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A consideration of the forcings of climate change using simple physics

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1. Motivation

THIS DISCUSSION PAPER IS MOTIVATED BY THE RECENT DEBATES ABOUT the "truth" of climate change research and the shift in public opinion about whether man made climate change is actually happening or not. It occurred to me that discussions were always centred on either instrumental records from the late 19th Century onwards, or past climate reconstructions from proxy data like tree rings, or climate models' predictions. All these require training to be appreciated and discussed. Any measurement comes with uncertainty, any proxy data comes with a theoretical model linking it to the climate variable it is supposed to measure, and of course all climate models, however complex, come with simplifications. This state of affairs is very unfortunate because it takes away from people the freedom to understand for themselves the scientific issues when these appear to be solely understandable by experts in the field in question.

It is the goal of this Discussion Paper to show that one does not need to have a PhD degree in Statistics or Physics to grasp the problem. One does not need to go into the fine detail of the physical mechanisms or how a particular time series (e.g. for global mean temperature) is constructed to realize how large is the anthropogenic forcing of the climate. It is simply a matter of putting numbers on the size of this well understood effect using well established and straightforward physics.

The main idea of this paper is really just this: rather than focus on the *projections* of climate change at the end of the century resulting from combustion of fossil fuels, let us simply pause and reflect on the *magnitude of the climate forcing* that this causes.

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This approach requires a metric, a unit that will allow one to convert a given increase in concentration of atmospheric carbon dioxide (the forcing) into something more palpable, like a mass of ice sheet melting. And this is where Physics comes in handy, because it provides straightforward ways to measure the anthropogenic forcing in physical units, whether of sea level change, in units of sea ice melting, or of other related physical phenomena.

Again, I emphasize that no climate predictions are made here: all I am going to do over the course of the paper is to measure the amount of energy available as a result of the greenhouse effect of carbon dioxide, and estimate how large this energy is compared to the energy needed to achieve a given climate phenomenon, such as a rise in sea level. If one finds that the energy required for the latter (or another phenomenon) is orders of magnitude larger than the energy available from the effect of atmospheric carbon dioxide molecules, then obviously one should become quite sceptical about alarming climate change predictions. If, on the other hand, the two energies are comparable, then one cannot in good faith ignore the risk.

Let me from the outset answer the obvious criticism raised by this approach, which is that having a certain amount of energy available does not imply that this energy can be used entirely for a given purpose. For instance converting all the energy available into kinetic energy of the atmosphere (winds) would "express" the anthropogenic forcing in units of speed. Such an exercise would be pointless, however: there cannot be a 100% conversion of heat energy into the energy of motion. I am however here on much safer ground because the "units" I will consider in section 3 are associated with conversion of heat into heat. In section 4, I will put the anthropogenic forcing into perspective by comparing it directly to observed radiative changes so that no energy conversion will be needed there either.

2. Anthropogenic forcing

My starting point is the assumption that human activities are responsible for an increase in atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases such as methane and nitrous oxide. Figure 1 shows the year-on-year growth in the concentration of carbon dioxide in the atmosphere, that is the difference in concentration from one year to the next, expressed in parts per million by volume or simply ppmv at the Mauna Loa observatory in Hawaii, which has the longest available time series of atmospheric CO_2 concentration. The current level is close to 380ppmv, and to be clear, a concentration of 380ppmv means that at a given temperature and pressure, the volume occupied by carbon dioxide molecules is only 0.038% of that occupied by other atmospheric molecules.

One might rightly wonder why a single location might be indicative of global variations in atmospheric concentrations. The reason for this is the relatively rapid mixing of CO_2 molecules in the atmosphere. As a convincing evidence for this, measurement sites spread across the globe record differences in annual mean concentrations of less than one percent despite the very different seasonal patterns of carbon dioxide absorption and emission at the earth's surface[1].

There are certainly natural fluctuations in the year-on-year growth rate of carbon dioxide shown in Figure 1, but the curve does not oscillate between negative and positive values over the 50 year record. I am assuming that a growth rate of 1 ppmv/yr can reasonably be attributed to human activities, which is conservative.

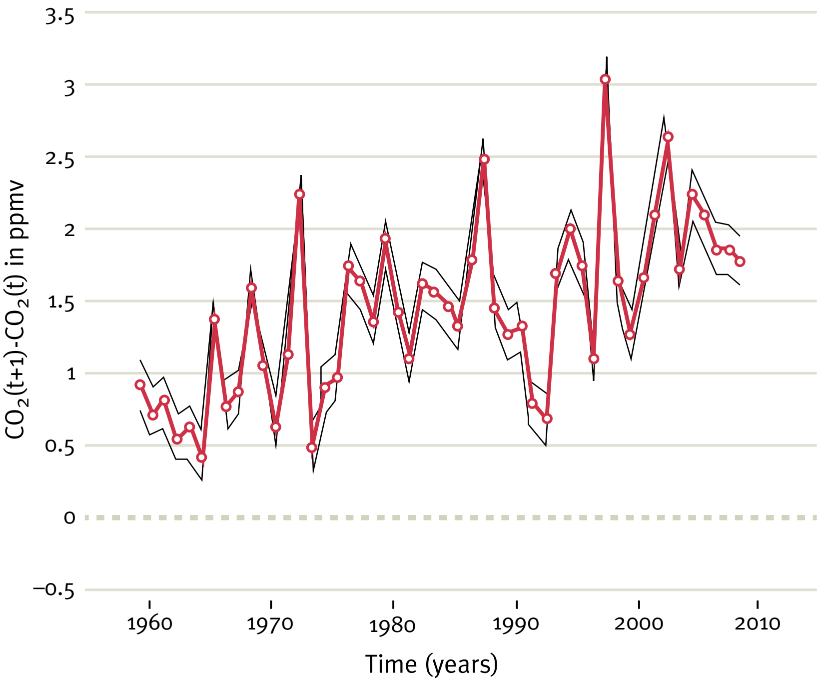


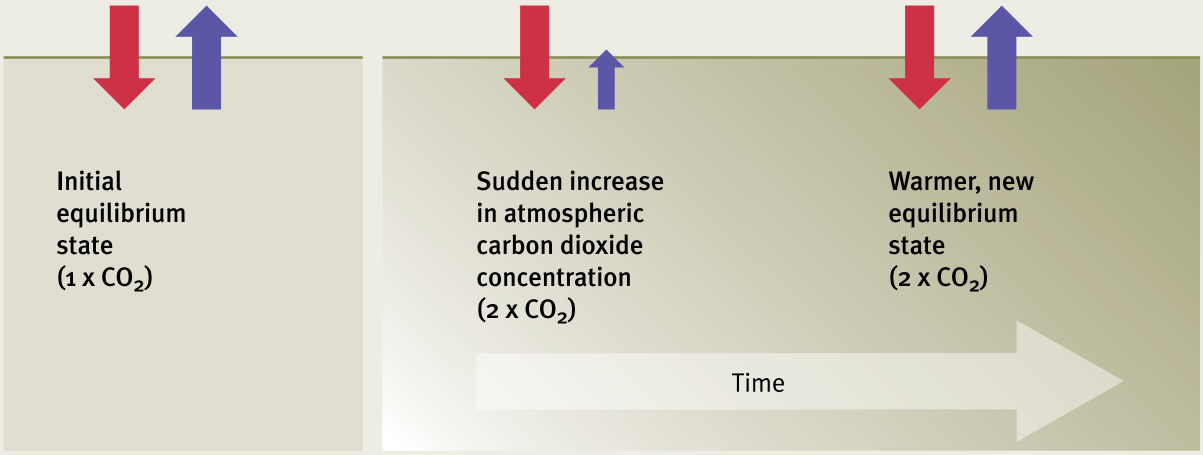
Figure 1. Difference of annual mean atmospheric carbon dioxide (CO_2) concentration in ppmv at the Mauna Loa observatory. The error in annual mean CO_2 concentration is estimated at 0.12ppmv so the error in the difference between consecutive annual means is taken as √2 × 0.12 = 0.17 ppmv (± this value is given as the thin black lines)[1].

How does this anthropogenic increase in atmospheric carbon dioxide concentration turn into a climate forcing? The mechanism is the greenhouse effect of carbon dioxide, but let me stress that this statement is not precise enough to define the "forcing" meaningfully. As more CO_2 molecules are added to the atmosphere, it becomes harder for the Earth to cool to space because of the increased opacity of the atmosphere to long wavelength (infrared) radiation. But this last statement is only true if atmospheric conditions (i.e., temperature, water vapour, clouds, etc) are held fixed. To illustrate this it is enough to understand what happens in a thought experiment where the atmospheric carbon dioxide concentration is suddenly doubled and kept constant through time. There is initially an imbalance with less heat being lost than solar energy gained. But in time, a new equilibrium is reached in which the Earth emits *as much* infrared radiation as it did before the perturbation was introduced. This is more fully explained in Box 1. I will thus define the anthropogenic forcing caused by increasing atmospheric carbon dioxide concentration as the reduction in the infrared emission of the planet under *fixed (i.e. preindustrial) climate conditions*. I will denote this forcing by the symbol Q(t), where the 't' symbol in brackets indicates that this quantity varies over time. Rather than keep referring to Q(t) as the reduction in infrared cooling caused by raising CO_2 concentrations above their pre-industrial level, I will simply refer to it as the "anthropogenic heat flux" from now on, acknowledging that a reduction in cooling corresponds to a heating. The equation describing how this forcing depends on the concentration of CO_2 in the atmosphere, relative to pre-industrial levels, is given in Box 2. It should be noted that this heating is available all over the earth, including over ice sheets and sea ice.

The heat flux, Q(t), and the assumed simple concentration of CO_2 over time, C(t), are plotted over a 300-year time slice in Figure 2 (solid red and black curves, respectively). This choice of time span was made simply because it encompasses the beginning of the industrial revolution (mid 18th century) and the time

Box 1. A thought experiment illustrating the time dependent nature of the relationship between CO_2 doubling and planetary infrared emission.

Upward radiative energy fluxes (red = net absorbed solar energy in the visible and shorter wavelengths, blue = emitted infrared, i.e. heat given off by the earth) as seen from space in a "thought experiment". On all panels the green line indicates the "top-of-the-atmosphere". On the left is shown an hypothetical initial equilibrium climate state: as much downward solar energy is absorbed per unit of time as is emitted upward by the earth. In the middle panel this equilibrium has just been perturbed by suddenly doubling atmospheric carbon dioxide concentrations. The climate has not had time to change yet, and because of the increased opacity caused by the CO_2 doubling, less infrared radiation is emitted by the earth per unit time (smaller blue arrow). There is thus an imbalance between absorbed solar and emitted infrared fluxes: energy accumulates and the earth gets warmer. The final evolution of this climate under fixed (doubled) atmospheric carbon dioxide concentration is shown in the right panel. It is a new equilibrium state with, as in the left panel, no imbalance between absorbed solar and emitted infrared energy fluxes because the earth has had time to get sufficiently warmer and thus emits more infrared energy to offset the opacity effect of having twice as much atmospheric CO_2. The point of this diagram is to emphasize that the infrared energy fluxes in the right and left panels are the same (assuming the same amount of absorbed solar energy), although atmospheric concentrations of carbon dioxide differ by a factor of two.



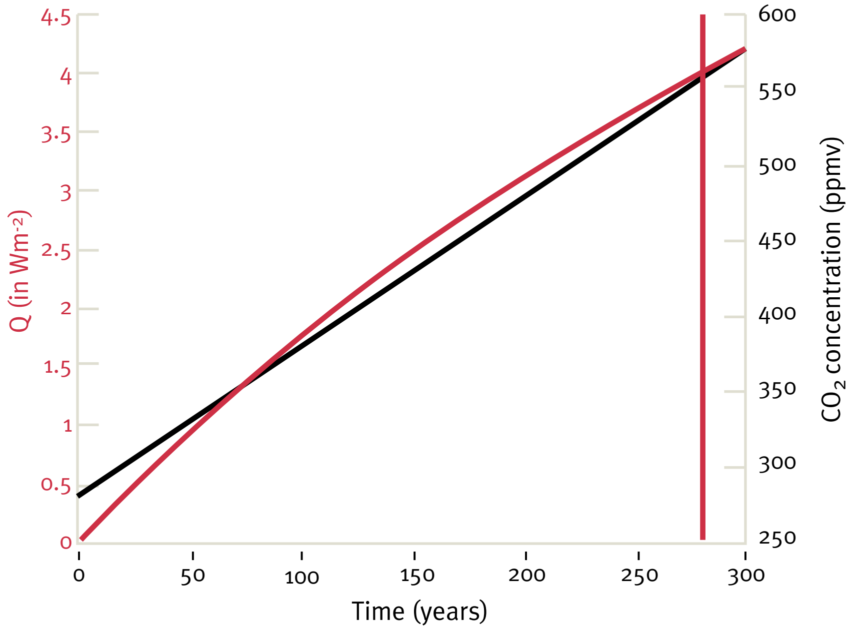


Figure 2. Assumed simple atmospheric CO_2 concentration C(t) (black, in ppmv), and the resulting anthropogenic heat flux Q(t) (red, in Wm^{-2}) as a function of time (in years with year 0 taken as the start of the industrial revolution). The vertical red line indicates the time of atmospheric CO_2 concentration doubling.

Box 2. The anthropogenic heat flux

It is well established, based on laboratory measurements of infrared absorption and emission by carbon dioxide molecules and radiative transfer modelling, that if C(t) denotes the concentration of CO_2 as a function of time, t, then the cooling flux of the planet by infrared radiation, at otherwise fixed pre-industrial climate conditions, is reduced by an amount Q(t) satisfying:

$$Q(t) = 4 \log_2 (C(t)/C_0) \text{ (measured in } Wm^{-2}\text{)}$$

where C_0 is the CO_2 concentration at an initial time t = 0, which we take as the start of the industrial revolution, when $C(0) \equiv C_0 = 280$ppmv. This reduction in the cooling infrared radiation flux applies to the lower 10-15km of the atmosphere and its lower surface (ocean, land, biosphere and cryosphere).

The value of $4Wm^{-2}$ for a doubling of CO_2 concentration used in the above equation not only reflects the reduction in upward infrared emission to space by this layer, but also increased downward emission from the upper atmosphere[2]. The logarithmic dependence is shown in Myhre et al[3]. Finally, note that Q(t) is the average value of the anthropogenic heat flux over all latitudes and longitudes. The spatial distribution is such that a larger heat flux is found at low than at high latitudes[4] but this difference will be ignored here.

of CO_2 doubling, which is some 280 years at a rate of 1ppmv per year increase. The time of CO_2 doubling will be indicated in the Figures of this paper by a red line, and is a standard benchmark for atmospheric CO_2 increase in climate studies[2].

Before proceeding, I would like to stress the idealized nature of the anthropogenic scenario described above. For one thing, the use of a constant linear growth rate in atmospheric carbon dioxide concentration does not capture accurately the time evolution of this quantity: the rate was probably smaller than 1ppmv/yr near the start of the industrial revolution and is larger at present (Figure 1 suggests current values closer to 2ppmv/yr).

Conversely, it is a deliberate choice not to consider other forcing agents of human origin such as methane and aerosols. The net anthropogenic forcing represents the collective effect of many different and partially offsetting processes and addressing all of them is beyond the scope of this paper. I would simply argue in my defence that if the greenhouse effect due to carbon dioxide alone, as measured by Q(t), is found to be large when expressed in more telling units of equivalent physical change in the next section, then restricting oneself to carbon dioxide provides a plausible answer to the question of the strength of the anthropogenic forcing. Finally, readers well versed in the climate literature might be surprised not to see mention of climate feedbacks in estimating Q(t). This issue is fully addressed in section 5.

3. Cryospheric melting and sea level rise

In this section, I aim to show how big the anthropogenic climate forcing from CO_2 is by giving examples of physical processes that would be equivalent in magnitude and can perhaps be more readily understood by a non-specialist.

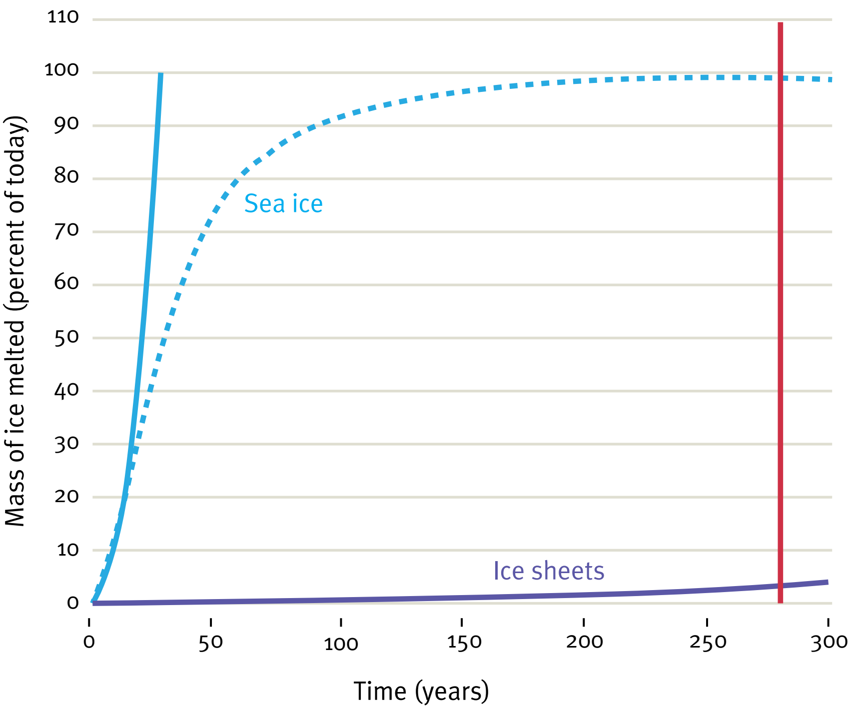


Figure 3. The anthropogenic heat flux Q(t) "measured" in equivalent units of mass of melted ice sheet (blue) and sea ice (light blue) as a function of time (in years). Both masses are expressed as a fraction of their current value. For sea ice, the continuous line is a calculation at fixed surface area while the dashed line is a calculation at fixed thickness (1m). The red line indicates the time of atmospheric CO_2 concentration doubling.

Let me start by "converting" the anthropogenic heat flux into a more charismatic quantity, namely the melting of the ice sheets of Antarctica and Greenland. The heat energy required to melt a mass of ice sheet is proportional to the mass of ice multiplied by the latent heat of fusion of ice, that is the energy measured in Joules required to turn one kilogram of ice into liquid water.

A reasonable assumption is that all the energy available from the anthropogenic heat flux can be assigned to this melting because ice is a good absorber of infrared radiation falling directly on to it (conversion of heat into heat). Thus, the mass of ice that is melted at each point in time, denoted $m_{melt}(t)$, is simply found by accumulating Q(t) over time and over the surface area A_{is} covered by the ice sheets. The simple mathematics are given in Box 3.

Figure 3 (dark blue curve) shows the mass of ice that the anthropogenic heat flux could melt as a percentage of the current mass of ice sheet. We can see that measured in these terms, the anthropogenic heat flux is equivalent to only a very small fraction of ice melt, on the order of a few percent over the 300-yr time period displayed.

A consequence of melting the ice sheets is a rise in sea level and this provides another telling measure to consider. The corresponding sea level rise is found by dividing the increase in volume of liquid by the area of the ocean and is shown in Figure 4 (continuous blue curve). As can be seen, in this new unit of measure, the anthropogenic heat flux appears much more significant for human society,

Box 3. Ice-sheet melting and sea level rise

To melt a mass, m_{melt}, of ice sheet requires an energy equal to the latent heat of fusion of ice ($l_f = 3 \times 10^{5}\ Jkg^{-1}$) multiplied by the mass melted, m_{melt}.

The mass of ice melted, $m_{melt}(t)$, is simply found by accumulating Q(t) over time and over the surface area, A_{is}, covered by the ice sheets. Mathematically this reads:

$$l_f m_{melt}(t) = A_{is}\int_o^t Q(t')dt'$$

The result is displayed in Figure 3 (dark blue curve), as a fraction of the current mass of ice sheet (around 2.5×10^{19} kg)[5] and using the current value $A_{is} = 1.36 \times 10^{13}$ m², which is about 3% of the earth's surface[6].

The associated sea-level rise is found by dividing the increase in volume of liquid water resulting from ice-sheet melting by the ocean's surface area. The volume of water resulting from the melting is given by

$$\text{Volume} = m_{melt}(t)/\rho_l$$

where $\rho_l = 1000$ kgm^{-3} is the density of (fresh) liquid water. Since the ocean's surface is $A_o = 3.6 \times 10^{14}$ m² —about 70% of the earth's surface – the change in sea level due to this equivalent ice-sheet melting, denoted $\Delta h_{is}(t)$, is given by:

$$\Delta h_{is}(t) = \frac{A_{is}}{A_o \rho_l l_f}\int_0^t Q(t')dt'$$

The result is displayed in Figure 4 (continuous blue curve).

with a rise of sea level of about 2.5m by the time of CO_2 doubling.

Let me reflect on these numbers. The forcing Q, expressed as a fraction of ice sheet melted appears negligible. But viewed as a sea level change this same effect is enormous. This is simply because even a few percent of the ice sheets contain a massive amount of water. From a socio-economic perspective, the calculation shows that there is enough additional energy available to cause a severe disruption to human activities. Indeed, in the "Risk and Impact" literature, sea level changes are considered moderate below a 0.35m rise by 2080[7] while the numbers in Figure 4 are nearly an order of magnitude larger. Or, to make a rise of sea level of 2m more palpable, it would, according to a recent study of the risk of rising sea level to population and land area[8], affect a population on the order of 175 million.

I will now consider how large the anthropogenic heat flux is in relation to the metre-thick or so layer of sea ice formed as a result of surface cooling of the ocean at high latitudes. The result is displayed in Figure 3 (light blue continuous line), which shows the mass of melted sea ice as a percentage of the current sea ice mass, assuming a fixed surface area and a thinning of the sea ice and no seasonal cycle – in other words the analogous calculation to that carried out for the ice-sheets on land. We see a rapid decline of the sea ice cover, with 100% of the current mass disappearing just a few decades after the start of the increasing atmospheric carbon dioxide concentrations. (I should add that I have used a current value for the mass of sea ice[5], of 2×10^{16} Kg, and a value of $2.25 \times 10^7 km^2$ for the sea ice area[9]).

This 'sea-ice thinning' scenario is of course not the only way that the sea ice can melt. An alternative calculation can be carried out by assuming a fixed thickness but letting the surface area shrink. This 'shrinking' scenario is shown by the light blue dashed line in Figure 3. As the sea ice area decreases, less of the infrared radiation can be absorbed because less area of ice is exposed, so it takes longer to melt the sea ice by "shrinking" than by "thinning". (Such a calculation can also be applied to the ice sheet case but the difference between "thinning" and "shrinking" scenarios is negligible). The conclusion remains however unchanged: there is enough additional energy available in Q(t) to cause a severe change—the disappearance of more than half the sea ice cover on a timescale of a few decades.

The melting of sea ice only induces a very small increase in sea level because the sea ice is already floating on the sea. The increase results from the fact that sea water is slightly denser than the freshwater from which sea ice is made. If all the sea ice melted, the global sea level would go up by only 1 mm or so.

One can also carry out an analysis for a rise in sea level due to thermal expansion of the ocean, which without double counting, we can assume takes place in parallel with the melting of the ice-sheets. I will assume in the following that the sea level rise results from the warming of an ocean layer whose contact area with the atmosphere is the whole surface area of the oceans, and I will denote the pre-industrial volume of this layer as V_o. The energy available to increase the temperature of this layer per unit time and area is the anthropogenic heat flux Q(t), but some of this energy will also be used to do work against gravity as the sea level rises (i.e.; against the pressure of the surrounding water below and air above). It can nevertheless be shown that the latter effects are tiny compared to the change in heat content of the ocean layer. Box 4 provides the relevant equations.

Box 4. Thermal expansion of the ocean

Cumulating Q(t) over time, the change in ocean heat content is given by the following expression:

$$m_o c_o \Delta T_o(t) = A_o \int_0^t Q(t')dt'$$

where A_o is the surface area of the ocean, m_o is the mass of the ocean layer considered, c_o is the specific heat capacity of seawater and $\Delta T_o(t)$ is the change in ocean temperature from its pre-industrial level.

If we denote the change in sea level induced by ocean warming by Δh_{te} for "thermal expansion", using the equation of state for seawater we find that the change in the ocean volume due to thermal expansion is given by:

$$A_o \Delta h_{te} = \Delta V = V_o \alpha_T \Delta T_o$$

in which α_T is the thermal expansion coefficent. Rearranging, one obtains:

$$\Delta h_{te}(t) = \frac{\alpha_T}{\rho_o c_o} \int_0^t Q(t')dt'$$

in which I have introduced a typical seawater density $\rho_o = 1027\ kgm^{-3}$ and used $m_o = \rho_o V_o$. The sea level change due to thermal expansion is plotted in Figure 4 (green).

The energy required to raise the global sea-level by 1 cm through thermal expansion of the oceans is therefore 1 cm x $A_o \rho_o c_o / \alpha_T$, while from Box 3, the energy required through melting the ice sheets is 1 cm x $A_o \rho_i l_f$. The ratio of these quantities is $\rho_o c_o / \alpha_T \rho_i l_f$ which turns out to be ≈ 137. As a result, the total rise in sea level from both effects ($\Delta h_{is} + \Delta h_{te}$, shown as the blue dashed curve in Figure 4) is dominated by the ice sheet contribution by a factor of $137\ A_{is}/A_o \approx 4$.

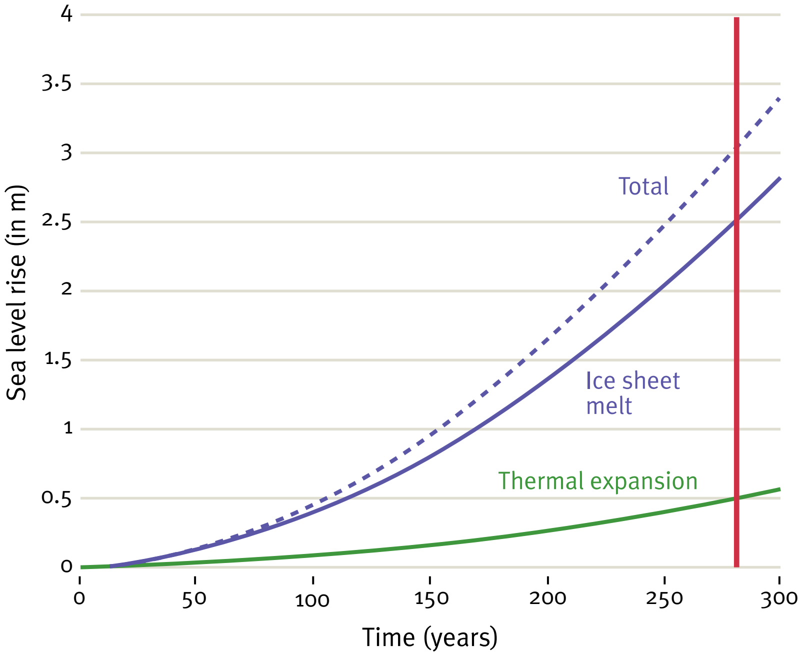


Figure 4. The anthropogenic heat flux Q(t) “measured” in units of sea level rise (in metres) as a function of time (in years); melting of the ice sheets (Δh_{is}, continuous blue) and thermal expansion of the oceans (Δh_{te}, green), and the sum of these two effects (dashed blue line). The time of atmospheric CO_2 concentration doubling is again indicated by the vertical red line.

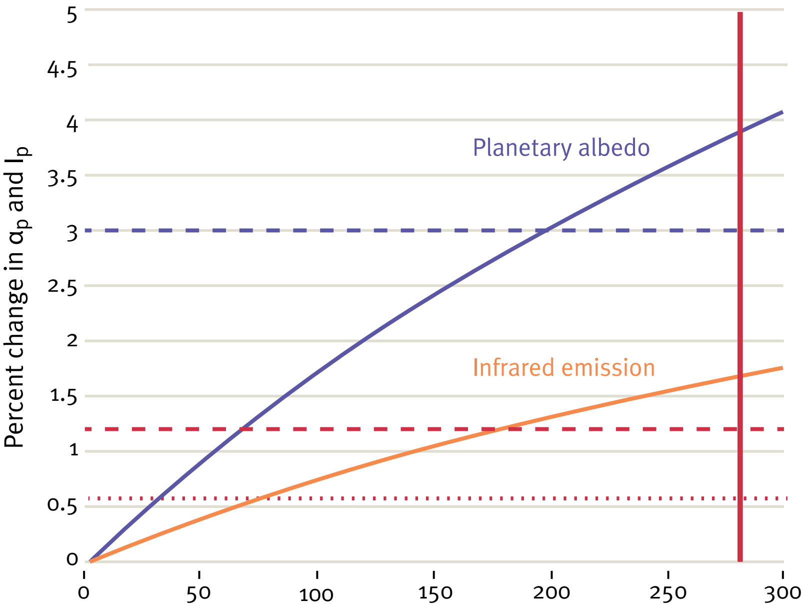


Figure 5. A measure of the anthropogenic heat flux in terms of equivalent percent change in planetary albedo (continuous blue) and infrared emission (continuous red). The dashed curves indicate the observed seasonal change in these quantities (blue for α_P, red for I_P). A typical positive yearly excursion of $\delta I_P / I_P$ is also plotted as the horizontal red dotted line. The vertical red line indicates the time of atmospheric CO_2 doubling.

The corresponding sea-level rise due to the thermal expansion of the ocean (the green curve in Figure 4) is smaller than that due to ice sheet melt since it takes more energy to raise the sea level by 1cm through thermal expansion of seawater than through melting ice (see Box 4 for details). Taken together and neglecting the tiny contribution from the melting of sea-ice, these two effects yields a sea level change of about 3m by the time of CO_2 doubling, as shown by the blue dashed curve in Figure 4.

4. Planetary albedo and infrared radiation

I now wish to put the anthropogenic heat flux in a completely different perspective. As introduced in section 2, Q(t) physically reflects a reduction in the rate at which the earth cools by emitting infrared radiation to space. Rather than cumulate over time the associated “trapping” of energy, as was done in the previous section, I now wish to compare Q(t) directly to seasonal variations in the radiative heating and cooling of the planet. The reason for this choice is that these seasonal fluctuations are large, being caused by the tilting of the earth’s axis of rotation and other geometric effects such as the elliptical orbit of the earth around the sun and the irregular distribution of continents at the earth’s surface.

As a result, significant seasonal fluctuations in planetary infrared emission or reflected solar radiation are observed. Thus both provide a natural benchmark to determine whether any other type of radiative perturbation is large or small. Although discussing quantities with units of Wm^{-2} will seem at first sight to lose the more telling aspect of the units used in section 3, it will provide an observational counterpart to the numbers obtained from simple physical arguments in section 3.

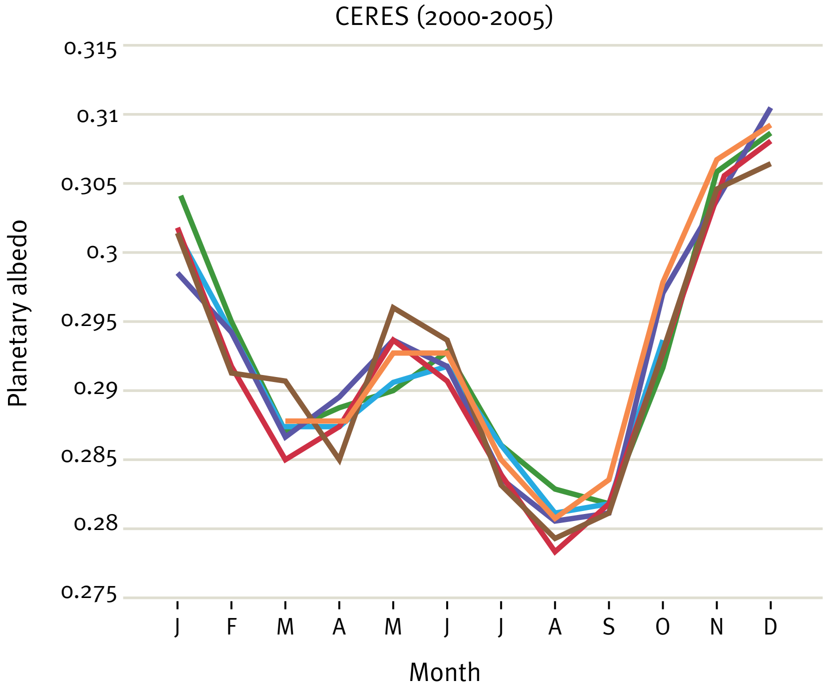


Figure 6. Monthly evolution of the planetary albedo, as measured by the CERES mission. Each curve represents a different year (2000-2005).

Box 5. Equivalent changes in planetary albedo and infrared radiation

The aim is to find the change in planetary albedo that equates to the increase in the anthropogenic heat flux. The solar flux is $S_o/4$, where $S_o = 1368$ Wm^{-2} is the "Solar constant" (though it varies – see the Grantham Briefing Paper 5 on "Solar Influences on Climate") and the factor of 4 takes into account the spherical geometry of the Earth. The reflected solar energy is given by $\alpha_P S_o/4$ so that the equivalent change in albedo, $\delta\alpha_P$, is given by:

$$\delta\alpha_P (S_o/4) = Q(t)$$

or equivalently

$$\delta\alpha_P(t)/\alpha_P = 4Q(t)/S_o\alpha_P$$

To estimate the change in the Earth's infrared radiation δI_P that would be equivalent to the anthropogenic heat flux due to CO_2, i.e., $\delta I_P (t) = Q(t)$, I note that in equilibrium, the infrared radiation of the earth exactly opposes the net absorption of solar radiation (see Box 1), i.e.,

$$I_P = S_o(1 - \alpha_P)/4$$

As a result, the relative change in I_P is:

$$\delta I_P (t)/I_P = 4Q(t)/S_o(1 - \alpha_P)$$

As seen from space, the earth receives energy in the form of shortwave electromagnetic radiation from the Sun and cools to space by reflecting a fraction of this energy back and by radiating energy in the infrared. In Figure 5, I have plotted the percent decrease in the reflection coefficient α_P (the "planetary albedo") which would match exactly the anthropogenic heat flux, Q(t). The underlying equations are shown in Box 5. On average the earth reflects about 30% of the solar energy it receives (i.e. α_P is about 0.3) and from Figure 5 we see that by the time atmospheric CO_2 has doubled, the anthropogenic heat flux is equivalent in magnitude to about a 4% reduction in planetary albedo. One can similarly also calibrate Q(t) against a decrease in the planet's emitted infrared radiation I_P (see Box 5 for underlying equations), and this is shown by the red curve in Figure 5. In this new "unit", the anthropogenic heat flux is measured by a 1.5 % relative change in infrared emission at the time of atmospheric CO_2 doubling.

Let me now compare those changes to seasonal observations, starting with the planetary albedo provided by the CERES satellite mission over the 2000 – 2005 period[10] (Figure 6). The highest planetary albedo is found in December, consistent with the persistent snow cover over Antarctica in Austral summer and the tilt of the earth towards the sun at that time of year. Two relative minima are found in March-April and August-September, which is consistent with the lower albedo of low latitude regions that are the most exposed to the sun at that time of year. The typical variation observed, as measured by the standard deviation of the monthly time series, is $\delta\alpha_P$ =0.009 with a mean value of 0.29, i.e., a relative change 0.009/0.29 = 3% (dashed blue

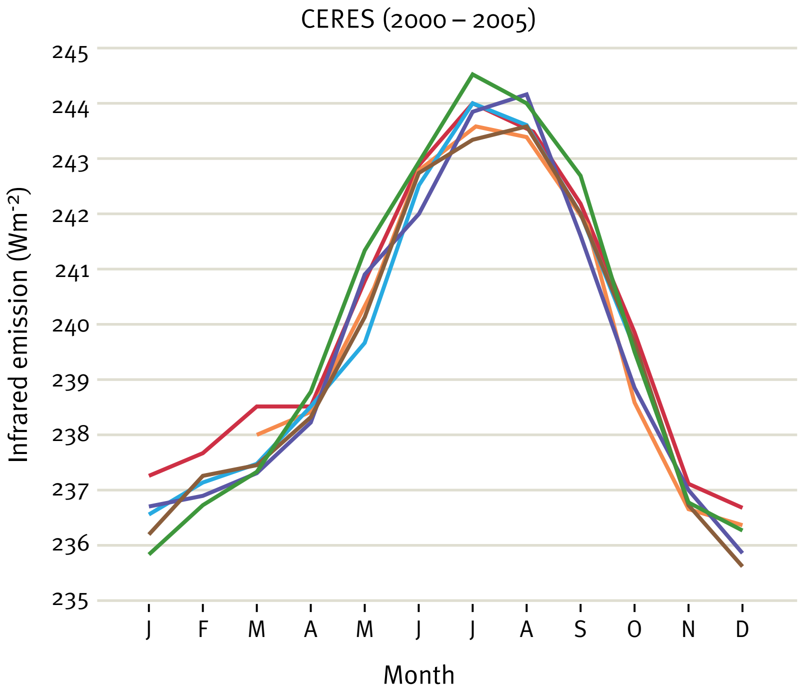


Figure 7. Monthly evolution of the planetary infrared emission (in Wm^{-2}), as measured by the CERES mission. Each curve represents a different year (2000 – 2005).

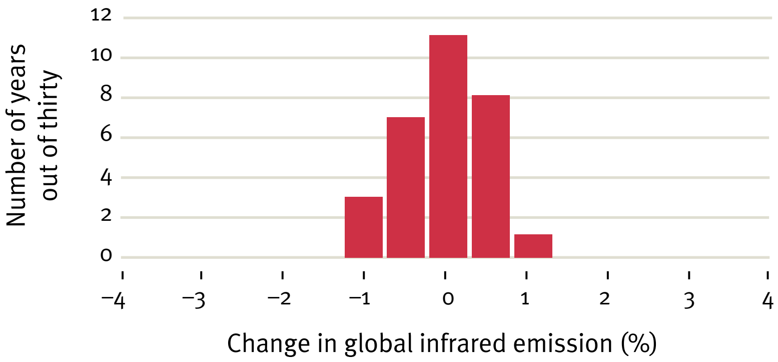


Figure 8. Distribution of the departures of annual mean planetary infrared emission from the 30-yr mean record (in %) obtained from NOAA polar orbiting satellites (1980 – 2009).

curve in Figure 5). This benchmark is reached by the anthropogenic heat flux after 200 years.

CERES observations of the planetary infrared emission are next shown in Figure 7. As was found for the planetary albedo, differences in geometries of the Northern and Southern hemispheres leave an imprint on the planetary infrared emission: the earth emits more in July than it does in January, reflecting the larger surface temperature reached in the more land-covered Northern Hemisphere in Boreal Summer. The standard deviation of the monthly time series is 2.85 Wm^{-2}, with a mean value of 239.65 Wm^{-2}, a 1.2 % relative change in I_P (dashed red curve in Figure 5). It is seen that this value is reached by Q(t) after about 180 years in Figure 5.

The instrumental record of planetary infrared emission is longer than that of planetary albedo, and out of curiosity, it is worth going beyond the seasonal changes at the core of this section to investigate inter-annual variations in I_P. To do so I will use the 30-yr record provided by the NOAA polar orbiting satellites[11]. In Figure 8, the distribution of $\delta I_P/I_P$ is shown, constructed from annual deviations from the 30-yr mean. One notes that inter-annual changes are small in comparison to the seasonal cycle variations. For example, the median for the population of records satisfying $\delta I_P/I_P > 0$ is $\delta I_P/I_P$ = 0.55 %, about half the size of the seasonal amplitude noted above. This typical value for inter-annual excess of planetary infrared emission is plotted as a dotted red line in Figure 5. It is reached by Q(t) after about 70 years. No positive annual mean excursions of I_P on record exceed a 1.25 % increase or decrease.

In summary, I aimed in this section at putting the anthropogenic heat flux Q(t) into perspective through a direct comparison with observations of natural variation in the earth's incoming and outgoing heat fluxes. The seasonal cycle offers a robust natural benchmark to do so and the result of the comparison is very clear: the anthropogenic forcing, Q(t), is well above the amplitude of the seasonal cycle by the time of doubling of atmospheric carbon dioxide concentrations.

5. Limitations of the previous calculations

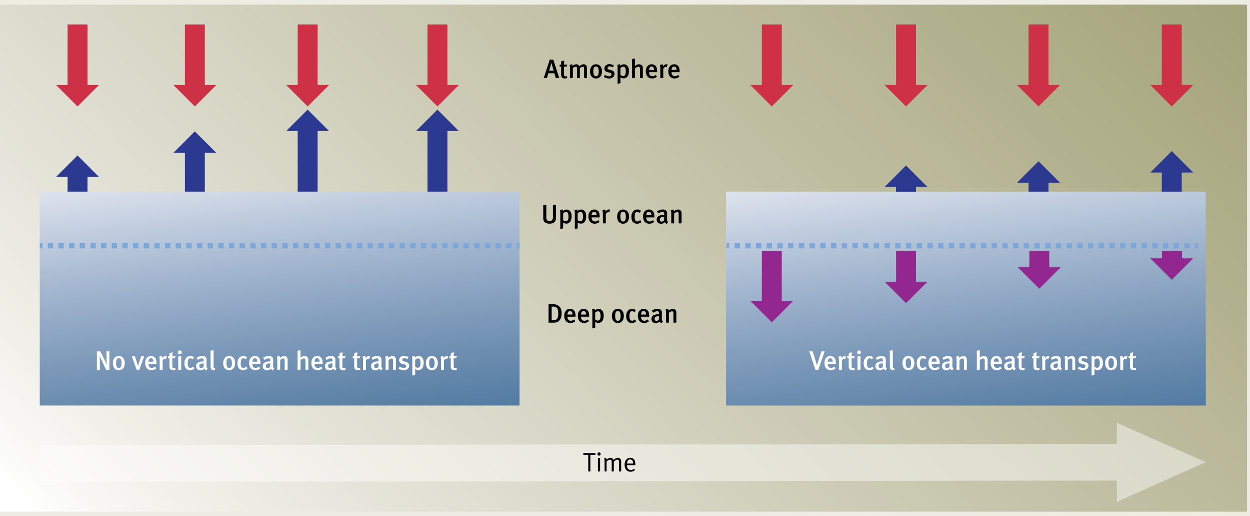
As emphasized in section 1, none of the calculations carried out in sections 3 and 4 are climate predictions. As the earth warms, over time it emits more infrared radiation, thereby opposing the initial reduction in infrared emission caused by the increase in atmospheric carbon dioxide concentration, as explained in Box 1. The net energy available to produce changes such as those discussed in section 3 is thus less than Q(t) in a truly interactive climate system. Q(t) must therefore be seen as an upper-bound on the energy available to perturb the climate system. The calculations above were a logical first step in that they show that this upper bound is enough to produce major changes in sea ice cover distribution (disappearance) and sea level (a rise of a few meters) on a timescale measured in decades to centuries, and certainly less than a millennia. So the forcing is potentially large, but the above calculations do not allow one to go further and predict how large the actual changes will be.

One might therefore be tempted then to disregard the "fixed climate assumption" and the use of Q(t) as a plausible measure of the anthropogenic forcing. I would suggest, however, that because of the effect of the ocean circulation on climate, the calculations presented in the earlier parts of this paper are more relevant to the "fully interactive" climate system than might initially be supposed. As alluded to in the previous paragraph, the factor limiting the interpretation of Q as a true measure of radiative changes is the presence of feedbacks in the climate system. These indeed ultimately control the size of the equilibrium response of the climate system to the anthropogenic forcing, achieved over several centuries. But feedbacks are not the only mechanism controlling its *transient* response on shorter timescales: the storage of heat by the ocean is another key influence.

To illustrate the idea, consider the situation depicted in Box 6 in which, as in Box 1, one investigates the mechanism of adjustment of the climate to a sudden doubling of atmospheric carbon dioxide concentration. The left panel shows an hypothetical world in which there is a motionless ocean and no significant exchange of heat from the upper to the deeper ocean layers. In this climate system, the time it takes to respond to an increase in the greenhouse effect of CO_2 is controlled by the

Box 6. A thought experiment illustrating the impact of vertical ocean heat transport on the adjustment to anthropogenic forcing

Two idealized responses of the climate system to an imposed fixed radiative perturbation (red downward arrow) — here resulting from an imposed doubling of atmospheric carbon dioxide concentrations as in Box 1. Left-hand diagram: In absence of vertical ocean heat transport, the upper ocean warms and rapidly (in a decade or so) opposes the radiative perturbation by emitting more infrared radiation (blue upward arrow, which grows over time as the surface warms). Right-hand diagram: With vertical ocean heat transport (purple arrows, decreasing with time as the deep and surface ocean temperatures equalise), the surface is tied to the deep ocean and the warming occurs on a much longer timescale — it takes several centuries to oppose the radiative perturbation. In each case the distance between the tip of the blue and red arrows measures the energy available for warming the ocean and, accordingly, raise sea level. The right panel scenario becomes relevant when the ventilation timescale for the upper ocean (i.e. the time it takes to renew the volume of water the upper ocean layer contains) is comparable to the timescale t_c given in section 5 — this holds for the present day ocean.



heat capacity of the upper ocean layer. For a typical layer of thickness $d = 100$m, and typical strength of climate feedbacks $\lambda_C = 0.9\text{-}2\ \mathrm{Wm^{-2}K^{-1}}$, in line with estimates of climate sensitivity[5], the adjustment timescale t_c is given by $t_c \equiv (\rho_o c_o d / \lambda_C)$. This timescale is of the order of a decade. Beyond that, there is as much excess heat radiated to space as a result of the warmer upper ocean than is trapped as a result of the increased greenhouse effect of carbon dioxide. With a static ocean there is therefore no significant accumulation of heat in the climate system. Considering that it was shown earlier that Q(t) must cumulate over several decades to produce significant changes, the calculations of section 3 and 4 would therefore be irrelevant if the climate system really were like this.

One does not need to have a PhD degree in Statistics or Physics to grasp the problem ... it is simply a matter of putting numbers on the size of anthropogenic forcing of climate using well established and straightforward physics

Now consider a more realistic model of the climate system in which there is exchange of heat from upper to deeper ocean layers, as there is today (Box 6, right hand panel). If the associated vertical heat transport is large enough, one can imagine a scenario in which, rather than being used to heat the upper ocean, the excess heat induced by the greenhouse effect of CO_2 is instead transferred to the deep ocean. In this case, the surface experiences only slow changes in temperature because it is tied to the large thermal inertia of the deep ocean. The corresponding characteristic timescale for the deep ocean is several centuries rather than a decade or so. In this scenario, heat is accumulated in the deep ocean, driving thermal expansion, and the sea level rise calculations in section 3 become relevant.

6. Conclusions

In summary, I have focused in this paper on the strength of the anthropogenic forcing of climate rather than on the magnitude of the predicted climate response to this forcing. Direct conversions of the additional thermal forcing associated with the enhanced greenhouse effect of CO_2 into latent heat and thermal expansion suggest that there is enough energy to produce important changes in sea level (rise measured in metres) and sea ice cover (complete disappearance) by the time of doubling of atmospheric carbon dioxide concentrations.

From a different perspective, using satellite observations of global radiative exchange between the earth and space, it is evident that the anthropogenic forcing reaches a magnitude larger than seasonal variations in either reflected solar energy or planetary emission of infrared energy by the time of atmospheric CO_2 doubling. Thus by both conceptual and observational benchmarks it is clear that the anthropogenic forcing of climate is “large”.

It is true that acknowledging a large forcing does not imply a large “response”: there might well be powerful negative feedback mechanisms in nature enhancing the sensitivity of the earth’s planetary emission of infrared radiation to temperature, thereby keeping the climate close to its pre-industrial state. If so, such mechanisms must involve physics which is absent from the current generation of global climate models, which are based on our best physical understanding, because their collective behaviour is at odds with the presence of such an efficient negative feedback.

The approach used here was very rudimentary, and climate experts might be shocked by the drastic simplifications I have used. But that was precisely the point: an attempt to get an intuitive feeling for the size of the anthropogenic forcing through “back-of-the-envelope” calculations. Though not offering clear cut conclusions because of this limited objective—a focus on the “forcing” rather than the “response”—it is hoped that the value of this approach is that it allows a large audience to make up its own mind about the question: is it possible that the greenhouse gases we are adding to the atmosphere could have a large impact on our climate?

About the author

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Dr Czaja’s research focuses on atmosphere-ocean interactions and the basic physics of oceanic and atmospheric circulations. If interested in running yourself illustrative climate models, like the one developed at Imperial for the Environmental Physics course, please visit Dr Czaja’s webpage at: http://www.sp.ph.ic.ac.uk/~arnaud/.

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