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COASTAL EROSION AS A DESTABILIZING FACTOR OF CARBONATE BALANCE IN THE EAST SIBERIAN ARCTIC SEAS

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The carbonate balance in the Arctic seas of East Siberia is in reciprocal relationship with climate change and destructive coastal dynamics. Thermal and wave erosion of permafrost coast associated with global warming destabilizes the marine CO_2 – carbonate system by increasing dramatically the partial pressure of CO_2 in coastal waters to 800–900 ppm and facilitating its release into air. The ongoing warming and growing activity of coastal processes can reduce the ability of the eastern Arctic seas for CO_2 uptake.

INTRODUCTION

Arctic seas are important regulators of atmospheric carbon dioxide in the Northern Hemisphere. In the summer season they may be expected to act as sinks of excess CO_2, but there is evidence [*Razumov, 2003; Pipko et al., 2005*] that the surface waters are oversaturated with CO_2 which evades into the atmosphere in some areas of Arctic seas. The potential of seawater for CO_2 uptake from the atmosphere depends on the relative percentages of components in the CO_2 – carbonate system, or the carbonate balance. This balance in coastal-shelf waters is subject to the influence of climate-controlled erosion processes in the permafrost coast.

EFFECT OF COASTAL EROSION ON THE CARBONATE BALANCE OF COASTAL-SHELF WATERS IN ARCTIC SEAS

The uptake of atmospheric CO_2 by the eastern Arctic seas and increasing fluxes of organic carbon and carbonates (dissolved or solid) affect the seawater carbonate balance. In the East Siberian seas, the rapidly retreating coast with high contents of ground ice is the main source of terrigenous input to the shelf. Coastal erosion (mainly by thermal processes and waves) supplies about $4 \cdot 10^6$ tons of organic carbon into the Laptev and East Siberian seas, which is more than in all other Arctic seas [*Grigoriev et al., 2006*]. A part of carbon dioxide that is absorbed from the air and released in organic carbon oxidation is spent on dissolving calcium carbonate, whereby seawater becomes more alkalic. The water alkalinity in the East Siberian Sea did not change much from the 1920s to the early 1950s but it grew by the early 1990s (by 0.21 mg·equivalent/liter on average and by 0.25–0.40 mg·equivalent/liter in the southern sea part).

Carbon dioxide can either evade from seawater or invade into it at specific weather conditions in the ice-free season with moderate winds and calm spells. For instance, $CaCO_3$ saturation west of the Kolyma Delta is within 0.77 while the CO_2 partial pressure is from 89 to 164 ppm [*Razumov, 2003*]. This pressure being almost 2–4 times as low as the atmospheric

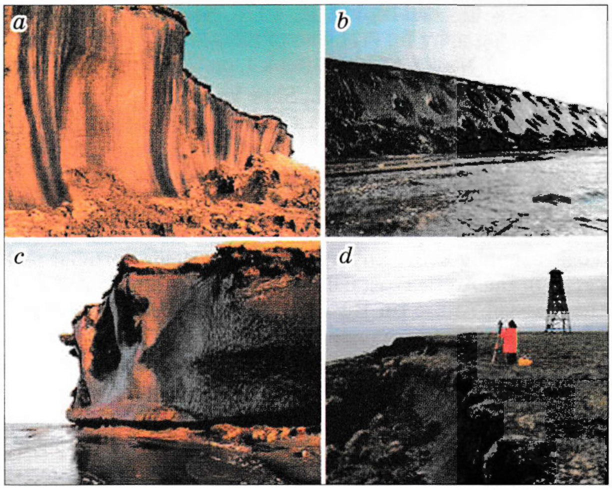

Fig. 1. Ice-rich coastal cliffs of Arctic seas:

a – Bolshoi Lyakhovsky Island, *b* – Anabar-Olenek coast, *c* – Muostakh Island, *d* – Bykovsky Peninsula.

mean of high latitudes, one can expect invasion of carbon dioxide. In the Kolyma Delta, however, more CO_2 is rather released than absorbed as its partial pressure in seawater reaches 300 to 600 ppm, possibly, due to intense oxidation of organic carbon carried by the river.

Thermal and wave erosion of permafrost coast is responsible for significant variations of physicochemical parameters and, as a consequence, interferes with the CO_2 – carbonate balance in the coastal zone. The rate of coastal erosion in the eastern Arctic seas changes in space and time depending on summer air temperatures and ice conditions, as well as on recurrence and duration of storms. Erosion slowed down during relative cooling between the 1950s and early 1970s in the Russian eastern Arctic, and the coast of the Laptev and East Siberian seas retreated at a mean rate of 2–6 m/yr [*Are, 1985*]. The coast of the two seas consists mainly of silt-size loamy sand and sandy loam with thick ice wedges up to 7–8 m wide, the total ice content of soil reaching 30 to 90 vol. % (Fig. 1).

Relative climate warming through the past forty years increased the duration of ice-free seasons in the eastern Arctic, the surface area of open water, and the frequency of storms. The mean summer air temperature rose 1.3–1.5 °C above the climate norm, the storm recurrence increased by 3–4 %, and the total duration of active wave dynamics on the permafrost coast grew, on average, from 58 to 100 hr/yr. The coastal retreat in zones of rapid erosion in the Laptev and East Siberian seas accelerated to 4–8 m/yr on average reaching locally as high as 12 m/yr (Fig. 2), with the maximum erosion rate 17–25 m/yr [*Razumov, 2000; Grigoriev and Zhang, 2008*]. As the ice-rich coast is being rapidly eroded, oxidation of organic carbon rises dramatically the partial pressure of carbon dioxide in seawater (to 800–900 ppm) and facilitates its release into air (Fig. 3) [*Razumov, 2003; Pipko et al., 2005*].

Thus, carbon dioxide is released from the coastal zone of the East Siberian Sea between the New Siberian islands and the Chaun Bay, in common meteorological conditions, and is absorbed by water in the eastern sea part. The release grows with increasing thermal erosion and occurs even offshore as far as the De Long Strait. Active thermal erosion of mainland and islands in the southeastern Laptev Sea results in prevalent release of CO_2.

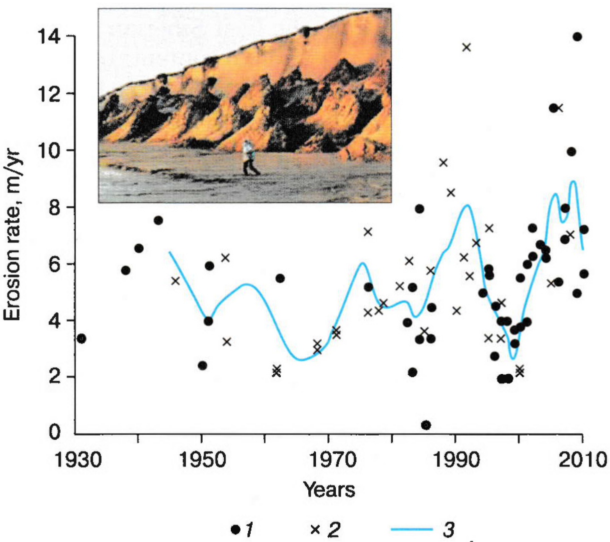

Fig. 2. Variations in mean rate of coastal retreat in the Laptev (*1*) and East Siberian (*2*) seas in zones of rapid thermal erosion.

3 – erosion rates averaged over two seas. Inset shows a typical coastal exposure of ice complex, Shirokostan Peninsula.

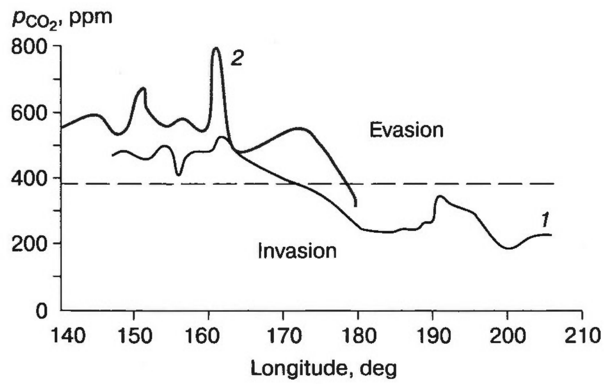

Fig. 3. CO_2 partial pressure in coastal-shelf waters of Arctic seas of East Siberia in the conditions of common ice-free season (curve *1*) and erosion of ice-rich coast (curve *2*).

Dashed line is present atmospheric CO_2.

EFFECT OF DESTABILIZED CARBONATE BALANCE ON REGIONAL CLIMATE

Warming in the Arctic decreases the magnitude of the partial CO_2 pressure gradient between water and air (Fig. 4) due to greater activity of processes destroying the permafrost coast. Organic carbon, which was formerly stored in permafrost, comes into the sea. This reduces the capacity of Arctic seas for taking up carbon dioxide, and the water-air gradient of CO_2 partial pressure becomes prone to reversal, i. e., the release becomes more probable than the uptake (Fig. 4). The release of CO_2, in turn, would decrease its partial pressure in water and increase the $CaCO_3$ percentage on dissociation of bicarbonates. Thereby the system may be expected to recover its equilibrium with atmospheric CO_2 and, possibly, return to invasion of carbon dioxide (Fig. 5).

However, this does not happen for the shortage of solid carbonates in the eastern Arctic seas. Their dissolution consumes a relatively small part of CO_2 which is released into the water on oxidation of organic carbon provided by coastal erosion. Its greater part becomes gaseous thus increasing the partial pressure. This destabilizes the carbonate balance in the coastal-shelf waters along the zones of rapid coastal retreat.

As the water temperature rises, the solubility of carbon dioxide decreases while its partial pressure grows and thus favors the evasion. In the eastern Arctic seas, this regularity works in water with a salinity over 20 ‰ but is less pronounced in the shelf where salinity is below 13 ‰ (Fig. 6). Therefore, the carbonate balance in coastal waters may shift to lower CO_2 partial pressures but higher $CaCO_3$ and pH (Fig. 5), possibly, because the aggressive part of free CO_2 is spent on dissolution of solid carbonates brought from the mainland. The system responds to this shift by CO_2 invasion despite the relatively high water temperature.

Thus, destabilization of the CO_2 – carbonate system of the Arctic seas is attendant with release of carbon dioxide and the ensuing accumulation of calcium carbonate. The uptake of atmospheric CO_2, and dissolution of carbonates as its consequence, reflect the stable state of the CO_2 – carbonate system of both seas. The climate, the dynamics of destructive processes in the permafrost coast, and the carbonate balance in the eastern Arctic seas are in reciprocal relationship. The loss of equilibrium in the CO_2 – carbonate system pushes up the otherwise caused climate change in the Arctic.

This may be explained as follows. The thermodynamic model of the annual ocean-air cycle [*Kagan et al., 1986*] predicts that doubling of atmospheric CO_2 (from 280 to 560 ppm) should cause a 1.4 °C warming of the mean annual air temperature north of 60° N

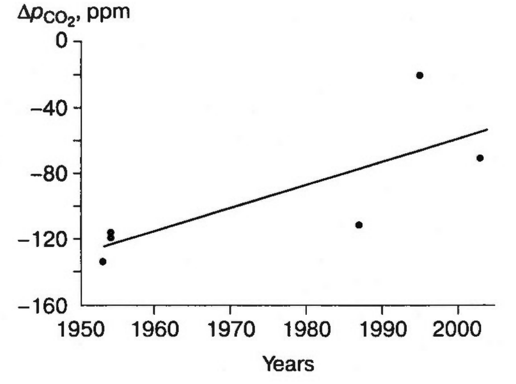

Fig. 4. CO_2 partial pressure gradient between water of eastern East Siberian Sea and air, according to [*Musina, 1960; Feely et al., 2001; Razumov, 2003; Pipko et al., 2005*].

Negative gradient corresponds to CO_2 uptake.

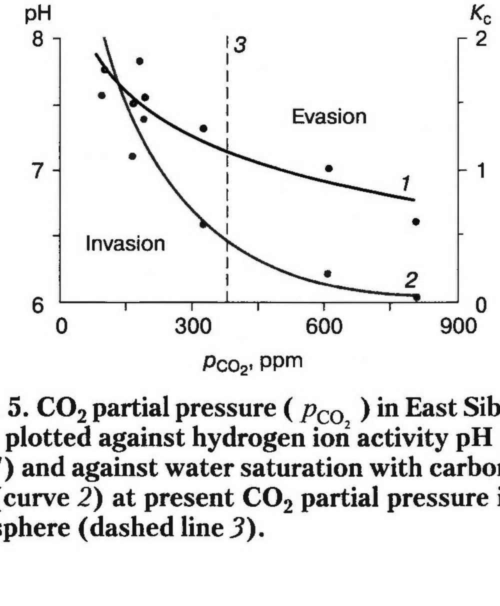

Fig. 5. CO_2 partial pressure (p_{CO_2}) in East Siberian Sea plotted against hydrogen ion activity pH (curve *1*) and against water saturation with carbonates K_c (curve *2*) at present CO_2 partial pressure in atmosphere (dashed line *3*).

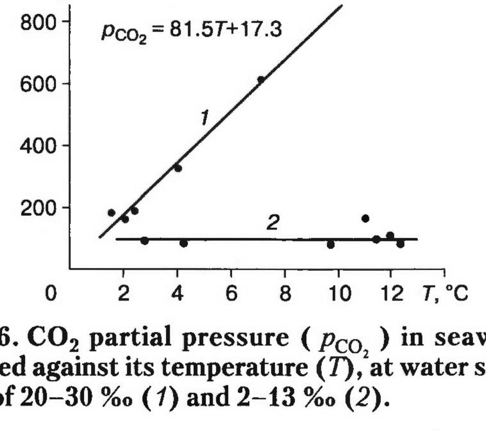

Fig. 6. CO_2 partial pressure (p_{CO_2}) in seawater plotted against its temperature (*T*), at water salinities of 20–30 ‰ (*1*) and 2–13 ‰ (*2*).

(0.75 °C for summer temperature and 1.7 °C for winter temperature). Over the period from the early 1960s to 2008, the CO_2 partial pressure in air in the Northern Hemisphere became 75 ppm higher, which, according to the thermodynamic modeling, can cause a 0.37 °C increase in the mean annual air temperature north of 60° N. Data from 14 weather stations from Vize Island to Dezhnev Cape show a mean annual air temperature rise of 1.0–2.7 °C in the same period (1.8 °C on average) [*Grigoriev et al., 2009*]. Thus, the contribution of atmospheric CO_2 increase into the observed warming is about 20 %.

Therefore, warming in the Northern Hemisphere more likely has other major controls than CO_2 increase. This may be 20- and 50-year cycles of the Earth's axis nutation driven by tidal forces [*Grigoriev et al., 2006*] and related changes in water circulation in the World ocean and global atmospheric transport.

CONCLUSIONS

Climate change to warming or cooling, which influences the coastal dynamics, may result from nutation cycles driven by tidal forces. Destabilization of the carbonate balance in seawater is not the cause of climate change but only can increase its magnitude.

In the contemporary climate conditions, the Arctic seas generally keep their potential for CO_2 uptake in spite of high organic carbon input to the water and summer warming. However, further warming and coastal erosion may aggravate the carbonate balance instability in the East Siberian Arctic seas and reduce considerably their CO_2 uptake capacity.

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