PERMAFROST THAW AND REDISTRIBUTION OF CARBON FROM LANDS AND OCEANS TO THE ATMOSPHERE: THE EAST SIBERIAN REGION

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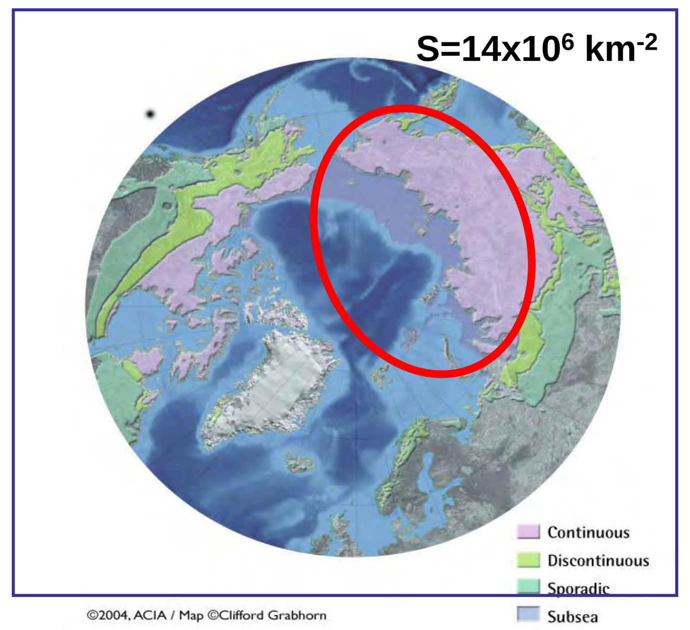
Motivation:

- Artic Ocean is small (~4% from total World Ocean), but it is unique because one is surrounded with **onshore and underlain with offshore permafrost which contains a huge reservoir of organic matter and trapped methane**, including methane in form of free gas and hydrates;
- **Area of subsea and land permafrost** (near 14mln km²) **is equal to the total area of the Arctic Ocean**, *Figure 1L*;
- East Siberian Arctic Shelf Shelf (**ESAS**) is the **broadest and shallowest shelf in the World Ocean and is the most strongly impacted by warming**, *Figure 1R*
- ESAS (area > 2 mln km²) is **accumulating an integrated signal of the terrestrial organic matter (OM) export from the vast riverine watersheds and eroded coastal ice-complex.**



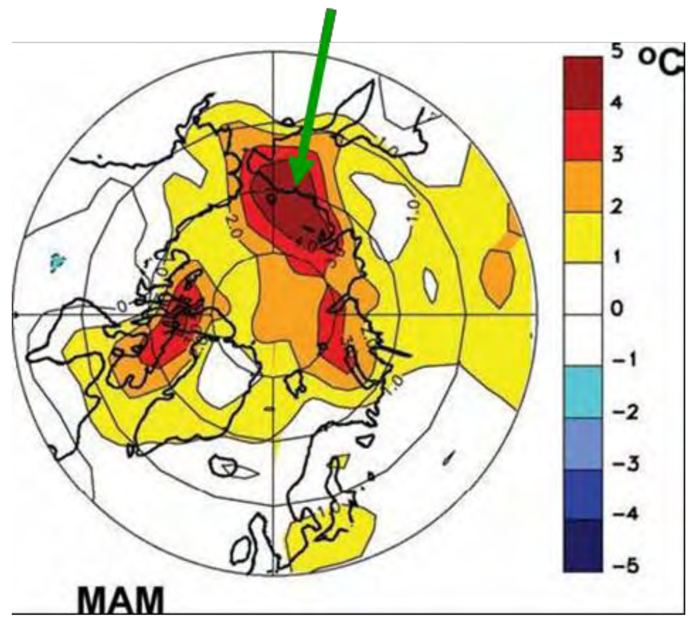


Figure 1. Left**:** distribution of subsea and onshore permafrost in the arctic region; Right: temperature anomalies over the East Siberian region (indicated by the green arrow)

- **Permafrost is warming and thawing** that causes an increase of transport of eroded carbon (due to coastal and bottom erosion) and fluvial carbon; other consequence is **thawing of sub-sea permafrost and destabilization of gas-hydrates/leaking of methane (see poster by Shakhova et al., *the same session*)** Part of fluvial and eroded carbon transforms to CO2, *Figure 2*.

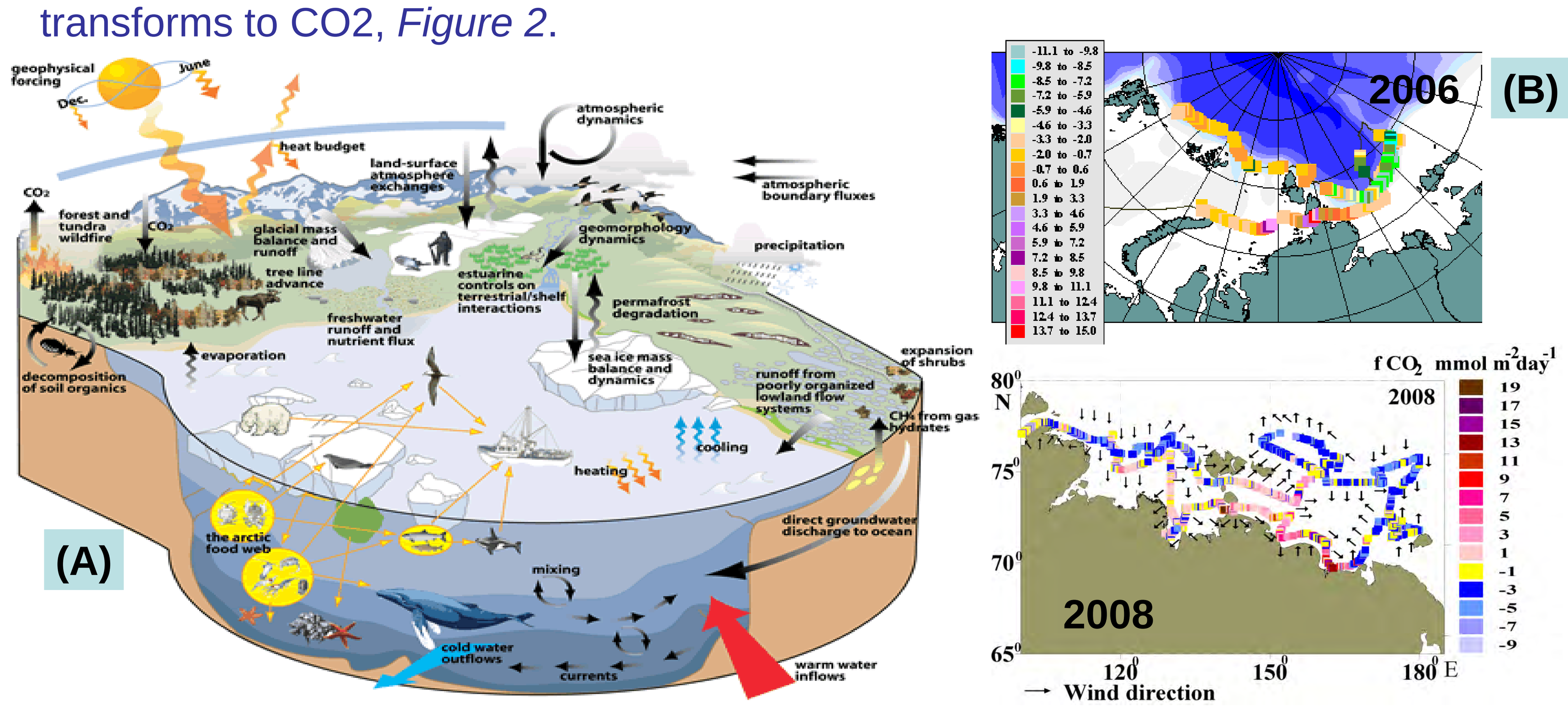


Figure 2. (**A**) Arctic System: Climate drives the Water cycle, the Water cycle drives the Carbon cycle, the Carbon cycle affects the climate; (**B**) **turbulent CO2 fluxes**

Major uncertainties constructing the ESAS marine carbon budget are:

1) Current estimates of riverine solid runoff, used for budget estimations, does not reflect the fact that majority of riverine POC settles in delta channels and never reach the shelf (*except of anomalous summer of 2008*), *Figure 3.*

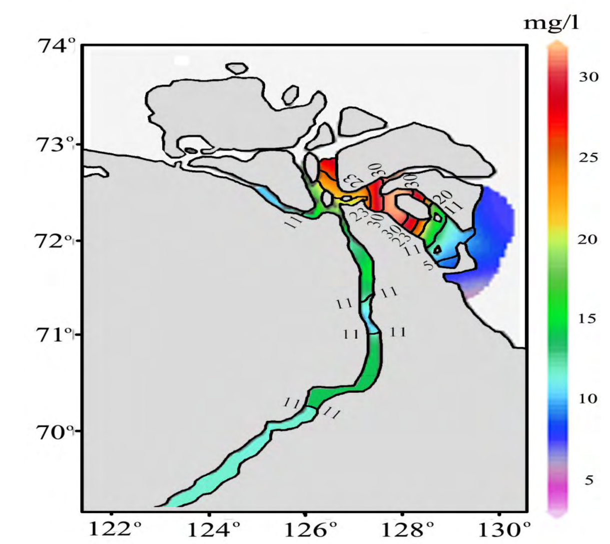


Figure 3. Particulate material distribution, mg l-1 in the lower stream/delta of the Lena River June-July 2003. Using the mean PM concentration of 20 mg l-1 and an annual river discharge of 525 km3 we calculate the "mean" solid discharge to be 10.5 Tg delivered to the delta channels. Annual discharge of POC may be equal to 0.38 Tg if we use a mean POC value of 0.75 mg l-1, which was obtained in 2003 along the Lena River during flooding (moderate or high estimates). If we accept *Lisytsin's* (1994) statement concerning the precipitation of 85-95% of total PM (and POC) on the marginal "filter", then only **about 1Tg of PM, and 0.03-0.04 Tg of POC reaches the Laptev Sea from the Lena River** [Semiletov et al., 2011].

2) Several studies show that transport of coastal eroded material (PM) into the Laptev and East Siberian seas ranges between 40-70 Tg [Grigoriev, 2010], which is a value almost two orders of magnitude higher than the Lena River PM discharge into the sea .

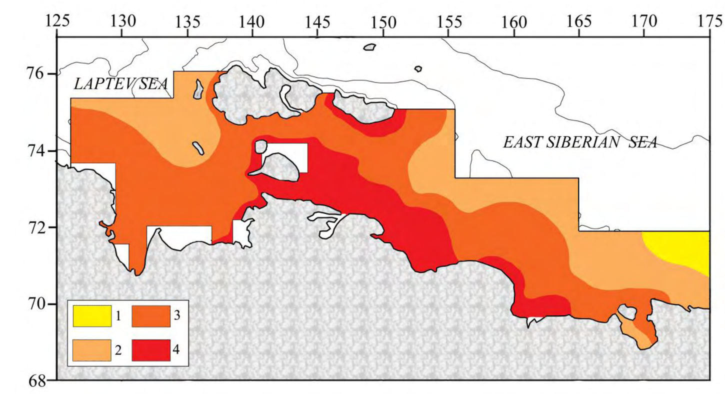


Figure 4 illustrates the dominant role of coastal erosion in offshore POC transport

Figure 4. Contribution of terrestrial organic carbon (CTOM, %) in the ESAS surface sediment: 1) <40%, 2) 40-69%, 3) 69-98%, 4) 98-100% [Semiletov et al., 2011, 2012]

3) Majority of the ESAS is a strong source of CO2 into the atmosphere, which reflects oxidation of terrestrial OM [Semiletov, 1999; Semiletov et al., 2007, 2011, 2012. 2013; Anderson et al., 2009, 2011; Pipko et al., 2011]. Air-sea CO2 flux is changed in values and directions from invasion ~5mM/m²/day in the in the Barents Sea, to evasion up to ~95mM/m²/day in the Laptev Sea, and up to 24-32 mM/m2/day in the East-Siberian Sea [Semiletov et al., 2013]. *Interannual variability of carbon dioxide fluxes is high*, up to 10 times [Pipko et al., 2011].

Acidification in the Arctic Ocean: two different ecosystems - two different acidification mechanisms

Recent syntheses of coastal carbon cycle studies by Chen and Borges (2009) suggest that the *polar continental shelves are likely to be potential sinks for atmospheric CO_2*. The largest pH changes in this century are anticipated in the surface waters of the Arctic Ocean (Bates and Mathis, 2009; Bates et al., 2009; Yamamoto-Kawai et al., 2009). ***In the ESAS the mechanism which lowers pH is different* from the well-known *ocean acidification effect*: the same "ESAS acidification" effect can be attributed to high pCO_2 values caused by remineralization of terrestrial OM introduced by coastal erosion and rivers.**

Our observational data from *the ESAS* show that the decay of POC and OC at the sediment surface results in low in situ pH values (as low as 7.24, total scale) making this *one of the most naturally acidified open marine environments* (Semiletov et al., 2012, 2014-submitted)

In some Laptev Sea areas acidification lowers the saturation state of calcite and aragonite in the surface waters to 0.4 and 0.2, and in the bottom water to 0.2 and 0, respectively (Semiletov et al., 2012); these values are even lower than those measured in the East Siberian Sea (Fig. 5D; and Anderson et al., 2011). Thus, all available data demonstrate that the **ESAS represents the most acidified ocean environment on the planet.**

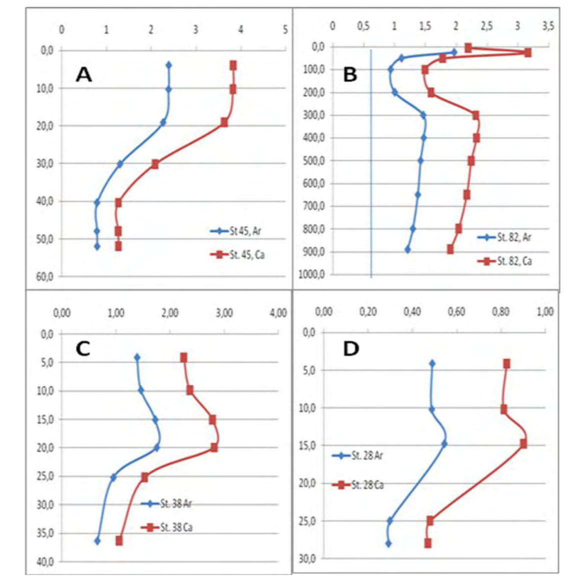


Figure 5. *$CaCO_3$ mineral saturation states* (Ωaragonite curve is marked in blue; Ωcalcite curve in red) *against depth (meters) observed in the Chukchi Sea: upper panel (coordinates of station (St.) 45 and St. 82 are 71,40 N, 175,17W and 75,70N and 178,80 W, "A" and "B" respectively); and in the ESS: bottom panel (coordinates of St. 38 and St. 28 are 70,70N and 169, 3E and* ***72,65N and 154,18E** , "C" and "D" respectively*) [Semiletov et al., in preparation]

CHALLENGE: ***The shallow ESAS has already entered the acidification state which is predicted for the 22nd century oceans after the world approaches the red line marked by atmospheric CO_2 doubling*** which could be associated with a reduction in the average pH of surface seawater (.~8.1) by 0.3-0.4 units (to 7.8-7.7) by the year 2100 (Orr et al., 2005).

Bottomline: it is critically important to understand and evaluate environmental changes associated with such a dramatic acidification with emphasis on the benthic communities most impacted by such acidification controlled by permafrost thaw and redistribution of carbon from land to the ocean

Selected author's publications (1996-2013):

Semiletov I.P., N.Ya. Pivovarov, I.I. Pipko, A.Yu. Gukov, T.I. Volkova, J.P. Sharp, Yu.S. Shcherbakov, and K.P. Fedorov, 1996, Dynamics of dissolved CH_4 and CO_2 in the Lena River Delta and Laptev Sea. *Trans. (Doklady) of the Russian Academy of Sciences, 350* (3), 401-404 (translated into English).

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Semiletov, I., I.I. Pipko, I.A. Repina, and N. Shakhova, 2007, Carbonate dynamics and carbon dioxide fluxes across the atmosphere-ice-water interfaces in the Arctic Ocean Pacific sector of the Arctic, Journal of Marine Systems, 66 (1-4), 204-226.

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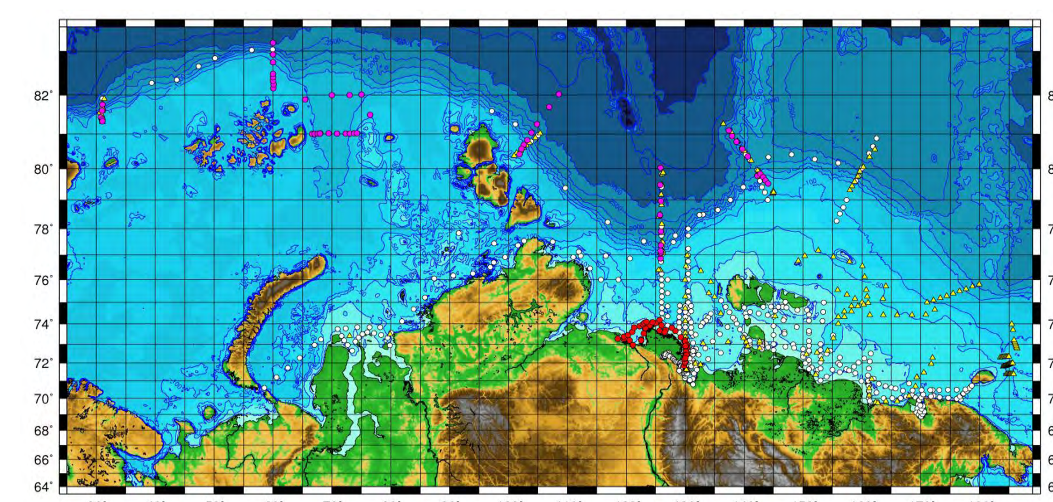
Pipko I. I., Semiletov I. P., Pugach S. P., I. Wáhlström, and Anderson L. G. (2011). Interannual variability of air-sea CO2 fluxes and carbon system in the East Siberian Sea, *Biogeosciences,* 8, 1987-2007, 2011, doi:10.5194/bg-8-1987-2011.

Semiletov I.P., Pipko I.I., Shakhova N.E., Dudarev O.V., Pugach S.P., Charkin A.N., McRoy C.P., Kosmach D., and Ö. Gustafsson (2011). Carbon transport by the Lena River from its headwaters to the Arctic Ocean, with emphasis on fluvial input of terrestrial particulate organic carbon vs. carbon transport by coastal erosion, *Biogeosciences,* 8, 2407-2426.

Semiletov I.P., Shakhova N. E., Sergienko V.I., Pipko I.I., and O. Dudarev (2012). On Carbon Transport and Fate in the East Siberian Arctic Land-Shelf-Atmosphere System, *Environment Research Letters,* 7, doi:10.1088/1748-9326/7/1/015201

Semiletov, I.P., Shakhova, N.E., Pipko, I.I., Pugach, S.P., Charkin, A.N., Dudarev, O.V., Kosmach, D.A., and S. Nishino (2013). Space-time dynamics of carbon and environmental parameters related to carbon dioxide emissions in the Buor-Khaya Bay of the Laptev Sea, Biogeosciences, 10, 5977-5996, www.biogeosciences.net/10/5997/2013/doi:10.5194/bg-10-5977-2013.



Conclusions are based on multi-year studies accomplished by authors and their collaborators in (1994-2014)