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WHAT IS THE MAIN MECHANISM OF EARTH'S TEMPERATURE CHANGES?

Abstract: The prevailing consensus among most of the society is that the observed increase in global temperature is primarily attributed to greenhouse gas emissions, particularly CO_2 resulting from the combustion of fossil fuels. The forthcoming analysis will demonstrate that the primary factors responsible for the Earth's temperature are changes in the heat flux from the Sun and the heat generated within the Earth. These factors subsequently impact the composition of the Earth's atmosphere. While human-generated greenhouse gases do contribute to this process, their influence is relatively minor. The results obtained should be crucial in shaping global policies related to industry and the environment.

Keywords: climate change, Earth, greenhouse gases, solar radiation, temperature

Introduction

The main mechanisms of Earth's temperature changes can be broadly categorized into natural processes and anthropogenic influences. Natural processes include the Earth's rotation and revolution, which contribute to diurnal and seasonal temperature variations, respectively. The Earth's rotation leads to daily temperature fluctuations due to varying exposure to solar radiation, while its axial tilt and orbit around the sun result in seasonal changes in temperature. These mechanisms are well documented, indicating that the Earth's temperature exhibits regular cycles influenced by solar radiation levels, which create distinct temperature zones throughout the year and day, influencing soil temperature and the broader climate system [1-3].

In addition to these natural mechanisms, human activities have significantly altered the Earth's energy balance, the most significant contemporary changes in Earth's temperature, primarily through the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and nitrogen oxides (NO_x). The combustion of fossil fuels for energy, industrial processes, and transportation has led to a substantial increase contributes to global warming. Studies indicate that human-induced emissions have been the dominant factor in the observed rise in global temperatures since the industrial revolution [4-6]. The increase in atmospheric concentrations of greenhouse gases has been linked to a rise in average global temperatures, with projections indicating a potential increase of 5.3 °C by 2100 if current trends continue without intervention [7]. This anthropogenic influence is critical in understanding the current trajectory of Earth's temperature changes. The increase in GHG concentrations

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alters the Earth’s energy balance, leading to an increase in radiative forcing, which in turn raises the equilibrium temperature of the Earth’s surface [6, 8].

Moreover, the consequences of these temperature changes are profound, affecting not only the climate but also ecosystems and human health. For instance, higher temperatures can exacerbate the formation of secondary air pollutants, leading to increased respiratory issues and other health problems [9]. Additionally, the impacts of climate change manifest in extreme weather events, altered precipitation patterns, and disruptions in natural ecosystems, which further complicate the climate system [10, 11]. Variations in soil moisture and temperature can influence the thermal properties of the ground, affecting heat transfer processes. For instance, the moisture content in soils can significantly impact their thermal conductivity and capacity, leading to variations in temperature responses during different climatic conditions [12, 13]. The interplay between soil temperature and atmospheric conditions is crucial for understanding localized climate effects and their broader implications for ecosystems and human activities. Research has suggested that solar-magnetic activity may play a role in global temperature dynamics, indicating that the Earth’s climate system is subject to both internal and external influences [14]. The interconnectivity of these factors underscores the complexity of climate change and its multifaceted impacts on both natural and human systems.

In summary, Earth’s temperature changes are primarily governed by both natural mechanisms, such as solar radiation and the Earth’s movements, and anthropogenic factors, particularly the increase in GHG emissions. The interplay between these elements not only drives temperature fluctuations but also poses significant challenges for environmental sustainability and public health.

From the perspective of process and chemical engineering, the Earth can be considered a semi-closed system, with minimal mass exchange but continuous energy flow (Fig. 1).

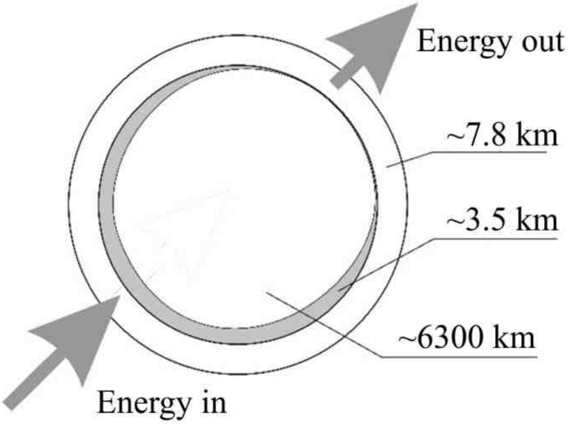

Fig. 1. Earth as a thermodynamic object (no proportions, schematically marked thickness of the atmosphere with hypothetical constant density - 7.8 km, hydrosphere - 3.5 km, lithosphere - 6300 km)

The principle of conservation of energy in relation to the Earth can be written in the form: energy entering the system (I) + energy generated on Earth (P) - energy emitted from Earth (O) = energy accumulation on Earth (A):

$$(I) + (P) – (O) = (A) \tag{1}$$

Within this system, encompassing the atmosphere, hydrosphere, and lithosphere, countless chemical, biochemical, and biological processes, and reactions occur every second [15]. These processes vary in rate and intensity across different locations on Earth. Therefore, an accurate depiction of these phenomena requires the inclusion of billions of cells, where various processes occur with additional exchange of heat, momentum, and mass between them. Most constants associated with these processes and reactions remain unspecified or unknown, that's why the results obtained from the elaborated mathematical models can be burden by serious mistakes. In such a case first approximation to describe the Earth's phenomena is qualitative description based on macroscopic balances of heat and mass, where the temperature and concentrations of greenhouse gases play a fundamental role. The basic data of the system are the following:

- mass of air $m_a = 5.3 \cdot 10^{18}$ kg,
- mass of water $m_w = 1.4 \cdot 10^{21}$ kg,
- contact area between air and water $F_w = 3.6 \cdot 10^{14}$ m^2,
- mean depth of ocean $z_w = 3.5$ km,
- diameter of Earth $D = 1.26 \cdot 10^7$ m,
- mean high of atmosphere (with hypothetical constant air density on sea level) $z_a = 7.8$ km,
- specific heat of air $c_a = 1000$ J $\cdot$ kg^{-1} $\cdot$ K^{-1},
- specific heat of water $c_w = 4200$ J $\cdot$ kg^{-1} $\cdot$ K^{-1}.

Even a cursory examination of the above data reveals that the mass and heat capacity of the atmosphere are significantly smaller when compared to that of hydrosphere, by approximately 3 or even 4 orders of magnitude. Consequently, any changes, no matter how minute, within the system will be initially observed in the atmosphere. The sensitivity of the atmosphere to changes surpasses that of the hydrosphere by a considerable margin.

Solar constant G_{sc} is equal 1366 W m^{-2}. It changes by only 0.2 percent at 11-year solar cycle. About 0.3 solar energy is rejected by the Earth system, therefore the system obtain the flux of energy equal:

$$(I) = 0.7 \cdot G_{sc} \cdot \pi \cdot D^2/4 = 0.7 \cdot 1366 \cdot \pi \cdot 1.26^2 \cdot 10^{14}/4 = 1.19 \cdot 10^{17}\ \text{J} \cdot \text{s}^{-1} = 3.8 \cdot 10^{24}\ \text{J}\cdot\text{year}^{-1}$$

The energy that reaches the system after transformation give the Earth's average temperature of approximately 15 °C [16]. If the processes of energies inflow and generated on Earth and energy outflow were equal, the average temperature on the globe would remain relatively stable. However, this has not been the case in the past and will not be in the future, primarily due to changes in the Earth's orbit, variations in solar activity and activity of mankind. With its high inertia, the Earth system experiences periodic, gradual, and extended fluctuations in temperature [17].

Apart from transformation of energy, one can also observe chemical, physicochemical, and physical changes. The processes most relevant to temperature changes are those related to CO_2 and water. The rate of CO_2 absorption is strongly dependent on temperature. As the temperature increases, the rate of absorption decreases, and at certain temperatures, desorption may occur. This implies that due to the variability of the energy flux coming from the Sun and various processes taking place on Earth, it is impossible to achieve a state of physicochemical equilibrium. However, CO_2 concentrations in the atmosphere and in the upper layers of hydrosphere are constantly close to equilibrium. The processes of assimilation and decomposition of organic matter, excluding human activity, have almost zero carbon balance. The similarity in the direction of water changes in the system to that of CO_2 can be observed. Water vapour and CO_2 are the primary greenhouse gases, and their energy absorption properties are alike [18, 19]. At 15 °C, the partial pressure of water is 1.7 kPa, and assuming that the air on the globe is 60 % saturated with moisture (a conservative assumption), the water vapour content in the air is 1 % (10,000 ppm). The current concentration of CO_2 in the air is approximately 400 ppm. The ratio of concentrations of water vapour and CO_2 in the air is 100:4. Consequently, it indirectly demonstrates that the main and decisive atmospheric compound that affects climate change is water vapour.

Analysis of ancient historical data

The correlation between the rise in temperature and CO_2 concentration in the atmosphere is well-established through historical data spanning tens of thousands of years (Fig. 2).

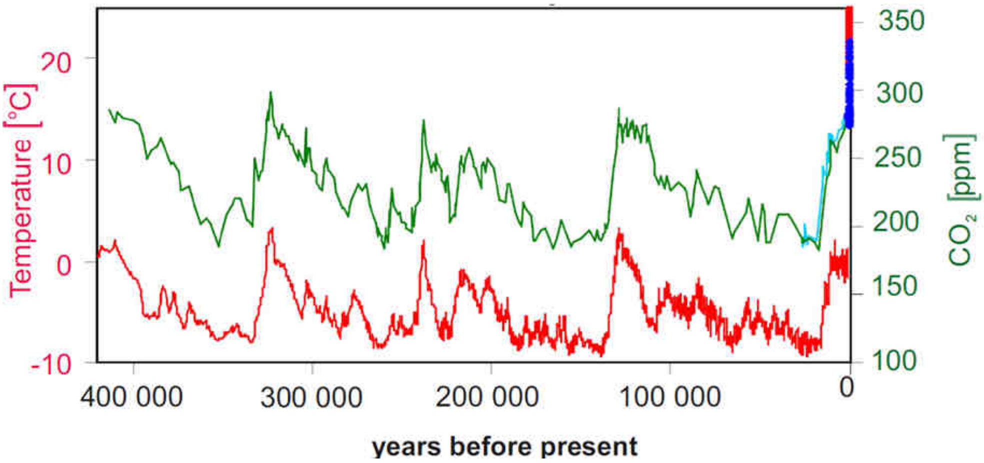

Fig. 2. Changes in temperature and CO_2 concentration over the last 420,000 years [20]

The underlying mechanism for these temperature fluctuations, which occur over extended periods, is attributed to Milankovic cycles [21]. Considering this, two fundamental inquiries arise:

1. Does CO_2 produce these temperature changes? or
2. Are changes in CO_2 concentrations caused by temperature changes?

Historical data show that the answer to the first question is negative. The likelihood of regular, additional, gigantic sources of CO_2 occurring during regular periods of warming in accordance with the Milankovic cycles is highly improbable. The answer to the second one will be possible with the help of Henry's law which relates gas solubility to partial pressure dependence.

$$p_A = H_A x_A \tag{2}$$

where: p_A - partial pressure of the gas A (for example CO_2) [Pa], H_A - Henry's constant; its value increases with temperature, [Pa], x_A - molar fraction of component A in the liquid.

It can be inferred from this law that as the temperature rises, the solubility of CO_2 or other gases in water diminishes [22]. Consequently, as the temperature increases, the rate of absorption of CO_2 decreases (or even the desorption of CO_2 from water into the atmosphere occurs), leading to an elevation in the concentration of CO_2 in the atmosphere, increasing the greenhouse effect [23]. As the flux of solar energy reaching the Earth declines over time, its temperature decreases, resulting in the occurrence of gas absorption in water. This cycle repeats throughout history. Therefore, the explanation for historical changes on Earth is as follows: changes in the rate of solar energy cause fluctuations in temperature, subsequently impacting the concentration of CO_2 (and water vapour as well, but it was not measure).

Another two questions require clarification. First one: it appears that following any disturbance of conditions on Earth, the physicochemical equilibrium should rapidly be restored due to the extensive contact area between the hydrosphere and the atmosphere. However, this is complicated by other factors. In addition to temperature, three factors play a role in determining the rate of absorption/desorption processes: the turbulence of the liquid and gaseous phases, the contact area between these phases, and the driving forces of these processes. These can be written for the liquid phase by the following equation:

$$N_A = k_L F_w (C_{AL}^* - C_{AL}) \tag{3}$$

where: N_A - molar rate of CO_2 [kmol · s^{-1}], k_L - mass transfer coefficient [m · s^{-1}], representing turbulence of liquid, F_w - contact area [m^2], C_{AL}^* - concentration of CO_2 in water at the interface [kmol · m^{-3}], C_{AL} - concentration of CO_2 in the bulk of water [kmol · m^{-3}].

The contact area F_w is more convenient to write in the form of:

$$F_w = a\,V \tag{4}$$

where: a - contact area of phases per unit volume [$m^2 \cdot m^{-3}$], V - volume [m^3].

If any of the three factors in equation (3) are small, the absorption/desorption process becomes slow. In typical gas absorption/desorption processes in industrial absorption columns, the contact area of the phases per unit volume is approximately 100 $m^2 \cdot m^{-3}$ or more. On Earth, this value is around 10^{-4} - 10^{-5}. Consequently, the ratio of contact area per unit volume in nature and in industrial absorption apparatus is approximately 10^{-6} or less. Additionally, the turbulence in the gas phases is similar in both cases, but the water turbulence in nature is significantly smaller than in industrial columns. Furthermore, the driving force of the absorption process in nature is also small. Therefore, it can be concluded that the absorption of CO_2 and its subsequent desorption in terrestrial conditions is a slow process, which necessitates a long duration lasting for months or even years. This observation aligns with historical data, where the increase in CO_2 levels follows a rise in temperature [24, 25].

The second question is the following: what is mechanism of temperature changes on Earth? The mechanism of temperature changes in historical times can be explained as follows: let the total fluxes ($I + P$) increase slightly in relation to the flux (O) at some point in time. Since the Earth's thermal inertia is high, the flux (O) would remain practically unchanged and there would have to be an accumulation of energy (A). This, in turn, would cause an increase in temperature and, as a consequence, an increase in concentration of water vapour and other greenhouse gases, an increase in the greenhouse effect as well as a decrease in the Earth’s albedo and, as a final result, an increase in the flux (*O*). If fluxes (*I* + *P*) do not increase further over the time, the flux (*O*) would balance the total fluxes after some time and equilibrium will be obtained. However, if the total flux (*I* + *P*) increased over time, there would be a constant process of energy accumulation (*A*), and as a result, the temperature on Earth would increase. In the case of decrease of fluxes (*I* + *P*) process will be run in opposite direction.

It was demonstrated that changes in Earth’s temperature and composition of atmosphere in historical times were primarily linked to variations in the heat flux from the Sun.

Analysis of period of the last ten thousand years

The temperature changes during the Holocene period on the Northern Hemisphere followed a sinusoidal pattern with an approximate period of 1500 ±500 years. In last 2000 years in Europe (Fig. 3), there was a period known as the Medieval Warming around the year 1000, followed by a significant drop in temperature [26].

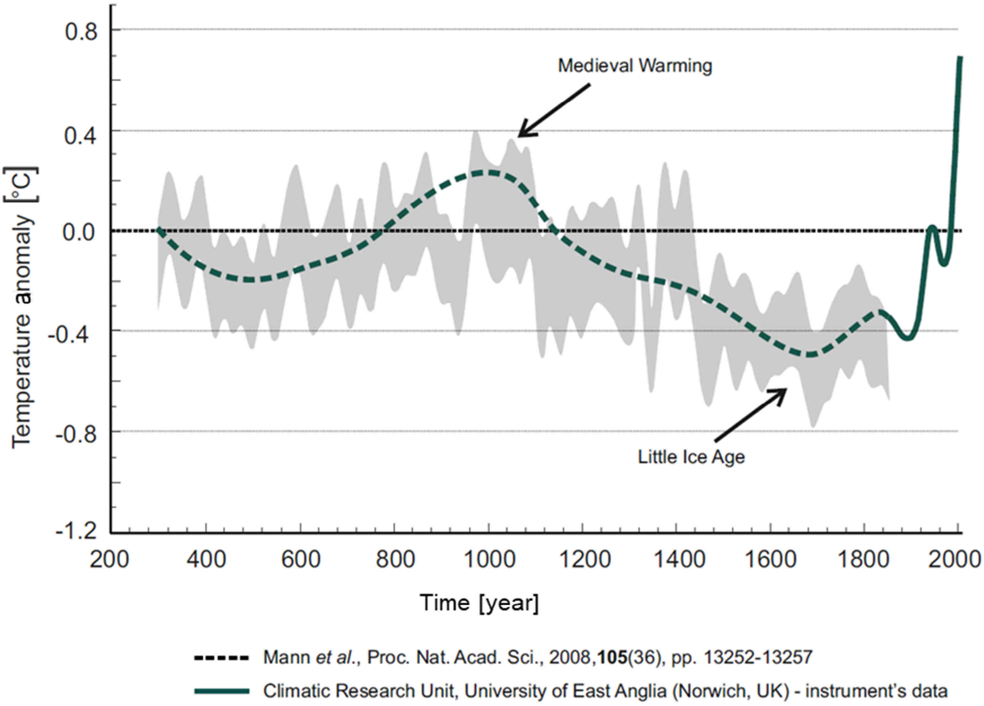

Fig. 3. Temperature changes over the last 2000 years (smoothed data) [27]

This decline reached its lowest point between 1600 and 1700, which is referred to as the Little Ice Age. From 1700 onwards, the temperature has been almost steadily rising. It is worth mentioning that this temperature increase began much earlier than the rapid surge in the combustion of fossil fuels. This indirectly suggests that we are currently experiencing a period of slight natural warming of the Earth [28, 29].

The composition and temperature of the atmosphere are expected to undergo changes due to the additional heat and mass fluxes generated within the system, resulting from the burning of fossil fuels. To determine whether the observed increase in temperature is a result of natural processes or the burning of fossil fuels, simplified calculations were conducted. Long-term measurements from the years 1965 to 2015, obtained from the Mauna Loa Station in Hawaii, were utilized for this analysis. These measurements indicate that the average annual temperature increase is approximately 0.009 °C, while the average annual increase in CO_2 concentration in the atmosphere during this period is approximately 1.6 ppm. The fossil fuels extracted globally during the average year is approximately $m_p = 7 \cdot 10^{12}$ kg · year^{-1} when computed as carbon and were burned, with negligible amounts being processed into other chemicals. Consequently, the resulting CO_2 is expected to be in the gas phase. The average heat of combustion for the fuel is $H_p = 30{,}000{,}000$ J · kg^{-1} therefore the amount of heat released to the atmosphere during the year as a result of burning fossil fuels is equal:

$$q = m_p\, H_\mathrm{p} = 7 \cdot 10^{12} \cdot 3 \cdot 10^{7} = 2.1 \cdot 10^{20}\ \mathrm{J} \cdot \mathrm{year}^{-1} \qquad (5)$$

Assuming that the carbon heat flux solely results in an increase in air temperature, after simple calculation it is obtained $\Delta t = 0.04$ °C. Similar calculation for CO_2 give increase of concentration 3.2 ppm.

The observed magnitude of these values is significantly different from the expected ones. This implies that only a portion of the energy and CO_2 produced through the combustion of fossil fuels is retained in the atmosphere. Approximately 80 % of this energy and half of CO_2 are instead transferred to the hydrosphere. Calculations indicate that the resulting increase in water temperature should be exceedingly minimal. However, experimental observations [30] contradict this, revealing substantial heat accumulation in the oceans and seas. Furthermore, the data suggests that this heat accumulation surpasses the amount generated by the combustion of fossil fuels by a significant margin. This contradiction can be explained by the mechanism of mass and heat exchange between the atmosphere and hydrosphere, as well as the turbulence phenomena that occur in both phases. Air turbulence is very high, causing air pollutants and local energy changes to spread rapidly throughout the air mass. On the other hand, water turbulence is only high in the layers located at the gas-liquid surface. In the remaining volume of the hydrosphere, water turbulence is very small. As a result of the convection of mass (CO_2) and heat, water layers near the interface easily absorb mass (CO_2) and heat, but the process of transferring mass and heat deep into the oceans is slow. This explains the significant increase in the temperature of the subsurface layers of the oceans. The rise in temperature of the surface layers of water leads to a decrease in the CO_2 absorption rate, an increase in the CO_2 concentration in the atmosphere, and a simultaneous increase in the partial pressure of water vapour in the air. Consequently, this mechanism intensifies the greenhouse effect.

Another two comparison should be mention. First, because the solar constant G_{sc} changes by 0.2 percent, it means that the changes of Sun heat flux is equal:

$$\Delta q = (I) \cdot 0.002 = 3.8 \cdot 10^{24} \cdot 0.002 = 7.6 \cdot 10^{21}\ \mathrm{J} \cdot \mathrm{year}^{-1} \qquad (6)$$

It means, that the changes of Sun heat flux Δq are more than one order higher then heat flux release from burning of fossil fuels q.

The second comparison deals the heat flux release from burning the fossil fuels and possible theoretical heat flux transfer between atmosphere and hydrosphere. The last flux is described by equation:

$$q_G = \alpha_G F_w \Delta t \tag{7}$$

where α_G is heat transfer coefficient in the gas phase (atmosphere) $[\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}]$.

The average value of α_G, because of great turbulence of atmosphere should be bigger than $5\ \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$. So assuming this value we obtain:

$$q_G = 5 \cdot 3{,}6 \cdot 10^{14} \cdot 0.04 = 7.2 \cdot 10^{13}\ \mathrm{J} \cdot \mathrm{s}^{-1} = 2.1 \cdot 10^{21}\ \mathrm{J} \cdot \mathrm{year}^{-1} \tag{8}$$

Comparison this value with q it shows, than heat release from burning fossil fuel is much lower than possible heat transfer flux. This indirectly shows that mechanism described above is correct.

Theoretical case

In the following analysis, a purely hypothetical scenario will be examined, wherein all the energy currently generated on Earth is derived from nuclear fuels instead of fossil fuels. Under this circumstance, the quantity of heat emitted into the atmosphere would remain unchanged. Consequently, the temperature of the atmosphere would rise, leading to a thermal imbalance. As a result, a portion of this excess heat would be transfer to hydrosphere, causing an increase its temperature. This rise in temperature would subsequently trigger the evaporation of a specific mass of water, thereby elevating the concentration of water vapour in the atmosphere. Simultaneously, as the water temperature increased, the process absorption of natural CO_2 would diminish, resulting in an increase in its concentration in the atmosphere. Consequently, the overall increase in the Earth's temperature and greenhouse effect would be comparable to, albeit slightly lower than, the current observed levels. Furthermore, the entire mechanism governing changes in temperature and concentration would closely resemble the patterns currently observed.

Conclusion

The necessity to identify the primary factors responsible for the rise in the Earth's temperature over the years prompts an examination of historical and present conditions on our planet. By applying the fundamental principles of chemical engineering, we can derive the following conclusions:

1. Based on historical data, it is evident that the rise in Earth's temperature was a result of factors beyond human control. The primary contributor is the surge in solar radiation, which leads to melting of glaciers, changes of albedo and significant fluctuations in the levels of non-condensable greenhouse gases and water vapour in the atmosphere.
2. Water vapour is the primary component of the greenhouse effect, with a concentration in the atmosphere that is two orders of magnitude higher than that of CO_2 and several orders of magnitude higher than that of other greenhouse gases.
3. As the Earth's temperature rises, the concentrations of non-condensable greenhouse gas components increase. Additionally, the water vapour pressure also increases. As the temperature continues to rise, the increment of water vapour concentration in the atmosphere increases at a faster rate compared to the increment of other greenhouse gases concentration.

4. From the mid-twentieth century onwards, there has been a significant surge in the extraction of fossil fuels and radioactive raw materials by humanity. The utilization of these resources for energy production has led to the emission of additional heat and CO_2 into the Earth system. However, it is important to note that the heat flux generated from human activities is minuscule when compared to the energy flux received by the Earth from the Sun.
5. The temperature changes on the globe are attributed to the variable heat fluxes originating from the Sun and the thermal energy produced on Earth. These heat fluxes result in temperature increases, which subsequently lead to higher concentrations of water vapour and other greenhouse gases. Consequently, these components contribute to the elevation of the Earth's temperature. The diagram in Figure 4 illustrates the simplified sequence of these processes. To mitigate the impact of rising temperatures on our planet, it is imperative that we should minimize heat sources. While we have no control over solar heat flux, we can take action to reduce our **non-sun heat footprint**. In accordance with Pascal's wager, this means not only ceasing the burning of fossil fuels, but also discontinuing the use of nuclear power plants.

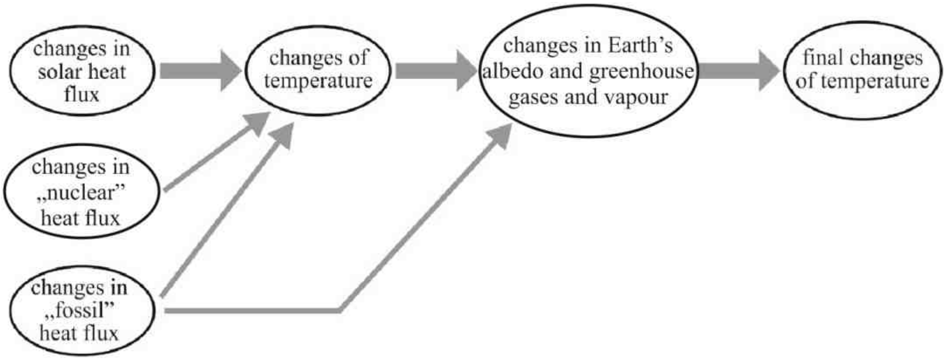

Fig. 4. Sequence of the heat and mass processes in the system

6. The thermal state of Earth can be accurately indicated solely by temperature, without considering carbon dioxide levels.

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