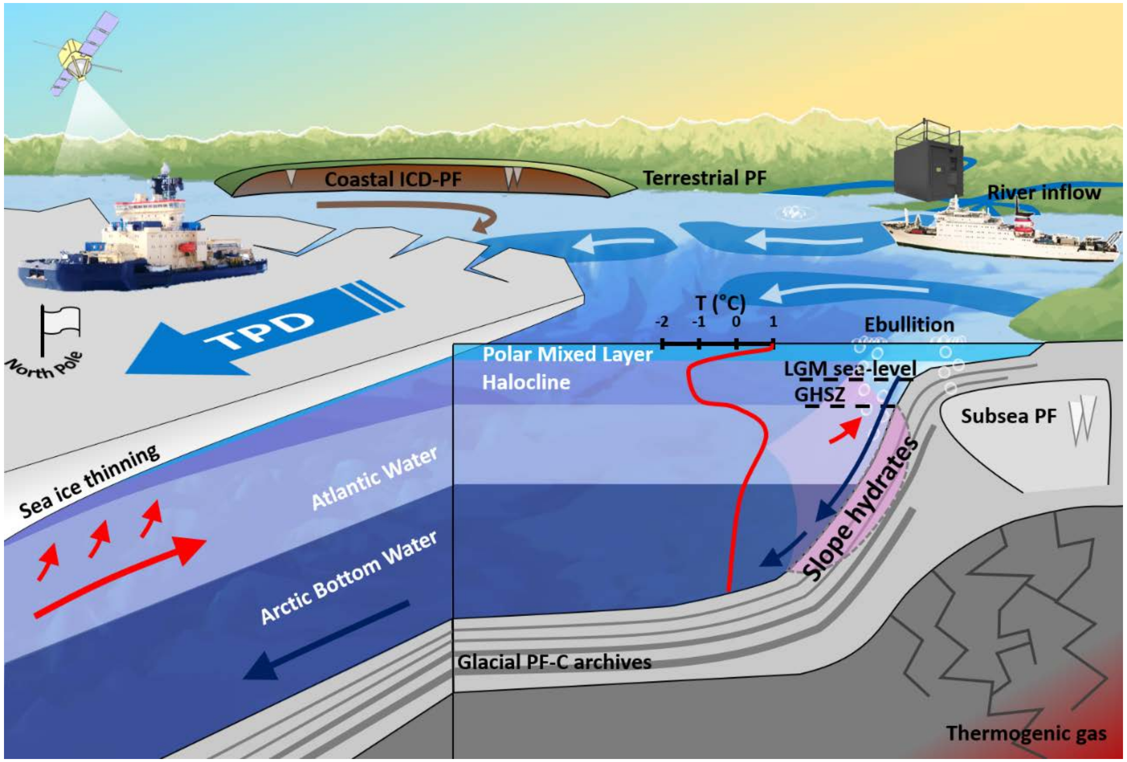
Sat data must be validated vs ship-based PM/POM data to understand better scales of C-pumping in the arctic land-shelf system

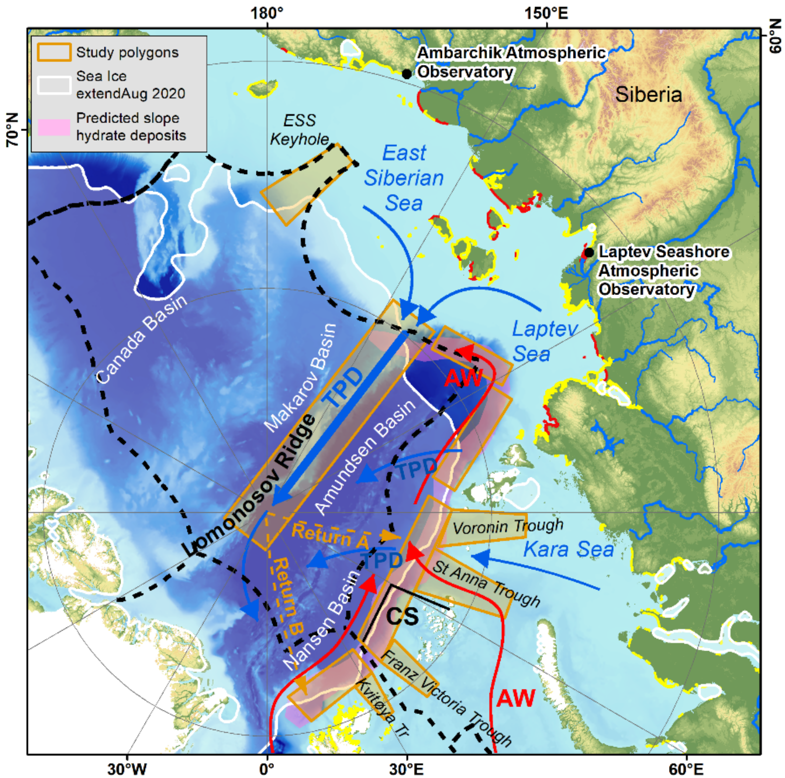
Concluding perspectives

- **ESAS/Pacific Arctic land-shelf-basin system is a key natural laboratory**
- **Sedimentation and major biogeochemical processes on the shallow ESAS are driven by coastal erosion and river impact**
- **Pacific Arctic Shelf is a source of freshened, corrosive, and methane enriched waters to the deep Arctic ocean basin-N. Atlantic: its role to prevent sea ice from warm touch of AW (?)**
- **Permafrost carbon thawing and hydrate collapses are one of the Grand Challenges in Geosciences**
- **Moving closer to system understanding allowing predictive capacity of future GHG fluxes**
- **Russia-International community has golden position to lead breakthrough science over coming years: Face the Future....**

Eurasian-Arctic Shelf-Basin Interactions of Climate-Cryosphere-Carbon-Contaminants - EURASIAN ARCTIC C4 -

A broad cross-disciplinary theme (33 co-PIs) addressing internationally top-prio research challenges






Thank you for your attention!