



Thermal pollution causes global warming

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Abstract

Over longer time-scales there is no net heat inflow to Earth since incoming solar energy is re-emitted at exactly the same rate. To maintain Earth's thermal equilibrium, however, there must be a net outflow equal to the geothermal heat flow. Performed calculations show that the net heat outflow in 1880 was equal to the geothermal heat flow, which is the only natural net heat source on Earth. Since then, heat dissipation from the global use of nonrenewable energy sources has resulted in additional net heating. In, e.g. Sweden, which is a sparsely populated country, this net heating is about three times greater than the geothermal heat flow. Such thermal pollution contributes to global warming until the global temperature has reached a level where this heat is also emitted to space. Heat dissipation from the global use of fossil fuels and nuclear power is the main source of thermal pollution. Here, it was found that one third of current thermal pollution is emitted to space and that a further global temperature increase of 1.8 °C is required until Earth is again in thermal equilibrium.

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1. Introduction

A global rise in temperatures is undoubtedly real according to the Intergovernmental Panel on Climate Change (IPCC) (Macilwain, 2000). An increasing body of observations gives a collective picture of a warming world and other changes in the climate system (IPCC, 2001). The estimated temperature increase during the past century was between 0.4 and 0.8 °C with the 10 warmest years all occurring within the last 15 years (EPA, 2001).

Even though there is a scientific consensus about an ongoing global warming, there is no consensus

about its cause. Most studies, however, assume that it is a result of the increasing greenhouse gas concentrations into the atmosphere, i.e. the greenhouse effect. The greenhouse explanation is based on the fact that the global mean temperature increase coincides with increasing emissions of carbon dioxide (and other greenhouse gases) into the atmosphere, which has been increasing since 1800, from about 275 to 370 ppm today (CDIAC, 2002). It is presumed that increases in carbon dioxide and other minor greenhouse gases will lead to significant increases in temperature. It is generally believed that most of this increase is due to the increased burning of fossil fuels. This theory is adopted by international environmental politics though there is a growing scientific scepticism about the greenhouse explanation. The main absorbers of infrared in the atmosphere are water vapour and

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clouds. Even if all other greenhouse gases were to disappear, we would still be left with over 98% of the current greenhouse effect. Another reason to scepticism is that existing models cannot be used to forecast climate (Lindzen, 1992). The IPCC's own Third Assessment Report included an entire chapter in its science report assessing the regional climate information from climate models. It concludes that a "coherent picture of regional climate change via available regionalization techniques cannot yet be drawn" (IPCC, 2001).

Another explanation to global warming is that it is a result of natural variations in solar irradiance, see, e.g. Lean and Rind (2001) and Mende and Stellmacher (2000).

Before global warming, Earth's mean temperature was 13.6 °C, at which temperature it was in thermal equilibrium (NOAA–NCDC, 2001). During a global mean day, incoming short-wave radiation (SWR) was heating the ground surface. Later that day, it was cooled off as the same amount of energy was re-emitted to space as outgoing long-wave radiation (OLR). The ground surface was then back at its mean temperature at which the OLR was limited only by the geothermal heat flow rate ($\sim 0.07 \text{ W m}^{-2}$) from the interior of the Earth.

Before global warming, the geothermal heat flow was the only net heat source on Earth. Since then, heat dissipation from the global use of nonrenewable energy has resulted in an additional net heat source.

Genchi et al. (2000) showed that heat dissipation from traffic, air conditioning, and other human activities, during a warm day in Tokyo, adds up to a heat production of 140 W m^{-2} in Tokyo with a resulting air temperature increase of about 3 °C. A similar estimation for Stockholm results in 70 W m^{-2} . The

Swedish energy consumption, mainly based on fossil fuel and nuclear power, corresponds to a national heat generation of 0.16 W m^{-2} though the country is sparsely populated ($20 \text{ person km}^{-2}$).

There are several studies, e.g. Lachenbruch and Marshall (1986) and Beltrami (2001), in which the global temperature change is evaluated from measured temperature profiles in the upper hundred meters of boreholes. These temperature profiles reflect long-term changes in ground surface temperature and can thus be used to analyse the changes in climate. Here, the analysis starts with the mean temperature of the ground surface. At this balance temperature, occurring net heat (geothermal heat and thermal pollution) is emitted to space as OLR. The aim of this study was to analyse to what extent heat dissipation, from the global use of nonrenewable energy, contributes to global warming.

2. Global temperature

This study is based on global monthly temperature data, from 1880 until today (NOAA–NCDC, 2001). These temperatures are separated into land area temperature (LAT), sea surface temperature (SST), and a combined global mean temperature (MEAN). MEAN is calculated by area weights corresponding to the global sea area (71%) and land area (29%). During the year, SST is rather constant while the LAT varies considerably. LAT is about 3–12 °C lower than SST during the year. Fig. 1 indicates the LAT increase since 1880 to be 1.2 °C (to 9.3 °C) while the SST increase is 0.5 °C (to 16.4 °C). The corresponding combined global mean temperature has increased by 0.7 °C (to 14.3 °C). Before that, during the years

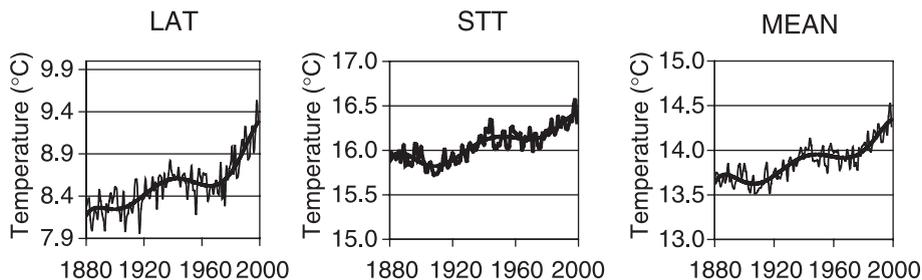


Fig. 1. Land area temperature (LAT), sea surface temperature (SST), and combined global mean temperature (MEAN). (NOAA–NCDC, 2001).

1856–1880, the global mean temperatures were almost constant (Jones et al., 2001).

3. Net heat sources

There are two major net heat sources on Earth: the geothermal heat flow and net heating generated by human activities. Thermodynamics tells us that all energy will eventually dissipate into heat. The increasing utilisation of nonrenewable energy sources, mainly fossil fuels and nuclear power, has thus resulted in additional net heating on Earth. The utilisation of renewable energy, i.e. solar energy in some form, also results in heat dissipation but does not cause any additional heating.

3.1. Geothermal heat flow

Continental geothermal heat flow measurements are made in boreholes usually drilled to a depth of a few hundreds meters. Measurements on the ocean floor are made in the sediments (IHFC, 2001). Pollak and Chapman (1977) made the first comprehensive evaluation which included 5500 measurements of which 70% were oceanic data and resulted in a global average close to 0.060 W m^{-2} . Parasnis (1985) later showed that the very high values occurring along the mid-Oceanic ridges give an oceanic mean heat flow of 0.0798 W m^{-2} . By compensating for oceanic heat flow that originates from sub-sea lava eruptions, the geothermal heat flow is $0.045\text{--}0.065 \text{ W m}^{-2}$ for both continental and oceanic measurements.

The most recent compilation of heat flow data (Pollak et al., 1993) numbers almost 25,000 measurements. On a $5^\circ \times 5^\circ$ longitude–latitude grid, 62% of the Earth's surface was covered by measurements, while the heat flow of the remaining area of the planet was estimated. The resulting heat flows for the continents and the oceans were 0.065 and 0.101 W m^{-2} , respectively, with a global mean value of 0.087 W m^{-2} .

3.2. Thermal pollution

The global annual use of fossil energy including nuclear power (IEA, 1999; BP-AMOCO, 2002) is almost 9000 million metric ton oil equivalent (Mtoe).

All of this energy, which corresponds to $11.63 \text{ TWh Mtoe}^{-1}$, will dissipate into heat. The heat of not fully combusted fuel will also be released, when this organic substance is decomposed. Consequently, the total amount of heat generated by fossil fuels is 10^{14} kWh . By distributing this energy over the total area of the Earth, an additional 0.02 W m^{-2} is heating the planet.

4. Earth's radiative balance

The driving force of the Earth's atmosphere is the absorption of solar energy at its surface. Over long time-scales, compared to those controlling the redistribution of energy, the planet is in thermal equilibrium because the absorption of SWR from the sun is balanced by OLR, from Earth to space, at exactly the same rate. During clear days, the atmosphere is transparent to SWR, which passes through without energy loss. At the same time, this atmosphere is almost opaque to OLR. Thus, the OLR is heating the atmosphere while radiated layer by layer through the atmosphere. At the top of the atmosphere, the OLR, q [W m^{-2}], emitted from Earth to space as given by the Stefan–Boltzmann law:

$$q = \sigma T_e^4 \quad (1)$$

Here, T_e [K] is Earth's effective mean temperature and the Stefan–Boltzmann constant $\sigma = 5.6697 \times 10^{-8} [\text{W m}^{-2} \text{K}^{-4}]$.

Measurements show that the mean OLR from Earth is 237 W m^{-2} (Salby, 1996). Eq. (1) indicates that our planet is then in thermal equilibrium at an effective temperature of 254.2 K. This blackbody temperature of the atmosphere is the effective mean temperature of Earth and its atmosphere. It corresponds to a shell-like layer of temperature, T_e , surrounding the planet at a mean altitude of approximately 6.5 km.

4.1. Net OLR

If Earth was monitored from outer space, the annual mean values would show an effective temperature of 254.2 K, where the incoming SWR is balanced by the OLR, i.e. a zero net heat flow.

Detailed measurements on this long time-scale would, however, show a net outgoing heat flow that originates from geothermal heat and the use of nonrenewable energy sources.

The global mean temperature at ground surface is 33.1 K warmer than the effective Earth temperature, demonstrating the thermally insulating qualities of the atmosphere. This temperature difference drives the global net heat flow from the Earth. Because of the very small mean temperature gradient through the atmosphere, convective heat transfer is not induced. This is also the basis of performed calculations, i.e. by using annual mean temperatures of the ground surface and the atmosphere the resulting radiation is the outgoing net heat radiation. The suggested approach implies that the geothermal heat flow < net OLR < (geothermal heat flow + thermal pollution) until the global equilibrium temperature is reached.

The global mean temperature gradient through the atmosphere is approximately linear between the ground surface of temperature T_s [K] and the Earth's blackbody layer of temperature T_e [K]. Clouds always cover about half of the planet's area, which means that the global mean day is partly cloudy with light rain. During the day, SWR heats the ground surface, which is later cooled off by the same amount of OLR. When all incoming energy has been emitted, the only remaining energy sources are the geothermal heat flow and thermal pollution. This constant heat flow is radiated layer by layer through the atmosphere (Fig. 2). By using the Stefan–Boltzmann law, between the N atmospheric layers the net OLR, Δq (W m^{-2}), becomes:

$$\begin{aligned} \Delta q &= \frac{\sigma}{N} \sum_1^N (T_n^4 - T_{n+1}^4) = \frac{\sigma(T_1^4 - T_{N+1}^4)}{N} \\ &= \frac{\sigma(T_s^4 - T_e^4)}{N} \end{aligned} \quad (2)$$

For net OLR rates $< 0.1 \text{ W m}^{-2}$, Eq. (2) can be simplified as:

$$\Delta q = \frac{\sigma(T_s^4 - T_e^4)}{N} \approx \sigma(T_s - T_e)^4 \quad (3)$$

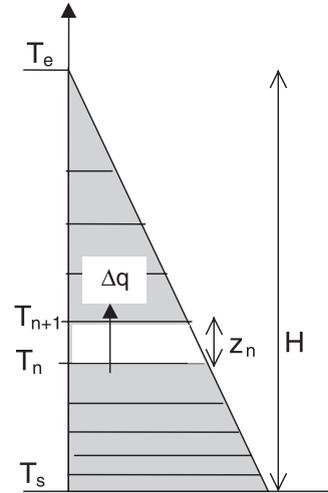


Fig. 2. The net OLR is emitted layer by layer through the atmosphere. T_s = ground surface temperature; T_e = effective temperature of the atmosphere.

The error of this approximation is less than 0.01% for relevant global mean temperatures (see Appendix A). The thickness of the atmospheric layers, which is increasing with the altitude, is correlated to the optical depth of the atmosphere.

The calculated net OLR since 1880, based on global mean monthly temperatures (separated in LAT and SST), is shown in Fig. 3. It is seen that the global temperature rise has resulted in a net OLR increase from 0.068 W m^{-2} in 1880 to 0.074 W m^{-2} in 1999. The insignificant use of fossil fuel at the end of the 19th century denotes that the occurring global net heat outflow at that time (0.068 W m^{-2}) is equivalent to the geothermal heat flow. This heat flow rate agrees with earlier heat flow estimations by Parasnis (1985), but is lower than the most recent estimation by Chapman (1998). A more detailed separation in land and sea areas of different mean monthly temperatures would give a somewhat higher geothermal heat flow value.

Consequently, the net OLR has increased by 0.006 W m^{-2} since 1880. This means that about one third of today's thermal pollution (0.02 W m^{-2}) is emitted from Earth. In the long term, our use of nonrenewable energy will cause a global temperature increase up to

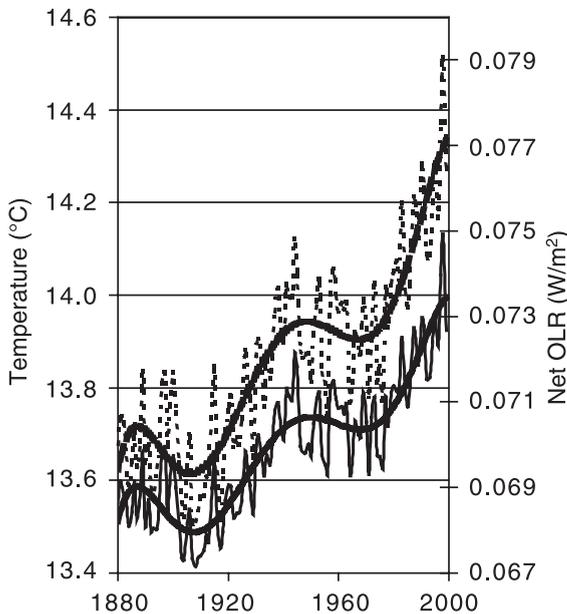


Fig. 3. The global net OLR (solid) increases with the global mean temperature (broken upper curve).

a point where the net OLR balances the net heat generation. Meanwhile, nature has some means of delaying global warming.

5. Nature counteracts global warming

At present, the Earth's temperature is not in thermal equilibrium, i.e. the net OLR is still not as high as generated net heat. Natural cold sinks in water, ground, and atmosphere slow down the effect of thermal pollution. The main sources of natural cold are in water and ice. The total volume of global water is $1.4 \times 10^{18} \text{ m}^3$, of which 94% is seawater while $3 \times 10^{16} \text{ m}^3$ (2%) of the water is ice in the form of glaciers and ice fields (Singh and Singh, 2001).

The water of the oceans reduces the global warming by getting warmer. The melting of permafrost and ice means no temperature increase, but increasing volumes of melt water. Ice fields and glaciers have a large cooling capacity. The melting of 3×10^{16} ton of ice requires about 3×10^{18} kWh of energy. Since the annual total heat dissipation is 10^{14} kWh, the ice

fields and glaciers would last 30,000 years, with present use of nonrenewable energy and no other cold sink.

A continental warming means that the underground is also warming up, which eventually will be seen as a reduced geothermal heat flow as the geothermal gradient decreases (Chapman, 1998).

The atmosphere itself also has a huge heat storage capacity. In this case, part of the thermal energy is stored in the heating of air, i.e. global warming. Subsequent increase in evaporation means that additional energy is stored in the atmosphere.

The effects of the increasing humidity of the atmosphere are complex. It increases its heat storage capacity, i.e. it absorbs more heat without getting warmer. The resistance to OLR will also increase, which indicates an increasing temperature gradient. On the other hand, the increasing humidity of the atmosphere will reflect a greater part of incoming solar radiation. Consequently, less OLR is emitted which must reduce Earth's effective temperature, T_e .

6. Steady-state global warming

The future steady-state global temperature was estimated by assuming that continued warming follows the same pattern as during the last century. This means that the previous LAT/SST increase ratio of 2.4 was assumed constant. Therefore, the land area temperature increase was assumed a factor 2.4 greater than the sea surface temperature increase. Today's consumption of nonrenewable energy was also assumed unchanged.

In a steady-state situation, all net heat generated is emitted to space. Therefore, by adding the calculated geothermal mean heat flow (0.068 W m^{-2}) and the total thermal pollution (0.020 W m^{-2}), the total net OLR becomes 0.088 W m^{-2} . Eq. (3) then gives that this net OLR requires a SST of $17.8 \text{ }^\circ\text{C}$ and a LAT of $12.0 \text{ }^\circ\text{C}$, resulting in a future global mean temperature of $16.1 \text{ }^\circ\text{C}$.

Thus, the global thermal pollution will at steady state have increased the sea surface temperature by $1.9 \text{ }^\circ\text{C}$, the land area temperature by $3.9 \text{ }^\circ\text{C}$, and the global mean temperature by $2.5 \text{ }^\circ\text{C}$. Since part of this heating has already begun, further temperature

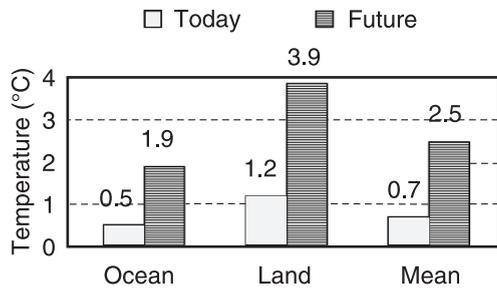


Fig. 4. Calculated global temperature increase (ocean, land, and mean) today and in the future (at thermal equilibrium).

increases of 1.4 °C (Ocean), 2.7 °C (Land), and 1.8 °C (Mean) should be expected (Fig. 4).

7. Discussion and conclusions

Around 1880, before global warming, Earth was in thermal equilibrium at a mean temperature of 13.6 °C. The occurring net OLR was then equal to the geothermal heat flow. Calculations based on the undisturbed global temperatures (monthly mean values of sea and land temperatures) indicate that the geothermal mean heat flow is 0.068 W m^{-2} , which is slightly lower than the most recent estimations. A more detailed calculation, by separating sea and land areas in several areas of different temperatures, would result in a slightly greater geothermal heat flow.

Since 1880, the increasing use of nonrenewable energy has resulted in a thermal pollution, which today corresponds to a global heating of 0.02 W m^{-2} . This heating has so far resulted in a global temperature increase of 0.7 °C. As a consequence, the

net OLR has increased and in 1999 one third of the thermal pollution was emitted as OLR. The current use of nonrenewable energy requires a further global temperature increase of 1.8 °C, until Earth is again in thermal equilibrium. Then the total net heat generation (0.088 W m^{-2}) will be emitted as OLR (Fig. 5).

Earth counteracts global warming by its natural cold sources. This has started to show as a temperature increase of ground, air, and water. Ice fields and glaciers offer another huge cold reserve and the world's total nonrenewable energy use would annually melt only about 0.003% of current ice, with present use of nonrenewable energy and no other cold source.

Increasing concentrations of gases, aerosols, and humidity into the atmosphere will increase the Earth's albedo. This would mean that less solar energy reaches the Earth's surface and thus less OLR to be emitted. Therefore, the Earth's effective temperature should decrease.

What can we then do to put a stop to global warming? Today's policies are aiming at reducing the CO₂ emissions. There are also ideas of storing CO₂ in deep deposits. Some countries plan to expand their nuclear power industry. All these ideas would reduce the CO₂ emissions but would not reduce the global net heat generation. In the case of nuclear power, it would become even worse because of the large amounts of heat generated by nuclear power production. There are also visions of importing clean energy from space. Even if this energy would be renewable on Mars, it would cause global warming since such systems would release net heat on Earth. The only sustainable way is to use our own renewable

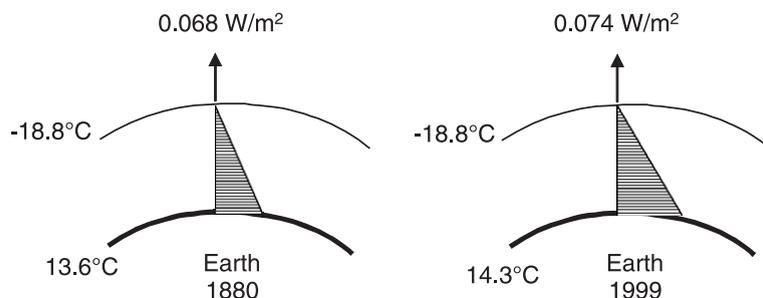


Fig. 5. The net heat generation in 1880 (geothermal heat flow) was balanced by the net OLR. Since then, the increasing net heat generation has caused a temperature increase that will continue until the Earth is again in thermal equilibrium. Today's global temperature (14.3 °C) emits one third of the additional net heating, resulting from the use of nonrenewable energy.

energy. With renewable energy systems, it is not even possible to disturb the energy balance of Earth.

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Appendix A

The Net OLR, Δq [$W\ m^{-2}$], from the ground surface to the atmosphere is given by the Stefan–Boltzmann law. The linear temperature change between the surface temperature of the Earth (T_s) and the effective temperature of the atmosphere (T_e) indicates that the radiation occurs layer-by-layer through the atmosphere (Fig. 2). Since the net OLR is constant through the atmosphere, the net OLR through layer n is

$$\Delta q = \sigma(T_n^4 - T_{n+1}^4) = \sigma[T_n^4 - (T_n + \Delta T_n)^4]$$

where σ is the Stefan–Boltzmann constant. This expression can be rewritten as

$$\Delta q = \sigma \Delta T_n^4 \left[4 \left(\frac{T_n}{\Delta T_n} \right)^3 - 6 \left(\frac{T_n}{\Delta T_n} \right)^2 + 4 \left(\frac{T_n}{\Delta T_n} \right) - 1 \right]$$

If $\Delta T_n \ll T_n$, then

$$\begin{aligned} \Delta q &= \sigma \Delta T_n^4 \left[4 \left(\frac{T_n}{\Delta T_n} \right)^3 - 6 \left(\frac{T_n}{\Delta T_n} \right)^2 + 4 \left(\frac{T_n}{\Delta T_n} \right) - 1 \right] \\ &\approx 4\sigma \left(\frac{T_n}{\Delta T_n} \right)^3 \Delta T_n^4 \end{aligned} \quad (4)$$

The linear temperature gradient through the atmosphere gives that

$$\Delta T_n = \frac{z_n}{H} (T_s - T_e) \quad (5)$$

where z_n is the thickness of layer n , and H the distance to the effective atmospheric temperature as shown in Fig. 2. Eqs. (4) and (5) give that

$$\Delta q \approx 4\sigma \left(\frac{T_n}{\Delta T_n} \right)^3 \Delta T_n^4 = 4 \left(\frac{T_n}{\Delta T_n} \right)^3 \left(\frac{z_n}{H} \right)^4 \sigma (T_s - T_e)^4$$

It can be shown that

$$4 \left(\frac{T_n}{\Delta T_n} \right)^3 \left(\frac{z_n}{H} \right)^4 = 1.000 \text{ for } \Delta q < 0.1\ W\ m^{-2},$$

i.e. for $\Delta q < \text{total net heat generation}$

$$\therefore \Delta q \approx (T_s - T_e)^4$$

This approximation gives an error $< 0.01\%$ for relevant global mean temperature.

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