The greenhouse effect: a closer look

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Interest in carbon dioxide (CO_2) and water vapour (WV) as greenhouse gases (GHGs) has waxed and waned over 200 years, the twists and turns being neatly summarised by Mudge (1997). The early pioneers, Arrhenius, Tyndall, Fourier and Callendar, were mostly interested in CO_2 from the standpoint of explaining ice ages. Today's concerns are that increased amounts of CO_2 in the atmosphere will cause Earth to warm up, possibly 'disastrously', over the next century. This article looks at the processes involved in the Greenhouse Effect (GHE), discusses the uncertainties, in particular the role of water vapour (WV), and reviews the overall situation.

Structure of the atmosphere

Figure 1 shows the names given to different parts of the atmosphere. There is a fourth layer above the mesosphere called the thermosphere, but it does not concern us here; indeed only the troposphere and stratosphere do. The tropopause has a range of heights, being lower in the high, cold, latitudes than over equatorial regions. All of the 'weather' and most clouds are in the troposphere.

How the Sun warms the Earth

Solar energy input

Averaged over a year, the maximum intensity of solar radiation (the *Solar Constant*) just outside Earth's atmosphere, at right angles to the incoming rays, is about $1366 Wm^{-2}$. It is averaged over a year because Earth is in an elliptical orbit, being closest to the Sun on 3 January and furthest away on 4 July, causing the maximum radiation to vary over the year by 6.3%. Averaged over all latitudes and times of day and year, $342 Wm^{-2}$ of solar energy (wavelength $0.2\mu m$ to $4.0\mu m$) arrives at the top of Earth's atmosphere. The radiation values given here, and in Figures 2 and 4, are from Kiehl and Trenberth (1997).

As the radiation propagates downwards, about 20% ($67 Wm^{-2}$) is absorbed by the atmosphere, warming it, while 23% ($77 Wm^{-2}$) is scattered and reflected back to space from the air, clouds and aerosols, 58% ($198 Wm^{-2}$) arriving at the surface. Some of this is then reflected back to space, the 'albedo' ranging from 3% to 10% for the sea, to 90% for fresh snow, with an average of 9% ($30 Wm^{-2}$). Overall, $107 Wm^{-2}$ is lost back to space, just under half ($168 Wm^{-2}$) of the original input being retained at the surface (Figure 2) – 15% ($24 Wm^{-2}$) of this warms the surface (land and sea), which then warms the air in contact with it; 45% ($78 Wm^{-2}$) evaporates water and the remaining 40% ($66 Wm^{-2}$) is radiated as infrared (IR) radiation.

The sensible heat flux

The surface is not heated evenly by solar radiation because conditions vary from place to place causing some areas to warm more than others and thermals to develop there. These rise and expand, cooling in the process, until they reach air of the same temperature, whereupon ascent stops. The air cools upon expansion for reasons described by the gas laws of Boyle, Dalton,

Figure 1. Structure of the atmosphere.

Charles and the Ideal Gas Equation (Pressure x Volume = Temperature x a Constant) as well as the First Law of Thermodynamics (the Conservation of Energy). Provided the rising thermals do not mix to any great extent with the surrounding air, or exchange heat with it (a process defined as *adiabatic* from the Greek words for 'impassable'), the cooling is from 6 degC to 10 degC for each kilometre increase in height, this being known as the *dry adiabatic lapse rate*. The process of warmed air moving upwards is known as the *sensible heat flux*, 'sensible' because it can be sensed as a temperature change. These convective processes do not act alone in transporting heat away from the surface, but usually in combination with advection by the wind and the turbulence within it, the overall process being a complex mix of the two in varying proportions.

The latent heat flux

Water evaporated at the surface is carried aloft as water vapour (WV) within the warmed currents of air. This is known as the *latent heat flux*, 'latent' because the change is hidden, there being no change of temperature, just a change of state from liquid to gas. If the rising air cools to the dew point (or frost point), the WV condenses out, forming cloud droplets (or ice crystals). When the vapour condenses, all the heat that evaporated the water at the surface is released, warming the air at that altitude. Consequently the *wet adiabatic lapse rate* of moist air is only about half that of dry air. The important point, however, is that the WV transfers heat away from the surface, releasing it high in the atmosphere – often many thousands of kilometres distant.

Thus the troposphere is heated from the bottom-up by these two fluxes. In the stratosphere, heating is from the top-down, induced by the interaction of incoming UV solar radiation with oxygen, producing ozone. For this reason, the temperature increases with height in the stratosphere. Consequently where the troposphere and stratosphere meet, at the tropopause, the temperature is at a minimum (Figure 1).
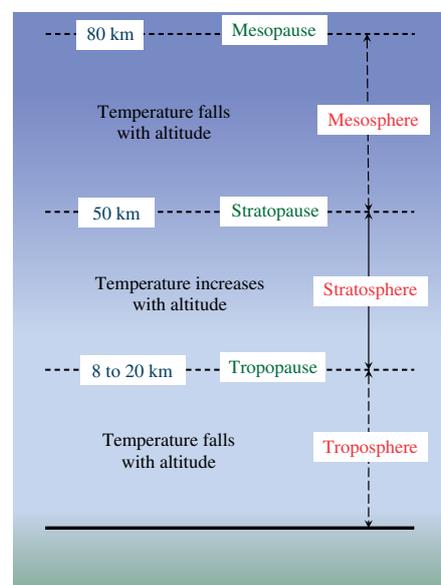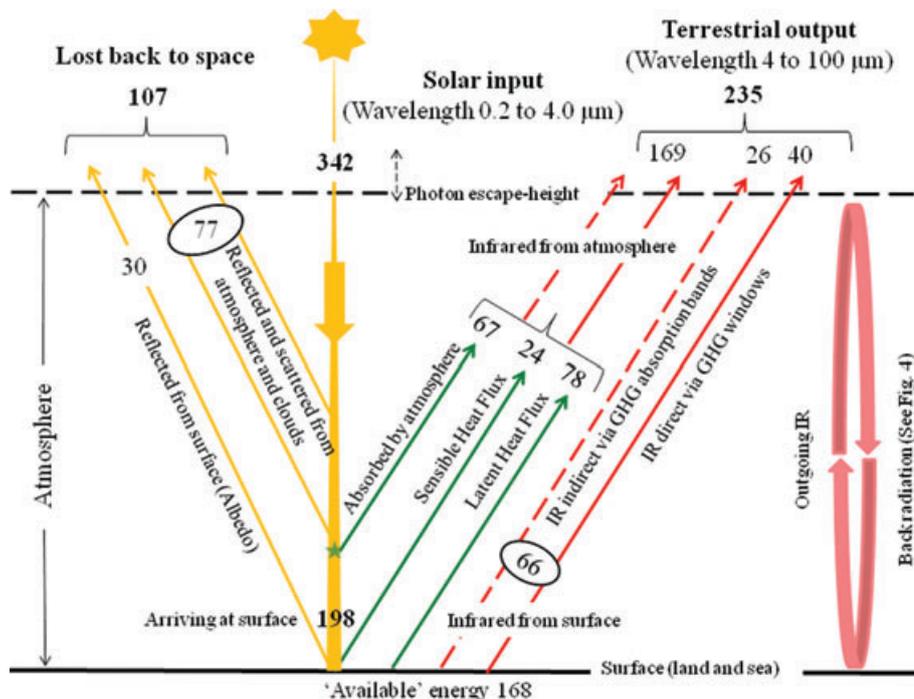
Figure 2. Energy exchange of solar and terrestrial radiation. Yellow lines represent short-wave radiation received from the Sun. Green lines represent the physical transport of heat (by convection and advection). Solid red lines represent the direct transmission of IR radiation to space through the GHG windows. Broken red lines represent IR radiation travelling to space via the GHG absorption bands by repeated absorption and re-radiation. The values shown are averages for the whole globe over a year. See text for discussion.

The infrared flux

The sensible and latent heat fluxes transfer 61% (102Wm^{-2}) of the received solar energy away from the surface, leaving 39% (66Wm^{-2}) which is radiated as IR (in the range 4μm to 100μm). However, warmed by the sensible and latent heat fluxes (and by direct absorption of some of the incoming solar radiation), the atmosphere itself also radiates in the IR bands (Figure 2).

Terrestrial energy output

If Earth did not lose as much energy as it receives from the Sun it would warm up until it achieved equilibrium with the input. It was shown earlier that, on average, Earth receives 342Wm^{-2} input from the Sun, of which 107Wm^{-2} is lost back to space by reflection and scattering. So, to be in equilibrium, Earth must lose the difference, or 235Wm^{-2} (Figure 2). The only way this energy can be lost is via an exchange of electromagnetic radiation with space.

All bodies above absolute zero (−273.15°C) emit radiation, the amplitude and the frequency being quantified by the laws of Stefan, Wien and Planck, which state that the energy radiated by a *black body* (a perfect radiator) is directly proportional to the fourth power of the thermodynamic (absolute) temperature. The range of frequencies and the peak frequency are also dependent on temperature; Earth's temperature is such that it radiates mostly

in the IR, and so it cools by radiating sufficient IR to space to balance the amount incoming as solar radiation.

The greenhouse effect

Exactly how Earth maintains a stable temperature is a complex matter involving the propagation of IR radiation within the atmosphere and its interaction with the various gases that constitute it.

Composition of Earth's atmosphere

Our atmosphere is made up (by volume) of nitrogen (78.09%), oxygen (20.95%) and argon (0.93%), totalling 99.97%, leaving 0.03%. These three main gases are virtually transparent to all IR wavelengths and if the atmosphere was composed solely of them, the 235Wm^{-2} required to achieve balance would be radiated directly to space from the surface and from all depths of the atmosphere, unimpeded.

Carbon dioxide

Most of the remaining 0.03% of the *fixed-composition* atmosphere is carbon dioxide (CO_2) and this is different to the three main gases because it absorbs IR radiation in several bands (Figure 3(a)). It does this because the CO_2 molecule consists of three atoms (triatomic) rather than just the two of the

main gases (diatomic), allowing it to flex, spring-like, under the influence of radiation. However, gases that absorb radiation also radiate it, again through the same flexing action. Consequently the IR radiation emitted from the surface and from within the atmosphere (in the CO_2 absorption bands) is not only absorbed by the CO_2 but is also re-radiated by it. This absorption and re-radiation takes place throughout the depth of the atmosphere.

There are other GHGs such as methane but they are of lesser overall importance than CO_2 and WV.

Water vapour

Like CO_2, being triatomic, WV also absorbs and re-radiates IR radiation, Figure 3(b) illustrating its absorption spectrum. However, unlike CO_2, the amount of WV varies greatly from place to place and over time; it can constitute as much as 3% of the total volume of the atmosphere under some conditions. We will return to the complex part WV plays in the GHE later. First let us look at CO_2 in isolation.

Influence of the carbon dioxide

If Earth's atmosphere contained no GHGs, all the IR radiation would be propagated directly to space and would be 'lost'. The world would be cooler than it is by around 33 degC, having an average temperature of around −18°C instead of its present +15°C, for reasons that will now be explained.

If the atmosphere contains a small amount of CO_2, while the IR radiation outside of its absorption bands still radiates unimpeded directly to space, that within the absorption bands now makes its way upwards through innumerable absorptions and re-radiations in all directions, much of it back to the surface. Only at high altitudes does the CO_2 become sufficiently diffuse for the IR photons (in the absorption bands) to begin escaping into space. By this complex route of propagation – directly through the CO_2 windows and indirectly through its absorption bands – Earth cools, losing the required 235Wm^{-2} (Figure 2).

However, at those altitudes where the CO_2 is sufficiently diffuse for the photons to escape, the temperature is much lower than at the surface, and at low temperatures the radiating efficiency of the air, as a black body, is lower than that at the higher temperatures at the surface (again as quantified by the laws of Stefan, Wien and Planck). So to achieve the radiation balance required, this upper part of the atmosphere must be at a temperature that produces the required overall loss of 235Wm^{-2}. If the atmosphere is not warm enough to radiate the necessary amount of energy, heat is retained and the
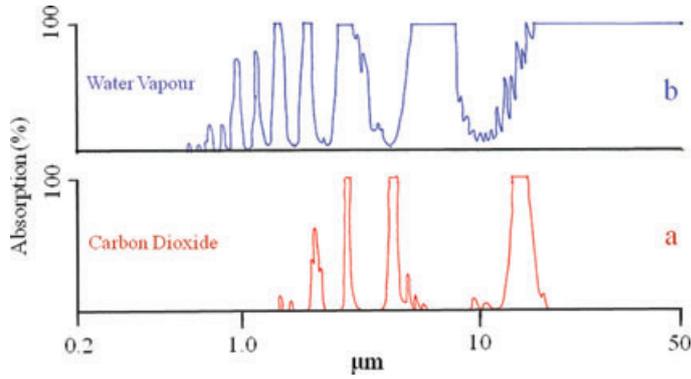
Figure 3. Absorption spectra of water vapour and carbon dioxide.

atmosphere below warms up. Accumulation of energy and the accompanying increase in temperature continues until the upper atmosphere, from where the radiation to space can occur, achieves the necessary temperature to radiate the required amount of energy to balance the solar input. The altitude at which the escape occurs is not a single height but operates over a range of altitudes, photons escaping in increasing numbers as the air gets thinner. This is the GHE.

Back radiation

Because the CO_2 molecules re-radiate IR in all directions, as much IR radiation is directed downwards towards the surface as upwards to space. At present, this results in $324 Wm^{-2}$ of 'back-radiation' arriving at the surface through multiple absorptions and re-radiations which, added to the $66 Wm^{-2}$ from the incoming solar energy budget, totals $390 Wm^{-2}$. This is re-radiated back up again in endless recycling (Figure 4). The average amount of energy retained through this natural greenhouse effect is thus $390 Wm^{-2}$ less the $235 Wm^{-2}$ lost to space, leaving $155 Wm^{-2}$, keeping the surface of the planet 33 degC warmer than it would be without any CO_2. For this we must be grateful, for without the GHE life would probably not have evolved on Earth.

Effect of increased levels of CO_2 in the atmosphere

If the amount of CO_2 in the atmosphere increases, through human or volcanic activity or by the release of gas from the seas, the increased number of CO_2 molecules causes the altitude from which the photons (in the absorption bands) can escape to space to rise. So the loss to space now occurs at a slightly lower temperature (due to the lapse rate) and the temperature of the air at the new altitude has to rise to restore balance. This means that the temperature below has to increase to achieve this – hence the proposition that increasing CO_2 levels will increase the temperature all the way down to the surface, although the relationship of the surface temperature to that at which the photons escape may not be simple.

It can be calculated that a doubling of the pre-industrial concentration of CO_2 from 284 parts per million (ppm) in 1832 (315 in 1958 and currently 392: see ftp://ftp.cmdl. noaa.gov/ccg/co2/trends/co2_mm_mlo.txt) would result in about an extra $4 Wm^{-2}$ being retained, which is added to the $155 Wm^{-2}$ due to the 'natural' GHE. How this might then change the temperature is less simple to estimate because many interactions intervene, as discussed later, but it is considered, in isolation, to be no more than about one degree.

A common misconception in visualising the greenhouse effect

It is useful to look at a common misunderstanding of how the GHE operates. The effect is often looked at from the point of view of someone standing on the surface with the atmosphere above treated as one single slab, like a pane of glass in a greenhouse. What causes the confusion is that at the surface there is already more than sufficient CO_2 (and WV) to prevent the IR radiation (in the absorption bands) escaping *directly* to space (that is the atmosphere is 'saturated' with GHGs in the lower troposphere). The argument put forward from the ground-centred viewpoint is that if the atmosphere is already opaque to IR (in the absorption bands), through the presence of sufficient CO_2, then adding more will make no difference. This sounds logical, but it is not the case for, as shown above, part of the IR radiation escapes to space from the high atmosphere, not directly from the surface, after innumerable absorptions and re-emissions.

This misunderstanding probably arises through the inappropriately-chosen name *greenhouse effect*. Because the glass of a greenhouse is transparent to incoming solar radiation and opaque to outgoing IR radiation, the processes involving CO_2 interfering with the passage of IR radiation has been dubbed the *greenhouse effect*, and CO_2 a *greenhouse gas*. But a greenhouse works mostly by preventing the warmed air from being carried off by convection and the wind. It has little, if anything, to do with the radiation-transmission properties of glass.
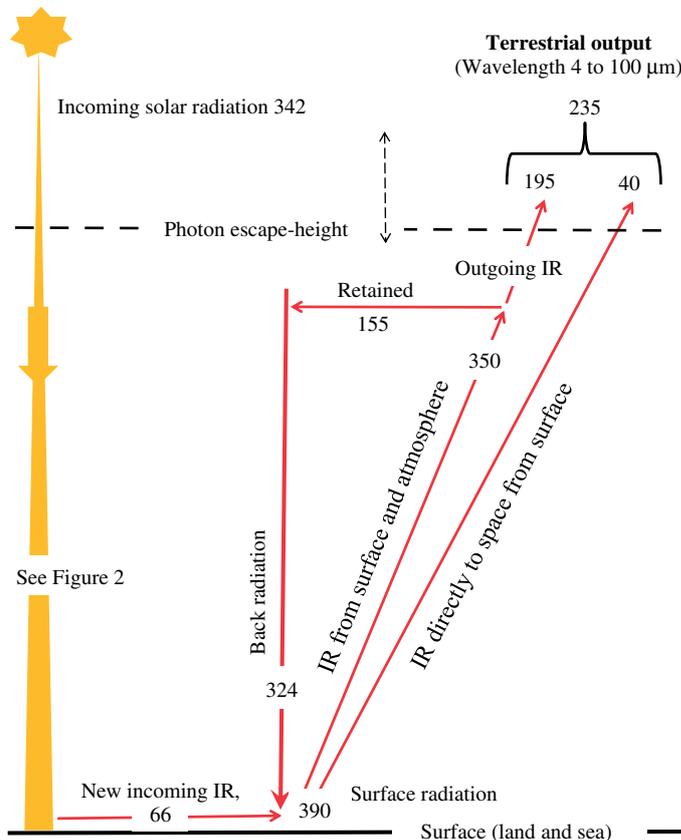
Figure 4. Back radiation due to the greenhouse effect. See text for details.

The plastic sheet (polyethylene) used in horticultural tunnel-greenhouses is transparent to IR radiation, but it still acts as an effective greenhouse (although it may cool more on clear nights).

Water vapour as a greenhouse gas

So far we have looked at CO_2 in isolation. But CO_2 does not operate alone. It acts in concert with all the other climate variables, reminiscent of Charles Darwin's *entangled bank* with its interacting and competing plants and animals. While there are many complicating factors in the GHE, WV is amongst the most important. It is the more plentiful of the two main GHGs, has the widest spectral absorption bands (Figure 3(b)) and causes most of the warming. It is also the source of all clouds.

Water vapour operates as a GHG in exactly the same way as CO_2 does, its quantity in the rarefied high atmosphere controlling the height at which IR photons escape to space, just as the amount of CO_2 does. In the cold higher altitudes and latitudes, the amount of WV is, of course, much less than at the warm surface, but so too is the amount of CO_2, due to the thinness of the atmosphere – indeed this is why the GHE works. Just as an increase of CO_2 raises the altitude at which radiation escapes, so too does an increase of WV, thereby raising the temperature below in exactly the same way as more CO_2 does. In this, they are indistinguishable.

Water vapour as a positive feedback

Although it is the most powerful of the GHGs, climate modellers treat WV completely differently to CO_2, their reasoning being that WV can change rapidly in amount, varies greatly geographically and is not a fixed proportion of the atmosphere. To take account of this, the concept of the *Global Warming Potential* has been created, which says that GHGs, such as CO_2, which have longer lifetimes in the atmosphere, should be given greater 'weight' than those that change quickly, because of their long-term cumulative effects. So instead of treating WV on a par with CO_2, modellers treat it *only* as a feedback, postulating that an increase in temperature at the surface, due to increases in CO_2, will increase evaporation, and that this extra WV, being a GHG, could then amplify the warming and perhaps even result in a 'runaway' temperature increase.

However, this treatment of WV seems narrow and restrictive, perhaps inevitably so in view of all the complex interacting processes which cannot be modelled. In particular, I see two problems. First, even though the models treat WV only as a feedback, it will change, nevertheless, for many natural reasons, quite independently of any possible anthropogenic CO_2-induced changes. One obvious channel is through the changes of sea surface temperature (SST) occurring during the positive and negative phases of the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Strangeways, 2007). These SST changes will increase (or decrease) evaporation from the oceans and so affect the amount of WV in the atmosphere, and so the GHE, quite independently of CO_2 influences. These changes are substantial and largely unpredictable and are likely to have more effect on the WV content of the atmosphere than that due to possible CO_2 feedbacks, and this happens in the short term (years rather than decades).

Secondly, and more importantly, if WV positive feedbacks do occur, they must have happened naturally before now, many times, for there is no reason why an entirely natural increase in temperature would not also be amplified via the WV positive feedback loop. The initial warming does not have to be due only to CO_2, any warming would do, even warming due to a natural increase of WV. This possibility does not seem to have been addressed by the climate community. Neither does there appear to be any evidence in the instrument records of this happening (for example in the datasets of the Climatic Research Unit of Land Air Temperature or those of the Hadley Centre of Sea Surface Temperature). It might be argued, of course, that the greater part of all past global temperature increases did indeed arise from WV amplification of a small change due to some other cause, such as the Sun, but I have never seen this suggested. If the concept of WV amplification is correct, then it will have occurred often throughout geological time and there may be evidence of it even in the instrument records. However, if none of the past temperature changes involved any WV amplification there is no reason why a temperature change due to CO_2 will be amplified by WV either.

Supporting the view that WV feedback may not be that simple is the fact that despite rapidly increasing CO_2 levels and the resultant (or coincidental) rise of temperature from 1975 to 2000, much of the first decade of the twenty-first century has seen a cooling, especially of the global Sea Surface Temperature (Hadley Centre dataset HadSST2), when conditions were, theoretically, ideal for the WV feedback effect to be increasing the temperature further. There must, therefore, either be no feedback or there must be factors offsetting it – some negative feedback. The same can be said about the fall of temperature from 1940 to 1975, following the steep rise from 1910 to 1940.

The WV feedback logic would also suggest that the reverse could happen – a global cooling event would reduce the amount of WV in the atmosphere and this would amplify the cooling. But this does not seem to have happened either, unless all past cooling events were largely influenced by a WV feedback. Also, in neither the warming nor the cooling phases seen in the instrument record has there been any obvious 'runaway' effect. If WV positive feedback occurs, something must also limit it, perhaps clouds.

These matters are important because if the WV positive feedback effect is indeed attenuated or small or even non-existent, temperature projections from the computer models will be much too high. Most computer climate models include a substantial WV positive feedback. Should they?

Measurement of WV in the high atmosphere

A recent paper by Solomon *et al.* (2010) may throw a little light on the matter, for the authors report that the amount of WV in the lower stratosphere has varied over the last three decades, being higher when it was warmer in the 1980s and 90s, falling by 10% from around 2000. It is not known what caused these changes. These findings do, however, reinforce the view that the role of WV as a GHG and as an amplifier needs closer investigation. The recent fall in WV amounts reported in the paper may be connected with the concurrent cooling of the global SST either as cause or effect, or the two events may be entirely unconnected.

But the Solomon paper also brings another matter to our attention. While it is easy to measure relative humidity (RH) at the surface by taking wet-bulb temperature readings, and this has been done for 160 years or more, we still know very little about WV amounts high in the atmosphere. What little we do know comes from radiosondes that have been in operation for about 80 years. But early radiosondes' RH measurements were quite crude and even today, using the latest capacitive sensors, it is still difficult to measure RH at the low temperature and low barometric pressure of the higher atmosphere (Strangeways, 2003; 2007). In addition, satellite microwave sounders have measured WV for about 40 years. These measurements are made at just a few coarse levels and the sounders sample a large volume of atmosphere with a large footprint. They are not high precision and the data need correction to remove errors due to orbital and sensor-calibration drift (Strangeways, 2003; 2007). Our knowledge of upper-atmosphere WV

concentration and variation is thus severely restricted and this limits our understanding of its role as a GHG.

Water vapour and clouds

WV plays another, quite different, climatic role which needs to be mentioned briefly in conclusion. If surface temperatures increase through raised CO_2 levels (or for any reason), the sensible and latent heat fluxes will increase in response, taking more heat and WV away from the surface, the condensing WV increasing cloud-cover. While the type of cloud that might result is argued about, it seems most unlikely that there would not be some increase in low level cumulus and stratus. This would reflect more solar radiation back to space acting as a negative feedback. It requires but a small percentage increase of low level cloud to offset all the extra heat retained by any potential human-enhanced GHE.

Water vapour plays a key role in climate change. Its positive feedback effect and the negative feedback of clouds are two of the main unknowns in climate research and are poorly represented in climate models, but they are also amongst the most important. All of these uncertainties make it impossible to say with confidence what level of CO_2 will produce any given temperature in the future. Attempts to do so, for example as at Copenhagen in 2009, are unrealistic and also give a false sense of confidence, certainty and understanding.

Conclusions

The GHE is not as straightforward as its misleading name suggests. Its mechanisms are frequently misunderstood, being visualised in terms of an observer standing on the surface with an imaginary single sheet of glass overhead. In fact it is more complex than this simple view, involving the transmission of IR radiation through the full depth of the troposphere combined with the lapse rate of temperature and the reduction of air pressure/density with altitude.

When CO_2 is considered in isolation, the physics and maths of the GHE are straightforward. Adding more CO_2 will cause more heat to be retained. In this simple sense, the science *is* settled. But when placed in the context of the rest of the climate, with its numerous interactions, it becomes much more difficult to know what effect more CO_2 might actually have on temperatures. In this more realistic and complex sense, the science is far from settled.

Progress can only be made by finding answers to the many questions concerning WV amplification. If such a positive feedback does occur, then it must have occurred innumerable times in the past in response to natural increases (and decreases) of temperature and there could be evidence of this in the past records. If it did not occur in the past, then there is no reason why it should occur in the future due to any anthropogenic warming, and the climate models will be exaggerating future temperatures by two or three times or more.

The Royal Society (2010) recently acknowledged that uncertainties do remain in climate science, and they will be issuing a new statement shortly. This new formal recognition on their part is an important step forward which I welcome.

References

Kiehl J, Trenberth K. 1997. Earth's annual global mean energy budget. *Bull. Am. Meteorol. Soc.* **78**: 197–206.

Mudge FB. 1997. The development of the 'greenhouse' theory of global climate change from Victorian times. *Weather* **52**: 13–17.

Royal Society. 2010. http://royalsociety. org/Royal-Society-to-publish-new-guide-to-the-science-of-climate-change/

Solomon S, Rosenlof KH, Portmann RW, Daniel JS, Davis SM, Sandford TJ, Plattner G-K. 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science* **327**: 1219–1223.

Strangeways IC. 2003. *Measuring the Natural Environment. 2nd edition.* Cambridge University Press: Cambridge, New York, Melbourne, Madrid and Cape Town.

Strangeways IC. 2007. *Measuring Global Temperatures: Their Analysis and Interpretation.* Cambridge University Press: Cambridge, New York, Melbourne, Madrid and Cape Town.

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Diurnal variation in the marine wind

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Although wind varies diurnally over land, marine wind usually shows very little diurnal variation except close to the coastline, where sea breezes may be initiated affecting the daytime winds. This article shows that in certain conditions of offshore wind flow, the overland diurnal variation can influence the near surface wind strengths at quite long distances out to sea. The theoretical basis for expecting such variations is discussed, followed by a comparison of onshore and marine wind observations that provide some confirmation of the theory.

Land–sea differences

The diurnal variation of surface wind over land and its cause is well known. Land is a good insulator so that heat-gains due to insolation by day, and radiative losses by night, translate into large temperature changes at the surface. These changes then result in the formation of convective and stable atmospheric boundary layers by day and night, respectively, and these in turn lead to diurnal wind variations. The sea, however, is different. It is partly transparent so that radiative gains and losses occur over a significant depth and turbulent motions within the water conduct heat-changes over a large depth. As a result