Article

Impact of anthropogenic heat emissions on global atmospheric temperature

Dimitre Karamanev

Department of Chemical and Biochemical Engineering, University of Western Ontario, London, Ontario, Canada N6A 5B9; dkaraman@uwo.ca

Abstract: The use of different primary energy sources in human society has led to two major polluting emissions in the environment: energy (mostly heat), and chemical substances (mostly carbon dioxide). In this paper, the total global anthropogenic emissions of heat to the atmosphere during the industrial era (years 1850-2018) were determined and their effect on the change of global atmospheric temperature was calculated. The concept of a theoretical three-phase Earth reactor was introduced to estimate global atmospheric temperature increase caused by anthropogenic heat emissions. The resulting calculations closely approximated the actual atmospheric temperature change recorded during the last 170-year period. These results suggest that the temperature change of the atmosphere (global warming) is entirely due to anthropogenic heat emissions.

Keywords: Anthropogenic heat emissions; global energy use; atmospheric temperature; carbon dioxide emissions

1. Introduction

Traditionally, there have been two known types of living organisms defined by the primary form of life energy they consume – phototrophs and chemotrophs, which use the energy of light and chemical energy, respectively [1]. In addition, a third type of organism was recently discovered. It was named an electrotroph due to its ability to consume electrical energy [2]. In all three groups of organisms, the various types of energy needed to sustain life (i.e. mechanical, thermal, electrical, chemical) are produced via conversion of the three primary forms of life energy, which takes place *inside* the living organisms (in vivo). The main exception are humans, who in addition to the in vivo energy conversions, make use of energy conversions *outside* of their bodies (ex vivo) by producing forms of energy not directly needed for life. Historically, the first and still the most important ex vivo energy conversions practiced by humans is the conversion of chemical to heat energy (fuel oxidation), or the command of fire. Millennia later, people began exploring the oxidation of alternative fuels, specifically fossil-based ones. The process of chemical fuel oxidation involves two significant types of emissions to the environment: *mass* (primarily carbon dioxide and water vapor) and *energy* (mostly thermal, plus some electromagnetic in the visible and infrared spectrum).

With the continuing industrialization of society dramatic increases in both carbon dioxide and heat emissions have been taking place on a global scale. Since the beginning of the 20th century, the CO_2 concentration in the atmosphere has reached such high levels that it has been purported to be the primary cause of the dramatic increase of atmospheric temperature observed, commonly referred to as "global warming". To prove experimentally the effect of CO_2 as a greenhouse gas on atmospheric temperature, one should be able to determine the difference between the incoming and outgoing radiation energy (radiative flux imbalance, RFI) at the top of the atmosphere [3]. The energy balance on Earth shows that when RFI=0, the long-term average global surface temperature does not change significantly. However, when RFI is non-zero, the Earth temperature changes. For example, if the incoming radiative flux is higher than the outgoing one, the temperature on Earth will increase due to the resulting energy accumulation. In order for the RFI to produce the currently observed global warming, the energy imbalance at the top of the atmosphere would need to be so small, that it would fall below the margin of error of individual flux measurements [4]. Therefore, in order to assess the impact of CO_2 emissions on atmospheric temperature increase, mathematical models have been widely used. Unfortunately, the processes in the atmosphere are extremely complex and their modeling requires the use of many variables and constants that are either assumed or fitted. As a result, the Intergovernmental Panel for Climate Change concluded in its latest report [5] that the probability of global warming being caused by increasing atmospheric CO_2 emissions is 95%. While this number seems high, it is still far from 100%. There have been many projected events of different nature with a higher expected probability that never actually occurred.

As mentioned above, there are two main anthropogenic emissions to the environment: mass and energy, which are primarily comprised of carbon dioxide and heat, respectively. While the global effect of CO_2 on the environment has been studied extensively, anthropogenic heat accumulation has only been studied mostly on a local scale and is referred to as "urban heat islands" [6]. The global effect of direct anthropogenic heat release into the atmosphere has not been studied yet, since the amount of anthropogenic heat flux is assumed to comprise only 1% of greenhouse gas forcing [7].

This work analyzes heat release into the atmosphere by human society. The estimated atmospheric temperature increase brought on by this phenomenon is compared to the recorded global atmospheric temperature increase.

2. Analysis of anthropogenic heat emissions

In order to estimate the amount of anthropogenic heat energy introduced into the atmosphere, the following analysis and calculations were performed.

Anthropogenic sensible heat is transferred primarily to water, land mass and atmosphere. Heat transfer to ice and vegetation is considered insignificant for the purposes of this analysis. In this work only anthropogenic heat, transferred directly to the atmosphere will be dealt with. The main reason for that is the substantial difference between the volumetric heat capacity of air, as opposed to these of land mass and water. The volumetric heat capacity of air at sea level (0.0012 J/m^{3}K) is three orders of magnitude lower than those of fresh and ocean water (3.0 - 4.18 J/m^{3}K) or soil (0.3-3.1 J/m^{3}K) [8]. Therefore, when a certain amount of heat is transferred to either water or soil, it will result in a temperature increase that is thousands of times lower than in the case where the same amount of heat is transferred to air having the same volume (please see Eq. 2 below). Even taking into account that the atmospheric heat is assumed to be much better distributed in the entire atmosphere due to various convection processes, there is still a significant temperature difference between the atmosphere from one side and the land and water from the other. Furthermore, the small increase in water temperature would not significantly impact evaporation. Hence, only anthropogenic heat introduced directly into the atmosphere will be considered here. The calculations below are based on sensible heat transfer only, without taking into account long-wave radiation effects.

Precision of the measurements. There is very little information in the available literature on the anthropogenic heat emission to the atmosphere. The available data on the overall heat losses from different energy conversion technologies is not related directly to the heat loss to the atmosphere. For example, as shown below, the direct heat losses of internal combustion engine automobiles are approximately 71%, while the emissions of heat to the atmosphere, when including indirect heat emissions, are 93% of the fuel energy. That is because of the transformation of significant amount of the "useful" mechanical energy (29%) to atmospheric heat as a result of different friction processes. While it was possible to estimate quite precisely the heat emissions to the atmosphere for some types of energy conversions, in other cases they were wild guesses. The precisions of the individual heat emission estimates to the atmosphere are shown in Table 1. The total errors are shown as error bars in Fig. 3. It should be noted that the atmospheric heat releases by emitters, determined with lower error (below 10%, such as the automobiles, jet engines and heat engines for electrical power generation), account for more than half of the total emissions. However, the fraction of the high-error emitters (above 30%, such as the industrial use of oil and in the railway transport), account for only 1/5 of the total. Therefore, the overall determination of the atmospheric heat releases is relatively precise.

The amounts of anthropogenic sensible heat energy introduced into the environment, and specifically into the atmosphere, as a result of conversion of primary to final forms of energy are shown in Table 1.

Table 1. The global primary energy use [12] and anthropogenic heat emissions in 2018.

Type of primary energy	Primary energy amount (Gtoe)	Primary energy users	Energy used	Sensible heat release %	Sensible heat release (Gtoe)	Average release %	Estimated error of % release
Oil	4.05	Automobiles	1.280	93	1.20	67%	10
		Trucks	0.743	83	0.62		10
		Rail	0.041	97	0.06		40
		Aviation	0.336	100	0.336		5
		Navigation	0.275	25.5	0.070		20
		Industry, non-energy	0.648	7	0.045		50
		Industry, energy	0.292	7.4	0.022		20
		Commercial, residential	0.441	80	0.353		20
Coal	3.84	Electricity generation	2.460	7.4	0.182	14%	5
		Industry	0.798	20	0.160		30
Natural gas	3.26	Electricity generation	1.30	7.4	0.096	22%	5
		Industry	0.60	11	0.066		40
		Commercial, residential	0.70	80	0.56		20
		Non-energy	0.19	0	0		+10
Biofuels and waste	1.33	Commercial, residential	0.72	80	0.576	47%	20
		Electricity generation	0.20	7.4	0.015		5
		Industry	0.20	20	0.04		50
Nuclear	0.71	Electricity generation	0.71	22	0.156	22%	5
Hydro	0.36	Electricity generation	0.36	0	0	0	0
Electricity*	1.73	Final types of energy	1.73	40	0.69	40%	50
	1.88	Transmission losses	1.88	8	0.15	8%	5
Total**	13.55		13.10		5.39	40%	

*Not a primary energy source.

**The total energy used is less than the total primary energy input because some minor inputs, emitting insignificant amount of heat, are not listed in the table.

Electric power plants. Thermoelectric power plants, particularly nuclear, coal and natural gas ones, are among the greatest emitters of heat to the environment. All of these power plants use heat engines (turbines) to convert thermal energy into mechanical energy. Since the efficiency of conversion of heat to mechanical energy in turbines is between 30 and 50%, at an average of 33% [9], an enormous amount of waste heat is released to the environment, equal to 67% of the entire energy content of fuel. Almost all of this heat is released during the process of condensation of steam leaving the turbine. Three main technologies are used to transfer waste heat from thermal power plants to the environment: indirect (recirculating), dry cooling, and direct (once through) [10].

Indirect heat release is a result of evaporative water cooling in cooling towers. The heat released during this process is converted to latent heat of water vaporization. The vapor produced, after rising upwards in the atmosphere and subsequently precipitating, converts latent heat to the equivalent amount of sensible heat, which is transferred to the air. Therefore, the amount of heat emitted by thermal power plants' indirect cooling process will be considered here as part of the overall atmospheric heat input.

Dry cooling technology is based on the process of heat transfer from a power plant to the atmosphere through the use of heat exchangers similar to radiators in automobiles. Therefore, it will also be considered here as an atmospheric heat input.

In the case of direct heat removal, waste heat from the power plant is transferred to fresh or ocean water. Since this heat is not transferred to the atmosphere, it will not be considered here.

It has been estimated that direct heat removal is used in the generation of 89% of electricity by thermoelectric power plants worldwide [11]. Therefore, 11% of the total heat loss of coal, natural gas and biofuel-based thermoelectric power plants worldwide is released into the atmosphere by indirect and dry cooling, and the rest (89%) is transferred to water bodies. In the case of fossil fuel power plants, global energy statistics designate the chemical energy provided by these fuels as "fuel energy supply" (Fig. 1). At an average efficiency of 33%, the heat energy transferred to the environment is equal to 67% of the total fuel energy supply. Therefore, the emissions of thermal energy to the atmosphere by fossil fuel and biofuel power plants is equal to 0.67*0.11= 0.074, or 7.4% of the energy content of fuels used for electric power generation.

However, in the case of nuclear power plants, the amount of "global nuclear energy supply" is usually reported as the amount of electrical energy generated by the plants, and does not include any waste heat [12]. Since nuclear power plants have approximately 33% efficiency, the amount of waste heat is double the amount of electrical energy generated. Eleven percent of the waste heat is released into the atmosphere globally. Therefore, the total amount of heat released into the atmosphere by nuclear power plants is equal to 2*0.11=0.22, or 22% of the "world nuclear energy supply" [12] (Fig. 1).

Atmospheric heat release by hydroelectric power plants is negligible, and is assumed to be zero.

2.1. Oil

Transport. Another major source of anthropogenic heat input to the atmosphere is the transportation sector. There are two main types of engines used: internal combustion and airplane jets.

Road and rail transportation. The average energy efficiency of internal combustion engines is estimated to be 28% [13]. The remaining chemical energy of the fuel is transferred directly to the atmosphere by means of exhaust gases and heat exchange between the metal parts of the engine (such as the radiator) and the surrounding air. Part of the mechanical energy generated by the engine (28% of the chemical energy of fuel) is used to overcome air friction, as well as mechanical drag forces in the drive train and in the brakes. The entirety of this energy is further transferred as sensible heat to the atmosphere. The only types of energy that are not transferred to the atmosphere as sensible heat are radiation heat (considered insignificant here) and the rolling resistance of the wheels. There are some notable differences between automobiles (including light trucks and vans) and large transport trucks:

In automobiles, rolling resistance is 7% [13]. Therefore, automobiles transfer 93% of the chemical energy of their fuel to the atmosphere as sensible heat. Automobiles account for 62 percent of global surface transportation energy consumption [14].

In large transport trucks, the rolling resistance is 17% [13]. Therefore, transport trucks transfer 83% of the chemical energy of their fuel to the atmosphere. Trucks account for 36 percent of global transportation energy consumption [14].

Rail transportation. Approximately 2% of global surface transport is comprised of railways [12]. It is assumed that rail transport converts 97% of the chemical energy of its fuel to the atmosphere as sensible heat.

Sea navigation. There are two major types of sea vessels: transport and cruise ships. Both of them primarily use internal combustion engines. Since cruise ships account for only a small amount of the entire fleet, we will bundle them together with transportation ships. Ship engine cooling is achieved by circulating ambient water [15], and therefore is not transferred to the atmosphere. In addition, practically all the mechanical power of the propeller is also transferred to water (Landeka and Radica, 2016). Therefore, the energy transferred to the atmosphere is released mainly by the stack, which accounts for 15% of the fuel energy [15].

Turbine jet engines. The energy of fuel (kerosene) used in aircraft jet engines is converted directly to heat (heat loss) at a rate of approx. 75% [16]. The rest of the fuel energy is converted to mechanical energy, which is ultimately also converted to heat mostly due to friction processes and ends up in the atmosphere. Therefore, the heat energy released into the atmosphere by a turbojet engine is approximately 100% of the chemical energy of fuel.

Non-energy industrial use of oil. In this application petroleum is used primarily as feedstock in chemical and other industries, as well as for road paving. It is assumed that there are no significant heat emissions due to the associated chemical transformations.

Industrial use. Heat emissions to the atmosphere resulting from industrial oil use are assumed to be similar to those from power plants, i.e. 7.4%.

Commercial and residential use. Use of oil products in this context is mostly for space heating. It has been shown that the average heat release from buildings into the atmosphere is 50% [17].

2.2. Coal

Electricity generation. Globally, most of the coal is used in thermoelectric power plants. As mentioned above, the heat release into the atmosphere is 7.4% of the chemical energy of coal.

Industrial use. The second most significant use of coal is in industry, where it is chiefly employed for the production of iron and cement. The reported thermal balance of coal-based iron production facilities indicates that the heat emission to the atmosphere is approximately 20% [18]. There are different technologies for cement production, and it is estimated that the heat release to the atmosphere is 30% [19,20]. The overall heat emissions of industrial processes to the atmosphere was taken as 25%.

2.3. Natural gas

Electricity generation. As mentioned above, natural gas power plants emit 7.4% of the chemical energy of their fuel to the atmosphere as a heat loss.

Industrial use. It is assumed that the most ubiquitous use of natural gas in industry is for the electricity generation, where the heat release to the atmosphere is 7.4%.

Commercial and residential use. In this application natural gas is used primarily for space heating. As in the case of space heating by oil, the heat release to the atmosphere is approximately 50%.

Most of the natural gas used in industry for **non-energy** purposes functions as chemical feedstock. Therefore, it is assumed that the resulting atmospheric heat emissions are negligible at 0%.

2.4. Biofuels and waste

Commercial and domestic use of biofuels is mostly for space heating, at 50% atmospheric heat emissions.

Electricity generation involving biofuels and organic waste is performed using thermoelectric power plants, where heat emissions to the atmosphere are 7.4%, as mentioned above.

The use of biofuels and organic waste in **industry** is assumed to release 20% of heat to the atmosphere.

2.5. Nuclear energy

Nuclear energy is used exclusively in thermoelectric power plants. As mentioned above, in this case the heat release represents 22% of the world's nuclear energy supply.

2.6. Hydro power

Electricity generation by hydroelectric power plants is not associated with any significant heat release to the atmosphere, and is assumed here to be zero.

2.7. Electricity

Among all the types of energy shown in Table 1, electricity is the only form of energy that is not a primary energy source. However, after being produced, there are two main types of thermal losses associated with electricity: first as a result of ohmic resistance during electricity transmission and second, due to the transformation of electricity to the final forms of energy on the consumer end.

The heat released during the conversion of electricity to the **final useful type of energy** such as mechanical (in motors), thermal (space heating), electromagnetic (lighting) and so on is estimated next. 48.4% of electricity generated worldwide is used for commercial and residential purposes, where it was assumed that 50% of it is released to the atmosphere [17]. The rest (51.6%) is used in industries and other applications. It is roughly estimated that 30% of that energy is released to the atmosphere. Therefore, the total atmospheric heat input from the final use of electricity is estimated at 40%.

Thermal losses associated with electrical power **transmission** comprise 8% of global electrical energy generation [21]. These losses are sustained in the form of sensible heat transferred directly to the atmosphere.

2.8. Heat generated by living organisms

The total amount of life forms on Earth is estimated to be approximately 550 gigatons in terms of carbon [22]. Of these, only chemotrophs living on the surface of Earth (such as humans) or in the air [22] are considered here as significant sources of heat emission to the atmosphere. It has been estimated that the global amount of chemotrophs has increased by less than 1% in the last 120 years [23], and therefore, the change in their heat release to the atmosphere during that period is considered negligible.

3. Total anthropogenic heat release into the atmosphere

The anthropogenic heat release into the atmosphere was determined by multiplying each specific energy input by the fraction of that energy going to the atmosphere as heat (Table 1). In summary, the total amount of energy used globally in 2018 was 13.55 gigatons of oil equivalent (Gtoe), and out of that 2.33 Gtoe was released to the atmosphere as sensible heat.

Table 1 also shows each primary energy source's contribution to total atmospheric heat release during year 2018. It is assumed that this contribution did not change significantly over time since 1920s. It was used to calculate atmospheric heat emissions by each type of primary energy source during the period 1920-2018. Before 1920, the main primary energy sources were biofuels and coal, the latter mainly used in steam engines (stationary and railways), steel production and space heating. Because of the absence of statistical data, it was assumed that a total of 80% of the primary energy used at that time period was transferred to the atmosphere as heat.

The amounts of different types of primary energy used globally by humans between the years 1850 and 2018 are shown in Fig. 1. The underlying data was obtained from Smil [9] for primary energy sources prior to 1960; Smil [24] for electricity generation prior to 1960 and IEA [12] for both primary energy sources and electricity for the period 1970-2018. Since the energy use from traditional biofuels globally was fairly constant between the years 1800 and 1920, that amount (an average of 24 EJ per year) was subtracted from the total for all the years between 1850 and 2018.

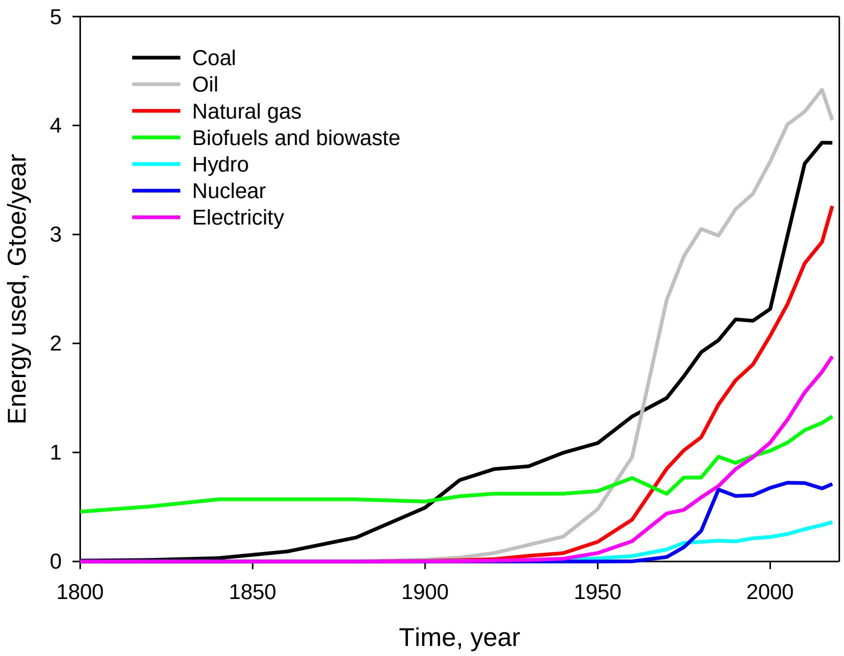

Figure 1. Annual global use of different primary energy sources.

4. The Earth reactor

Among the most important topics in chemical engineering is the one involving multiphase chemical (and biochemical) reactors. Three-phase reactors in particular, contain gas, liquid and solid phases. Transport processes, such as heat and mass transfer, are among their most important features [25]. In general, the processes of sensible heat energy transfer and mass transfer in multiphase reactor systems are governed by similar mathematical models [26]. This similarity is known as "the heat and mass transfer analogy".

Let us consider the Earth's atmosphere and the surface of the Earth as a three-phase chemical reactor, where the atmosphere is the gas phase, the oceans are the liquid phase and land is the solid phase (Fig. 2). The "wall" of the Earth reactor is spherical, and is located at the top of the atmosphere. The wall is permeable to electromagnetic waves of any wavelength and any direction, but does not allow flow of mass or sensible heat in or out. As an initial approximation, we can treat the transfer of energy (sensible heat) and the transfer of mass (CO_2) in the three-phase, gas-liquid-solid, Earth reactor as two similar processes using the heat and mass transfer analogy. After all, the releases of CO_2 and heat are simultaneous (in the case of burning of fossil fuels) due to their stoichiometric relationship. Mass and energy transfers between the atmosphere and the adjacent ocean and land surfaces by both convection and diffusion are also roughly similar, as are the processes of mass and energy transport within the atmosphere.

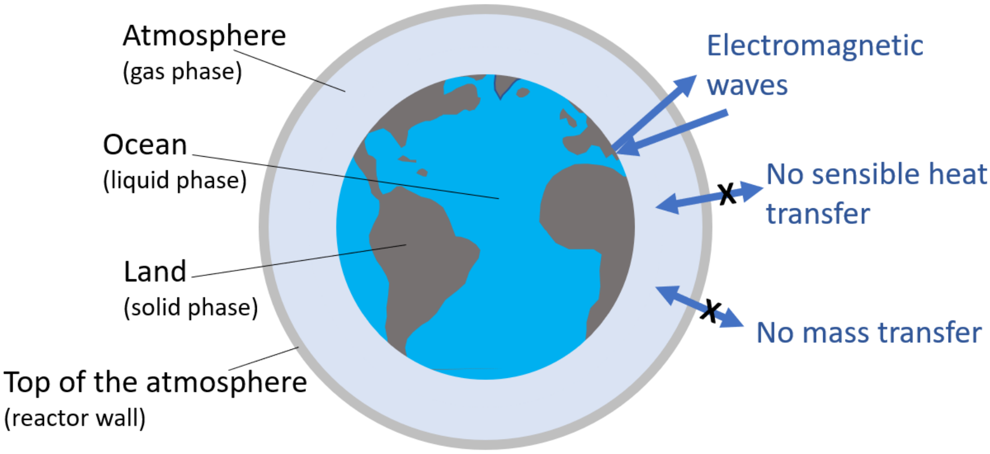

Figure 2. The Earth reactor.

5. Calculation of temperature rise of the atmosphere

Analysis of carbon dioxide emissions in the period 1750-2011 has revealed that a total of $2.0 \cdot 10^{14}$ kg of CO_2 was released into the atmosphere as a result of human activity [5]. Of that amount, $0.88 \cdot 10^{14}$ kg, or 43%, remained in the atmosphere at the end of that time period (resulting in an increase of the atmospheric carbon dioxide concentration), while the rest was re-adsorbed by ocean and land ecosystems. On the basis of the heat and mass transfer analogy explained above, one can assume that approximately 43% of the heat released as a byproduct of human activities globally since 1850 has remained in the gas phase (atmosphere), while the rest has dissipated to the liquid (oceans) and solid (land) phases. The amount of anthropogenic heat energy remaining in the atmosphere after re-absorption by oceans and land (43% of the total) is shown in Table 1.

The total amount of heat introduced by humans into the atmosphere between the years 1850 and t was calculated as:

$$\hat{H}(t) = \int_{t=1850}^{t} H(t)dt \tag{1}$$

where H(t) is the annual heat input to the atmosphere at year t. The integration was performed using the rectangle rule.

The equation for determining the temperature change ΔT of a substance due to the exchange of heat energy H with the surroundings is as follows:

$$\Delta \mathrm{T} = \frac{\mathrm{H}}{\mathrm{mC}} \tag{2}$$

where C is the heat capacity of a substance having a mass m. As a first approximation, it was assumed that anthropogenic heat input is equally distributed throughout the entire Earth's atmosphere. Since CO_2 is well mixed within the atmosphere [5], using the heat and mass transfer analogy, it can be assumed that the sensible heat released by human activity, is also well mixed. The total mass

of the atmosphere is $m=5 \cdot 10^{18}$ kg [27]. The heat capacity of air at atmospheric pressure is $C=1000$ J/kgK and does not change significantly with decreases in pressure (i.e. with the altitude) [28]. The temperature increase $\Delta T(t)$ between the year 1850 and the year t was calculated by substituting $H=\hat{H}(t)$ in Eq. 2. The initial temperature rise ΔT at year 1850 was set to 0, which allowed for the calculation of the atmospheric temperature rise $\Delta T(t)$ between the years 1850 and 2018.

The calculated atmospheric temperature increase since 1850 is shown in Fig. 3. Fig. 3 also shows the observed average land-mass global temperature change measured since 1800 [29]. A very close match can be seen between the actual recorded temperatures and the ones calculated on the basis of anthropogenic heat emissions to the atmosphere.

These results suggest that the atmospheric temperature increase during the industrial era is entirely due to the heat introduced into the atmosphere by human activity and seems not to be affected by carbon dioxide emissions.

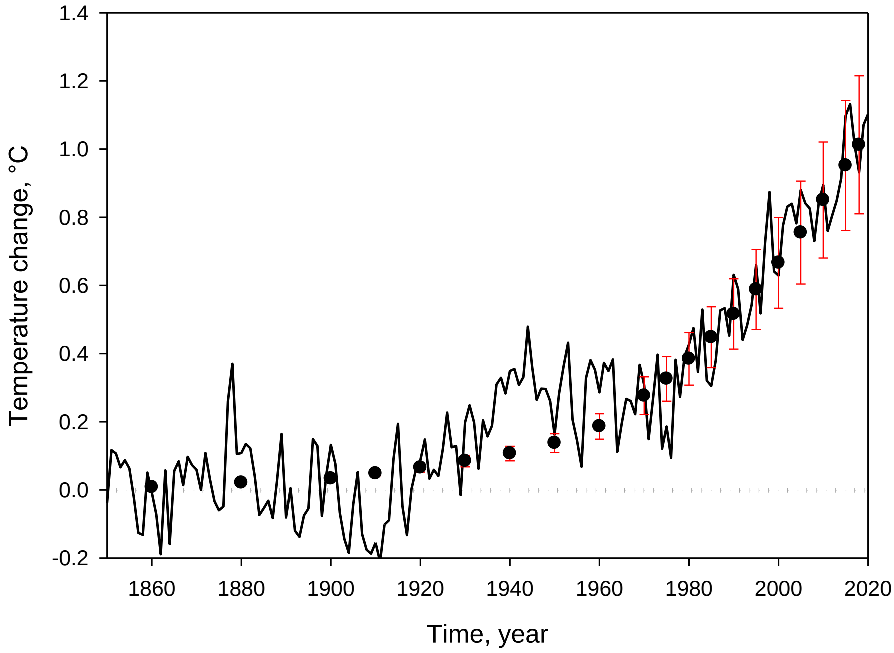

Figure 3. The atmospheric temperature change since 1850. Line: measured data; black points: data calculated using Table 1 and Eq. 2.

6. Historical relationship between mass (CO_2) and energy (heat) emissions

As mentioned above, there is expected to be a close relationship between anthropogenic carbon dioxide and heat emissions to the atmosphere. As the proportion of fossil energy in the entire global energy mix has been higher than 70% since the 1950s, it is expected that amount of anthropogenic carbon dioxide emissions would correlate with the amount of heat emitted to the atmosphere. Figure 4 shows this relationship. It can be seen that carbon dioxide emissions are almost proportional to atmospheric heat input. The difference in the slopes between and after 1970 is probably due to the change in the ratio between different primary energy sources. Therefore, the expectation is that any future reduction in atmospheric heat emissions will be closely correlated with a reduction in the carbon dioxide emissions. For example, the transition from fossil fuel based to renewable power generation will have similar positive effect on both atmospheric heat emissions and the CO_2 emissions. However, there are some exceptions. In recent years, thermoelectric power generation authorities (which employ nuclear, fossil and bio- fuels) are quite interested in moving from water cooling to air cooling, in order to reduce the load on water resources [11]. Unfortunately, this move would significantly increase heat emissions to the atmosphere and therefore would inevitably result in an atmospheric temperature increase. In addition, according to the above findings, since nuclear and biofuel power plants emit a similar amount of heat to the atmosphere as fossil fuel plants do, these three types of power plants present a similar global warming potential. The concepts of carbon capture and storage may not be practical if the atmosphere continues to be heated by anthropogenic heat emissions.

7. Conclusions

The atmospheric temperature rise due to anthropogenic heat emissions to the atmosphere was calculated for the period 1850-2018. The calculations were based on a heat and mass transfer analogy using the concept of an Earth reactor. It was shown that the temperature increase of the atmosphere due to anthropogenic heat emissions is very close to the global land-sea temperature rise measured experimentally (global warming). Therefore, on the basis of the above calculations, in order to manage global warming, a strong emphasis must be placed on reducing heat emissions to the atmosphere. In most cases, a heat emission reduction is closely associated with a reduction in CO_2 emissions.

References

1. Starr, C. Biology: the unity and diversity of life; 2001;
2. Karamanev, D. Production of Microbial Biomass using Electrical Current. *Provisional US Pat.* **2003**.
3. von Schuckmann, K.; Palmer, M.D.; Trenberth, K.E.; Cazenave, A.; Chambers, D.; Champollion, N.; Hansen, J.; Josey, S.A.; Loeb, N.; Mathieu, P.; et al. An imperative to monitor Earth's energy imbalance. *Nat. Clim. Chang.* **2016**, *6*, doi:10.1038/NCLIMATE2876.
4. Stephens, G.L.; Li, J.; Wild, M.; Clayson, C.A.; Loeb, N.; Kato, S.; L'Ecuyer, T.; Stackhouse, P.W.; Lebsock, M.; Andrews, T. An update on Earth's energy balance in light of the latest global observations. *Nat. Geosci.* **2012**, *5*, 691–696, doi:10.1038/ngeo1580.
5. Stocker, T.F.; Qin, D.; Plattner, G.K.; Tignor, M.M.B.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P.M. Climate change 2013 the physical science basis: Working Group I contribution to the fifth assessment report of the intergovernmental panel on climate change; Cambridge University Press, 2013; Vol. 9781107057999; ISBN 9781107415324.
6. Dong, Y.; Varquez, A.C.G.; Kanda, M. Global anthropogenic heat flux database with high spatial resolution. **2016**, doi:10.1016/j.atmosenv.2016.11.040.
7. Flanner, M.G. Integrating anthropogenic heat flux with global climate models. *Geophys. Res. Lett* **2009**, *36*, 2801, doi:10.1029/2008GL036465.
8. Oke, T.R. *Boundary Layer Climates*; Routledge, 2002;
9. Smil, V. Energy Transitions. In *Power Density*; The MIT Press, 2019.
10. Meldrum, J.; Nettles-Anderson, S.; Heath, G.; Macknick, J. Life cycle water use for electricity generation: A review and harmonization of literature estimates. *Environ. Res. Lett.* **2013**, *8*, 015031, doi:10.1088/1748-9326/8/1/015031.
11. Lohrmann, A.; Farfan, J.; Caldera, U.; Lohrmann, C.; Breyer, C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nat. Energy* **2019**, *4*, 1040–1048, doi:10.1038/s41560-019-0501-4.
12. IEA Key World Energy Statistics 2020 2020.
13. National Network for Energy Efficiency, A.G. Energy Efficiency Opportunities 2010.
14. Energy Information Administration, U. International Energy Outlook, Transportation sector energy consumption 2016.
15. Prasad Sinha, R. Ship Energy Efficiency Performance Estimation Using Normal Daily Report Operational Data. **2015**, doi:10.4172/2168-9873.1000167.
16. NAS Commercial aircraft propulsion and energy systems research: Reducing global carbon emissions; National Academies Press, 2016; ISBN 0309440963.
17. Simon, F. Energy and Sustainability in Chile: Simulation Modeling of Low-carbon Technologies and Energy Efficiency in Buildings, 2017.
18. Lu; Wang; Tang; Chen An All-Factors Analysis Approach on Energy Consumption for the Blast Furnace Iron Making Process in Iron and Steel industry. *Processes* **2019**, *7*, 607, doi:10.3390/pr7090607.
19. Kumar Verma, Y.; Mazumdar, B.; Ghosh, P. Thermal energy consumption and its conservation for a cement production unit. *Environ. Eng. Res.* **2020**, *26*, doi:10.4491/eer.2020.111.
20. Khurana, S.; Banerjee, R.; Gaitonde, U. Energy balance and cogeneration for a cement plant. *Appl. Therm. Eng.* **2002**, *22*, 485–494, doi:10.1016/S1359-4311(01)00128-4.
21. Jackson, R. et al. Opportunities for Energy Efficiency Improvements in the U.S. Electricity Transmission and Distribution System; Oak Ridge National Laboratory, 2015;
22. Barnosky, A.D. Megafauna biomass tradeoff as a driver of Quaternary and future extinctions; 2008;

23. Bar-On, Y.M.; Phillips, R.; Milo, R. The biomass distribution on Earth. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115*, 6506–6511, doi:10.1073/pnas.1711842115.
24. Smil, V. *Energy and Civilization*; MIT Press, 2017;
25. Coulson, J.M. *Chemical engineering*; 1996;
26. Geankoplis, C.J. Transport processes and unit operations; 1993;
27. Gill, A.E. Atmosphere-Ocean Dynamics; 1982;
28. Green, D.W. *Perry's Chemical Engineers' Handbook*; McGraw-Hill Education, 2008; ISBN 9780071422949.
29. NASA's Goddard Institute for space studies GISS Surface Temperature Analysis (GISTEMP). 2020.