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On the critical mass of greenhouse gas

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G.V. Kurdyumov Institute for Metal Physics,
National Academy of Sciences of Ukraine, Kiev, Ukraine

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В останні роки змінення клімату Землі непокоїть громадськість світу. Зростання стихійних лих, раптові температурні коливання в окремих регіонах світу та інші відхилення клімату від традиційної поведінки кліматологи пов'язують з глобальним потеплінням. Наукова громадськість з кліматології розділилася щодо питання механізму природи потепління клімату Землі. Одні дослідники вважають, що з моменту початку промислової революції виробнича діяльність людства з кожним роком збільшує кількість вуглекислого газу у повітрі. Як установлено, поряд з іншими газами він відповідає за парниковий ефект. У зв'язку з цим останнім часом відбулося кілька міжнародних конференцій, на яких ухвалено рішення про скорочення викидів вуглекислого газу в атмосферу.

Інша частина кліматологів, на підставі спостережень за ативністю Сонця, вважає, що потепління спричинено проявом циклічного часового періоду цієї активності, і незабаром цей цикл закінчиться. Причому в подальшому можливе настання нового льодовикового періоду. У статті запропоновано іншу можливу реальну причину потепління клімату. На засадах загальної теорії зворотного зв'язку показано, що чотири основні позитивні зворотні зв'язки, що викликають вторинну емісію водяної пари, CO_2, CO_4 та зменшення альбедо, впливають на кліматичну систему Землі. Якщо на цей час рівень первинної антропогенної емісії парникових газів зростатиме, то загальна маса парникового газу внаслідок зазначених вище зворотних зв'язків досягне певної критичної величини, що зумовить самопосилення парникового ефету, який спричинить біфуркаційний перехід кліматичної системи Землі у стан саморозігріву з необмеженим зростанням середньої температури земної поверхні.

Ключові слова: парниковий газ, позитивний зворотний зв'язок, підвищення температури, біфуркаційний перехід.

Introduction. Many systems have a critical parameter when a system passes from its original state into a qualitatively new state with new characteristics. In this paper we show that at a certain point or threshold when greenhouse gases reach a critical mass, the earth's climate system could change to a qualitatively new state with potentially catastrophic consequences for humankind and the nature. A key driver leading to such a state is a positive feedbacks upon the earth's climate system. There are several studies addressing the impact of such positive feedbacks on the greenhouse effect [Lashof et al., 1997; Torn, Harte, 2006; Scheffer et al., 2006] but we argue that many researchers do not give sufficient attention to the strength and power of this impact. We argue further that it is such positive feedback that is the main cause of rapid climate change.

The theory of feedback states the following. A feedback works in a system only if this system is active. It means that the system is able to amplify any external action on it out of its self-energy. This condition is called the energy criterion [Raisbeck, 1954]. The earth's climate system satisfies this criterion. Therefore, all conclusions by the theory of feedback can be used to research the influence of feedbacks on the earth's climate system.

To the possibility of these disastrous consequences have pointed ut earlier [Klimchuk, Tarasov, 2005]. Now we want to return to this question making some additions.

Analysis of feedback. An active system of any kind with feedbacks is shown schematically in Fig.1, where 1 is active system itself, 2 is the feedback unit, 3 is the summing unit, U_1 is the input action (signal), U_2 is the response of the system to the input signal U_{in}, U_{fu} is the response (signal) of the feedback, and U_{in} is the resulting action (signal) at the input of the system. The core of the feedback process is as follows. A part of the output response U_2 of the system comes through the unit of feedback in the form of U_{fu} to the summing unit, where it is added to the input action U_1, forming the resulting input signal U_{in}. If the signs (phases) of signals U_1 and U_{fu} coincide, the signal U_{in} and the response U_2 increase accordingly to feedback. Otherwise a feedback is negative. The equality of signals U_1 and U_{fu} means that the internal control or self-control is realized by the U_{fu} signal in systems with feedbacks. This is the essence of the principle of feedback.

The input action U_1 and the response U_2 of the system may have different physical nature. The signals U_1 and U_{fu} are always similar. The latter is implemented, when necessary, by the appropriate transformation of the nature of U_2 into a unit of feedback. Therefore, in considering the earth's climate system when the input action U_1 is understood as the increase of anthropogenic emissions of greenhouse gases, we can speak of positive feedbacks only when there are such responses U_{fu} that represent increases of secondary emissions of greenhouse gases generated in the earth's climate system due primarily to anthropogenic emissions of greenhouse gases. These positive feedbacks are discussed below.

It is easy to show that the transmission factor (function) K_{fu} of the system with a feedback shown by the structural scheme

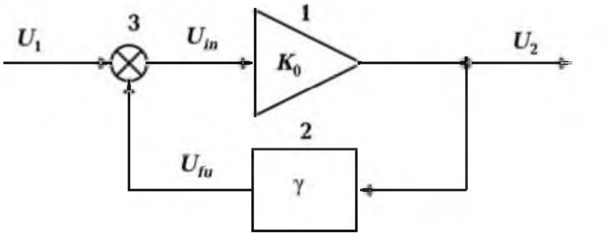

Fig. 1. Schematic structure of feedback.

in Fig. 1, is expressed by the following ratio [Bode, 1945]:

$$K_{\text{fb}} = \frac{U_2}{U_1} = \frac{K_0}{1-\gamma K_0} = \frac{K_0}{1-S} = \frac{K_0}{F}, \quad (1)$$

where $K_0 = U_2 / U_1$ is the transmission factor (function) of the system without a feedback, $\gamma = U_{\text{fu}} / U_2$ is the transmission factor (function) of a unit of feedback, $S = \gamma K_0$ is the loop amplification (reversion ratio) in the feedback loop in open position, and F is the recurrent difference.

In the ratio (1) it is assumed that the transmission functions of the summing unit 3 on signals U_1 and U_{fu} are equal to unity. The function γ is otherwise called the feedback factor and in the case of a positive feedback is usually denoted by α and in case of a negative feedback by β.

If the output of the unit of feedback 2 is disconnected from the adder 3 and the unit action is used at the input of system 1, the response at the output of the unit of feedback will be numerically equal to the loop gain S, which in case of multiloop feedbacks is usually called the reversion ratio. In research on the feedback theory the reversion ratio is usually denoted by T. We back out of this rule as in what follows we denote temperature by this letter.

In structural scheme in Fig. 1 for the open feedback loop:

$$S = \gamma K_0 = \frac{U_{\text{fu}}}{U_2}\,\frac{U_2}{U_1} = \frac{U_{\text{fu}}}{U_1}. \quad (2)$$

Taking into account that in case of a positive feedback the signs (phases) of signals U_1 and U_{fu} coincide and for a negative feedback they are different, in the former case $S > 0$, in the latter $S < 0$.

According to the value of S in case of a positive feedback, 3 modes of operations with such feedbacks are distinguished.

The first of them, which is called *subcritical*, is realized when $0 < S < 1$, $F < 1$, $K_{fu} > K_0$, $S = 1$, $F = 0$ correspond to the second mode called critical. This mode is also called the critical point or the point of bifurcation. In this mode the function K_{fu} has infinite break. Physically it means that the finite response U_2 of the system is possible at the indefinitely small input action U_1. That is why its functioning is also possible without U_1. In fact, when $S = 1$, according to (2), $U_{fu} = U_1$, which means that the feedback response is an exact copy of the input action. As a result, the system in a critical mode after dormancy breaking is able to continue its movement without the input action U_1 because the input action will be replaced by the response U_{fu}, which is self-sustaining, being its own cause and effect. Consequently, when $S = 1$, qualitative changes occur in the system. It passes from the mode of external action into the mode of self-triggering (self-exciting oscillation mode) and its movement becomes free self-sustaining, that is, a self-movement. This self-movement is stationary and takes place at a constant speed defined by the initial conditions.

And at last the third mode, called *supercritical*, is realized when $S > 1$. Under this mode the systems with a positive feedback are in a state of dynamic instability, under which the differential equations describing such systems have divergent solutions. As in every cycle of self-triggering the signal U_{fu} increases by the factor of $S > 1$, after dormancy breaking the self-movement of such systems exponentially evolves to the point of their self-destruction or transition into some stationary state. The latter is possible only if at some value of the output response U_2 the partial derivative $S' = \partial S / \partial U_2$ becomes negative. As a consequence, as U_2 increases further, the reversion ratio will fall to the value $S = 1$ and the system will pass into a state of stationary self-movement with the limiting value $U_2 = U_c = \text{const}$. If for some reasons U_2 exceeds U_c, the reversion ratio will become subcritical ($S < 1$). Self-triggering in the system will stop and as a result of self-braking the system will return to the stationary state $U_2 = U_c$ with $S = 1$. If, on the contrary, U_2 decreases, the reversion ratio will become supercritical ($S > 1$). As a result of this, self-triggering will increase and the self-acceleration of the system will return to the stationary state again with $S = 1$. Therefore, at any deflections of U_2 from U_c the system independently comes back to a stationary state. In equations of motion of such self-regulation systems these states correspond to limit stable cycles that are called attractors in mathematics. No matter how these cycles are reached, their realization is equivalent to the availability of internal self-regulation by means of negative feedbacks in the systems.

Examples of systems with or without attractor cycles are nuclear reactors and atomic bombs. The stationary mode of the former at the preset power levels is realized by the systems automatically controlling the critical value of the reversion ratio $S = 1$, which in this case is called the multiplication constant of secondary neutrons. There is no internal self-regulation in atomic bombs. That is why in atomic bombs if $S > 1$, the evolution of chain self-sustaining fission reactions tends towards unlimited growth, which leads to their self-destruction through explosion. The mass of the fissile material necessary for the bifurcation transition to the condition of the mentioned chain reaction to occur is called critical.

Discussion. Returning to the earth's climate system, we consider the increase of GhG emissions to be the input action for the earth's climate system, and the increase of mean temperature of the earth's surface to be the response. Then the function of the transmission of the climate system without taking into account its feedbacks can be described in the following way:

$$K_0 = \frac{\partial T_0}{\partial V_0}, \tag{3}$$

where ∂V_0 is the increase of the primary GhG emission measured in carbon dioxide equivalent during the same time interval, ∂T_0 is the increase of mean temperature induced by this emission and attributed to during the same time interval. By the primary GhG emission we understand the emission of carbon dioxide from human activities (anthropogenic emission).

Therefore, the time interval is not included explicitly in expression (3). As CO_2 is an essential part of GhG emissions, it is reasonable to express both primary and secondary GhG emissions in their carbon dioxide equivalents.

In a previous work [Klimchuk, Tarasov, 2005] we singled out 4 main loops of a positive feedback in the earth's climate system. These 4 loops result from secondary GhG emissions caused by the increase of mean temperature due to primary GhG emissions.

We think the positive feedback loop, caused by the secondary emission of water vapor from open reservoirs, to be the first and most important for the following reasons. First, water vapor is the most active greenhouse gas, which absorbs all energy of the infrared spectrum (i. e. the heat) of the earth and prevents its flowing into space. The open reservoirs occupy more than 70 % of the earth's surface. Second, the primary annual water vapor emission amounts to nearly 600 billion tons, which is 1000 times as much as the summed annual natural and anthropogenic carbon dioxide emissions. Therefore, the rise of mean temperature caused by primary GhG emissions results in the increase of evaporation from open reservoirs, that is, in the secondary water vapor emission which in turn increases mean temperature due to the accumulation of atmospheric heat energy. In this way an appropriate positive feedback loop is created, which leads to the regenerative self-amplification of the greenhouse effect.

When the water temperature rise the solubility of gases in water falls. This results in the secondary emission from the world's oceans. The amount of CO_2 dissolved in the world oceans is 55 times as much as the amount of atmospheric CO_2. We believe that the emission of CO_2 from the world's oceans is the second loop of a feedback in the earth's climate system.

However, recent experimental data have shown that such emissions are not only lacking but that the world's oceans absorbs about two thirds of anthropogenic CO_2 emissions. It is for this reason that biologists have raised the alarm about the possibility of a substantial increase in oceanic acidity. Under present conditions the world's oceans are powerful inhibitors of the rate of anthropogenic global warming. However, it will be shown below that secondary CO_2 emissions from the world's oceans do exist but appear in a very specific way.

We think the positive feedback loop caused by secondary CH_4 emissions from the permafrost zones, where its storage in the form of gas-hydrates is enormous, to be the third. The third positive feedback loop is caused by secondary CH_4 emission from the permafrost zones.

The fourth positive feedback loop results from the secondary decrease in the earth's reflectivity (albedo) due to continuing reduction in the area of ice and snow cover.

The decrease in the earth's reflectivity leads to the temperature rise of the earth's surface. It can be considered as a virtual emission of an equivalent value of CO_2 which gives the same temperature rise as the albedo decrease does.

We consider the impact of other possible feedbacks on the earth's climate system as insignificant.

Before defining feedback factors for the four positive feedback loops it is necessary to return to the problem of CO_2 absorption by the world's oceans. We will consider the records of ice core air bubbles obtained in ice coring at the Russian station Vostok in Antarctica, which generally agree with the data from a similar coring on the Concordia from the European Project for Ice Coring in Antarctica (EPIKA) program. In the article [Petit et al., 1999] provide graphs of time dependence for the surface air temperature of atmospheric CO_2 and CH_4 concentrations over 420.000 years. These graphs imply that the earth's climate is subject to cyclic changes of up to about 100.000 years per cycle. We agree with researchers who consider the relevant variation in the amount of solar radiation reaching the earth as the main cause of such cyclicity. Indeed, the solar cycles contributed to the rise of CO_2 concentration. But it does not prove that the amount of this concentration was defined only by the intensity of solar energy at that time.

The graphs how that at every increase in mean temperature, the atmospheric CO_2 and CH_4 concentrations rise. We are sure that at the same time the water evaporation increased and the earth albedo decreased. Consequently, in the past the earth's climate was affected by the three (ignoring any anthropogenic emissions at that time) mentioned positive feedback loops leading to the regenerative self-amplification of the greenhouse effect. As a result, actual changes in mean temperature exceeded greatly its initial variations caused by changes in amounts of solar radiation merely. The main difference from today was that the primary influence on the earth's climate system were variations in solar radiation, the amplification of which led to increases in mean temperature, which turned the world's oceans into sources of secondary CO_2 emission. That is to say, when mean temperatures increased, the value of CO_2 equilibrium partial pressure or its saturation pressure increased, resulting in CO_2 emissions.

Today anthropogenic CO_2 emissions are having a major impact on the climate system as a result of the partial pressure of CO_2 exceeding the equilibrium value corresponding to the present mean temperature, which has led to the world's oceans absorbing excess of CO_2 from the atmosphere. However, owing to the increase in mean temperature caused by anthropogenic GhG emissions, the equilibrium value of CO_2 partial pressure corresponding to mean temperature also continuously increases, which is decreasing the oceans' absorption of this gas. In this way a CO_2 positive feedback loop is created, with the secondary CO_2 emission being influenced by this decrease in absorption. Thus, the secondary CO_2 emission from the oceans occur. But they are smaller as some of CO_2 is absorbed by the world's oceans.

That is why by the increase in the primary GhG emission in (3) its effective value is understood which is equal to

$$\partial V_0 = \partial V_0' - \partial V_{car}, \tag{4}$$

where $\partial V_0'$ is the actual increase in the primary equivalent GhG emission at the fixed time interval, ∂V_{car} is the portion of CO_2 from the primary GhG emission absorbed by the World ocean at the same time interval.

Taking into account the above-mentioned, the feedback factors for the four considered positive feedback loops can be presented as follows:

$$\alpha_{car} = \frac{\partial V_{car}}{\partial T_0}, \quad \alpha_{var} = \frac{\partial V_{var}}{\partial T_0}, \quad \alpha_{met} = \frac{\partial V_{met}}{\partial T_0},$$

$$\alpha_{al} = \frac{\partial V_{al}}{\partial T_0}, \tag{5}$$

where ∂V_{car}, ∂V_{var}, ∂V_{met}, ∂V_{al} are the secondary equivalent emissions caused by the primary increase in mean temperature ∂T_0 and resulting from the secondary emission CO_2, of water vapor, CH_4, and the albedo decrease respectively.

The correctness of the factor α_{car} is determined by the fact that the absorption of CO_2 by the World Ocean is allowed for by (4).

Based on this and taking into account (2) and (3) the positive feedback factor α_{gh} and the reversion ratio S_{gh} of the greenhouse effect are defined as:

$$\alpha_{gh} = \alpha_{car} + \alpha_{var} + \alpha_{met} + \alpha_{al},$$

$$S_{gh} = \frac{\partial V_{\Sigma}}{\partial V_0}, \tag{6}$$

where ∂V_{Σ} is the increase of the summed equivalent secondary GhG emission.

From (6) it follows that the reversion ratio S_{gh} can be called the factor of secondary GhG emission.

Based on (1) the transmission function of the climate system subject to the possible regenerative self-amplification of the greenhouse gas emission becomes:

$$K_{gh} = \frac{\partial T_{gh}}{\partial V_0} = \frac{K_0}{1 - \alpha_{gh} K_0} =$$

$$= \frac{K_0}{1 - S_{gh}} = \frac{K_0}{F_{gh}}, \qquad (7)$$

where ∂T_{gh} is the actual increase in mean temperature subject to the positive feedback influence caused by the increase ∂V_0 in the primary effective GhG emission, F_{gh} is the recurrent difference of the greenhouse effect.

Taking into account (3), the connection between the primary increase and the actual one in mean temperature in the presence of the regenerative self-amplification of the greenhouse effect is expressed as follows:

$$\frac{\partial T_{gh}}{\partial V_0} = \frac{\partial T_0}{\partial V_0 F_{gh}}, \quad \partial T_{gh} = \frac{\partial T_0}{F_{gh}},$$

$$F_{gh} = \frac{\partial T_0}{\partial T_{gh}}. \qquad (8)$$

Conclusion. Based on the reasoning above we come to the following conclusion. The observed rapid rise of the earth's mean temperature is caused by two factors. The first is the increase of the solar activity [Schaller et al., 2014]. It increases the mean temperature of the earth. But this temperature rise leads to the emission of greenhouse gases from the permafrost zones, increases water evaporation and decreases the albedo. To all this is added the greenhouse gas from man's productive activity. We consider them the primary greenhouse gases. Therefore, the Sun and man's activity caused the appearance of primary gases. These gases account for the second part of the mean temperature rise due to self-triggering of the earth's climate system owing to positive feedbacks. This part of the temperature rise is the second factor of the observed general temperature rise.

Indeed, from (8) it follows that if now $S_{gh} > 0$, $F_{gh} < 1$, then $\partial T_{gh} > \partial T_0$. According to (6), the latter is possible provided the summed secondary GhG emissions are commensurable with the effective value of the primary GhG emissions. The calculations in [Torn, Harte, 2006; Scheffer et al., 2006] suggest such a possibility, making the situation dangerous. We think that positive feedback gives rise to a danger more serious than its impact of the earth's temperature only.

Increase in secondary GhG emissions caused by the same primary increase in mean temperature continues to occur as the absolute value of the latter becomes larger. From the graphs in [Petit et al., 1999] it follows that over the latest periods of global warming (in accordance with graphs) the concentration of atmospheric CO_2 has not exceeded 0.03 % but now CO_2 has 0.038 % and continues to rise rapidly. Furthermore, the earth is close to "the zero mark" of a regular period of global warming resulting from the earth's increased absorption of solar power. Consequently, mean temperature can only continue to rise in the future. At this shows of date facts of global warming (IPCC — Intergovernmental Panel on Climat Change). That is why it is inevitable in the coming decades when the summed secondary GhG emission equalizes the primary GhG emission, i. e., the factor of the secondary greenhouse gas emission equals amounts to the critical value $S_{gh} = 1$. The further increase of this factor will lead to the bifurcation transition of the earth's climate system in which self-triggering of the secondary GhG emissions results in a state of self-heating with the tendency for mean temperature to rise indefinitely. This process can enter a stationary state only after the complete evaporation of the earth's entire water surface. In such a case, the pressure on the earth's surface will reach 300 atm and the temperature will exceed 500 °C. The total mass of atmospheric GhG with which the mentioned bifurcation will take place we call *critical*. The potentialities of the greenhouse effect are clearly demonstrated by planet Venus.

Due to the supercritical carbon-dioxide atmosphere of this planet, the surface temperature of Venus is between 430—470 °C with the pressure on the planet's surface at 100 atm.

It is accounted for by the fact that in this case the available zones of heat and cold will exhibit their persistence under gradual temperature rise. As a result, some parts of the earth experience rain showers (dumping of accumulated water vapor) while others experience equalizes hurricanes and tornadoes as a result of thermodynamic disequilibrium.

Every new emission of a primary (anthropogenic) GhG causes the growth (or concentration) of the GhG shielding layer which will reduce the amount of the earth's heat radiation escaping into space. This reduction will occur exponentially with the emission of every new primary GhG portion as the intensity of any radiation going through the shielding layer falls exponentially, that is, the earth's capacity to shield heat improves. It means that value $K_0 = \partial T_0 / \partial V_0$, in (3) and (7) is the increasing time function, which increases the danger of the early occurrence of this state.

The conclusion to be drawn from this discussion is the view of some climatologists that the future temperature rise in the earth's atmosphere poses no risk to be dangerous. It causes our anxiety.

Taking into account inestigations about impact at climate positive feedback are contining [Plattner et al., 2009; MacDougall et al., 2015; MacDougall, Knutti, 2016; Rugenstein et al., 2016] we propose that researchers calculate estimates of the time dependence $\partial F_{gh} / \partial t$ i. e., the rate of approach to the self-heating bifurcation and estimate the likely time necessary for the transition to this state under the condition of future growth of the increase in the primary GhG emission.

On the critical mass of greenhouse gas

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In recent years, changes in the Earth's climate have raised concern all around the globe. Climatologists have been drawing connections between global warming and a growing number of natural disasters, unexpected temperature fluctuations in some regions of the world and a number of other climatic aberrations. Within the scientific community, the opinions as to the nature and mechanism of the Earth's climate change have split. Some contend that since the beginning of the industrial revolution, the carbon dioxide levels in the air have been steadily rising due to human production activities. Along with other gases, carbon dioxide has been inculpated for the greenhouse effect. In connection with this, a number of recent international confeences have adopted resolutions to reduce carbon dioxide emissions into the atmosphere. Another group of climatologists bases its findings on observations of solar activity, arguing that global warming is caused by a recurring spike in solar activity, with the current increase due to end soon, potentially giving way to a new ice age down the road. In the following work, we put forth yet another hypothesis regarding global warming. The influence of four main positive feedback loops caused by the secondary emission of water vapor, CO_2, CO_4, and decreased albedo on the earth's climate system is shown on the basis of the general theory of feedback. If the present level of primary anthropogenic emissions of greenhouse gas (GhG) keeps, the total mass of atmospheric greenhouse gas can run up to such a critical value that the mentioned feedbacks, which give rise to self-amplification of the greenhouse effect, can cause the bifurcation transition of the climate system to the state of self-heating tending to the unlimited rise of mean temperature of the earth's surface.

Key words: greenhouse gas, positive feedback, temperature rise, bifurcation transition.

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