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Mini-Review

The Arrhenius Approach and the Effects of Anthropogenic Heat on the Temperature of the Earth´s Surface

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Mini-Review

The simpler approaches to model the temperatures at the Earth´s surface were based on simple steady-state radiative energy balance equations, where the Sun´s radiation absorbed at the surface equals the radiation emitted by the Earth to Space (Figure 1).

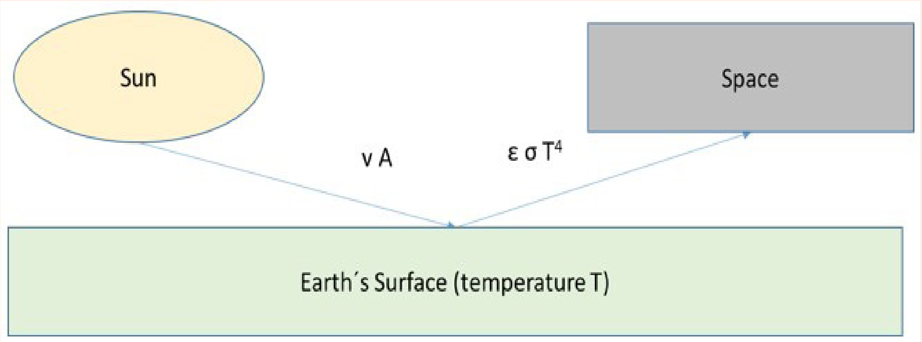

Figure 1: The simpler version of a radiative energy balance equation for the surface of the Earth (see text for details of the symbols).

In mathematical terms, the equation is:

$$vA = \varepsilon\,\sigma\,T^4$$

where:
v is the fraction of the Sun´s radiation absorbed by the Earth´s surface (globally evaluated as v=0.69),
A is Sun´s radiation (on average considered to be around A=342.5 W m^{-2}),
ε is the emissivity of the Earth´s surface (often set at ε=1),
σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}), and
T is the absolute temperature of the Earth´s surface (K).

Solving for T we have:

$$T = [(\,v\,A\,) / (\,\varepsilon\,\sigma\,)\,]^{1/4}$$

This equation, using the indicated common average values for the whole Earth, result in an estimate of the average global temperature at the surface of the Earth (T) of 254K, 34K lower than the average observed value of 288K. The estimates by this simple model do not fit the observations, as the model does not consider the presence of the Earth´s atmosphere. The need for including the atmosphere in modelling the surface temperature of the Earth was first recognized in the pioneer work of Fourier in 1827 [1], who wrote: “the interposition of air greatly modifies the effects of heat at the surface of the globe”. In his radiative terms, Fourier explained: “the heat of the Sun, arriving in the form of visible light, has the ability to penetrate transparent solid or liquid substances, but loses this ability almost completely when it is converted, by its interaction with the terrestrial body, into dark radiant heat”. The difference between long and short-wave radiation was understood. In sequence, the examination of the separate effects of carbon dioxide and water vapor in absorbing radiation was studied experimentally by Tyndall [2]. He concluded: “it is exceedingly probable that the absorption of the solar rays by the atmosphere (…) is mainly due to the watery vapours contained in the air (…). This aqueous vapour, which exercises such a destructive action on the obscure rays, is comparatively transparent to the rays of light. Hence the differential action, as regards the heat coming from the sun to the earth, and that radiated from the earth into space, is vastly augmented by the aqueous vapour of the atmosphere”. However, he also indicated: “similar remarks would apply to the carbonic acid diffused through the air”. At the end of the XIX century, the need for a comprehensive model that could include atmosphere in the explanation of the temperature of the Earth´s surface was clear. The first well-known model in this topic was due to Arrhenius [3] in his very influential study “On the influence of Carbonic Acid in the Air upon the Temperature of the Ground”. In his work, centered in the potential role of carbon dioxide, Arrhenius provides a good explanation of the heat balance of the atmosphere. He states that “the atmosphere must radiate as much heat to space as it gains partly through the absorption of the sun´s rays, partly through the radiation from the hotter surface of the earth” and by “the quantity of heat that is conveyed (by other sources) to the air at the point considered”. The model proposed (3) can be represented, with minor changes, in the diagram of (Figure 2).

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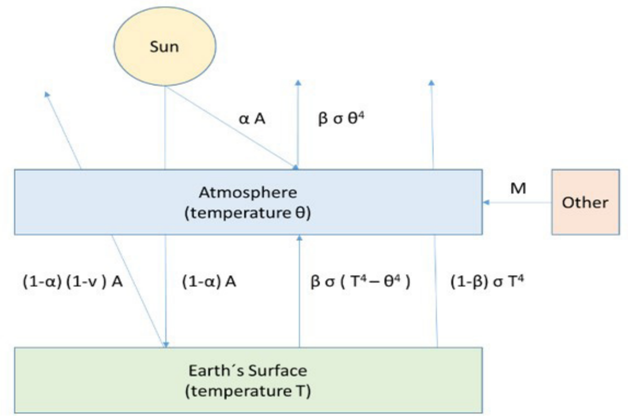

Figure 2: A representation of the heat balance of the Earth´s surface and the atmosphere, adapted from that of [3], See text for details with symbols and equations.

The new variables and parameters first used in (Figure 2) are:
α as the absorption coefficient of the atmosphere for the radiation of the Sun,
β as the absorption coefficient of the atmosphere for the heat that radiates from the Earth´s surface (equal to the emission-coefficient of the atmosphere),
θ as the absolute temperature of the atmosphere (K), and
M as the quantity of heat obtained "from other parts of the air or from the ground" (Wm^{-2}).
In mathematical terms, the heat balance of the atmosphere is expressed as:

$$\beta \sigma \theta^4 = \alpha A + \beta \sigma (T^4 - \theta^4) + M$$

In the equation, the heat radiating from the atmosphere to space (the left term of the equation) is equal to the heat from the Sun´s radiation absorbed by the atmosphere, the heat from the Earth´s radiation absorbed by the atmosphere and any other extra sources (the right terms of the equation). For the heat balance of the Earth´s surface, it is possible to have a similar approach. To simplify calculations, we can assume, as Arrhenius did, that "the heat that is conducted from the interior of the earth to its surface may be wholly neglected". In mathematical terms, this heat balance equation is expressed as:

$$(1-\alpha)(1-v) A + (1-\beta) \sigma T^4 + \beta \sigma (T^4 - \theta^4) = (1-\alpha) A$$

In the equation, the Earth´s surface loses just as much heat by radiation to space (short and long wave) and to the atmosphere (terms at the left side of the equation) as it gains by absorption of the Sun´s rays (right side of the equation).

The elegance of the Arrhenius approach is that it allows combining the two previous equations to solve for the temperature of the Earth´s surface:

$$T = \{[(v - \alpha v + \alpha/2) A + M] / [\sigma (1 - \beta/2)] \}^{1/4}$$

These results are useful to evaluate the consequences on temperature of changing each of the elements of the system. Arrhenius was particularly interested in evaluating the consequences on the Earth´s surface temperature (ΔT) of changes in the absorption-coefficient of the air for radiation from Earth ($\beta 1$ instead of β):

$$\Delta T = \{[(1 - \beta/2) / (1 - \beta 1 /2)]^{1/4} - 1 \} T$$

For example, for an initial value of T=288K, a change from $\beta = 0.79$ to and $\beta 1 = 0.84$, would result in a temperature increase of around ΔT=3.0K. According to the calculations of Arrhenius (1896) a change of temperature of this magnitude would correspond to a change from an atmosphere with the "normal" composition of carbon dioxide and water vapor (in 1896) to an increase of 50% in carbon dioxide.

Naturally, due to the special interest of Arrhenius on the potential consequences of changes in carbon dioxide in the atmosphere, his approach has been widely used to justify the importance of carbon dioxide in global warming. However, the approach and the elegant mathematical solution provided by the Arrhenius model can also be used more widely to evaluate the consequences of changing other variables. In particular, the model can be used to evaluate the effect of adding other sources of heat in the atmosphere (M). If other sources, as anthropogenic heat fluxes, are added to the atmosphere, we can explore the corresponding changes in the Earth´s surface temperature (ΔT). To facilitate the calculations, Arrhenius used a ratio (φ) between the extra energy source (M) and energy of the Sun (A), such as $\varphi = M / A$. The resulting change in the Earth´s surface temperature (ΔT) from the extra energy (M) is calculated as:

$$\Delta T = \{[(1 + v - \alpha v + \varphi) / (1 + v - \alpha v)]^{1/4} - 1 \} T$$

For an example with values of T=288K, v=1, and α=0.40, a value of φ of only 0.05 (5% of the sun´s radiation) would result in an increase in the earth´s temperature by 2.2K [3] explains that M represents the "quantity of heat that is conveyed to the air at the point considered", and that, because of the atmospheric currents, "the mean M for the whole Earth is zero, for the equatorial regions negative and for the polar regions positive". In his work, Arrhenius did not take into account that other sources of energy "conveyed to the air" could include those resulting directly from anthropogenic causes. However, following Arrhenius discussions, the ratio φ is likely to be important especially in winter and in higher latitudes, in areas with less radiation and important extra heat fluxes. In addition, in areas with a lower v value (higher albedo) as with snow cover, the relative importance of the other sources of heat (φ) increases. The effect of this extra energy from anthropogenic sources in increasing surface temperature provides a simple explanation of the well-known phenomenon of the urban heat islands. Howard (1833) published one of the first studies providing evidence that air temperatures are often higher in a city than its surrounding countryside in his work on the Climate of London, and [4] was one of the first analyzing the energetic basis of the urban heat island [5] provides a good study on the anthropogenic heat flux of several cities around the world, with values estimated for 2015 of 26.2Wm^{-2} in London to 52.8Wm^{-2} in Tokyo. Compared with the average annual solar radiation for the latitude of those two cities, 275Wm^{-2} and 345Wm^{-2}, respectively (Figure 3), the values of the ratio φ would be around 0.10 to 0.15. Again, the use of the equation from the Arrhenius approach with the example values v=1 and α=0.40 and the average annual temperatures of 285K and 289K for London and Tokyo, respectively, would result in an increase in temperature of 4.2K and 6.7K for those two cities.

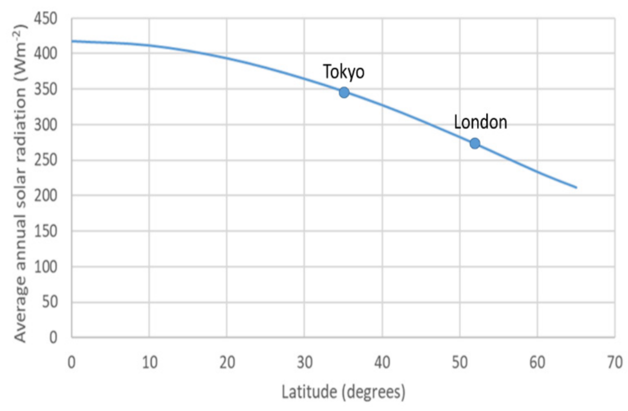

Figure 3: Average annual solar radiation reaching the top of the atmosphere as related to latitude, showing the cities of London and Tokyo.

The importance of the anthropogenic heat fluxes in urban areas is shown for some larger countries in (Figure 4), indicating some variability, with lower values associated to countries with lower levels of energy consumption.

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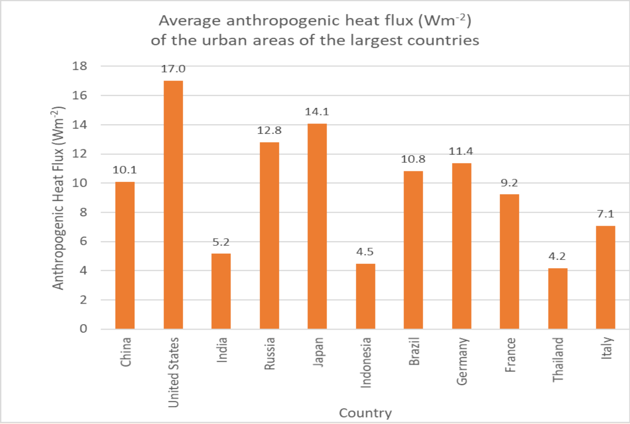

Figure 4: The average anthropogenic heat flux of the urban areas of the largest countries (From FAO data on energy consumption of the country proportional to the urban population and the urban area).

Jin et al. (5) provided a very good global spatial representation of the anthropogenic heat fluxes around the globe, where differences are between urban and rural areas (with very low values for the anthropogenic heat fluxes) and differences between countries in their energy consumption levels are observable. However, the scale of the effects of anthropogenic heat is not limited to the city boundaries [6] already detected regional impacts of anthropogenic heat on the climate of the Ruhrarea region (Germany)). And the excellent work of [7], taking Great Britain and Japan as type examples, concluded that increases in temperature at the country level were better explained by energy consumption than by current climate models. Finally, several works have been suggesting that “thermal pollution” or “waste heat” are the dominant causes of temperature increase at the global level [8]. In any case, the Arrhenius approach allows for the understanding of the main factors associated to the spatial distribution of temperature anomalies. Whereas CO_2 concentrations in the atmosphere are very homogeneous around the globe, the ratio φ is very variable, possibly explaining partly the observed geographical differences in temperature anomalies. These considerations indicate that simple modelling approaches, such as the one started by [3], are useful to explain the main factors affecting the temperature of the surface at any point of the Earth. It becomes apparent that, while the Arrhenius approach has been widely used to justify the role of the carbon dioxide concentration in the atmosphere in global warming through the changes in the absorption coefficient (β) the use of the same approach to understand the role of extra heat sources (φ) has not yet been considered. From the examples showed it is clear that anthropogenic heat has an important effect in the creation of the urban heat islands, and that effect can extend to regions or countries. Under this approach, it becomes clear that the effects of anthropogenic heat are more pronounced in urban areas of countries with higher levels of energy consumption and at higher latitudes. This may partly explain the spatial variability of the temperature anomalies that cannot be justified by the current CO_2 explanations and is more in line with the current hypothesis that anthropogenic or “waste heat is the dominant root cause of global warming” [9].

References

1. Fourier M (1827) Mémoire sur les températures du globe terrestre et des espaces planétaires. Mem. De l´Academie Royale des Sciences de l´Institut de France 7: 569-604.
2. Tyndall J (1861) On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connection of Radiation, Absorption, and Conduction. Philosophical Transactions.
3. Arrhenius SA (1896) On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. Philosophical Magazine 41: 237-276.
4. Oke TR (1982) The energetic basis of the urban heat island. Quart JR Met Soc 108: 1-24.
5. Jin K, Wang F, Chen D, Liu H, Ding W, et al. (2019) A new global gridded anthropogenic heat flux dataset with high spatial resolution and long-term time series. Scientific Data 6:139.
6. Block A, Keuler K, E Schaller (2004) Impacts of anthropogenic heat on regional climate patterns. Geophysical research letters 31: L12211.
7. Murray J, D Heggie (2016) From urban to national heat island: the effect of anthropogenic heat output on climate change in high population industrial countries. Earth´s Future 4: 298-304.
8. Nordell B (2003) Thermal pollution causes global warming. Global and Planetary Change 38: 305-312.
9. Bian Q (2020) Waste heat: the dominant root cause of current global warming. Environmental Systems Research 9(8): 11.

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