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Time lag between changes in global temperature and atmospheric CO_2 content according to the results of numerical experiments with Earth system models

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ABSTRACT

On the base of numerical experiments with the general circulation climatic model MIROC-ESM and climate model of intermediate complexity IAP RAS CM it was shown that the sign of the time lag between changes in global temperature T and atmospheric carbon dioxide content q_{CO2} depends on the type and the time scale of the external forcing applied to the Earth system. In particular, modern climate models are able to reproduce the q_{CO2} lagging behind T under conditions that are valid for the pre-industrial Holocene, so it does not contradict the idea of the importance of anthropogenic contribution to modern climate change.

Keywords: climate change, casual relationships, time lags

1. INTRODUCTION

One of the main characteristics of the contemporary climate change is the increase in global surface temperature T of the Earth system (ES). According to the observational data, T increased by 0.85 K in 1880-2012 (with an uncertainty interval of 0.65-1.06 K), and by 0.72 K in 1951-2012 (with an uncertainty interval of 0.49-0.89 K)[1]. At the beginning of the 21st century, warming slowed, while this slowdown is partly an artifact of data processing[2].

According to generally accepted ideas (as shared by 97% of climate scientists[3-8]), the main cause of the warming is the anthropogenic greenhouse effect of carbon dioxide, accompanied, and sometimes compensated by anthropogenic impact of other nature, as well as the internal variability of the ES and natural impacts on the climate. This is confirmed by empirical models[9-15] and global climate models[16-23].

However, there are alternative hypotheses about the nature of the warming that deny the fact that the contribution of human activity to climate change is decisive[3]. The existence of disagreement on the nature of global warming in the scientific community increases the probability of ignoring this problem by the public and policy makers[24], so the climate skeptics' hypotheses should not simply be ignored - scientific arguments against these hypotheses are necessary.

One of the widely used arguments in support of these hypotheses is the mutual lag between changes in T and the carbon dioxide content in the atmosphere q_{CO2}, derived from the Antarctic ice cores. According to these data, during the end of glaciation, q_{CO2} changes generally lag behind the corresponding changes in T for several centuries[25-29].

In addition, on the basis of measurement data for the 20^{th} – 21^{st} centuries[30] and reconstructions for the Little Ice Age 14^{th}-18^{th} centuries[31] it has been shown that interannual changes in q_{CO2} are also delayed relative to the corresponding changes in T. Since it is natural to expect that the "consequence" cannot lead its "cause", all these results are used as arguments to refute the notion of the anthropogenic greenhouse effect leading role in the ongoing climate changes.

These arguments have been criticized from various perspectives[32-38], however, the notion that the lag between changes in climate variables is a reliable indicator of cause-and-effect relationships in the ES has only occasionally been questioned as part of this criticism. It was shown that the lag between changes in variables determined by the methods of cross-correlation and regression analysis does not characterize the cause-effect relationships between them in the General case[39].

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It was also shown that this type of the lag can be obtained due to the nonlinearity of the climate system[40]. However, it can be shown that the nonlinearity of the ES is not necessary for its occurrence. Moreover, it is possible to show specific mechanisms of changes in q_{CO2} and T, at which changes in the leading variable are the result of changes in the lagging one. Thus, in numerical experiments with the conceptual climate-carbon cycle model, the lag of T relative to q_{CO2} was obtained under the external forcing, implying that changes in q_{CO2} arise as a response to changes in T[41]. Similar results were obtained in numerical experiments with the global climate model of intermediate complexity, and a qualitative explanation of this effect was given[42, 43]. By contrast, a lag of q_{CO2} relative to T was obtained under the external forcing in the form of anthropogenic emissions of carbon dioxide and methane, implying that q_{CO2} changes are the main cause of T changes[44, 45].
The aim of this work is to show that lag between changes in T and q_{CO2} depends on the type of external forcing on the ES and its time scale. In particular, modern climate models are able to reproduce both the lag of q_{CO2} relative to T under conditions valid for the pre-industrial Holocene and the lag of T relative to q_{CO2} in the 21st century. Thus, it is proved that paleoreconstructions data do not contradict the idea of the anthropogenic contribution importance to the modern climate change. It also indicates the impossibility of determination the direction of the causal relationship between two correlated variables by the time shift between their changes without involving any physical ideas about the nature of their interaction.

2. METHOD

In this paper, time shifts between T and q_{CO2} are investigated on the basis of numerical experiments with the climate model developed at the A.M. Obukhov Institute of the Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM)[46-50] and the climate model MIROC-ESM[51].

The IAP RAS CM is an Earth system model of intermediate complexity[1, 52-56]. As other Earth system models, it is equipped with modules calculating the state of the atmosphere, ocean, land surface, and biogeochemistry. The short-wave radiation transfer takes into account the parameters of the Earth's orbit, surface albedo, cloudiness, water vapour, ozone, and tropospheric and stratospheric sulphate aerosols. The longwave radiation transfer depends on temperature and humidity of the atmosphere, cloudiness, carbon dioxide, methane, nitrous oxide and freons. Large-scale atmospheric dynamics (with a timescale longer than the synoptic one) is computed explicitly. Synoptic processes are parametrised. This allows to significantly diminish the computational burden of the model. The IAP RAS CM horizontal resolution of the is 4.5º in latitude and 6º in longitude with 8 vertical levels in the atmosphere (up to 80 km) and 3 levels in the ocean. The globally averaged equilibrium sensitivity to doubling of the carbon dioxide content in the atmosphere is 2.2 K.

Earth system model MIROS-ESM belongs to the class of general circulation models. It uses the MIROC-AGCM General circulation model as the atmospheric module[51], which is coupled with the atmospheric chemistry model (CHASER)[57, 58] and the atmospheric aerosol content calculation model (SPRINTARS)[59-62]. The oceanic compartment is represented by the general circulation model taking into account sea ice (COCO)[51]. The model NPDZ (Nutrient-Phytoplankton-Zooplankton-Detritus) is used as a block of ocean biogeochemical processes[63]. The model MATSIRO (Minimal Advanced Treatments of Surface Interaction and RunOff)[64] is used as a module of processes in the active land layer, which integrates together with the TRIP model (Total Runoff Integrating Pathways)[65] to calculate river flow and the SEIB-DGVM terrestrial ecosystem model[66].

The differences between the MIROC-ESM and the IAP RAS CM are as follows: 1) in the atmosphere and ocean modules of MIROC-ESM, unlike IAP RAS CM, the quasi-geostrophic approximation is not used; 2) the oceanic module of the MIROC-ESM does not use the assumption of the temperature profiles universality, which can lead to a longer response time to external forcing; 3) the model of the oceanic carbon cycle in the MIROC-ESM is spatially resolved rather then globally averagedas it is in the IAP RAS CM; 4) this model takes into account the contribution of organic loop to the oceanic carbon cycle; 5) the terrestrial carbon cycle module in the MIROC-ESM takes into account the dynamics of the areal extent of different types of vegetation; 6) the equilibrium sensitivity of the MIROC-ESM to the doubling in atmospheric CO_2 content is 4.7 K[67] (in the IAP RAS CM it is 2,2 K).

The data series for T and q_{CO2}, as obtained in numerical experiments with these models under the external forcing following the CMIP5 (Coupled Models Intercomparison Project, phase 5) protocol[68-70] in accordance with the experiment ‘historical’ for 1700-2005 and the scenario RCP 2.6 (Representative Concentration Pathway 2.6) for 2006-2100, are analyzed. In both parts of the simulation, the boundary conditions were CO_2 emissions into the atmosphere from fossil fuel combustion, atmospheric concentrations of CH_4, N_2O and tropospheric sulphate aerosols, solar constant values, agricultural land area (arable land and pasture) affecting both surface albedo and CO_2 emissions into the atmosphere due to land use, and the optical thickness of stratospheric sulphate aerosols, changes in which are associated with volcanic eruptions.

Scenario RCP2.6 was chosen because it implies the existence of maxima in global temperature and CO_2 content in the atmosphere in the 21st century, and this in turn makes easier to assess the time lag between their changes.

A numerical experiment reproducing the climate of the Holocene was also carried out with the IAP RAS CM. This simulation with the IAP RAS CM is a backward in time extension of the historical simulation with the same model. The Holocene simulation (covering the last 10 kyr) is forced by: a) changes of the Earth orbit parameters (which are calculated internally according to[71]); b) ^{10}Be-reconstructed total solar irradiance[72]; c) stratospheric (volcanic) aerosols optical depth[73] (but for 500-2000 CE only); d) CO_2 emissions into the atmosphere due to fossil fuel burning[74]; e) ice core-derived concentrations of two other well-mixed greenhouse gases (CH_4 and N_2O) in the atmosphere[75]; f) extent of crops and pastures and population density according to the HYDE-3.2 database (History Database of the Global Environment, version 3.2)[76]; g) total burden of tropospheric sulphates[77] extended back in time assuming that this burden did not change significantly until 1850 CE. The Holocene simulation reasonably reproduces long-term regional surface air temperature changes during last two millennia when compared with the PAGES2k (Past Global Changes, project for the last 2 kyr) reconstruction[78]. The 20th century increase in T in this simulation with IAP RAS CM is 0.58 ºC, which agrees reasonably with the HadCRUT4 dataset[79, 80] (~ 0.7 ºC).

Time shift between changes in T and q_{CO2} obtained in the 'historical+RCP 2.6' experiment according to the common technique[27, 34] is computed from the lag at which the cross-correlation function between the q_{CO2} and T series reaches a maximum. It corresponds to the delay determined analytically by the phase shift between the functions $q_{CO2}(t)$ and $T(t)$, where t stands for time.

Time lag between changes in T and q_{CO2} obtained in the Holocene simulation is calculated applying the method of cross-wavelet analysis[81].

3. RESULTS

It is found that in the simulation 'historical+RCP2.6' the lag between changes in T and q_{CO2} depends on the historical period. When anthropogenic emissions of CO_2 into the atmosphere are relatively small, changes in T are mainly due to volcanic activity or variations in the total solar irradiance.

For example, in 1815 there was an eruption of Tambora volcano, which was the strongest in the last few centuries.

In simulation with the IAP RAS CM, the response to this eruption (coupled with an unknown eruption of 1809) was a decrease in T occurring over the next few years and amounting to about 1 K (see Fig. 1). In simulation with the MIROC-ESM the corresponding decrease of T amounts to about 0.6 K.

This response is similar to that obtained from indirect data and numerical experiments with other climate models (see review[82]). In turn, q_{CO2} is reduced by 7 ppm in IAP RAS CM and by 10 ppm in MIROC-ESM in several next years. This decrease in q_{CO2} after an eruption is not determined by data for atmospheric CO_2 obtained from ice core analysis, which is probably due to insufficient temporal resolution of these data[82]. It should be noted that similar q_{CO2} response was obtained in numerical experiments with HadGEM2-ES model[83] and in a similar experiment with the NCAR CSM1.4-carbon model[84].

In addition, a strong reduction in q_{CO2} (up to 15 ppm) was obtained in a numerical experiment with a set of earth system models as a response to the eruption of 1258, which was even stronger than the Tambora eruption in 1815[85].

Thus, during periods characterized by weak CO_2 emissions into the atmosphere and strong natural forcing, q_{CO2} changes are delayed relative to T changes. This delay amounts several years.

In the 21st century, where according to scenario RCP2.6 q_{CO2} reaches a maximum, and then decreases, on the contrary, T is delayed relative to q_{CO2} (Fig. 1). This illustrates the dependence of the time lag between q_{CO2} and T sign on the type of the external forcing to the ES.

It is possible to show that under the external forcing to the ES in the form of CO_2 emissions into the atmosphere time lag Δ_{Tq} between changes in q_{CO2} and T is proportional to the value of the model equilibrium sensitivity to the atmospheric CO_2 doubling ΔT_{2CO2}. This may be one of the reasons that in the 21st century, when anthropogenic CO_2 emissions into the atmosphere dominate over other effects on the ES, the lag between T and q_{CO2} in MIROC-ESM is greater than in IAP RAS CM (Fig. 1 and Table 1)

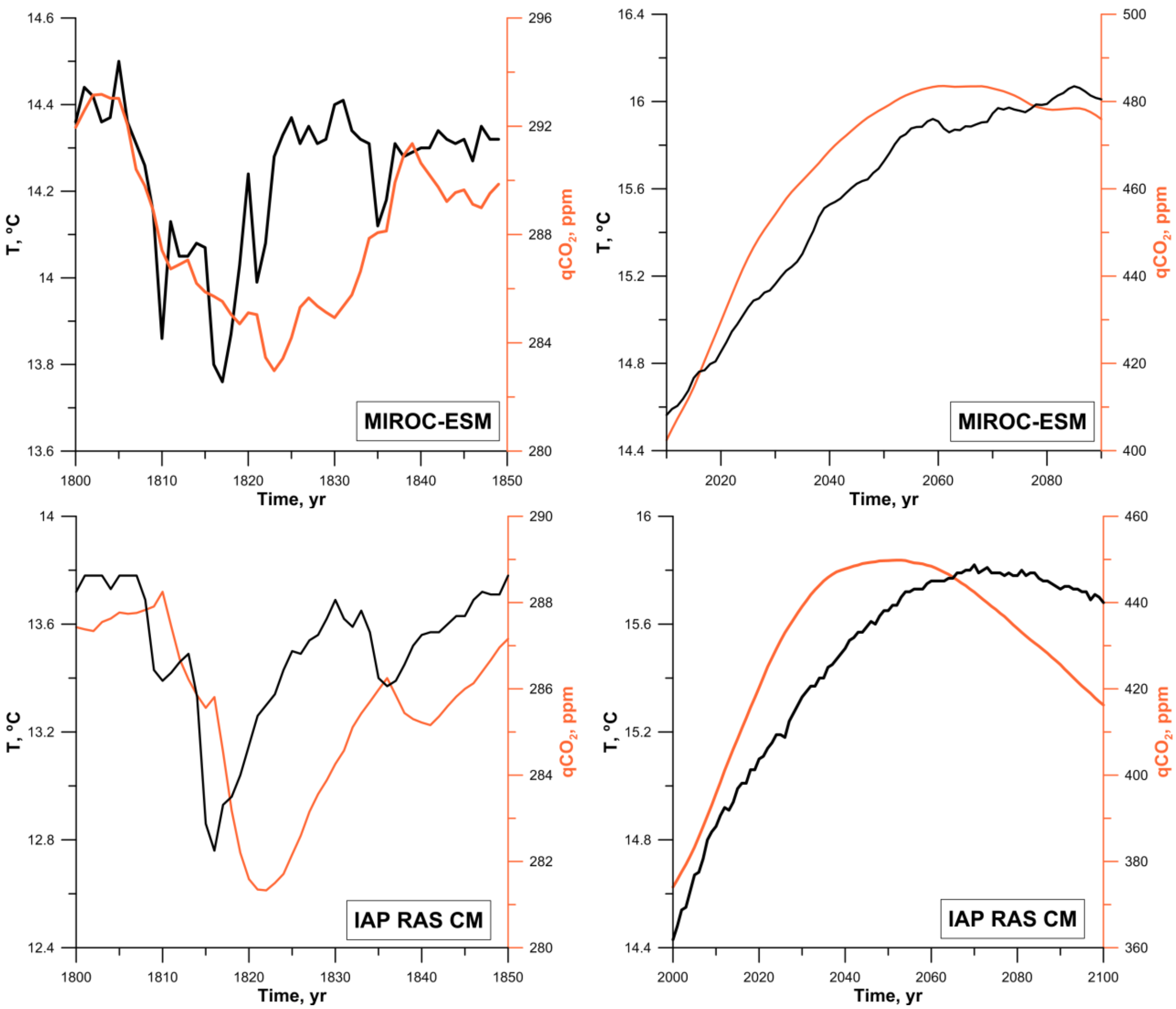

Figure 1. Changes in T and q_{CO2} in simulations 'historical + RCP 2.6' with climate models MIROC-ESM and IAP RAS CM. The T and q_{CO2} series obtained from the MIROC-ESM model for the 21st century are smoothed with a window of 10 years.

Table 1. Time lags Δ_{Tq} (years) between changes in global temperature T and the atmospheric CO_2 content q_{CO2} obtained in simulations with MIROC-ESM and IAP RAS CM. Values $\Delta_{Tq} > 0$ ($\Delta_{Tq} < 0$) correspond to T leading q_{CO2} (q_{CO2} leading T).

Historical period	MIROC-ESM	IAP RAS CM
1800-1849	8	4
2006-2100	-15	-8

The Holocene simulation with the IAP RAS CM is an extension back in time of the historical simulation with the same model. Thus, The study of the time series for T and q_{CO2} obtained in the Holocene-simulation (with IAP RAS CM), continued until 2300 in accordance with the scenario RCP 2.6, showed that the sign of time lag between changes in T and q_{CO2} depends not only on time interval, but also on time scale of these changes. In the pre-industrial period, when the natural forcing dominates over the anthropogenic one, harmonics with periods less than 500 years are generally characterized by q_{CO2} lagging T, and harmonics with large periods, on the contrary, are characterized by T lagging q_{CO2} (in cases where the determination of the time lag is statistically robust). At the same time, for the end of the calculation corresponding to the period of the most intense anthropogenic CO_2 emissions into the atmosphere, T is lagging q_{CO2} also for harmonics with a shorter period. The delay of q_{CO2} with respect to T, observed for harmonics with periods less than 60 years in the last 2000 years of the simulation and absent at earlier stages, is probably due to the influence of volcanic forcing, which is zero before 500 CE, according to the scenario used.

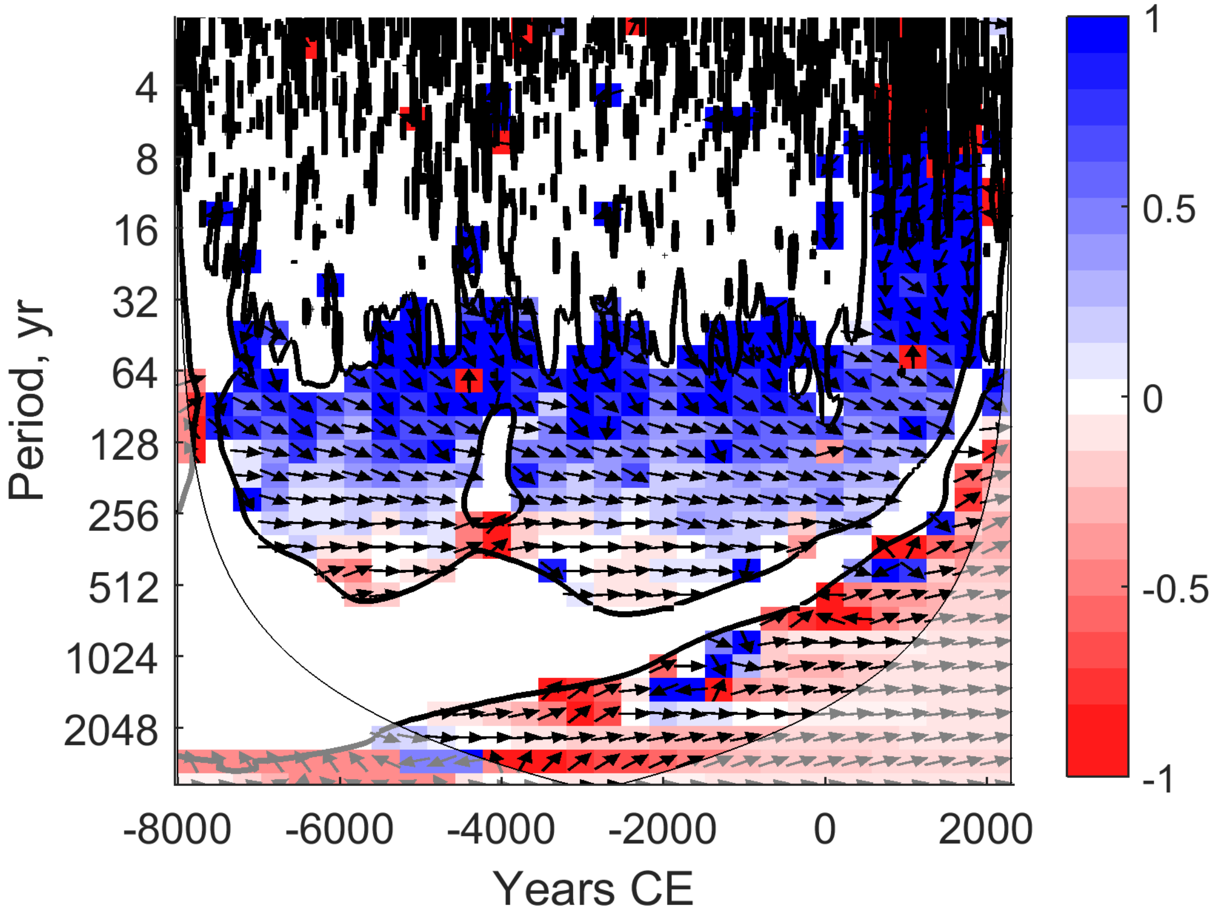

Figure 2. Squared wavelet coherence between T and q_{CO2} time series, obtained in Holocene-simulation with IAP RAS CM. The 5% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and T leading q_{CO2} by $\pi/2$ pointing straight down). Color bar on the right indicates the value of the phase shift between T and q_{CO2} in radians (blue - T leading q_{CO2}, red - q_{CO2} leading T).

This result is similar to that obtained in idealized numerical experiments with IAP RAS CM and a conceptual climate model with a carbon cycle[42, 43]. At the qualitative level, it can be explained as follows.

In the pre-industrial period, when anthropogenic CO_2 emissions into the atmosphere are small, changes in its atmospheric content are response to the climate change, in particular, to changes in the global temperature. Thus, climate warming leads to the flow of CO_2 into the atmosphere from terrestrial ecosystems as a result of soil and biota respiration increase, which is not fully balanced by increased photosynthesis. As a result, a positive anomaly of CO_2 in the atmosphere and a flux of this gas into the ocean are generated. The release of CO_2 from seawater due to its temperature increase is negligible compared to this flux. Thus, the increase or decrease in atmospheric CO_2 depends on the ratio of CO_2 fluxes from land ecosystems into the atmosphere and from the atmosphere into the ocean.

The flux of CO_2 into the atmosphere from land ecosystems depends not only on temperature, but also on their current carbon content. If the warming is long and slow enough (has a large timescale), the terrestrial carbon stock is reduced to such an extent that the CO_2 flux from land ecosystems into the atmosphere becomes smaller than CO_2 flux from the atmosphere into the ocean. Then the atmospheric CO_2 content q_{CO2} starts decreasing, although the temperature T is still rising. Externally, this is manifested in the fact that changes in q_{CO2}, which are a response to changes in T, are ahead of them in phase.

4. CONCLUSIONS

In this paper the results of numerical experiments with the general circulation climatic model MIROC-ESM and climate model of intermediate complexity IAP RAS CM are reported. On the base of these experiments it was shown that the sign of the time lag between changes in global temperature T and atmospheric carbon dioxide content q_{CO2} depends on the type and the time scale of the external forcing applied to the Earth system (ES). Climate models are able to reproduce both the q_{CO2} lagging behind T (for their changes with a timescale less then several hundred years under conditions that are valid for the pre-industrial Holocene), and T lagging behind q_{CO2} (for changes in the industrial period and pre-industrial changes with a large time scale). This illustrates the fact that the phase shift between two variables, in the general case cannot be used to judge the direction of the causal relationship between them. In particular, q_{CO2} lagging behind T obtained from observations and paleo-reconstructions does not contradict the idea of the importance of anthropogenic contribution to modern climate change.

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