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GEOGRAPHY

Russian Mountain Glaciers in a "Thawing" World: The First Estimates of the Balance of Greenhouse Gases in the Caucasus and Altai

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Abstract—In the modern sense, glaciers are a unique large terrestrial biome. They combine autotrophic–heterotrophic ecosystems with the most significant contribution of abiotic processes. The biome serves as an important supplier of biogenic elements and climatically active substances accumulated over glacial epochs. The cycle of biogenic greenhouse gases (GHGs) is one of the most important biospheric functions of any large ecosystem. Ablation, which is especially prominent on mountain glaciers, can have a significant impact on the GHG cycle under current warming. We have studied two mountain glaciers located in the European (North Caucasus, 2020) and Asian (Altai, 2021) parts of Russia. The purpose of this work was to estimate the current values of GHG fluxes in the influence zone of the glaciers losing their mass under warming. Due to the accumulation of cryoconites (fine-grained soils, mainly of aeolian genesis) on the ice surface, the ablation zones, on average, serve as weak sources of CO_2 for the atmosphere (15.3 mg CO_2 m^{-2} d^{-1}), whereas the glacier accumulation zones are weak sinks (–21.5 mg CO_2 m^{-2} d^{-1}). Young terminal moraines formed over the last 20 years are more significant additional sources of CO_2 (45.2 to 446.3 mg CO_2 m^{-2} d^{-1}) and methane. The spatial variations in methane fluxes are highly substantial, and its contribution to radiative forcing (–0.4 to +225.6 mg CO_2-equiv. m^{-2} d^{-1}) may be comparable to that of CO_2. Compared to these GHGs, the net fluxes of nitrous oxide in the glacial ecosystems studied are negligible. The contribution of soil-like bodies of young moraines significantly increases the weighted average estimation of CO_2 emission on glaciers from 2 to 1015 kg C km^{-2} yr^{-1}. The results obtained highlight the role of glaciers as preserving biospheric agents of the GHG exchange in the atmosphere.

Keywords: supra- and periglacial sediments, cryoconites, soil-like bodies, modern climate warming, net balance, carbon dioxide, methane, nitrous oxide

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In the 2000s, there was a conceptual change in the understanding of glaciers as a special terrestrial biome. There has been a shift from studying the structure and physicochemical interactions of glacial biota to assessing the biospheric functions [3]. An important argument in this case is the huge area occupied by glaciers (15.5 million km^2), which puts them in line with the largest biomes of the Earth. The cycle of biogenic greenhouse gases (GHGs), which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), is one of the most important biospheric functions of any large ecosystem. Glaciers in the modern "thawing" world are unique, because they are autotrophic–heterotrophic ecosystems, where abiotic GHG exchange dominates [4]. For many aquatic and terrestrial ecosystems, glaciers are also a donor of biogenic elements and climatically active substances accumulated during glacial eras [9]. The scale of additional GHG emissions into the atmosphere during the retreat of perennial ice may be significant. Both the biogenic and abiogenic components of the carbon cycle are significantly accelerated due to current warming [2, 9, 12]. Mass loss due to warming is especially noticeable on mountain glaciers, amounting to 332 Gt per year [11]. This fact allows us to consider them not only as an indicator of climate change, but also as a model of what may happen to the GHG balance with the loss of thick ice caps. In addition, detailed studies of GHGs on glaciers have not previously been conducted in Russia.

We observed the GHG fluxes on two mountain glaciers with a negative mass balance: Garabashi Glacier (43°18′ N, 42°28′ E, North Caucasus, August 6–15, 2020; total glacier area 3.8 km^2; measurements were taken at altitudes from 2383 to 3831 m a.s.l.) and Left Aktru Glacier (50°5′ N, 87°45′ E, Altai Republic, July 15–27, 2021; 5.4 km^2; 2075–2918 m a.s.l.). The

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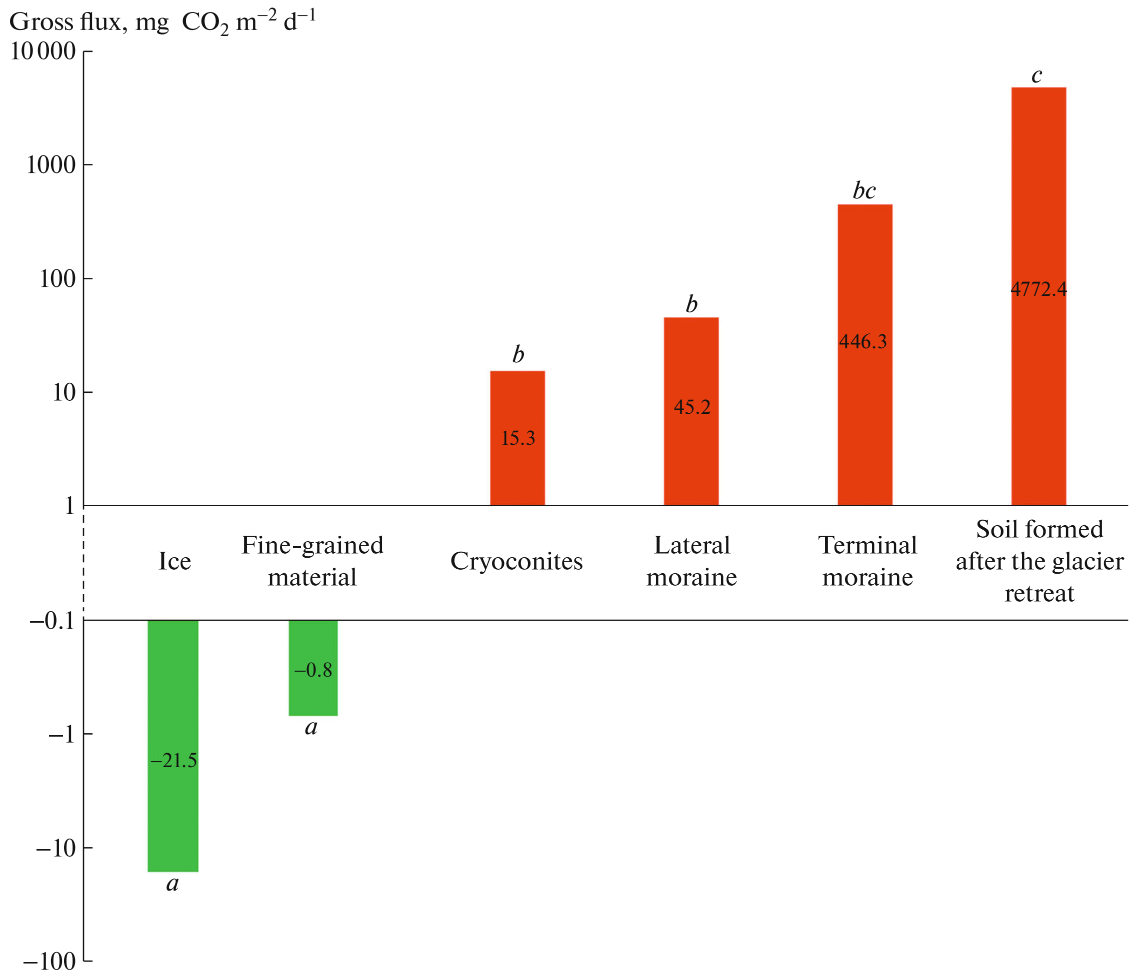

Fig. 1. Gross CO_2 fluxes in the mountain glacier ecosystems, ranked in ascending order (Altai, Left Aktru, 2021). Positive values indicate the CO_2 source for the atmosphere (red), and negative values indicate the sink from the atmosphere (green). Positive values are plotted on a logarithmic scale; negative values, on the −log(abs(*y*)) scale. Different letters correspond to significant differences in the mean (Mann–Whitney, $p < 0.05$), and the same letters indicate no pairwise differences.

mass of ice on Garabashi Glacier decreased by 16 m water equivalent during the period 1997–2020, the total volume decreased by 27% [7, 10]. Processes similar in direction and velocity occur in the Altai Mountains despite the weakening influence of continentality [8]. In both cases, it is explained by an increase in air temperature. Losses of ice mass are accompanied by a significant increase in the areas of moraine sediments.

Field measurements were performed in closed chambers using mobile high-precision gas analyzers; gas chromatography was used for the laboratory estimations. The total number of measurements was 264.

The mean value of gross CO_2 fluxes[1] for all studied ecosystems of Aktru Glacier was +944.4 ± 269.5 mg CO_2 m^{-2} d^{-1} (from −199.7 to +8127.8, $n = 86$)[2], which does not differ significantly from similar data obtained for Garabashi Glacier (+915.2 ± 615 mg CO_2 m^{-2} d^{-1}; from −7.9 to +13 200, $n = 25$). The gross CO_2 fluxes varied widely in the zone of glacier influence during the warmest period of the year, differing between the ecosystems by 4–5 orders of magnitude (Fig. 1). In the areas of balance and accumulation, the gross exchange on ice is generally a weak sink from the atmosphere (−21.5 mg CO_2 m^{-2} d^{-1}), which is most likely caused by dissolution in thaw water.

Cryoconites (CC), special soil-like organo-mineral forms, are currently of great importance. This is associated with their active participation in the exchange processes on the surface of the glacier [4]. If

[1] In contrast to the commonly used term "net flux," which implies mainly the gas exchange of biota, the term "gross flux," adopted here also includes the abiotic processes of CO_2 absorption and release on the glacier.

[2] The positive fluxes indicate the net source of gases for the atmosphere, and negative fluxes indicate the sink from the atmosphere.

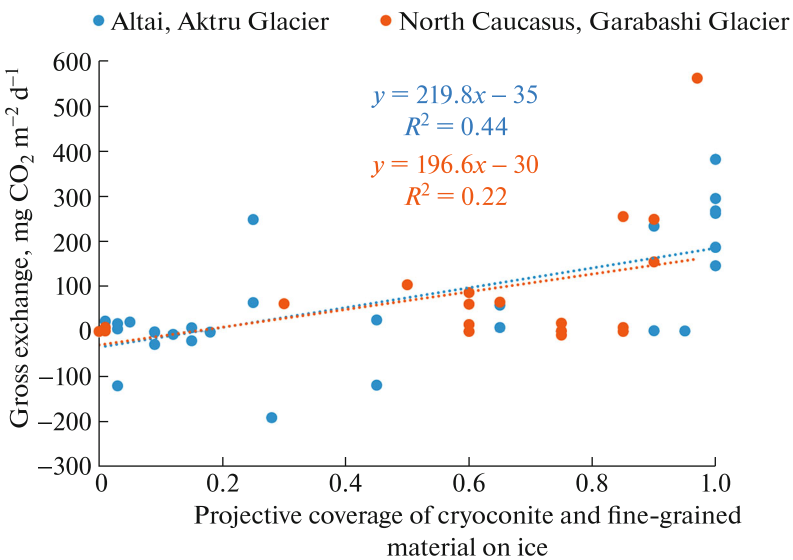

Fig. 2. Dependence of the gross CO_2 fluxes on the projective coverage of cryoconite and fine-grained material on the surface of the glaciers studied. The linear regressions and their coefficients of determination are given.

the ablation area exhibits a state close to a C-balance, the gross exchange increases by an order of magnitude (+15.3 mg CO_2 m^{-2} d^{-1}) at the zones with CC, reflecting the increasing contribution of microbial respiration. Compared to CC, lateral moraines "breathe" slightly more actively (+45.2), because they contain large boulders, pebble material, and sand on steep slopes, from which clay particles are quickly washed out. Compared to the lateral zones, the terminal moraine demonstrates rates of exchange an order of magnitude higher (+445.3). This fact is associated with the significant accumulation of fine-grained soil as a result of sedimentation by water currents, and the fixation of plants here. But even in this case, the rate of gross fluxes is an order of magnitude inferior to emission from the local sod-cryometamorphic permafrost soils (Turbic Cryosols), which were formed about a thousand years ago after contraction of the glacier (Fig. 1).

CCs on the glacier surface significantly reduce its albedo. Comparison of the results obtained for the glaciers studied shows that the slopes of the dependence of the true albedo on the CC density do not differ for them (Analysis of Variance (ANOVA), p = 0.16), demonstrating a high positive linear relationship ($R^2 = 0.82$). The latter is important, because not only the absorption of solar energy and the rate of thawing, but also the gross CO_2 fluxes depend on the presence of CC. The slopes of the dependencies for the two glaciers in this case also coincide ($p = 0.11$), demonstrating a positive linear relationship, which allows us to use a single equation to predict the spatial distribution and the variability of gross CO_2 fluxes on the ice surface (Fig. 2).

Two glaciers have common features; their rate of the net exchange of methane on the young moraines can be 1–2 orders of magnitude higher than its fluxes on ice with CC (Fig. 3). Although certain zones of the periglacial ecosystems can be both a sink from the atmosphere (in the presence of vegetation) and the source of methane for the atmosphere, demonstrating a high variability from –44.9 to +225.7 mg CO_2-equiv.[3] m^{-2} d^{-1}. In the latter case (the moraine with an age of more than 50 years old), the emission of methane was comparable in radiative effect with the maximum flux of CO_2 on the young moraines.

Ice with an albedo > 0.4 represents a very weak sink of nitrous oxide from the atmosphere: –0.67 ± 0.58 mg CO_2-equiv. m^{-2} d^{-1} (physicochemical process of absorption), and the terminal moraine is a weak source of nitrous oxide (+1.12 ± 0.80). CC and fine-grained material occupy an intermediate position of the sources of low significance, and the lateral moraines did not show N_2O fluxes significantly different from zero. The values of nitrous oxide net exchange, obtained in the mountain glacier ecosystem, cannot be considered as significant even for the local GHG budget. If we calculate the specific contributions of the three GHGs in CO_2-equivalent, it appears that more than 99% of the total effect is provided by carbon dioxide.

On the ice surface, the leading role of CC matter in the total GHG exchange is undoubted. If the area-weighted average gross flux of all GHGs is about –

[3] When converted to CO_2 equivalent, a factor of 25 is assumed for methane, 298 for nitrous oxide (IPCC 2021: Climate Change, 2021).

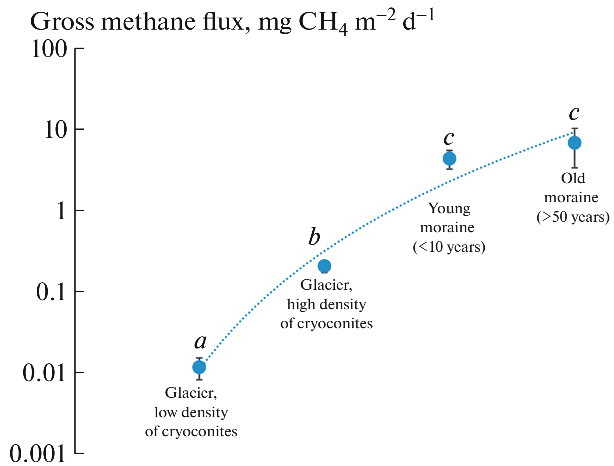

Fig. 3. Gross methane fluxes in the ecosystems of the influence zone of Garabashi Glacier (North Caucasus, 2020). "Low density of cryoconites" in the figure combines zones with the fractional projective coverage of cryoconite and fine-grained material from 0 to 0.2; "high density," from 0.5 to 1. The averages and their standard errors are given on a logarithmic scale. Different letters correspond to significant differences in the mean (Mann–Whitney, $p < 0.05$); the same letters indicate the absence of pairwise differences.

1.8 mg CO_2-equiv. m^{-2} d^{-1}, for the current glacier surface, and corresponds to 6% of CCs presenting in the area, then the flux may increase to 16 mg CO_2-equiv. m^{-2} d^{-1} with a gradual increase in the projective coverage of CC during thawing. This highlights their potential contribution to metabolic processes during warming, because the CC mass on the glacier actively increases during ablation, which is especially noticeable in the lower zone of the glacier.

The gross CO_2 fluxes are most significantly correlated with the altitude ($r = -0.83$, $p < 0.01$), the CC presence ($r = +0.55$, $p < 0.01$), and the slope angle ($r = -0.48$, $p < 0.01$).

The negative relationship with the slope is explained by the washout of fine-grained soils and organic matter on more distinct slopes. The net flux of methane is related to the same variables. The data obtained for nitrous oxide are still insufficient. A significant correlation for the nitrous oxide fluxes has been established only with the altitude. In addition, there are average or high correlations of the fluxes of the three GHGs between each other. This shows that their exchange is generally affected by the same factors. The multiple linear stepwise regression analysis for the three GHGs in the zone of glacier influence, based on the same set of quantitative variables, showed that the model constructed on the basis of the altitude and the slope angle ($R^2 = 0.30$) is the most significant for the gross fluxes of carbon dioxide. A similar model obtained for the net CH_4 fluxes has greater explanatory power ($R^2 = 0.54$). In this case, the absolute altitude and the projective cover of plants are important. No significant model for N_2O could be built, mainly due to the lack of field data. To assess the joint effect of quantitative and qualitative variables, we conducted an analysis using distance-based linear modelling (DistLM) and permutational multivariate analysis of variance (PERMANOVA) [1]. From the entire set of variables, the type of ecosystem is most important for CO_2 to explain 73–76% of variance; for methane, the absolute altitude of the terrain (37–43%) is the most significant; for nitrous oxide, it is the grain size composition of the surface (32.9%).

Despite the optimal temperature of dissolution (+1°C), the CO_2 content of the water flowing over the ice surface is only 2.27–3.00 g CO_2 m^{-3}. Calculation for aqueous pH 7 gives a maximal of 5.07 g CO_2 m^{-3} at the same temperature, actual atmospheric pressure, and the observed gas concentration in the lowest atmospheric layer. Therefore, the freshly thawed water is half as poor in carbon dioxide as the water in phase equilibrium under these conditions, which can be explained by its reduced content in the thawing ice. The ice layers that were formed during the period when the CO_2 concentration in the atmosphere was significantly lower are currently involved in the ablation process. In particular, the data on Garabashi Glacier shows that, during the observation period, the ice layers that were formed 70–100 BP when the atmospheric concentration of carbon dioxide was within 303–311 ppm (compared to the current 415 ppm) were affected by ablation [13]. Therefore, we most likely cannot expect an increase in the concentration of carbon dioxide above the glacier because of its direct release from thawing ice. This is also confirmed by direct measurements of gas exchange in the areas where we visually have noted the bubbling release of air during thawing; however, no increase in the CO_2 content was recorded. The methane content in all water samples was equal to or lower than its calculated concentration in water at the interphase equilibrium under the given conditions; i.e., no additional sources of methane in the water samples were recorded.

According to the calculations of the total balance carried out on the basis of the field measurements and satellite and high-resolution aerial images, it was found that Aktru Glacier, on average, releases from its surface only 2 kg C (CO_2) km^{-2} yr^{-1}, which can be considered as about zero balance. For comparison, according to [5], the annual balance of the world's glaciers is within 12–14 kg C km^{-2} yr^{-1}. Nevertheless, the spatial range of the gross CO_2 exchange on the glaciers studied varies widely: from the highly variable sink from the atmosphere into the areas of accumulation (from −17 to −556 kg C km^{-2} yr^{-1}) to the noticeable source at the lower end of the area of ablation (from 200 to 334 kg C km^{-2} yr^{-1}). If we add the contribution of the adjacent soil-like zones of the young moraines to the area-weighted average value of the annual gross flux from the glacier surface, the obtained value increases significantly (1015 kg C km^{-2} yr^{-1}).

CONCLUSIONS

The results obtained characterize the role of glaciers, first of all, as preserving agents of the GHG balance in the modern biosphere. The ice itself does not represent any noticeable source or sink of GHGs during thawing. However, the progressive retreat of glaciers causes the formation of increasingly essential additional sources of biosphere-active substances from subglacial reservoirs. These sources have an impact on the rate and structure of the local and general biogeochemical cycle and energy exchange. The scale of such changes requires further evaluation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. M. J. Anderson, R. N. Gorley, and K. R. Clarke, *PERMANOVA + for PRIMER: Guide to Software and Statistical Methods* (PRIMER-E Ltd, Plymouth, 2008).
2. L. C. Andrew, Nature **565**, 31–32 (2019).
3. A. M. Anesio and J. Laybourn-Parry, TREE **27**, 219–225 (2012).
4. J. Cook, A. Edwards, N. Takeuchi, and T. Irvine-Fynn, Progr. Phys. Geogr. **40** (1), 66–111 (2016).
5. A. J. Hodson, A. M. Anesio, F. Ng, et al., J. Geophys. Res. **112** (G4), G04S36 (2007).
6. *IPCC 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Ed. by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Cambridge Univ. Press, 2021).
7. S. Kutuzov, I. Lavrentiev, A. Smirnov, G. Nosenko, and D. Petrakov, Front. Earth Sci. **7**, 153 (2019).
8. P. A. Toropov, M. A. Aleshina, G. A. Nosenko, and T. E. Khromova, Russ. Meteorol. Hydrol. **45**, 368–376 (2020).
9. J. L. Wadham, J. R. Hawkings, L. Tarasov, et al., Nat. Commun. **10**, 3567 (2019).
10. *WGMS (2020, Updated, and Earlier Reports). Global Glacier Change Bulletin No. 3 (2016-2017),* Ed. by M. Zemp, I. Gärtner-Roer, S. U. Nussbaumer, J. Bannwart, P. Rastner, F. Paul, and M. Hoelzle (ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, 2020). https://doi.org/10.5904/wgms-fog-2019-12
11. M. Zemp, M. Huss, E. Thibert, et al., Nature **568**, 382–386 (2019).
12. Y. Zhang, Shichang Kang, Da Wei, Xi Luo, Zhuangzhuang Wang, and Tanguang Gao, Fund. Res. **1**, 232–239 (2021).
13. https://www.co2.earth/co2-ice-core-data.

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