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Time lag between changes in global temperature and atmospheric CO_2 content under anthropogenic emissions of CO_2 and CH_4 into the atmosphere

K E Muryshev[1], A V Eliseev[1, 2, 3], S N Denisov[1], I I Mokhov[1, 2, 4], M M Arzhanov[1] and A V Timazhev[1]

[1]A.M. Obukhov Institute of Atmospheric Physics RAS, Moscow, Russia
[2]M.V. Lomonosov Moscow State University, Moscow, Russia
[3]Kazan Federal University, Kazan, Russia
[4]Moscow Institute of Physics and Technology (State University), Dolgoprudny, Russia

E-mail: kmuryshev@mail.ru

Abstract. Previously, it was shown that the time lag between changes in global temperature T and atmospheric CO_2 content q_{CO2} generally does not characterize cause-and-effect relationships in the Earth system. In particular, in the case of non-greenhouse radiative forcing the sign of this lag depends on the time scale of the forcing. In this paper, the time lag between changes in T and q_{CO2} under the external emissions of CO_2 and CH_4 into the atmosphere is studied. It was found that if the time scale of external emissions is large enough changes in q_{CO2} are lagging the corresponding changes in T, though the former is the main cause of the latter.

1. Introduction

The global surface temperature in the Earth system has been rising over the last century. The average warming in 1880-2012 amounted to 0.85 K (with the uncertainty range from 0.65 to 1.06 K), and in 1951-2012 - to 0.72 K (with the uncertainty range from 0.49 to 0.89 K) [1]. In accordance with generally accepted ideas, the main cause of the warming is the anthropogenic greenhouse effect, accompanied, and sometimes compensated by the other anthropogenic and natural impacts and internal variability of the climate system [2]. This is confirmed by empirical models [3-11] and global climate models [12-18].

However, there are some alternative hypotheses about the nature of the observed warming. According to them, the main contribution to its formation is made by natural (non-anthropogenic) factors [19-23]. One of the widely used arguments in support of these hypotheses is the time lag between changes in global temperature T and in atmospheric carbon dioxide content q_{CO2}, derived from the Antarctic ice cores: according to these data, changes in q_{CO2} lag behind changes in T for a few centuries [24-28].

In addition, in [29] it was shown that the interannual changes in q_{CO2} also lag behind the corresponding changes in T for the instrumental data for last decades. Since it is expected that the effect cannot lead its cause, such lags are used as an argument to refute the role of the anthropogenic greenhouse effect in climate change (e.g., [21]).

These arguments have been criticized at different grounds [30-36], but the lag between changes in climate variables as a reliable indicator of cause-effect relationships in the Earth system has not been questioned by the most of critics. In [37] it was shown that such time lags may be obtained as a result of the non-linearity of the Earth system. Nonetheless, it is possible to show that non-linearity of the Earth system is not necessary for these lags to occur [38, 39].

It should be noted here that cause-and-effect relationships exist between events, not variables or data series. Events are changes in the values of variables. In this sense, the event E_1, which is the change of temperature T during time interval t_1-t_2, of course, cannot be an effect of the event E_2, which is a q_{CO2} change during the next time interval t_2-t_3. But it is not forbidden for the event E_1 to be an effect of the event E_0, which is a change of q_{CO2} during the previous time interval t_0-t_1, even if the series for T lead the series for q_{CO2}. In accordance with the generally accepted definition, the mutual lag between the time series is determined via maximum cross-correlation function between them. In practice, it often means that at some time interval, the leading variable reaches the extreme earlier than the lagging variable does. Accordingly, if changes in T lead changes in q_{CO2}, then T attains an extremum earlier than q_{CO2} does. The latter is equivalent to the case that the event A_T, which is the change of the sign of T time increments, occurs before the event A_q, which is the change of the sign of the q_{CO2} increments. Respectively, event A_q cannot be the cause of event A_T. However, it is not forbidden for event B_q, which is the progressive growth of qCO2, to be the cause of event B_T, which is the progressive growth of T until its extremum is reached. In turn, the cause of the extremum T occurrence can be event A_X, which is the change the value of a third variable X.

These arguments show that it is impossible to determine the nature of the causal relationship between two correlated variables by time shift between their changes without the involvement of any ideas about the nature of their interaction. Moreover, it is possible to note specific mechanisms of q_{CO2} and T changes, in which the changes in the leading variable are the result of the changes in the lagging variable.

Thus, changes in T was found to lag the corresponding changes in q_{CO2} in numerical simulations with a conceptual climate model forced by the total solar irradiance changes, implying that changes in q_{CO2} are the response to changes in T [40]. In [38, 39] the similar results were obtained in numerical experiments with the global climate model of intermediate complexity, and a qualitative explanation of this effect was given.

The aim of this work is to show that similar effects can occur when the climate system is forced by the anthropogenic emissions of several (at least two) greenhouse gases, such as CO_2 and CH_4, into the atmosphere. In this case changes in q_{CO2} can lag the corresponding changes in T, although the former is the main cause of the latter’s genesis. The mutual lag between changes in CO_2 and T is investigated using the results of numerical experiments with climate models of different class.

2. IAP RAS Climate Model

Climate model developed at the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM) is described in [41, 42]. The model contains modules for the atmosphere, the ocean, the Earth surface, the carbon and methane cycles [42]. Oceanic carbon cycle is described using the globally-averaged Bacastow-type model, modified by the temperature dependence of chemical reactions constants [43]. For calculating the natural methane emission from wet ecosystems, is used the scheme from [44].

For the atmospheric methane cycle similarly to [45] the balance equation is used

$$\frac{dq_{CH4}}{dt} = \frac{E_{CH4}}{\beta} - \frac{q_{CH4}}{\tau_{tot}}, \qquad (1)$$

where q_{CH4} is the concentration of methane in the atmosphere, E_{CH4} is the total (natural and anthropogenic) emissions of methane into the atmosphere, β = 2.75 MtCH4/ppbv. For τ_{tot}, one writes

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{atm}} + \frac{1}{\tau_{soil}}, \quad (2)$$

where τ_{soil} = 150 years is the time of methane decomposition in the soil, and τ_{atm} is the temperature-dependent lifetime of methane in the atmosphere [42].

Anthropogenic methane emissions are imposed as boundary conditions. Natural emissions of this gas are represented as the sum of emissions from the soil, which are calculated interactively, and other (non-wetland) natural emissions. The latter non-wetland emission flux is prescribed equal to 65 MtCH4/yr [42].

3. Conceptual Earth system climate model

A conceptual climate model with carbon cycle used in this paper consists of the equations characterizing the global temperature and atmospheric CO2 and CH4 contents deviations from their initial. equilibrated values. The first equation describes the thermal balance of the climate system (see e.g., [35, 46]):

$$C\frac{dT}{dt} = R_{tot} - \lambda_0\left(T - T^{(0)}\right), \quad (3)$$

where $T^{(0)}$ = 13.7 °C is the base value of global temperature, C = 10^9 J m^2 K^{-1} [46] is the heat capacity per unit area, approximately corresponding to the heat capacity of the ocean layer of 350 m thickness, R_{tot} is the total radiative forcing, the term $\lambda_0(T - T^{(0)})$ characterizes all climatic feedbacks in a linear form (in particular, it includes the dependence of atmospheric humidity on temperature). The coefficient λ_0 is called the climate sensitivity parameter.

The radiative forcing R_{tot} can be divided into three components: the first corresponds to the greenhouse effect of CO_2, the second – to the greenhouse effect of CH_4, the third – to non-greenhouse radiative forcings (changes in the solar constant, volcanic eruptions, etc.).

$$R_{tot} = R_{CO2} + R_{CH4} + R_{x}. \quad (4)$$

In this work the only case of $R_x \equiv 0$ is considered.

The greenhouse radiative forcing of CO_2 is described in the following shape

$$R_{CO2} = R_0 \ln\left(\frac{q_{CO2}}{q_{CO2}^{(0)}}\right), \quad (5)$$

where $q_{CO2}^{(0)}$ = 278 ppm is the pre-industrial value of atmospheric CO_2, R_0 is the normalization coefficient. For modern climate models R_0 = 5.3 W m^{-2}, the value λ_0 is in the range of 0.6 to 1.6 W m^{-2} K^{-1} [47]. In the standard version of our conceptual model λ_0 = 1 W m^{-2} K^{-1}.

The radiative forcing of methane is calculated according to [48]. The methane content in the atmosphere and its natural emissions are calculated in the same way as in IAP RAS CM. Since the destruction of methane in the atmosphere leads to the formation of carbon dioxide (as a result of a chemical transformations chain), in the right part of the equation for q_{CO2} there is an additional term, depending on q_{CH4}. This equation has the following shape:

$$c_0 \frac{dq_{CO2}}{dt} = E_{CO2} - F_{land} - F_{oc} + \mu \frac{q_{CH4}}{\tau_{tot}}, \quad (8)$$

where q_{CO2} is the atmospheric carbon dioxide content [ppm], c_0 = 2.123 GtC/ppm(CO_2), E_{CO2} is the external (e.g., anthropogenic) CO_2 emissions into the atmosphere, F_{land} and F_{oc} are carbon fluxes from the atmosphere to the terrestrial ecosystems and to the ocean, respectively, $\mu = 0.27 \cdot 10^{-3}$ GtC/ppb(CH_4). The F_{land} and F_{oc} calculation scheme is described in [38].

4. Numerical simulations

With IAP RAS CM and the conceptual climate model forced by the carbon dioxide and methane anthropogenic emissions into the atmosphere (E_{CO2} and E_{CH4} respectively) numerical simulations were carried out. Emissions have been changing over the time according to:

$$E_{CO2}(t) = \{E_{CO2,0} \sin\left(\frac{2\pi}{P}t\right), \text{ при } t < \frac{P}{2}; 0 \text{ при } t > \frac{P}{2}\}, \quad (9)$$

$$E_{CH4}(t) = \{E_{CH4,0} \sin\left(\frac{2\pi}{P}t\right), \text{ при } t < \frac{P}{2}; 0 \text{ при } t > \frac{P}{2}\}, \quad (10)$$

where $t \in (0,+\infty)$ is the time, P is the time scale of the emissions changes. The appearance of functions (9), (10) is shown in figure 1. The CO_2 and CH_4 emissions are in-phase because of the assumption that anthropogenic emissions of both these gases on the interannual time scale are proportional to the intensity of human economic activity.

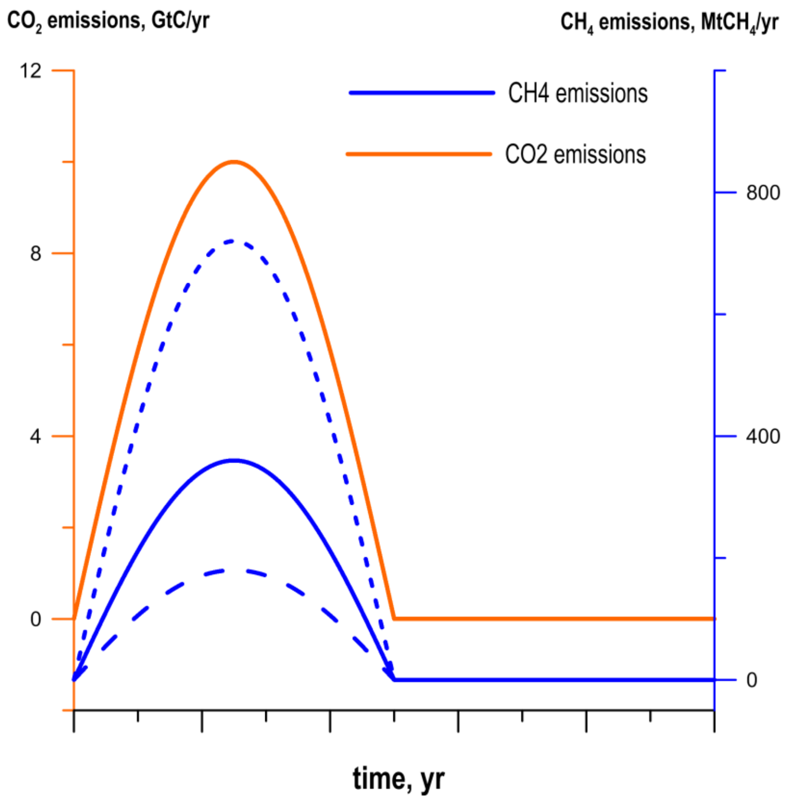

Figure 1. In-phase emissions of CO_2 and CH_4 in the shape (9), (10).

Numerical simulations were performed for $E_{CO2,0}$ = 10 GtC/year and $E_{CH4,0}$ = {180; 360; 720 MtCH4/year}. The amplitudes $E_{CO2,0}$ = 10 GtC/year and $E_{CH4,0}$ = 360 MтCH4/year correspond to the values of CO_2 and CH_4 anthropogenic emissions, typical for the late XX – early XXI century. The simulations were carried out for P values varying from 10 to 1500 years.

The time lag Δ between changes in T and q_{CO2} was determined via maximum cross-correlation function between these two variables. Typical values of the maximum correlation coefficient are ≥ 0.99. The dependence of time lag Δ on the time scale of the external forcing (emissions changes) P obtained in the numerical experiments with IAP RAS CM on one hand and conceptual model on the other hand are qualitatively coincide with each other (Figure 2 a, b).

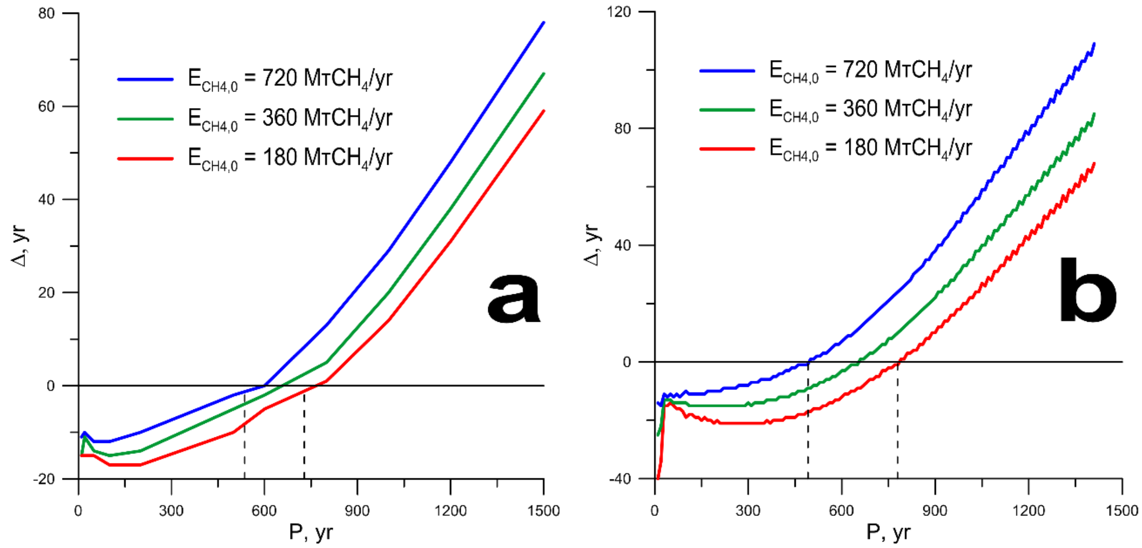

Figure 2. Time lag Δ between changes in the global surface temperature T and the atmospheric carbon dioxide content q_{CO2} in numerical simulations with IAP RAS CM (a) and with the conceptual model (b): Δ > 0 - stands for q_{CO2} lagging behind T.

It was found that changes in T can both lag behind the q_{CO2} changes and lead them in dependence on the time scale P of the external forcing (emissions changes). At the centennial time scale (P < 400 years), changes in T lag the corresponding changes in q_{CO2} (Δ < 0), while at the millennium time scale (P > 800 years) changes in q_{CO2} lag changes in T (Δ > 0), although the former is the main cause of the latter. The exact value of the critical time scale P_{cr}, at which lag between T and q_{CO2} changes its sign depends on the ratio $E_{CO2,0}/E_{CH4,0}$.

We note that non-linearity of the Earth system is not necessary for q_{CO2} lagging T at the millennium time scale in the simulations driven by CO_2 and CH_4 emissions. The analysis of the linearized and simplified version of the conceptual model (similar to [49]) shows that such lag can occur even in a system of three linear differential equations which allows to obtain closed form solutions. The necessary feature is the presence of two greenhouse gases with different relaxation times and different radiation efficiency.

The effect in hand can be explained qualitatively. The concentration of methane in the atmosphere due to its rapid oxidation (short relaxation time) decreases faster than CO_2 concentration. Due to this, the total radiative forcing maximum, located between the q_{CO2} and q_{CH4} maxima, is achieved earlier than the q_{CO2} maximum. The lag between the q_{CO2} maximum and the maximum of total radiative forcing R_{tot} is proportional to the time scale of CO_2 and

CH_4 emissions changes. In turn, the temperature maximum lags the maximum of R_{tot} by the time which is not larger than $\tau_T = C/\lambda_0$. This time scale does not depend on the parameters determining CO_2 and CH_4 emissions. Provided that the time scale of the CO_2 and CH_4 emission changes is large enough, the maximum of T is reached earlier than the maximum of qCO_2.

5. Conclusion

This paper describes a possible mechanism of mutual lag between changes in the global surface temperature T and the atmospheric CO_2 content q_{CO2}. This mechanism can operate when the Earth's climate system is forced by inphase anthropogenic emissions of carbon dioxide and methane. It is shown that changes in T can both lag behind the changes in q_{CO2} and lead them depending on the time scale P of the external forcing (CO_2 and CH_4 emissions changes). At the large P, changes in q_{CO2} lag behind the corresponding changes in T, although the former can be considered as the main cause of the latter's genesis.

This result is a consequence of the difference in q_{CO2} and q_{CH4} relaxation times. When the Earth system is forced by such CO_2 and CH_4 anthropogenic emissions into the atmosphere, the q_{CH4} maximum always leads the maximum of the total greenhouse radiative forcing of two gases R_{tot}, and the q_{CO2} maximum is always lag behind it. If the time scale of emissions changes is large enough, the value of q_{CO2} lag relative to the R_{tot} becomes greater than the corresponding T lag, that depends only on the feedback parameters in the climate system.

The described mechanism of time lag between q_{CO2} and T formation includes the processes typical for a wide range of the earth system models. As a result, we can expect the observed effect to occur in the other similar models.

It should be noted that the existence of the effect under discussion does not depend on how the temperature changes affect the methane emission from the soil. It is also insufficient that methane oxidized in the atmosphere is converted into CO_2. This means that similar effects can occur with the other greenhouse gases.

The results obtained show that in the general case it is impossible to determine the nature of the causal relationship between two correlated variables by the time shift between their changes without involving any ideas about the nature of their interaction.

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