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Earth Thermal Emissions and Global Warming

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Authors' contributions

This work was carried out in collaboration among all authors. Author RN co-designed the study, undertook the literature review, performed the analysis and wrote the first draft of the manuscript. Author AS co-designed the study commented on subsequent drafts of the manuscript. Author WR performed some of the analysis. All authors read and approved the final manuscript.

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ABSTRACT

When fossil fuels are extracted from the earth, they are naturally replaced by a layer of water. Water has high thermal conductivity as compared to coal, oil, and gas. This will increase the heat transfer rate from the underground in all directions but most importantly towards the surface of the earth and seas due to the greater temperature difference. Additionally, heat losses and thermal emissions from boreholes will be even higher and given that there are more than 4 million onshore hydrocarbon wells (producing and non-producing) around the world, the heat emissions could be significant. Added to this is the heat from thousands of coal mines across the world. We review the literature and report on temperature trends observed in areas subject to fossil fuel extraction. We find that land and sea areas subject to fossil fuel extraction are experiencing relatively high rates of temperature rise. We examine the case of the Arctic in some detail and compare sea-ice extent change in both the Arctic and Antarctica. We find that despite increasing levels of CO_2 observed in the Polar Regions, sea-ice extent is shrinking in the Arctic and expanding in the Antarctic. We believe that a possible cause of shrinking sea-ice in the Arctic could be geothermal heat rising to the surface as a direct result of fossil fuel extraction in regions such as Siberia and Alaska. To provide a crude approximation of the heat released from the earth's interior and

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subsequent impact on global average temperature as a result of earth insulation loss, we use worldwide oil and gas production data from 2007 until 2017. We find the subsequent impact on global surface temperature over this period to be 0.026°C compared with an observed temperature rise of 0.15°C. This amounts to 17% of total warming observed over the period attributable to earth insulation loss, which is significant. We end by making some suggestions on further research necessary to fully understand the possible effect of earth insulation loss on rising global temperature.

Keywords: Global warming; climate change; thermal emissions; fossil fuels; earth insulation; Arctic; Antarctica.

1. INTRODUCTION

Although not widely known, Eunice Foote is believed to be the first person to suggest that an atmosphere containing high levels of carbon dioxide would lead to a warmer world [1]. Her research findings were presented in 1856 (see [2]) at the annual meeting of the American Association for the Advancement of Science. Being a female, Foote was not permitted to present her own paper and instead, Professor Joseph Henry of the Smithsonian Institution spoke on her behalf [1]. A few years later, Foote's findings were reflected in the studies of English physicist John Tyndall.

From that period onwards, the idea of climate warming linked to increasing levels of atmospheric carbon dioxide became the subject of intense debate. A few decades after the work of Eunice Foote and John Tyndall, the Swedish scientist Svante Arrhenius, in 1896, quantified the effects of carbon dioxide concentration on temperature. He estimated that a doubling of carbon dioxide would increase the global mean temperature by up to 5°C to 6°C – a value not far off from current estimates. It was not until after the work of Guy Stewart Callender during the 1930s and 1940s [3], and that of American scientists Roger Revelle and Hans Suess [4], that the idea of increasing atmospheric carbon dioxide levels leading to increase in global temperature was beginning to find greater acceptance.

Although the link between increasing levels of greenhouses gases and global warming is now widely acknowledged, controversy remains as to the extent to which the greenhouse gases, in particular carbon dioxide, impact global temperature [5,6,7]. Hubert Lamb, who founded the Climatic Research Unit in East Anglia, UK and is regarded by many as the father of modern climatology, challenged the notion that elevated atmospheric carbon dioxide could explain all the observed global warming, and instead suggested that the direct heating effects of heat production could be playing a major role in warming the earth [8]. Despite decades of extensive climate change research, further effort is necessary to fully understand the role that earth thermal emissions may play in global warming.

2. THERMAL EMISSIONS AND GLOBAL WARMING

The role played by thermal emissions in elevating temperature has been the subject of research at the global scale (e.g. [9,10,11,12,13]); regional scale (e.g. [14,15,16]) and local scale (e.g. [17]). As noted by Zhang et al. [15], the idea that anthropogenic thermal emissions may contribute to global warming was first brought forward almost half a century ago (see [9]) but has largely been forgotten. In attempting to better understand the role of thermal emissions in global warming, Zhang et al. [15] investigated unexplained winter warming over northern Asia and North America. They concluded that thermal emissions are likely to be a missing forcing for the additional winter warming trends in observations.

The impact of thermal emissions from thermoelectric power plants on river temperature was recently quantified for the first time by Raptis et al. [18]. In the analysis comprising 565 power stations from across the world, they found the Mississippi receives the highest total amount of heat emissions (sourced from coal-fuelled and nuclear power plants) whilst the Rhine is the thermally most polluted river in the world in relation to the total flow per watershed. One third of the total flow of the latter is found to experience temperature increases of $\geq$ 5°C on average over the year.

Nordell and Gervet [12] made a case for just over a quarter of the observed warming attributable to increasing levels of atmospheric greenhouse gases, with the remainder resulting from heat emissions on Earth. They argued that heat emissions arise from fossil fuel burning, nuclear power generation, nuclear bomb tests and conventional bomb tests as well as natural processes including volcanic eruptions. Cowern and Ahn [19] argue that energy generation technologies such as nuclear (fission or fusion), fossil fuels and geothermal power plants produce human-made sources of heat energy which flows into Earth's climate system. They also stress that such thermal emissions contribute directly to Earth's heat budget and cause global warming.

Mu and Mu [13] were the first to quantify the impact on global temperature of heat emissions due to fossil fuel burning. They concluded that a 0.84°C global temperature rise had resulted as a direct result of fossil fuel burning over the period spanning the start of the industrial revolution and 2010. They also projected a global temperature rise of 0.27°C by 2020 on the basis of 2010 rates of fossil fuel extraction.

We believe that current understanding of the underlying drivers of accelerated global warming is incomplete and warrants further investigation. To help achieve this, it is useful to consider the human body analogy of the earth.

3. EARTH TEMPERATURE REGULATION AND THE HUMAN BODY ANALOGY

Sharif and Sharif [20] were the first to apply the human body analogy to the earth climate change and global warming phenomena. In their study, the authors highlighted the similarities between the human body and the earth. For example, 70% of the earth is covered by water and a similar percentage accounts for the amount of water that makes up the human body. 97% of human blood plasma is made up of pure water and 3% dissolved solutes. These are the same proportions found in seawater. The blood in the body is circulated via vessels, arteries, capillaries and veins, while water on the earth is circulated around by streams and rivers in a cycle very similar to the blood circulatory system. The blood circulatory system is often referred to as the *flowing rivers of life!*

Another, lesser known analogy is between body fat and hydrocarbons (oil, coal and gas) stored in the earth (see [13]). The main functions of the fats and fatty tissues in the human body are to keep the core body temperature constant and to store energy. Fats are hydrocarbon and the fatty cells are mainly found in the body around the middle part, prominently in the abdominal region and the brain to reduce heat losses and store energy for future use. Fats in the body are normally under the skin and around the organs but not in a separate layer.

Equivalently, the fats of the earth are the fossil hydrocarbons too and mainly are made of coal, petroleum and natural gas which are called fossil fuels. Here we will call them fossil hydrocarbons. They were formed millions of years ago (in excess of 650 million years) by natural processes such as anaerobic decomposition of buried dead organisms, leading to oil, gas and coal. Their time scale of formation is different from the time of human existence and this makes them not necessarily part of the evolution process and certainly not for human use. They therefore must have different functions and one of them could be to sustain the earth's natural ecosystem. One of their prime functions arguably could be to prevent the underground heat of the core earth reaching the surface, i.e. they act as the natural insulators for the earth. Fat is found mostly around the middle part of the body because of the larger heat transfer surface area, to control the body core temperature. Similar to the fat in the body, fossil hydrocarbons are not found in a continuous one layer inside the earth but between the porous structure of the rocks.

Fossil hydrocarbons are also found in some quantity in parts of the world that are north of the Equator, but in lesser amounts in places south of the Equator. It is interesting to note that according to the theory of Earth Evolution, about 300 million years ago, regions currently lying north of the Equator such as India were located south of it as shown in Fig. 1. This might explain why fossil hydrocarbons; mainly oil, gas-oil and gas are only found in larger quantities in some parts of the world, though they are found elsewhere but in small quantities and not economically feasible to extract. This may also explain why places like Australia, India, Latin America and South Africa have more coal than oil and gas (located in the southern hemisphere for a significant period), while places like Siberia and many parts of Russia as well as Norway have large quantities of oil because these regions were at the Equator millions of years ago.

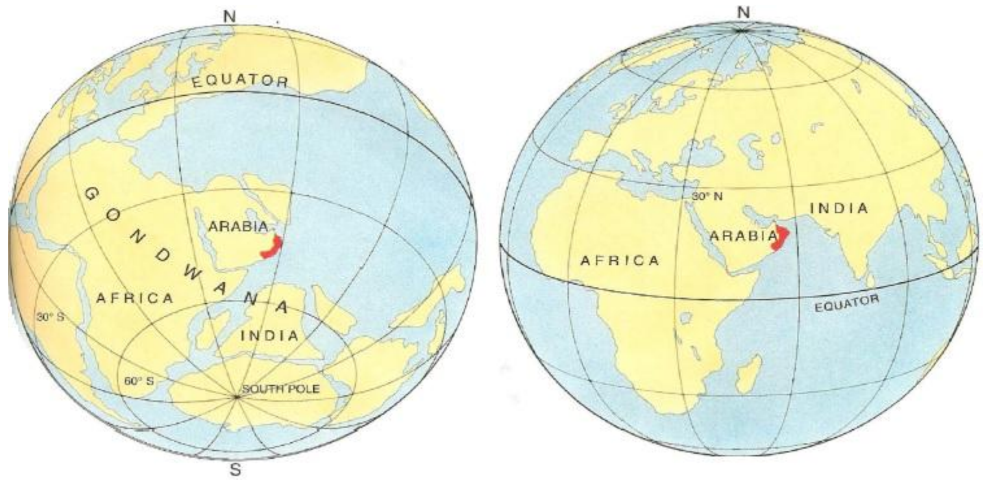

Fig. 1. The earth 300 million years ago (left) and now (right)
[Source: [21]

When fossil hydrocarbons are extracted from the earth, they are naturally replaced by a layer of water. Water has high thermal conductivity as compared to coal, oil, and gas. This will further increase the heat transfer rate from the underground in all directions but most importantly towards the surface of the earth and the oceans and seas due to the greater temperature difference. Additionally, heat losses and thermal emissions from boreholes will be even higher, and given that there are more than 4 million onshore hydrocarbon wells (producing and non-producing) around the world [22], the heat emissions could be significant. Added to this is the heat from thousands of coal mines across the world. The increased underground thermal activities horizontally and vertically will also increase the thermal expansion of the underground rocks with implications for sea-level rise. The importance of fully considering all potential drivers of sea-level rise including vertical land motion has been emphasised by Gehrels and Long [23].

4. TEMPERATURE CHANGES IN AREAS SUBJECT TO HYDROCARBON EXTRACTION

In the UK, some evidence has been found for elevated subsurface temperatures in areas of coal mining activity. Westaway and Younger [17] have shown that in Gateshead and Newcastle upon Tyne in north east England, both towns subject to considerable coal mining activity, significant sub-surface heat islands are present. They also note that discharge of groundwater at a mine water pumping station has a significant heat flux attributed in part to heat flowing from the Earth's interior. They conclude that similar conductive heat flow and groundwater flow responses are expected in other urban former coalfields in Britain.

In the Middle East, which has been subjected to the most intense sub-surface hydrocarbon removal activity the world has seen, large temperature increases have been reported.

For example, a recent study for Saudi Arabia [24] found that, between 1985 and 2013, temperature had increased around 0.65°C per decade which is four times higher than the global average. According to Leliveld et al. [25], summer temperatures in the Middle East and North Africa are set to rise over twice as fast as the global average. Extreme temperatures of 46°C or more are likely to be about five times more likely by 2050 than they were at the beginning of the century according to the research.

Evidence is emerging of rapid warming of sea areas subject to hydrocarbon extraction activity. According to an online data portal [26], the three offshore regions with the largest number of oil/gas rigs are the North Sea, Gulf of Mexico and the Arabian Gulf. Temperatures of the Arabian Gulf are rising three times faster than the world average according to a study by Al-Rashidi [27]. The author discovered that since 1985, seawater temperature in Kuwait Bay, northern Arabian Gulf, has increased on average 0.6°C per decade. Rapid warming of the Arabian Gulf waters has also been observed by Nandkeolyar et al. [28] and Shirvani et al. [29], the latter reporting Arabian Gulf sea-surface temperatures to have increased abruptly in the recent two decades.

Rapidly rising temperatures have been reported by Turner et al. [30] for the northern Gulf of Mexico who quantified trends in the 1985 to 2015 summer bottom-water temperature on the northern Gulf of Mexico continental shelf for data collected at 88 stations. The authors noted that this was the first analyses of decades-long temperature records for the continental shelf of the northern Gulf of Mexico. The observed bottom-water warming for the northern Gulf of Mexico was discovered to be over six times more than concurrent increase in annual global ocean sea surface temperatures.

Analysis of temperature records for the North Sea between 1982 and 2012 has revealed similar trends, with the average rise four times faster than the global average [31].

5. CLIMATE CHANGE IN AND AROUND THE POLAR REGIONS

Annual average atmospheric concentrations of carbon dioxide in both the Arctic and Antarctica are shown in Fig. 2 and are now above 400 parts per million. Despite CO_2 concentrations in the Antarctic lagging behind those in the Arctic, it is clear that concentrations are increasing in both locations. It is interesting to consider the impact that the rising CO_2 is having on temperature and sea-ice extent in the Polar Regions.

Despite rising atmospheric levels of CO_2, surface-temperature change in the Arctic and Antarctica differ substantially. A trend of 0.6°C decade^{-1} has been observed in the Arctic (considered one of the fastest warming regions) whilst a much lower change of 0.1°C decade^{-1} has been observed in the Antarctica (compared with 0.2°C decade^{-1} globally, since 1981 [33]).

Sea-ice extent change between 1978 and 2017 is shown in Fig. 3 for both the Arctic and Antarctica.

According to Fig. 3, Arctic sea ice extent underwent a strong decline from 1979 to 2012, but Antarctica sea ice underwent a slight increase. The positive trend in Antarctica sea-ice extent is intriguing because it appears to be physically counter-intuitive to global warming observations [33]. Various reasons have been put forward for this apparent discrepancy in the Antarctica including stratospheric ozone depletion that caused a deepening of the lows in the West Antarctic region [34], freshening of the Antarctic seawater [35] and changes in atmospheric circulation resulting from changes in the southern annular mode and ENSO and the greater frequency of La Nina events since the late 1990s [36,37].

We would like to argue that the difference could be explained by the loss of earth 'insulation' in the Arctic Circle. It has been estimated that by 2007, more than 400 oil and gas fields, containing 40 billion barrels of oil (BBO), 1136 trillion cubic feet (TCF) of natural gas, and 8 billion barrels of natural gas liquids had been extracted north of the Arctic Circle, mostly in the

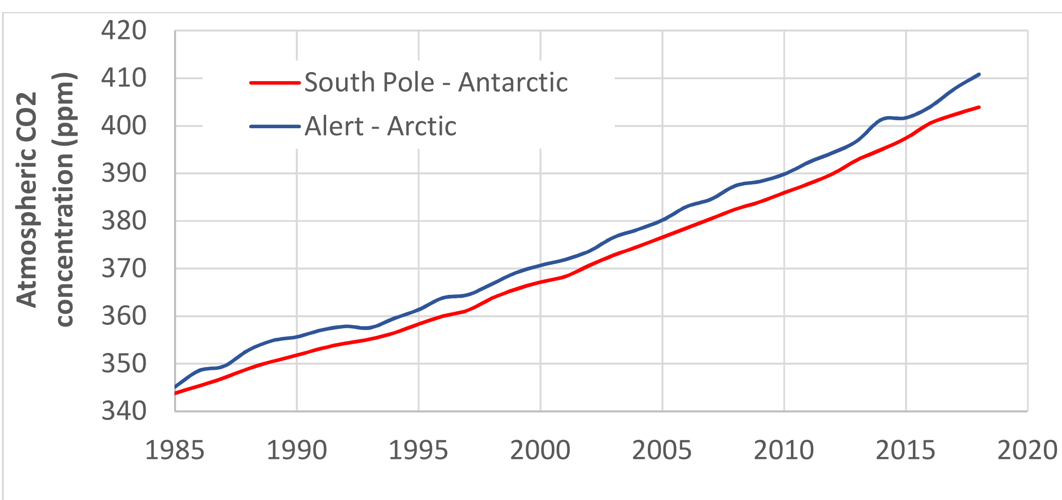

Fig. 2. Atmospheric CO_2 concentrations between 1985 and 2018 for South Pole and Alert monitoring stations -data sourced from [32]

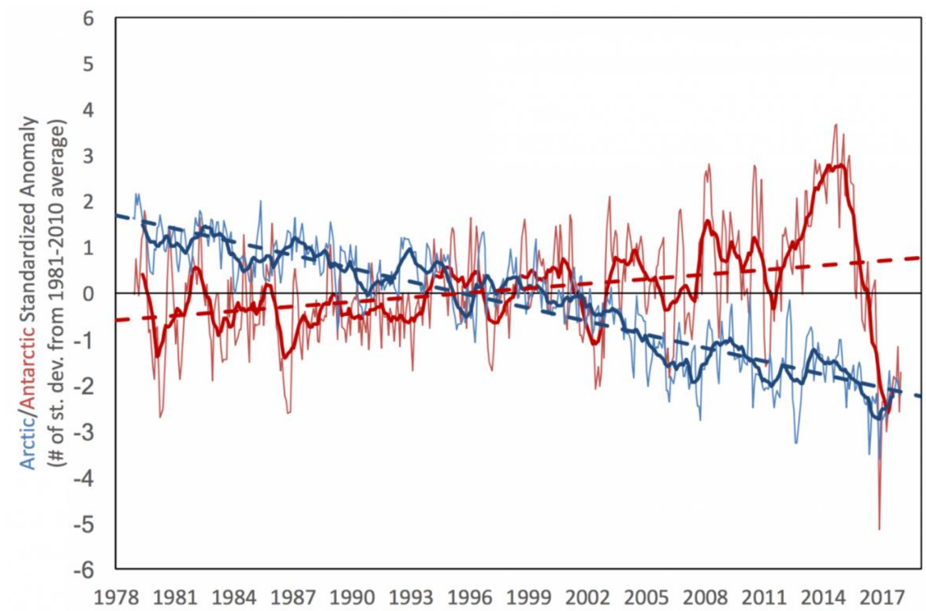

Fig. 3. Arctic and Antarctic sea Ice extent anomalies and trend (blue = Arctic & red = Antarctic), 1979-2017. Thick lines indicate 12-month running means, and thin lines indicate monthly anomalies [34]

West Siberian Basin of Russia and on the North Slope of Alaska [38]. Much greater volumes of hydrocarbon extraction will have resulted considering the Arctic region as also extending southwards from the Arctic Circle and encompassing countries with a particularly cold climate, permafrost and frozen sea-ice. Under this definition, this is a vast region comprising West Siberia and Sakhalin, Russia, northern Canada and Alaska (USA). Major producing regions include Drake Point gas field on Melville Island and Brent Horn field on Cameron Island (Canadian Arctic), Norwegian Continental Shelf (Barents Seas), Kara and Pechora Seas (Russian Arctic) and Prudhoe Bay (Alaska). In contrast to the Arctic, there has been no extraction of hydrocarbons in the Antarctica and all such activity is banned until 2048 under the Antarctic Treaty.

Geothermal heat as a mechanism for climate change in the Alaskan Arctic was first identified by Lachenbruch and Marshall over 30 years ago [39]. More recently, Harris [40] identified a significant correlation between hydrocarbon removal and air temperature. Investigating the mean annual air temperatures for Alaska in the last 30-50 years, a significantly more warming in and around Prudhoe Bay was noticed in comparison with adjacent areas. This was attributed to the shipment of oil through the Trans-Alaska oil pipeline commencing in 1977. It was postulated that since more than 17 trillion barrels of oil have passed through the pipeline, it has caused heating of the surrounding air which has also resulted in melting of the adjacent sea-ice. The heating is caused because the oil temperature at the point of extraction exceeds 40°C. This, the author argues, contrasts with the IPCC interpretation of warming in Alaska which assumes that the maximum climatic warming at Prudhoe Bay is typical of the entire region and as a result of greenhouse gases.

6. EARTH INSULATION LOSS AND GLOBAL TEMPERATURE CHANGE

It is possible to approximate the contribution to global temperature rise resulting from loss of earth insulation. We estimated this by obtaining the data on fossil fuel removal for a 10-year period (2007-2017) reported in the BP Statistical review of World Energy [41]. Total global production of oil and natural gas amounted to 45.42 billion tonnes and 36287.6 billion cubic metres, respectively, over the period 2007-2017. Since oil extraction also results in produced water (averaging 5 barrels of produced water for every barrel of oil [42]), total production over the 10-year period can be estimated as 181.68 billion tonnes. The oil and gas production data can be used alongside other relevant data shown in Table 1 to determine total heat rising to the earth's surface.

Table 1. Properties and mass of selected fossil fuels and produced water

	Specific heat (KJ/kg/°C)	Temperature (°C)	Mass Flow (kg)*
Oil	2.13	140	4.543×10^{13}
Oil-water	3.93	140	2.271×10^{14}
Natural gas	2.22	150	2.903×10^{13}

** For period 2007-2017*

The temperature data in Table 1 is an approximation of the reservoir conditions for oil and gas production. The associated produced water with the oil (oil-water) is assumed to have a similar temperature. This is possible at the higher pressure in the reservoir; otherwise water will be evaporated at such a high temperature.

The total heat transferred to air, (Q) in KJ is given by:

$$Q = mc\Delta T \quad (1)$$

where,

m = mass flow (kg)
c = Specific heat value (KJ/(kg°C))

The heat transferred as a result of oil (Q_{oil}), oil-water (Q_{ow}) and gas (Q_{gas}) is determined as follows (assuming global average air temperature of 15°C):

$$Q_{oil} = m_{oil} \times c_{oil} \times \Delta T_{oil} \quad (2)$$
$$= 4.543 \times 10^{13} \times 2.13 \times (140-15) = 1.21 \times 10^{16} KJ$$

$$Q_{ow} = m_{ow} \times c_{ow} \times \Delta T_{ow} \quad (3)$$
$$= 2.271 \times 10^{14} \times 3.93 \times (140-15) = 1.116 \times 10^{17} KJ$$

$$Q_{gas} = m_{gas} \times c_{gas} \times \Delta T_{gas} \quad (4)$$
$$= 2.903 \times 10^{13} \times 2.22 \times (150-15) = 8.70 \times 10^{15} KJ$$

Total heat transferred to air (Q_{total}) in KJ:
$$Q_{total} = Q_{oil} + Q_{ow} + Q_{gas} \quad (5)$$
$$= 1.324 \times 10^{17} KJ = 1.324 \times 10^{20} J$$

Given that the specific heat of air is about 1×10^3 J/(kg°C), (i.e. a 1×10^3 Joules of heat provides a temperature rise of 1^oC of a 1 kg atmosphere), the temperature rise (x) as a result of 1.324×10^{20} J of heat flow to the atmosphere (with a mass of 5.15×10^{18} kg according to Lide [43]) is determined as follows:

$$x = (1.324 \times 10^{20} \times 1 \times 1) / (1 \times 10^3 \times 5.15 \times 10^{18})$$
$$= 0.0257°C$$

It should be emphasised that the estimated temperature is a gross simplification in which the atmosphere is heated given the complex air-ocean-land interactions. Nonetheless it does show that there is warming attributable to earth insulation loss. Comparing the temperature increase with the observed global average temperature rise of approximately 0.15°C over the 2007-2017 period reveals that the insulation loss effect accounts for 17% of the observed warming, which is significant. We should also emphasise that this increase is only accounting for the thermal emission from the active oil and gas wells, but not including the depleted wells which continue to produce heat.

7. CONCLUSIONS

To adequately address the most pressing environmental issues of our time, it is important to fully identify the possible causes of global warming. We have shown, with reference to some relatively recent research findings, that both onshore and offshore areas subjected to fossil fuel extraction are experiencing high rates of land and sea warming, respectively. Various causes might be attributed to this including increased local CO_2 emissions in regions with cheap and plentiful fossil fuel resources and/or greater particulate pollution impacting on the amount of solar radiation absorbed. However, we believe that there is now some evidence to indicate that loss of earth insulation may be leading to heat from the earth's interior rising to the surface and contributing to global warming. With reference to the Polar Regions, we have shown that similar levels of CO_2 rise in both regions result in considerably more warming in the Arctic. We suggest that the possible link between earth insulation loss as a result of hydrocarbon extraction and the rapid warming of the Arctic should not be ruled out.

To provide a crude approximation of the heat released from the earth's interior and subsequent impact on global average temperature as a result of earth insulation loss, we used worldwide oil and gas production data from 2007 until 2017. We found the subsequent impact on global surface temperature over this period to be significant. Consequently, we believe that considerable further work is necessary to fully investigate the possible effect of earth insulation loss on rising global temperatures.

Data gathering needs to be at the heart of this effort, as usefully noted by Keeling [44], *"the only way to figure out what is happening to our planet is to measure it, and this means tracking changes decade after decade and poring over the records."*

Comparisons are necessary between changes in sub-surface temperatures in areas subject to hydrocarbon extraction and in areas without such activity. This will require deep bore-hole repeat temperature measurements. The borehole temperature database established by Huang and Pollack [45] could be extended with repeat temperature measurements. The data may also be used to revise the estimate of the earth's surface heat flux reported by Davies and Davies [46]. Data on geothermal heat emissions from operational and abandoned oil and oil-gas fields would also be useful and allowgeothermal heat flux values to be estimated. Sea-bed temperatures for Shelf Seas (in regions subject to fossil hydrocarbon extraction and those that are not) over time would also need to be investigated since much of the world's oil and gas production is offshore. Finally, calculations based on climate/physical models to quantify the heating produced by loss of earth insulation need to be performed.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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