Time lag between changes in global temperature and atmospheric CO₂ content under anthropogenic emissions of CO₂ and CH₄ into the atmosphere

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Abstract. Previously, it was shown that the time lag between changes in global temperature $T$ and atmospheric CO₂ 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 CO₂ and CH₄ 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 $q_{CO_2}$ 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 $q_{CO_2}$ during the previous time interval $t_0-t_1$, even if the series for $T$ lead the series for $q_{CO_2}$. 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 $q_{CO_2}$, then $T$ attains an extremum earlier than $q_{CO_2}$ 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 $A_{q_4}$, which is the change of the sign of the $q_{CO_2}$ increments. Respectively, event $A_{q_4}$ cannot be the cause of event $A_T$. However, it is not forbidden for event $B_q$, which is the progressive growth of $q_{CO_2}$, 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 relationships 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 $q_{CO_2}$ 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 $q_{CO_2}$ in numerical simulations with a conceptual climate model forced by the total solar irradiance changes, implying that changes in $q_{CO_2}$ 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 $q_{CO_2}$ 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

$$\frac{dq_{CH_4}}{dt} = \frac{E_{CH_4}}{\beta} - \frac{q_{CH_4}}{r_{sat}},$$

(1)
where $q_{\text{CH}_4}$ is the concentration of methane in the atmosphere, $E_{\text{CH}_4}$ is the total (natural and anthropogenic) emissions of methane into the atmosphere, $\beta = 2.75 \text{ MtCH}_4/\text{ppbv}$. For $\tau_{\text{tot}}$, one writes

$$\frac{1}{\tau_{\text{tot}}} = \frac{1}{\tau_{\text{atm}}} + \frac{1}{\tau_{\text{soil}}}$$

(2)

where $\tau_{\text{soil}} = 150$ years is the time of methane decomposition in the soil, and $\tau_{\text{atm}}$ 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 MtCH$_4$/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 CO$_2$ and CH$_4$ contents deviations from their initial, equilibrated values. The first equation describes the thermal balance of the climate system (see e.g., [35, 46]):

$$C \frac{dT}{dt} = R_{\text{tot}} - \lambda_0(T - T^{(0)})$$

(3)

where $T^{(0)} = 13.7 \text{ °C}$ is the base value of global temperature, $C = 10^9 \text{ J m}^2 \text{ K}^{-1}$ [46] is the heat capacity per unit area, approximately corresponding to the heat capacity of the ocean layer of 350 m thickness, $R_{\text{tot}}$ 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 $\lambda_0$ is called the climate sensitivity parameter.

The radiative forcing $R_{\text{tot}}$ 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.).

$$R_{\text{tot}} = R_{\text{CO}_2} + R_{\text{CH}_4} + R_x$$

(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

$$R_{\text{CO}_2} = R_0 \ln \left( \frac{q_{\text{CO}_2}}{q_{\text{CO}_2}^{(0)}} \right)$$

(5)

where $q_{\text{CO}_2}^{(0)} = 278$ ppm is the pre-industrial value of atmospheric CO$_2$, $R_0$ is the normalization coefficient. For modern climate models $R_0 = 5.3 \text{ W m}^{-2}$, the value $\lambda_0$ is in the range of 0.6 to 1.6 W m$^{-2}$ K$^{-1}$ [47]. In the standard version of our conceptual model $\lambda_0 = 1 \text{ W m}^{-2} \text{ K}^{-1}$.

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 $q_{\text{CO}_2}$ there is an additional term, depending on $q_{\text{CH}_4}$. This equation has the following shape:
\[ c_0 \frac{dq_{CO_2}}{dt} = E_{CO_2} - F_{\text{land}} - F_{\text{oc}} + \frac{q_{\text{CH}_4}}{\tau_{\text{oc}}}, \quad (8) \]

where \( q_{CO_2} \) is the atmospheric carbon dioxide content [ppm], \( c_0 = 2.123 \text{ GtC/ppm(CO}_2) \), \( E_{CO_2} \) is the external (e.g., anthropogenic) \( CO_2 \) emissions into the atmosphere, \( F_{\text{land}} \) and \( F_{\text{oc}} \) are carbon fluxes from the atmosphere to the terrestrial ecosystems and to the ocean, respectively, \( \mu = 0.27 \cdot 10^{-3} \text{ GtC/ppb(CH}_4) \). The \( F_{\text{land}} \) and \( F_{\text{oc}} \) 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 (\( E_{CO_2} \) and \( E_{\text{CH}_4} \) respectively) numerical simulations were carried out. Emissions have been changing over the time according to:

\[ E_{CO_2}(t) = \{ E_{CO_2,0} \sin \left( \frac{2\pi}{P} t \right), \quad \text{при } t < \frac{P}{2}; \quad \text{при } t > \frac{P}{2} \}, \quad (9) \]

\[ E_{\text{CH}_4}(t) = \{ E_{\text{CH}_4,0} \sin \left( \frac{2\pi}{P} t \right), \quad \text{при } t < \frac{P}{2}; \quad \text{при } t > \frac{P}{2} \}, \quad (10) \]

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.
Numerical simulations were performed for $E_{\text{CO}_2,0} = 10$ GtC/year and $E_{\text{CH}_4,0} = \{180; 360; 720\ \text{MtCH}_4/\text{year}\}$. The amplitudes $E_{\text{CO}_2,0} = 10$ GtC/year and $E_{\text{CH}_4,0} = 360\ \text{MrCH}_4/\text{year}$ 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 $\Delta$ between changes in $T$ and $q_{\text{CO}_2}$ was determined via maximum cross-correlation function between these two variables. Typical values of the maximum correlation coefficient are $\geq 0.99$. The dependence of time lag $\Delta$ 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.](image)

It was found that changes in $T$ can both lag behind the $q_{\text{CO}_2}$ 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 $q_{\text{CO}_2}$ ($\Delta < 0$), while at the millennium time scale ($P > 800$ years) changes in $q_{\text{CO}_2}$ lag changes in $T$ ($\Delta > 0$), although the former is the main cause of the latter. The exact value of the critical time scale $P_{\text{cr}}$, at which lag between $T$ and $q_{\text{CO}_2}$ changes its sign depends on the ratio $E_{\text{CO}_2,0}/E_{\text{CH}_4,0}$.

We note that non-linearity of the Earth system is not necessary for $q_{\text{CO}_2}$ 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 $q_{\text{CO}_2}$ and $q_{\text{CH}_4}$ maxima, is achieved earlier than the $q_{\text{CO}_2}$ maximum. The lag between the $q_{\text{CO}_2}$ maximum and the maximum of total radiative forcing $R_{\text{tot}}$ is proportional to the time scale of CO$_2$ and
CH\textsubscript{4} emissions changes. In turn, the temperature maximum lags the maximum of \( R_{\text{tot}} \) by the time which is not larger than \( \tau_T = C/\lambda_0 \). This time scale does not depend on the parameters determining CO\textsubscript{2} and CH\textsubscript{4} emissions. Provided that the time scale of the CO\textsubscript{2} and CH\textsubscript{4} emission changes is large enough, the maximum of \( T \) is reached earlier than the maximum of \( q_{\text{CO}_2} \).

5. Conclusion

This paper describes a possible mechanism of mutual lag between changes in the global surface temperature \( T \) and the atmospheric CO\textsubscript{2} content \( q_{\text{CO}_2} \). 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 \( q_{\text{CO}_2} \) and lead them depending on the time scale \( P \) of the external forcing (CO\textsubscript{2} and CH\textsubscript{4} emissions changes). At the large \( P \), changes in \( q_{\text{CO}_2} \) 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 \( q_{\text{CO}_2} \) and \( q_{\text{CH}_4} \) relaxation times. When the Earth system is forced by such CO\textsubscript{2} and CH\textsubscript{4} anthropogenic emissions into the atmosphere, the \( q_{\text{CH}_4} \) maximum always leads the maximum of the total greenhouse radiative forcing of two gases \( R_{\text{tot}} \), and the \( q_{\text{CO}_2} \) maximum is always lag behind it. If the time scale of emissions changes is large enough, the value of \( q_{\text{CO}_2} \) lag relative to the \( R_{\text{tot}} \) 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 \( q_{\text{CO}_2} \) 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\textsubscript{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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References

[1] Hartmann D, Klein T A, Rusticucci M, Alexander L, Brönnimann S, Charabi Y, Dentener F, Dlugokencky E, Easterling D, Kaplan A, Soden B, Thorne P, Wild M and Zhai P 2013 Observations: atmosphere and surface Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T Stocker et al (New York: Cambridge University Press) pp 659–740

[2] Bindoff N, Stott P, AchutaRao K, Allen M, Gillett N, Gutzler D, Hansingo K, Hegerl G, Hu Y, Jain S, Mokhov I, Overland J, Perlwitz J, Sebbari R, Zhang X 2013 Detection and attribution of climate change: from global to regional Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment
Report of the Intergovernmental Panel on Climate Change ed T Stocker et al (New York: Cambridge University Press) pp 867–952

[3] Lean J and Rind D 2008 Geophys. Res. Lett. 35 L18701
[4] Lean J and Rind D 2009 Geophys. Res. Lett. 36 L15708
[5] Imbers J, Lopez A, Huntingford C and Allen M R 2013 J. Geophys. Res. Atmos. 118 3192–99
[6] Stern D I and Kaufmann R K 2014 Clim. Change 122 257–269
[7] Mokhov I I and Smirnov D A 2018 Doklady Earth Sci. 480 (1) 602–606
[8] Schönwiese C D, Walter A and Brinckmann S 2010 Meteorol. Zeitschrift. 19 3-10
[9] Mokhov I I, Smirnov D A and Karpenko A A 2012 Dokl. Earth Sci. 443 381-387
[10] Canty T, Mascioli N, Smarte M and Salawitch R 2013 Atmos. Chem. Phys. 13 3997–4031
[11] Míkšovský J, Holtanová E ans Pišoft P 2016 Earth. Syst. Dyn. 7 231–249
[12] Hegerl G, Hasselmann K, Cubasch U, Mitchell J, Roeckner E, Voss R and Waszkewitz J 1997 Clim. Dyn. 13 613-634
[13] Stott P, Tett S, Jones G, Allen M, Ingram W and Mitchell J 2001 Clim. Dyn. 17 1-21
[14] Stone D, Allen M, Selten F, Klipphuis M and Stott P 2007 J. Climate. 20 504-516
[15] Stone D, Allen M, Stott P, Pall P, Min S K, Nozawa T and Yukimoto S 2009 Annu. Rev. Energy Resour. 34 1-16
[16] Sedlacek K and Knutti R 2012 Geophys. Res. Lett. 39 L20708
[17] Jones G, Stott P and Christidis N 2013 J. Geophys. Res. (Atmospheres) 118 4001-24
[18] Ribes A and Terray L 2013 Clim. Dyn. 41 2837-53
[19] Soon W, Posmentier E and Baliunas S 1996 Astrophys. J. 472 891–902
[20] Idso S 1998 Clim. Res. 10 69–82
[21] Quinn J 2010 Global Warming. Geophysical Counterpoints to the Enhanced Greenhouse Theory (Pittsburgh. Dorrance Publ.) p118
[22] Scafetta N 2012 J. Atmos. Solar.-Terr. Phys. 80 124–137
[23] Lindzen R 1990 Bull. Amer. Met. Soc. 71 288–299
[24] Monnin E, Indermohle A, Dallenbach A, Flockiger J, Stauffer B, Stocker T, Raynaud D and Barnola J 2001 Science 291 112-114
[25] Caillon N, Severinghaus J, Jouzel J, Barnola J M, Kang J and Lipenkov V 2003 Science 299 1728–31
[26] Mokhov I I, Bezverkhny V A and Karpenko A A 2005 Izvestiya. Atmos. Ocean. Phys. 41(5) 523–536
[27] Bereiter B, Luthi D, Siegrista M, Schupbach S, Stocker T and Fischer H 2012 Proc. Nat. Acad. Sci. 109 9755-60
[28] Parrenin F, Masson-Delmotte V, Köhler P, Raynaud D, Paillard D, Schwander J, Barbante C, Landais A, Wegner A, Jouzel J 2013 Science 339 1060-63
[29] Humlum O, Stordahl K and Solheim J 2013 Glob. Planet. Change 100 51-69
[30] Stocker T and Johnsen S 2003 Paleooceanography 18 1087
[31] Schmittner A, Saenko O and Weaver A 2003 Quat. Sci. Rev. 22 659–671
[32] Ganopolski A and Roche D 2009 Quat. Sci. Rev. 28 3361-78
[33] Shakun J, Clark P, He F, Marcott S, Mix A, Liu Z, Otto-Bliesner B, Schmittner A and Bard E 2012. Nature 484 49–54
[34] Kern Z and Leuenberger M 2013 Glob. Planet. Change 109 1–2
[35] Masters T and Benestad R 2013 Glob. Planet. Change. 106 141-142
[36] Richardson M 2013 Glob. Planet. Change 107 226–228
[37] Van Nes E H, Scheer M, Brovkin V, Lenton T M, Ye H, Deyle E and Sugihara G 2015 Nat. Clim. Change 5 445-448
[38] Muryshev K E, Eliseev A V, Mokhov I I and Timazhev A V 2017 Glob. Planet. Change 148 29-41
[39] Muryshev K E, Timazhev A V and Dembitskaya M A 2017 Fundamental Appl. Climatol. 3 84–102 (in Russian)
[40] Muryshev K E, Eliseev A V, Mokhov I I and Timazhev A V 2015 Dokl. Earth Sci. 463 863-867
[41] Mokhov I I and Eliseev A V 2012 Dokl. Earth Sci. 443 532-536
[42] Denisov S N, Eliseev A V and Mokhov I I 2013 Rus. Meteorol. Hydrol. 38 741-749
[43] Millero F 1995 Geophys. Cosmophys. Acta 59 661–677
[44] Gedney N and Cox P 2004 Geophys. Res. Lett. 31 L2050
[45] Osborn T J and Wigley T M 1994 Clim. Dynam. 9 181-193
[46] Andreae M, Jones C and Cox P 2005 Nature 435 1187-90
[47] Flato G, Marotzke J, Abiodun B, Braconnot P, Chou S, Collins W, Cox P, Driouech F, Emori S, Eyring V, Forest C, Gleckler P, Guilyardi E, Jakob C, Kattsov V, Reason C and Rummukainen M 2013 Evaluation of climate models Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T Stocker et al (New York: Cambridge University Press) pp 659–740
[48] Myhre G, Highwood E., Shine K and Stordal F 1998 Geophys. Res. Lett. 25 2715–18
[49] Legatt R, Polyakov I V, Bhatt U S, Zhang X and Bekryaev R V 2012 Tellus A. 64 18695