Evaluation of carbon cycle features in the Earth system model ARTS-ESM

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ИНСТИТУТ ГЕОГРАФИИ Российской академии наук
основан в 1918 году

($\star$) ARTS-ESM := ex-INMCM

preprint:

Introduction

ARTS-ESM is a new generation of the national Earth System Model, developed by the Consortium led by INM RAS. By early 2026, the low-spatial-resolution version ARTS-ESM-L [1] was presented ($2^\circ \times 1.5^\circ$ in longitude-latitude and 21 vertical sigma levels in the atmosphere, and $1^\circ \times 0.5^\circ$ and 40 vertical sigma levels in the ocean). This configuration is designed for long-term climate simulations, including the full CMIP7 Assessment Fast Track [2].
During preparation of the new model version, the carbon cycle module was significantly improved [3]. This research analyses the features of the carbon cycle and its impact on climate in the model.

Carbon cycle simulation in ARTS-ESM-L

1. **Land:**
   - dynamic vegetation, 13 PFTs;
   - 3 carbon pools – vegetation (C_{VEG}), soil (C_{SOIL}) and fast anthropogenic ($C^{\text{fast}}_{\text{SOIL}}$);
   - land use and harvesting are taken into account

$$\frac{\partial C_{\text{VEG}}}{\partial t} = F_{\text{PSN}} - F_{\text{PLR}} - \frac{C_{\text{VEG}}}{\tau_{\text{VEG}}} - F_{\text{LU}}(t) \cdot C_{\text{VEG}},$$

$$\frac{\partial C_{\text{SOIL}}}{\partial t} = \frac{C_{\text{VEG}}}{\tau_{\text{VEG}}} - F_{\text{harvest}} - \frac{C_{\text{SOIL}}}{\tau_{\text{SOIL}}} - F_{\text{LU}}(t) \cdot C_{\text{SOIL}},$$

$$\frac{\partial C^{\text{fast}}_{\text{SOIL}}}{\partial t} = F_{\text{harvest}} + F_{\text{LU}}(t) \cdot (C_{\text{VEG}} + C_{\text{SOIL}}) - \frac{C^{\text{fast}}_{\text{SOIL}}}{\tau_{\text{fast}}},$$

   here $F_{\text{LU}_j}(t + \Delta t) = \frac{S_j(t + \Delta t) - S_j(t)}{S_j(t)} \cdot \frac{1}{\Delta t}$ (S_j – area of j-th PFT in cell),
   $F_{\text{harvest}} = \alpha \cdot \frac{C_{\text{VEG}}}{\tau_{\text{VEG}}}$, $\alpha \in [0, 1]$.

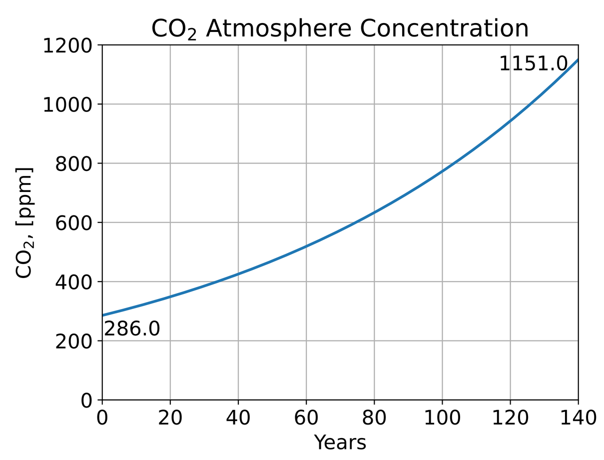
2. **Ocean:**
   - 1 carbon pool – dissolved inorganic carbon (C_{OCEAN}):

$$\frac{\partial C_{\text{OCEAN}}}{\partial t} = \text{adv}(C_{\text{OCEAN}}) + \text{diff}(C_{\text{OCEAN}}) + F_{\text{Atm2Oc}} + F_{\text{BIO}}$$

3. **Atmosphere:**
   There are 2 modes:
   - "*concentration-driven*" – CO_2 concentration is prescribed;
   - "*emission-driven*" – CO_2 concentration is calculated interactively based on prescribed anthropogenic emissions and global CO_2 fluxes between the atmosphere and terrestrial and oceanic ecosystems:

$$\frac{\partial C_{\text{ATM}}}{\partial t} = -F^{\Sigma}_{\text{PSN}} + F^{\Sigma}_{\text{PLR}} + F^{\Sigma}_{\text{SOIL}} + F^{\text{fast}^{\Sigma}}_{\text{SOIL}} - F_{\text{Atm2Oc}} + F^{\Sigma}_{\text{Anthro}}$$

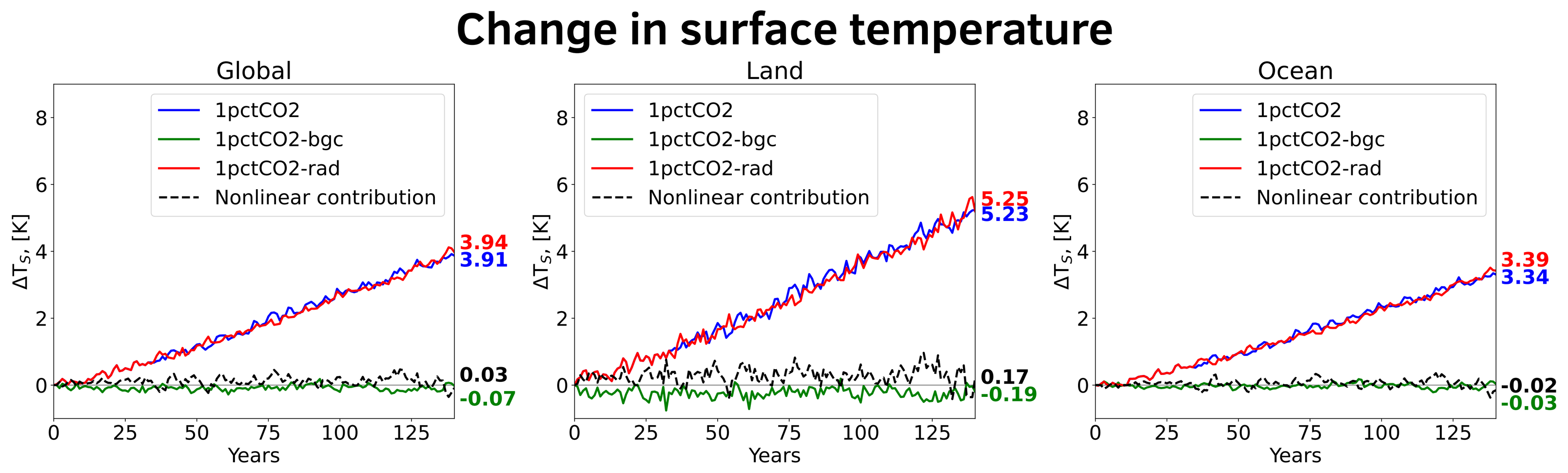
Evaluation of carbon cycle – climate feedbacks



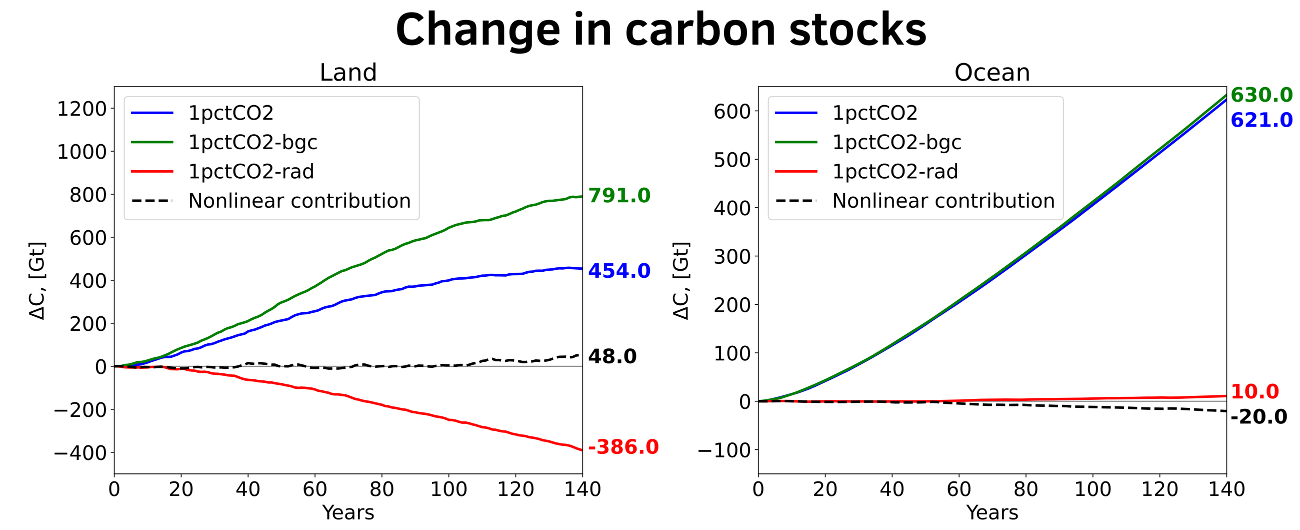
Experiments with prescribed 1% per year increase in qCO_2 until $4 \times$ piControl value [2]:

- *1pctCO2*: influence on both carbon cycle and climate
- *1pctCO2-bgc*: influence on only carbon cycle
- *1pctCO2-rad*: influence on only climate

Change in surface temperature



Change in carbon stocks



Estimates of carbon stock changes by $4\times CO_2$ (BGC-experiment)

	ARTS-ESM-L	CMIP6 models [4]		
		average	min	max
ΔC_{Land}, [Gt C]	791	756	305	1499
ΔC_{Veg}, [Gt C]	289	417	173	569
ΔC_{Soil}, [Gt C]	502	339	132	590
ΔC_{Ocean}, [Gt C]	630	666	597	781

Feedback parameters and climate sensitivity to CO_2 at $4\times CO_2$

Feedback of X value ($= C_{\text{Land}}, C_{\text{Ocean}}$) on impact (*1pctCO2*):

$$\Delta X = F(\Delta(qCO_2), \Delta T_S) = \beta\Delta(qCO_2) + \gamma\Delta T_S + \underbrace{f(\beta,\gamma)\Delta(qCO_2)\Delta T_S}_{nonlinear\ contribution} \approx \beta\Delta(qCO_2) + \gamma\Delta T_S;$$

$$\Delta X^{\text{BGC}} \approx \beta\Delta(qCO_2) + \gamma\Delta T^{\text{BGC}}_S \approx \beta\Delta(qCO_2);\ \Delta X^{\text{RAD}} \approx \gamma\Delta T^{\text{RAD}}_S;$$

γ – carbon – climate feedback: $\gamma \approx \frac{\Delta C^{\text{RAD}}}{\Delta T^{\text{RAD}}_S}$;

β – carbon – concentration feedback: $\beta \approx \frac{\Delta C - \gamma \cdot \Delta T_S}{\Delta qCO_2}$;

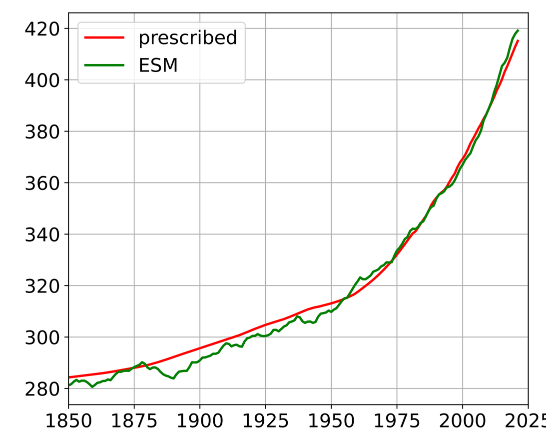
α – climate sensitivity: $\alpha = \frac{\Delta T_S}{\Delta qCO_2}$;

TCRE – transient climate response to cumulative emissions:
TCRE $= \frac{\text{TCR}}{\tilde{E}(2\times CO_2)}$, TCR $= \Delta T_S(2\times CO_2)$, $\tilde{E} = \Delta C_A + \Delta C_L + \Delta C_O$.

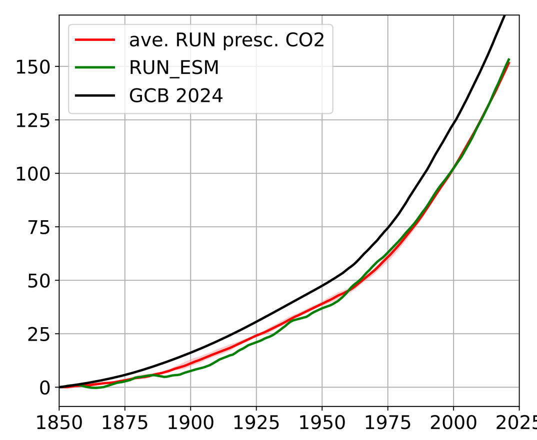
	ARTS-ESM-L	CMIP6 models [4]			
		average	STD	min	max
γ_{Land}, [Gt C / K]	−85	−45	51	−163	−5
β_{Land}, [Gt C / ppm]	0.91	0.97	0.40	0.37	1.81
γ_{Ocean}, [Gt C / K]	−2.41	−17.21	4.95	−24	−9
β_{Ocean}, [Gt C / ppm]	0.73	0.78	0.07	0.70	0.92
α_{GLB}, [K / ppm]	0.00448	0.00568	0.00123	0.00410	0.00751
TCRE, [K / 10^3 Gt C]	1.5	1.77	0.37	1.32	2.30

Historical experiments

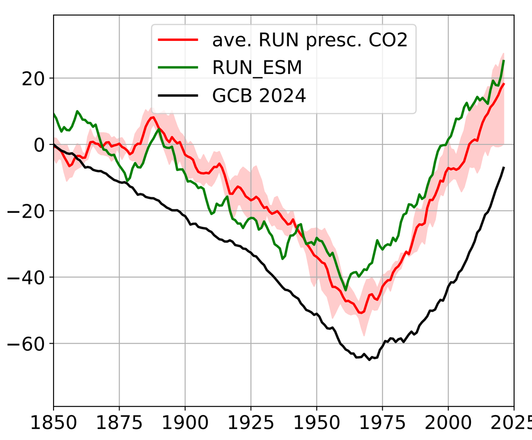
- period from 1850 to 2021
- 3 *historical* runs and 1 *esm-historical* run



CO_2 concentration (ppm)



Ocean carbon change (Gt C)

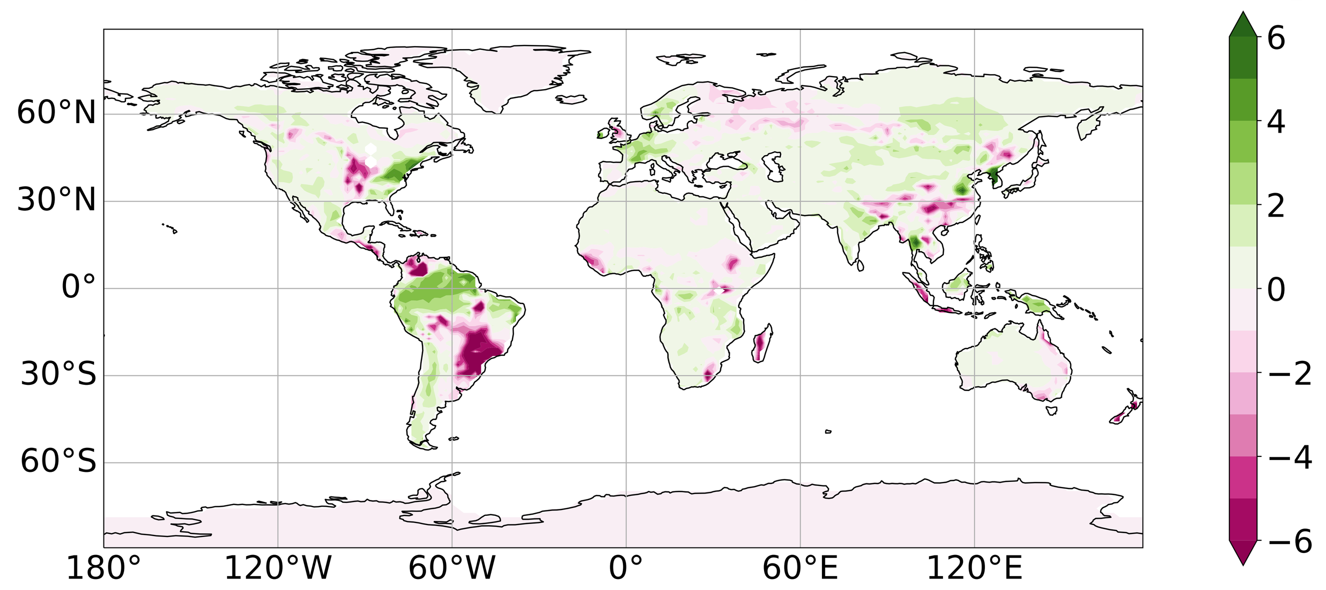


Land carbon change (Gt C)

	qCO_2, ppm	ΔC_{Ocean}, Gt C	ΔC_{Land}, Gt C
RMSE	3.3	12	21
R_{Corr}	0.998	0.99	0.88

($\star$) GCB2024 – Global Carbon Budget 2024 [5].

Changes in carbon stocks in terrestrial ecosystems 1850–2021 гг, [kg / m²]



Conclusion

The results of the ARTS-ESM-L carbon cycle model are consistent with those of the CMIP6 ensemble models and also agree with historical observations. Difference in the results between the prescribed and interactively calculated atmospheric CO_2 concentrations are very close and comparable to the magnitude of intermodel variability.

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References

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[2] Dunne et al., An evolving CMIP7 and Fast Track in support of climate assessment, *Geosci. Model Dev.*, 2025.

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