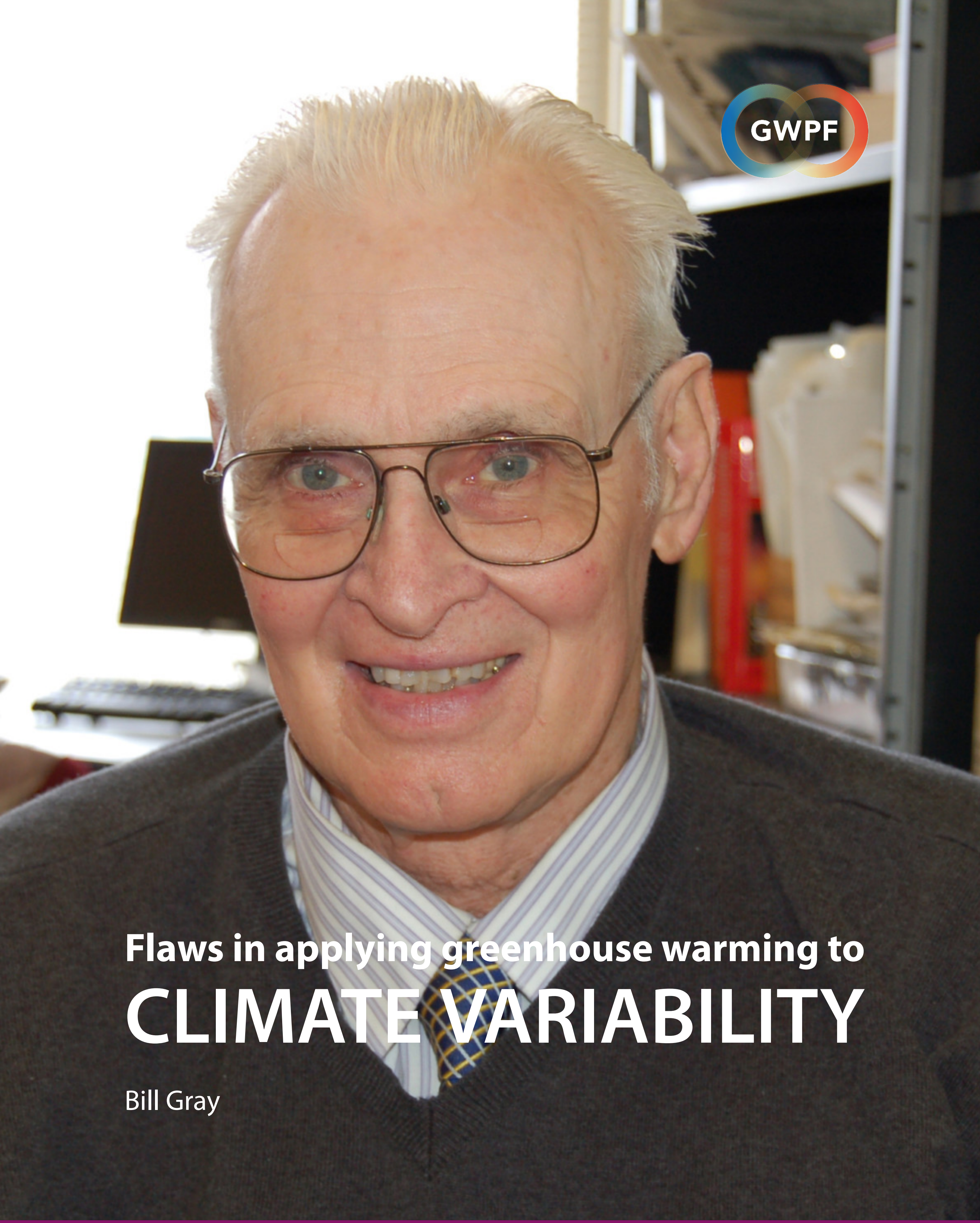


Flaws in applying greenhouse warming to CLIMATE VARIABILITY

Bill Gray

The Global Warming Policy Foundation

GWPF Briefing 30

Flaws in applying greenhouse warming to CLIMATE VARIABILITY

Bill Gray

Contents

About the author

Dr Gray was in the process of writing up the results discussed below when he passed away in 2016. Before he died, he asked us to compile his figures and preliminary text into a paper to be posted online. We have attempted to maintain his writing style and the tone that we think he would have wanted to convey. Dr. Gray studied tropical meteorology for over 50 years,[1] and we believe that his views on this important topic should be heard.

Please note that the views of this paper are Dr. Gray's and may not be our own personal views on climate change.

Barry Schwartz, Phil Klotzbach and Sarah Gray

1 Introduction

There is little controversy that the Earth has experienced a warming trend since the mid-19th century, with an acceleration of this warming from the mid-1970s to around 2000. Following a hiatus in global warming for about 15 years, the globe began warming again around 2014, associated with the El Niño that developed around that time. What is in dispute is whether these periods of warming are the result of changes to the Earth's energy balance due to

- human addition of greenhouse gases to the atmosphere
- natural variability of the climate system
- a combination of both factors.

The idea that the Earth's climate can be altered by addition of greenhouse gases is known as the greenhouse theory and is depicted in Figure 1.

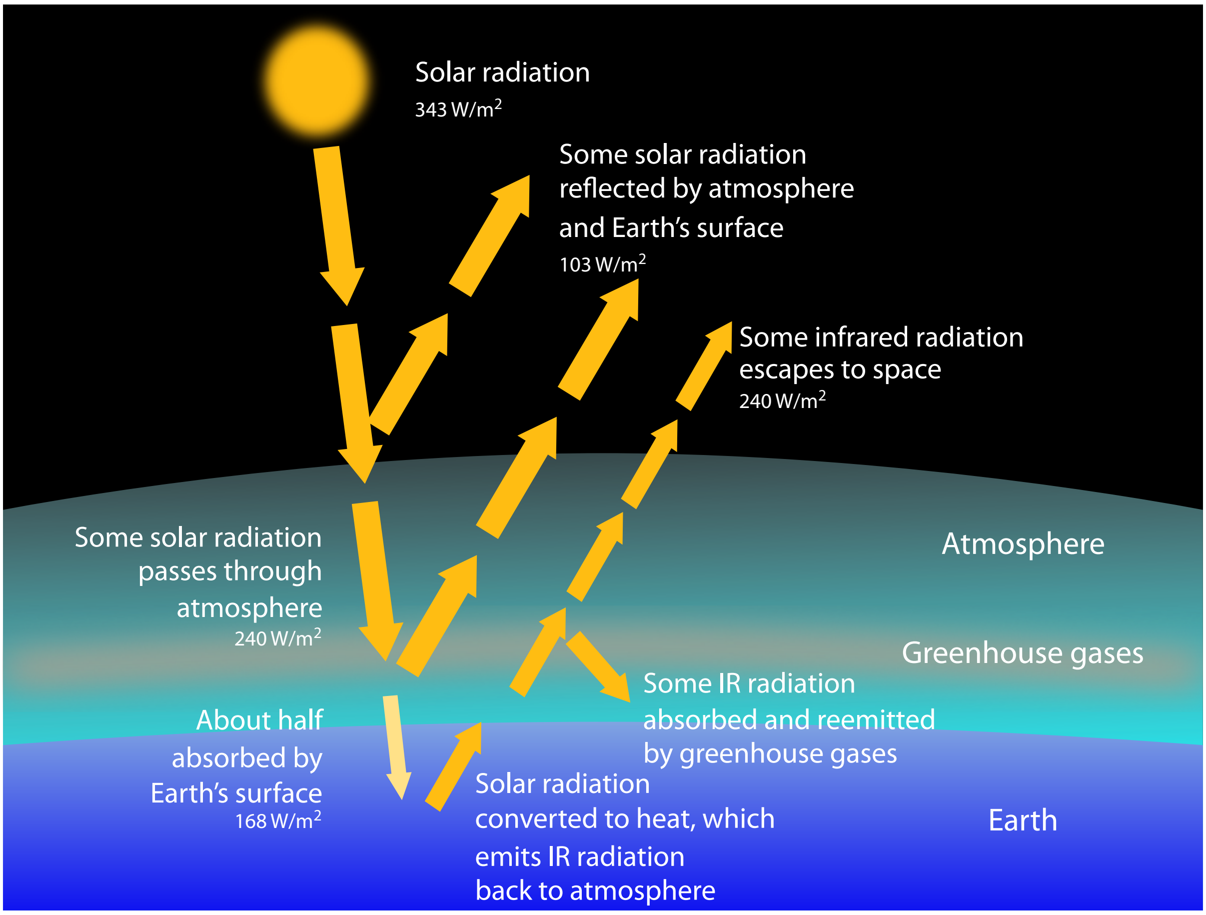


Figure 1: The greenhouse theory of global warming

Of most concern is the addition of carbon dioxide (CO_2) to the Earth's atmosphere as a result of the burning of fossil fuels and deforestation. This theory has been the subject of debate since its introduction by Joseph Fourier in 1824.

Climate sensitivity is complex and involves much more than the state of radiation balance and greenhouse gases. The globe's climate system is in a close state of energy balance. A global radiative average imbalance of 1 W/m^2 (or 0.3%) between the continuous solar radiation impinging on the Earth and infrared energy being fluxed to space can bring about significant climate changes *if* this small energy imbalance were to persist over a period from a few months to a year or two. The critical argument that is made by many in the global climate modeling (GCM) community is that an increase in CO_2 warming leads to an increase in atmospheric water vapor, resulting in more warming from the absorption of outgoing infrared radiation (IR) by the water vapor. Water vapor is the most potent greenhouse gas present in the atmosphere in large quantities. Its variability (i.e. global cloudiness) is not handled adequately in GCMs in my view. In contrast to the positive feedback between CO_2 and water vapor predicted by the GCMs, it is my hypothesis that there is a negative feedback between CO_2 warming and and water vapor. CO_2 warming ultimately results in less water vapor (*not more)* in the upper troposphere. The GCMs therefore predict unrealistic warming of global temperature. I hypothesize that the Earth's energy balance is regulated by precipitation (primarily via deep cumulonimbus (Cb) convection) and that this precipitation counteracts warming due to CO_2.

2 Carbon dioxide observations and exaggerated global warming predictions

Continuous measurements of atmospheric CO_2, which were first made at Mauna Loa, Hawaii in 1958, show that atmospheric concentrations of CO_2 have risen since that time. The warming influence of CO_2 increases with the natural logarithm (ln) of the atmosphere's CO_2 concentration. With CO_2 concentrations now exceeding 400 parts per million by volume (ppm), the Earth's atmosphere is slightly more than halfway to containing double the 280 ppm CO_2 amounts in 1860 (at the beginning of the Industrial Revolution).*

We have not observed the global climate change we would have expected to take place, given this increase in CO_2. Assuming that there has been at least an average of 1 W/m^2 CO_2 blockage of IR energy to space over the last 50 years and that this energy imbalance has been allowed to independently accumulate and cause climate change over this period with no compensating response, it would have had the potential to bring about changes in any one of the following global conditions:

- Warm the atmosphere by 180°C if all CO_2 energy gain was utilized for this purpose – actual warming over this period has been about 0.5°C, or many hundreds of times less.
- Warm the top 100 meters of the globe's oceans by over 5°C – actual warming over this period has been about 0.5°C, or 10 or more times less.
- Melt sufficient land-based snow and ice as to raise the global sea level by about 6.4 m. The actual rise has been about 8–9 cm, or 60–70 times less. The gradual rise of sea level has been only slightly greater over the last ~50 years (1965–2015) than it has been over the previous two ~50-year periods of 1915–1965 and 1865–1915, when atmospheric CO_2 gain was much less.[2]
- Increase global rainfall over the past ~50-year period by 60 cm.

If CO_2 gain is the only influence on climate variability, large and important counterbalancing influences must have occurred over the last 50 years in order to negate most of the climate change expected from CO_2's energy addition. Similarly, this hypothesized CO_2-induced energy gain of 1 W/m^2 over 50 years must have stimulated a compensating response that acted to largely negate energy gains from the increase in CO_2.

---

* (ln 400/280) = 0.357 in 2016 versus (ln 560/280 = 0.691) when CO_2 doubles near the end of this century.

3 The Earth's energy budget

Although increases in CO_2 act to block the normal longwave infrared (IR) radiation to space, this blockage is very small compared to the globe's basic energy budget. About 3.7 W/m^2 of IR energy is intercepted for a doubling of CO_2 (Figure 2). Since the mid-19th century, CO_2's influence on IR blockage has increased by around 1.4 W/m^2, or only 0.6% of the continuous average IR flux to space of 235 W/m^2. The continuous balancing of global average in-and-out net radiation flux is therefore much larger than the radiation flux from anthropogenic CO_2. For example, 342 W/m^2, the total energy budget, is almost 100 times larger than the amount of radiation blockage expected from a CO_2 doubling over 150 years. If all other factors are held constant, a doubling of CO_2 requires a warming of the globe of about 1°C to enhance outward IR flux by 3.7 W/m^2 and thus balance the blockage of IR flux to space.

This pure IR energy blocking by CO_2 versus compensating temperature increase for radiation equilibrium is unrealistic for the long-term and slow CO_2 increases that are occurring. Only half of the blockage of 3.7 W/m^2 at the surface should be expected to go into an temperature increase. The other half (about 1.85 W/m^2) of the blocked IR energy to space will be compensated by surface energy loss to support enhanced evaporation. This occurs in a similar way to how the Earth's surface energy budget compensates for half its solar gain of 171 W/m^2 by surface-to-air upward water vapor flux due to evaporation.

Note in Figures 2 and 3 that the globe's annual surface solar absorption of 171W/m^2 is balanced as follows:

- about half goes to evaporation (85 W/m^2)
- the other half (86 W/m^2) goes to
  - surface-to-atmosphere upward IR (59 W/m^2) flux
  - surface-to-air upward flux by sensible heat transfer (27 W/m^2).

Assuming that the imposed extra CO_2 doubling IR blockage of 3.7 W/m^2 is taken up and balanced by the Earth's surface in the same way as the solar absorption is taken up and balanced, we should expect a direct warming of only ~0.5°C for a doubling of CO_2. The 1°C expected warming that is commonly accepted incorrectly assumes that *all* the absorbed IR goes to the balancing outward radiation[†] with no energy going to evaporation. Figures 2 and 3 show how the surface solar energy absorption (171 W/m^2) is balanced by a near-equal division between temperature increase (enhancing IR and sensible heat loss) and surface evaporation. We should assume that the imposed downward IR energy gain for a doubling of CO_2 at the surface will likely be similarly divided. Such a division will cause an enhancement of the strength of the hydrologic cycle by about 2%.[‡] This analysis shows that the influence of doubling atmospheric CO_2 by itself (without invoking any assumed water vapor positive feedback) leads to only small amounts of global warming, and much less than predicted by GCMs.

4 GCM water vapor feedback and projected warming

A major premise of the GCMs has been their application of the National Academy of Science (NAS) 1979 study[3] – often referred to as the Charney Report – which hypothesized that a

---

[†] Through σT^4; that is, the Stefan-Boltzmann law.

[‡] 1.85 W/m^2 of extra global average evaporation over the ~85 W/m^2 energy equivalent of current evaporation.

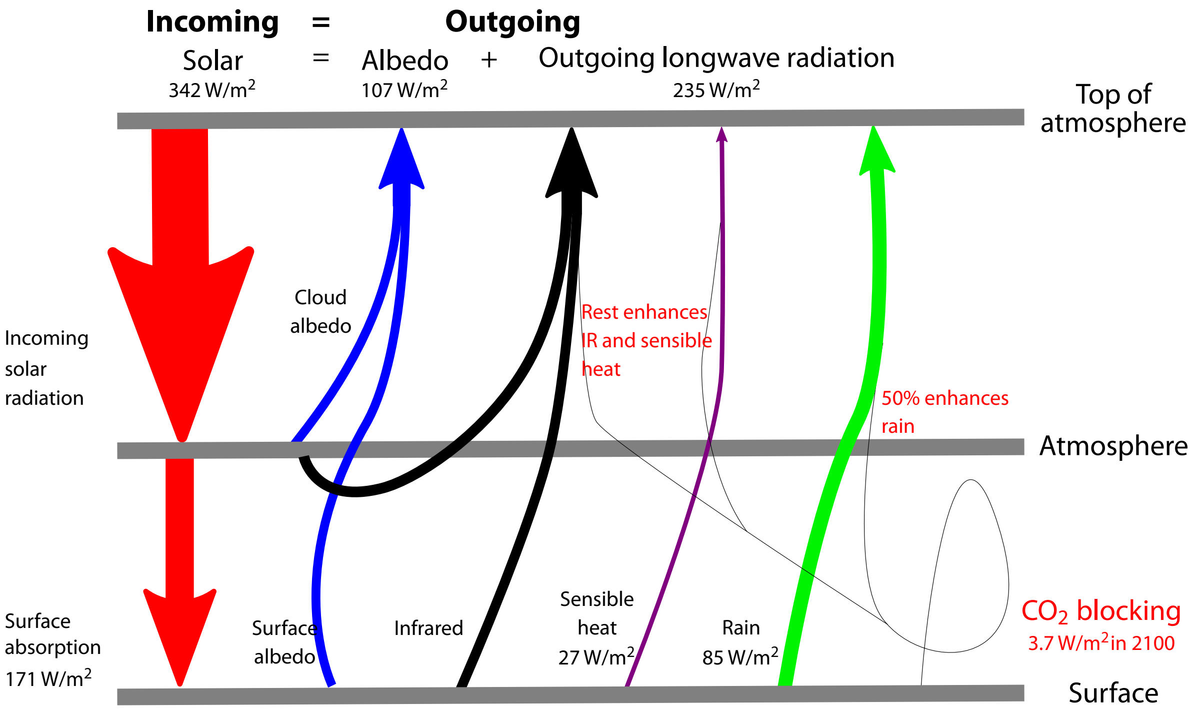


Figure 2: Vertical cross-section of the annual global energy budget.
Determined from a combination of satellite-derived radiation measurements and reanalysis data over the period of 1984–2004.

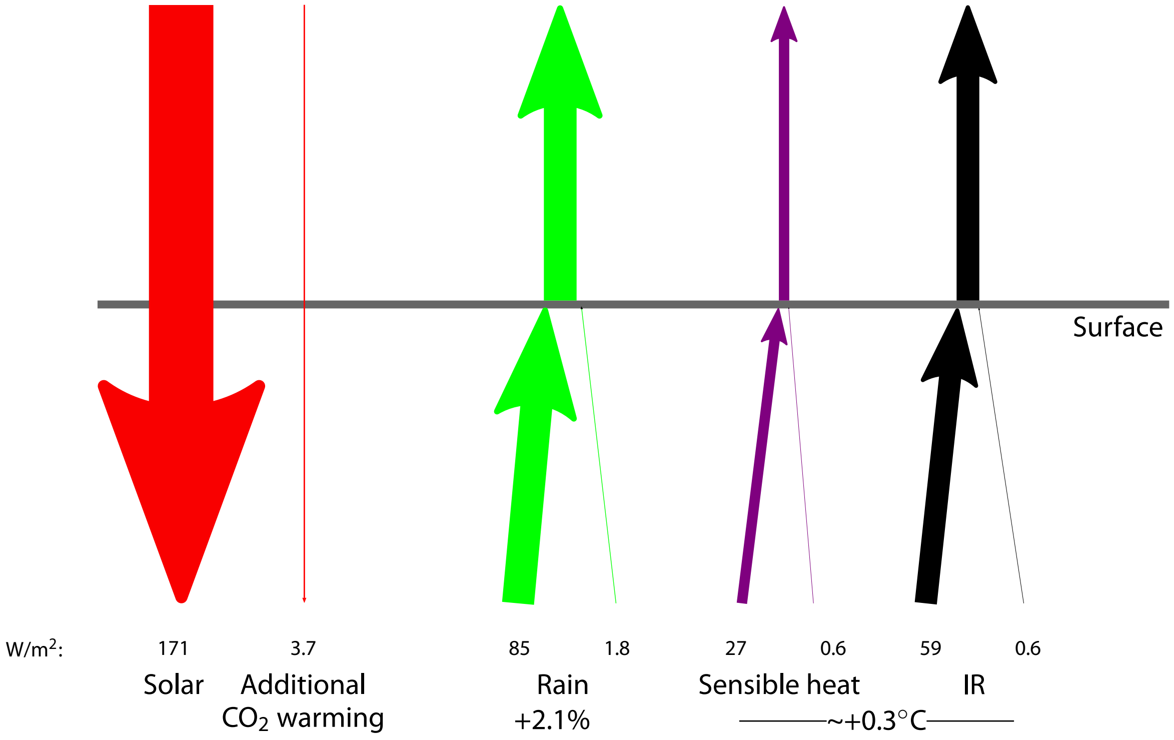


Figure 3: Effect of global warming on rainfall and temperature.
There is a 2.1% increase in evaporation and rainfall and ~0.3°C in global mean temperature at equilibrium for a doubling of CO_2 (and a blockage of IR energy to space of 3.7 W/m^2) with no positive or negative energy feedbacks.

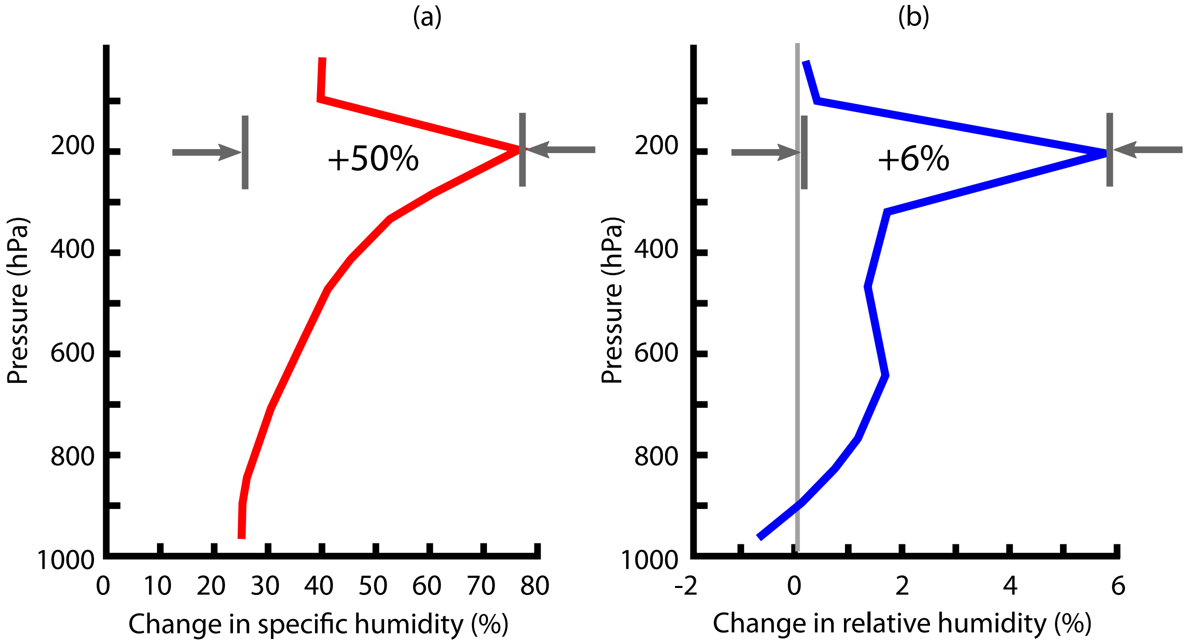


Figure 4: Early NASA model showing assumed increases in (a) specific humidity and relative humidity for a doubling of CO_2.

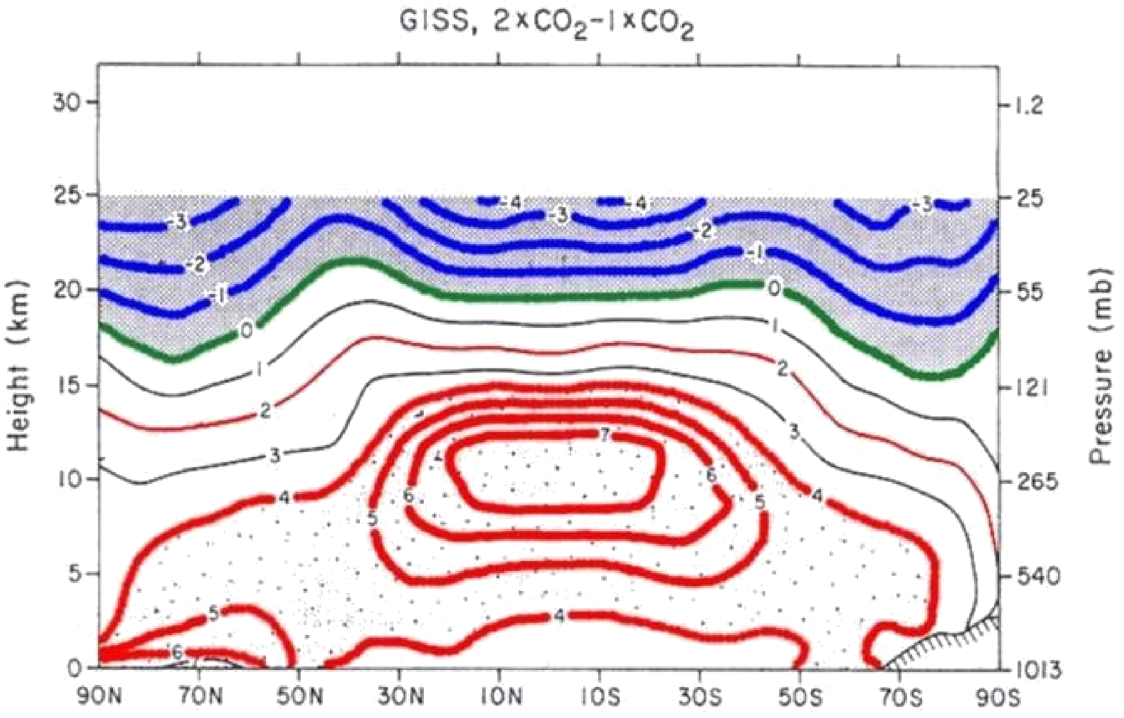


Figure 5: North–south vertical cross-section showing Hansen's early GCM's change in temperature (°C) that would accompany a doubling of CO_2.

doubling of atmospheric CO_2 would bring about a general warming of the globe's mean temperature of 1.5–4.5°C (or an average of ~3.0°C). These large warming values were based on the report's assumption that the relative humidity (RH) of the atmosphere remains quasi-constant as the globe's temperature increases. This assumption was made without any type of cumulus convective cloud model and was based solely on the Clausius–Clapeyron (CC) equation and the assumption that the RH of the air will remain constant during any future CO_2-induced temperature changes.

If RH remains constant as atmospheric temperature increases, then the water vapor content in the atmosphere must rise exponentially. With constant RH, the water vapor content of the atmosphere rises by about 50% if atmospheric temperature is increased by 5 °C. Upper tropospheric water vapor increases act to raise the atmosphere's radiation emission level to a higher and thus colder level. This reduces the amount of outgoing IR energy which can escape to space by decreasing σT^4.

Many climate models, such as Hansen's early NASA-GISS model, have even gone further than what the CC equation would specify for water vapor feedback. Hansen's early GISS model assumed that for increases of CO_2, upper tropospheric RH would *not* stay constant but actually *increase*, by nearly 50%. This caused his model to specify a tropical upper tropospheric atmospheric warming for a doubling of CO_2 of as much as 7°C (Figures 4–5).

Not only were Hansen's unrealistically large values of upper tropospheric moisture and temperature increases (for a doubling of CO_2) not challenged by his fellow modellers at the time, but they were actually closely emulated in several other prominent GCMs including NOAA-GFDL (Figure 6).

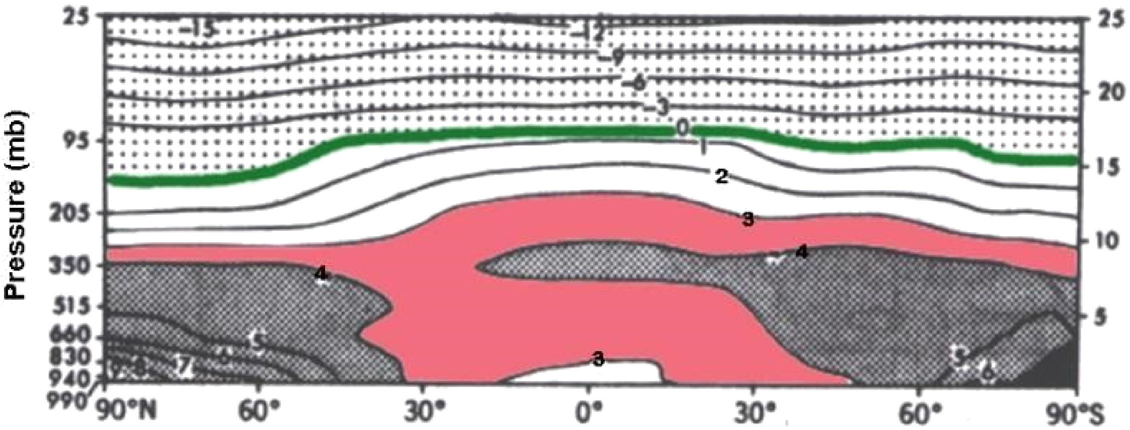


Figure 6: As in Figure 5 but for early NOAA-GFDL temperature predictions for a doubling of CO_2.

These model predictions of large upper-level tropospheric moisture increases have persisted in the current generation of GCM forecasts.[§] These models significantly overestimate globally-averaged tropospheric and lower stratospheric (0–50,000 feet) temperature trends since 1979 (Figure 7).

All of these early GCM simulations were destined to give unrealistically large upper-tropospheric water vapor increases for doubling of CO_2 blockage of IR energy to space, and as a result large and unrealistic upper tropospheric temperature increases were predicted. In fact, if

---

[§] The Coupled Model Intercomparison Project 5 (CMIP5).

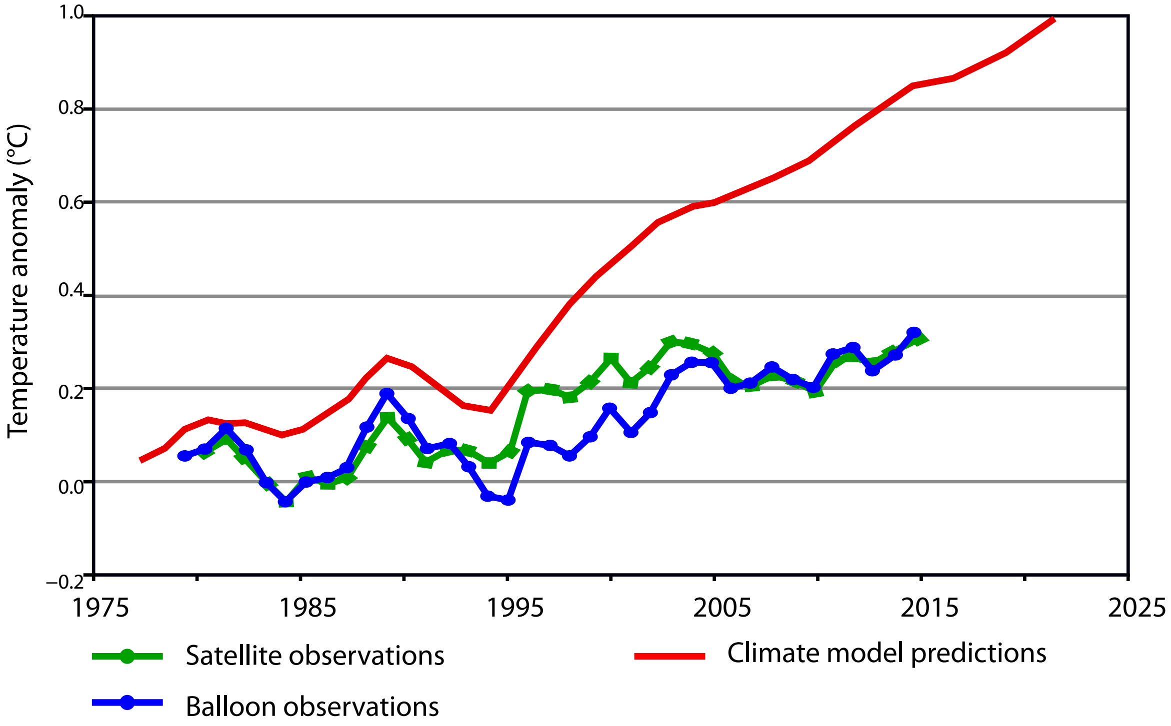


Figure 7: Temperature predictions versus observations.

Global temperature averaged from surface to ~50,000 ft: four balloon datasets, three satellite datasets and average of 102 IPCC CMIP5 climate model runs. After John Christy, (University of Alabama-Huntsville).

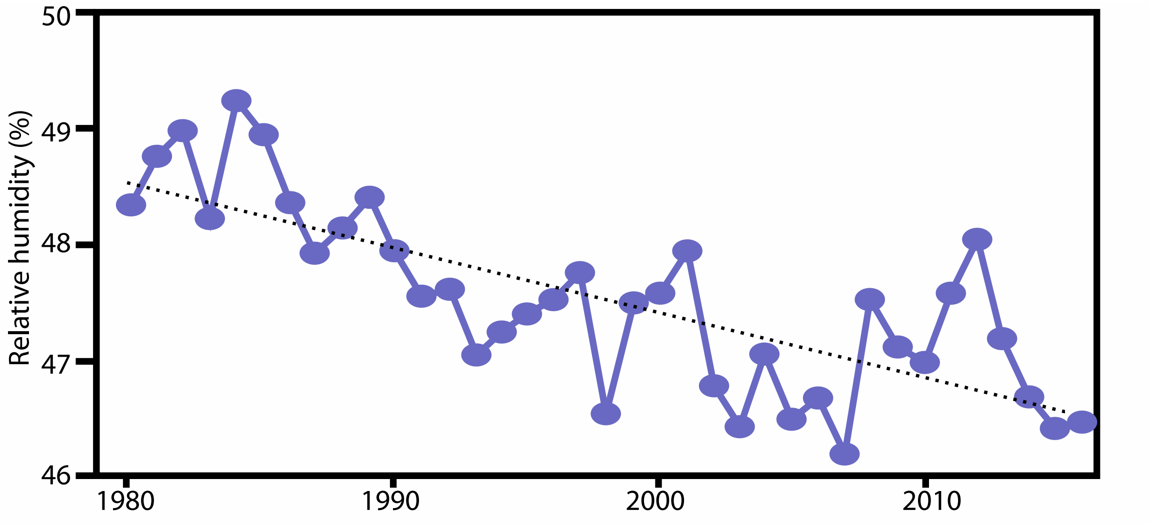


Figure 8: Decline in upper tropospheric RH.

Annually-averaged 300 mb relative humidity for the tropics (30°S–30°N). From NASA-MERRA2 reanalysis for 1980–2016. Black dotted line is linear trend.

data from NASA-MERRA2[4] and NCEP/NCAR[5] can be believed, upper tropospheric RH has actually been declining since 1980 as shown in Figure 8. The top part of Table 1 shows temperature and humidity differences between very wet and dry years in the tropics since 1948; in the wettest years, precipitation was 3.9% higher than in the driest ones. Clearly, when it rains more in the tropics, relative and specific humidity decrease. A similar decrease is seen when differencing 1995–2004 from 1985–1994, periods for which the equivalent precipitation difference is 2%. Such a decrease in RH would lead to a decrease in the height of the radiation emission level and an increase in IR to space. My analysis does not indicate an increase in 300 mb temperature either (see Table 1). This has also been discussed by Douglass *et al.*,[6] who show that tropical upper-tropospheric measurements and GCM results do not agree.

Table 1: Changes in 300 mb temperature, specific and relative humidity and precipitation in the tropics.

10 wettest vs 10 driest years since 1948 (3.9% rainfall difference)

	Longitudinal area	300 mb temperature	Humidity Specific	Humidity Relative
0	0–360	0.02	(0.02)	(1.66)
1	0–60E	0.13	(0.01)	(1.34)
2	60–120E	0.27	(0.01)	(2.33)
3	120E–180	0.23	(0.01)	(1.73)
4	180–120W	(0.34)	(0.02)	(0.41)
5	120–60W	(0.21)	(0.02)	(1.20)
6	60W–0	0.02	(0.02)	(2.69)

1995–2004 versus 1985–1994 (2.0% rainfall difference)

	Longitudinal area	300 mb temperature	Humidity Specific	Humidity Relative
0	0–360	0.16	(0.03)	(3.92)
1	0–60E	0.26	(0.02)	(2.84)
2	60–120E	0.24	(0.03)	(3.53)
3	120E–180	0.11	(0.05)	(4.84)
4	180–120W	(0.05)	(0.04)	(3.83)
5	120–60W	0.13	(0.02)	(3.24)
6	60W–0	0.25	(0.04)	(5.23)

Tropics 30°N–30°S; 0–360°. Monthly (high–low) precipitation values. From the NCEP/NCAR Reanalysis in tropical areas.

5 The Earth's natural thermostat – evaporation and precipitation

What has prevented this extra CO_2-induced energy input of the last 50 years from being realized in more climate warming than has actually occurred? Why was there recently a pause in global warming, lasting for about 15 years?[7] The compensating influence that prevents the predicted CO_2-induced warming is enhanced global surface evaporation and increased precipitation.

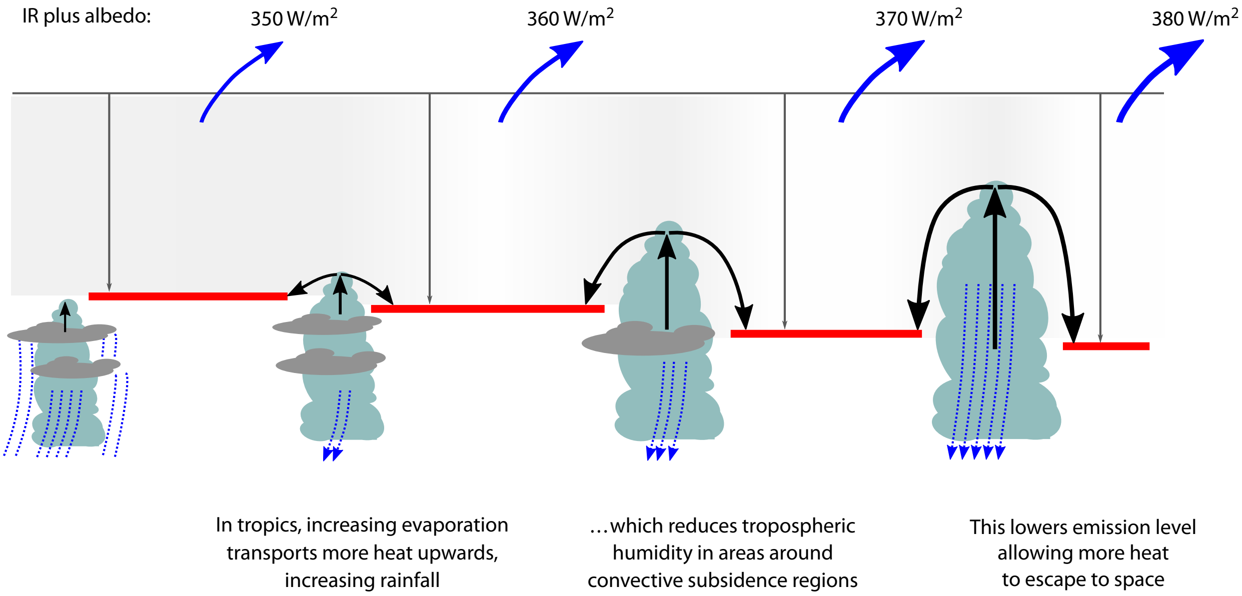
Annual average global evaporational cooling is about 80 W/m^2 or about 2.8 mm per day.[8] A little more than 1% extra global average evaporation per year would amount to 1.3 cm per year or 65 cm of extra evaporation integrated over the last 50 years. This is the only way that such a CO_2-induced , 1 W/m^2 IR energy gain sustained over 50 years could occur without a significant alteration of globally-averaged surface temperature. This hypothesized increase in global surface evaporation as a response to CO_2-forced energy gain should not be considered unusual. All geophysical systems attempt to adapt to imposed energy forcings by developing responses that counter the imposed action. In analysing the Earth's radiation budget, it is incorrect to simply add or subtract energy sources or sinks to the global system and expect the resulting global temperatures to proportionally change. This is because the majority of CO_2-induced energy gains will not go into warming the atmosphere. Various amounts of CO_2-forced energy will go into ocean surface storage or into ocean energy gain for increased surface evaporation. Therefore a significant part of the CO_2 buildup (~75%) will bring about the phase change of surface liquid water to atmospheric water vapour. The energy for this phase change must come from the surface water, with an expenditure of around 580 calories of energy for every gram of liquid that is converted into vapour. The surface water must thus undergo a cooling to accomplish this phase change.

Therefore, increases in anthropogenic CO_2 have brought about a small (about 0.8%) speeding up of the globe's hydrologic cycle, leading to more precipitation, and to relatively little global temperature increase. *Therefore, greenhouse gases are indeed playing an important role in altering the globe's climate, but they are doing so primarily by increasing the speed of the hydrologic cycle as opposed to increasing global temperature.*

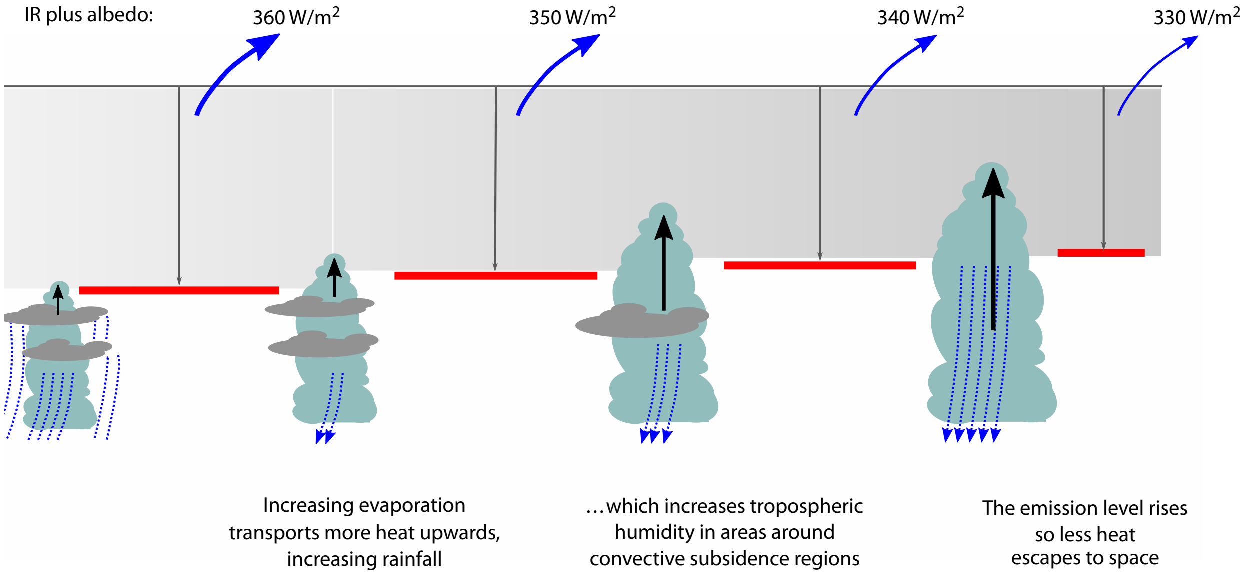
6 The role of deep cumulus convection in the modulation of outgoing IR to space

It is my hypothesis that the increase in global precipitation primarily arises from an increase in deep tropical cumulonimbus (Cb) convection. The typical enhancement of rainfall and updraft motion in these areas together act to increase the return flow mass subsidence in the surrounding broader clear and partly cloudy regions. The upper diagram in Figure 9 illustrates the increasing extra mass flow return subsidence associated with increasing depth and intensity of cumulus convection. Rainfall increases typically cause an overall reduction of specific humidity (q) and relative humidity (RH) in the upper tropospheric levels of the broader scale surrounding convective subsidence regions. This leads to a net enhancement of radiation flux to space due to a lowering of the upper-level emission level. This viewpoint contrasts with the position in GCMs, which suggest that an increase in deep convection will *increase* upper-level water vapour.

Figure 10 summarizes data from our observational studies of the variations of outward radiation (IR + albedo) energy flux to space due to increased precipitation.[9,10] In precipitation areas there is not a reduction of global net radiation (IR + albedo) to space, but an *increase* in radiation loss to space. At the broad scale, in clear and partly cloudy areas, the decrease in albedo radiative loss to space is typically as much as (or slightly more than) the increase in IR loss to space. Over rainy and cloudy areas, however, the increase in albedo energy loss



(a) Reality



(b) GCMs

Figure 9: Two contrasting views of the effects of how the continuous intensification of deep cumulus convection would act to alter radiation flux to space.

The top (bottom) diagram represents a net increase (decrease) in radiation to space.

to space is slightly more than the reduction in IR loss to space. The albedo enhancement over the cloud–rain areas tends to increase the net (IR + albedo) radiation energy to space more than the weak suppression of (IR + albedo) in the clear areas. Near-neutral conditions prevail in the partly cloudy areas. The bottom diagram of Figure 9 illustrates how, in GCMs, Cb convection erroneously increases upper tropospheric moisture. Based on reanalysis data (Table 1, Figure 8) this is not observed in the real atmosphere.

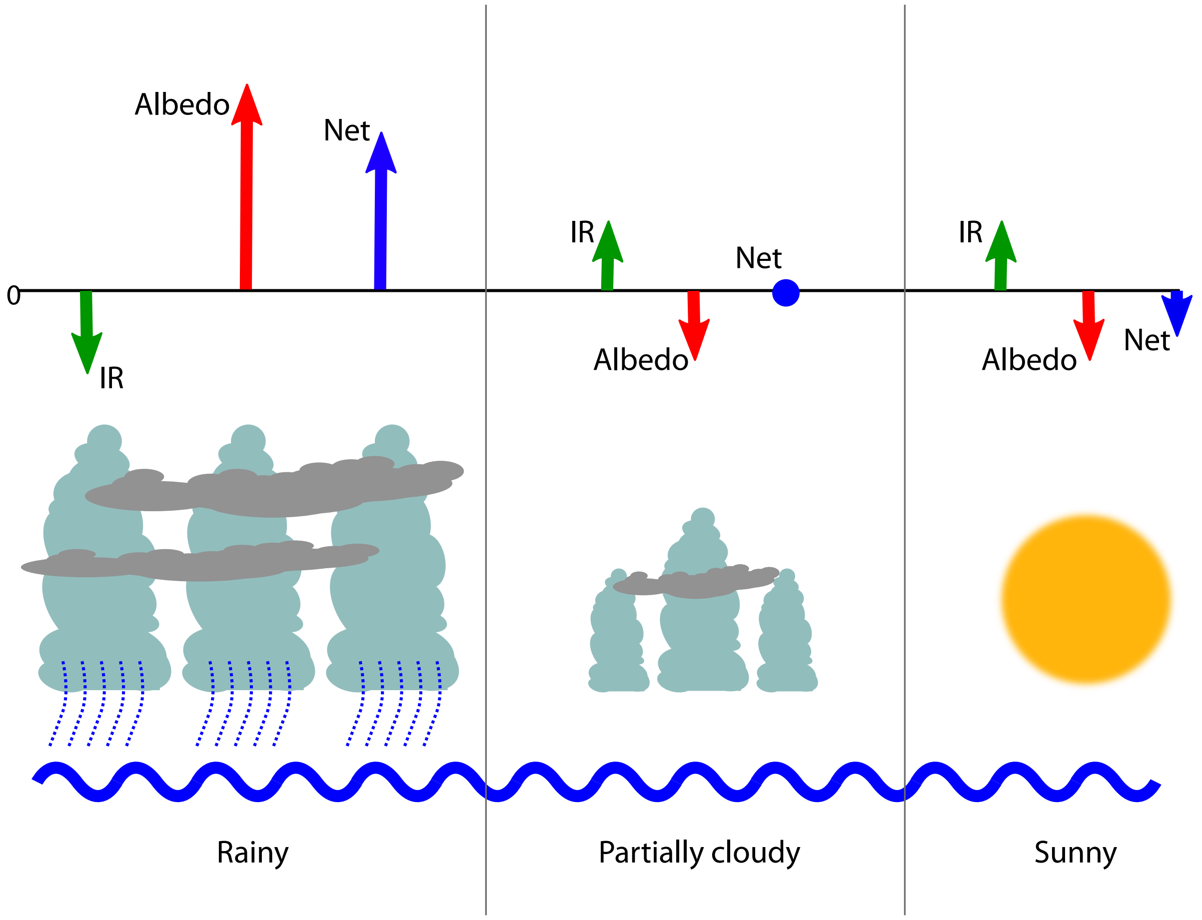


Figure 10: Conceptual model of typical variations of IR, albedo and net (IR + albedo) associated with three different areas of rain and cloud for periods of increased precipitation.

7 The oceans hold the key to understanding climate variability

From the above discussion it is clear that I do not believe CO_2 is a primary driver of climate warming. What then is responsible for long-term climate changes? Given that the Earth's surface is ~70% water, it seems reasonable that the oceans hold the key to understanding climate variability. The oceans are huge sources and sinks of energy, with long-term memory. Variability in deep water circulation occurs on timescales ranging from a few months to hundreds and thousands of years and results in changes in the rate and location of heat exchange associated with upwelling or downwelling of cold water, thus affecting sea surface temperatures. Atmospheric circulation patterns are directly impacted by changes in sea surface temperatures. For example, the El Niño–Southern Oscillation (ENSO) causes sea surface temperature variations that have been tied to seasonal changes in tropospheric circulation patterns.[11] Variability in ocean circulation patterns that occur on longer timescales may be responsible for longer-term changes to tropospheric general circulation patterns, thus leading to climate changes.

It is my hypothesis that it is variations in the global ocean's Meridional Overturning Circulation (MOC) that are the primary driver of climate change over the last few thousand years.[12] These variations are manifested in alterations of the rate of deep water formation of the Atlantic Thermohaline Circulation (THC)[13] and the Surrounding Antarctica Subsidence (SAS). Figure 11 shows how the MOC is a combination of the high-latitude deep-water formation of the Atlantic THC and the Antarctic SAS. These changes in rates of deep-water formation are driven by upper ocean salinity variations on various multi-decadal to multi-century timescales. Figure 12 shows typical Atlantic Ocean current differences when the Atlantic THC is strong (there is, on average, a greater rate of deep-water formation) and when it is weak (a lower rate of deep-water formation). The sea surface temperature realization of THC fluctuations is frequently referred to as the Atlantic Multidecadal Oscillation (AMO).[14]

A slowing down of the global ocean's MOC is the likely cause of most of the global warming that has been observed since the latter part of the 19th century.[15] I hypothesize that shorter multi-decadal changes in the MOC[16] are responsible for the more recent global warming periods between 1910–1940 and 1975–1998 and the global warming hiatus periods between 1945–1975 and 2000–2013.

Figure 13 shows the circulation features that typically accompany periods when the MOC is stronger than normal and when it is weaker than normal. In general, a strong MOC is associated with a warmer-than-normal North Atlantic, increased Atlantic hurricane activity, increased blocking action in both the North Atlantic and North Pacific and weaker westerlies in the mid-latitude Southern Hemisphere. There is more upwelling of cold water in the South Pacific and Indian Oceans, and an increase in global rainfall of a few percent occurs. This causes the global surface temperatures to cool. The opposite occurs when the MOC is weaker than normal.

The average strength of the MOC over the last 150 years has likely been below the multi-millennium average, and that is the primary reason we have seen this long-term global warming since the late 19th century. The globe appears to be rebounding from the conditions of the Little Ice Age to conditions that were typical of the earlier 'Medieval' and 'Roman' warm periods.

GCMs do not yet accurately model the globe's deep-water ocean circulation, but doing so is fundamental to any realistic understanding of global temperature change. Both the Atlantic THC and the Antarctic SAS play a role in this multi-century MOC weakening. This long-period combined weakening of the MOC is viewed as being driven by a global upper-ocean salinity decrease.[17] CO_2 changes play little role in these global-scale ocean changes. Figure 14 shows the long global warming curve of the last 130 years with the superimposed multi-decadal (25–35 years) periods of up-and-down global temperature change which are superimposed on this longer upward warming cycle. This long-period warming of ~0.7 °C is hypothesized to be a result of the long period slow down of the global ocean's MOC which is driven by natural multi-century variations of upper ocean salinity. The shorter period multi-decadal up-and-down global temperature changes we have experienced during the last 100–150 years are a result of stronger and weaker multi-decadal THC periods driven primarily by multi-decadal variations of Atlantic salinity.[18]

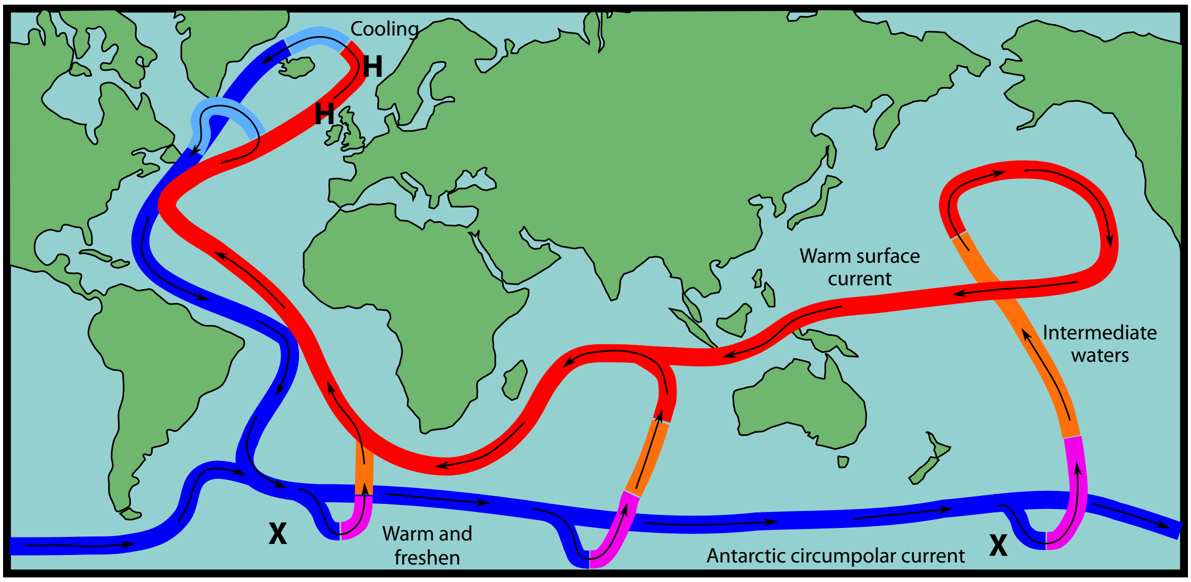
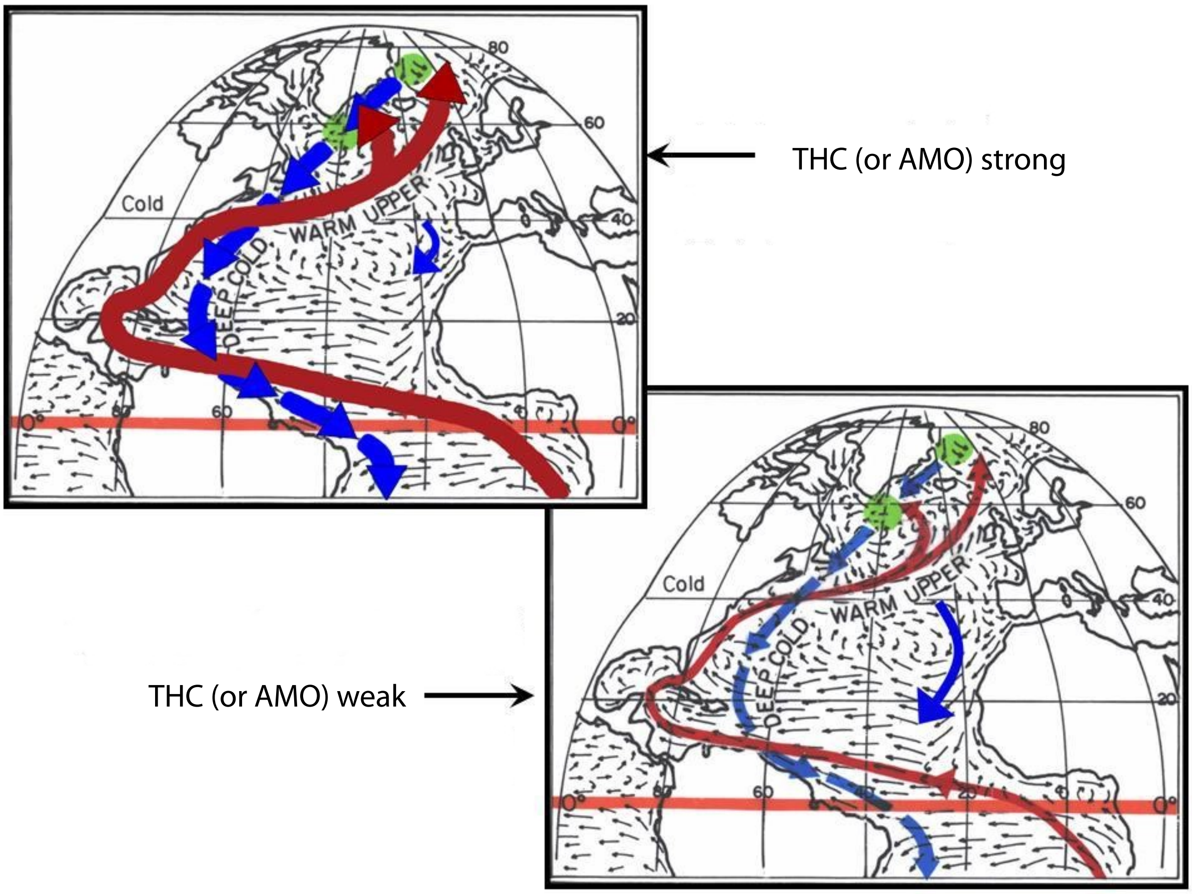


Figure 11: The meriodional overturning circulation.
Idealized representation of the globe's salinity driven ocean MOC, which comprises deep ocean sinking by the North Atlantic THC (marked H) and the SAS regions (marked X). Figure adapted from John Marshall (MIT).


THC (or AMO) strong

THC (or AMO) weak

Figure 12: The effect of strong and weak Atlantic THC.
Idealized portrayal of the primary Atlantic Ocean upper ocean currents during strong and weak phases of the thermohaline circulation (THC)

Figure 15 shows my hypothesized impact of a negative THC. I believe this is what has been responsible for the last century-and-a-half mean warming of 0.7°C. Superimposed on this long-term warming are the multi-decadal warming and cooling periods shown by the up-and-down red line that is influenced by the multi-decadal variation in the salinity-induced strength of the Atlantic Ocean THC (green line). When the Atlantic THC is weak, the globe typically undergoes multi-decadal weak warming periods. When the THC is strong, the globe typically experiences weak cooling periods.

8 Summary and conclusions

The Earth is covered with 71% liquid water. Over the ocean surface, sub-saturated winds blow, forcing continuous surface evaporation. Observations and energy budget analyses indicate that the surface of the globe is losing about 80 W/m^2 of energy from the global surface evaporation process. This evaporation energy loss is needed as part of the process of balancing the surface's absorption of large amounts of incoming solar energy. Variations in the strength of the globe's hydrologic cycle are the way that the global climate is regulated. The stronger the hydrologic cycle, the more surface evaporation cooling occurs, and greater the globe's IR flux to space. The globe's surface cools when the hydrologic cycle is stronger than average and warms when the hydrologic cycle is weaker than normal. The strength of

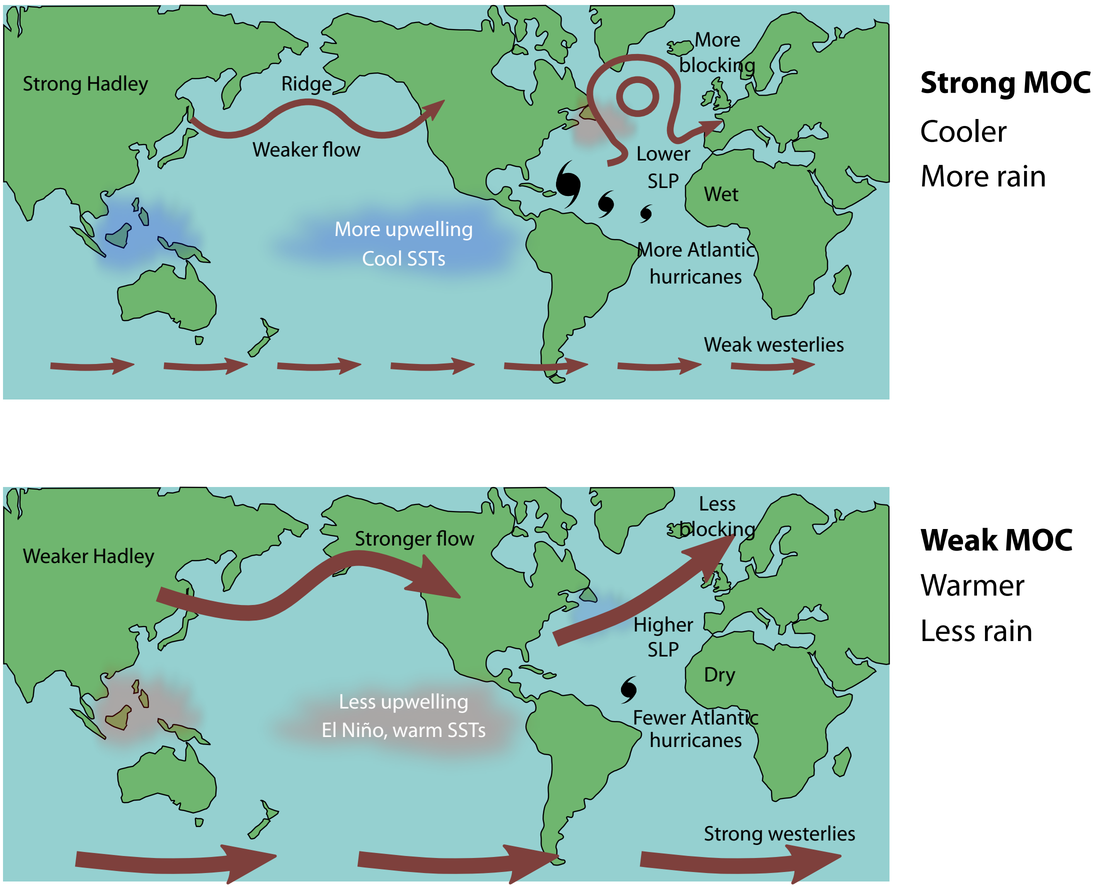


Figure 13: Effect of changes in MOC: top, strong MOC; bottom weak MOC.
SLP: sea level pressure; SST, sea surface temperature.

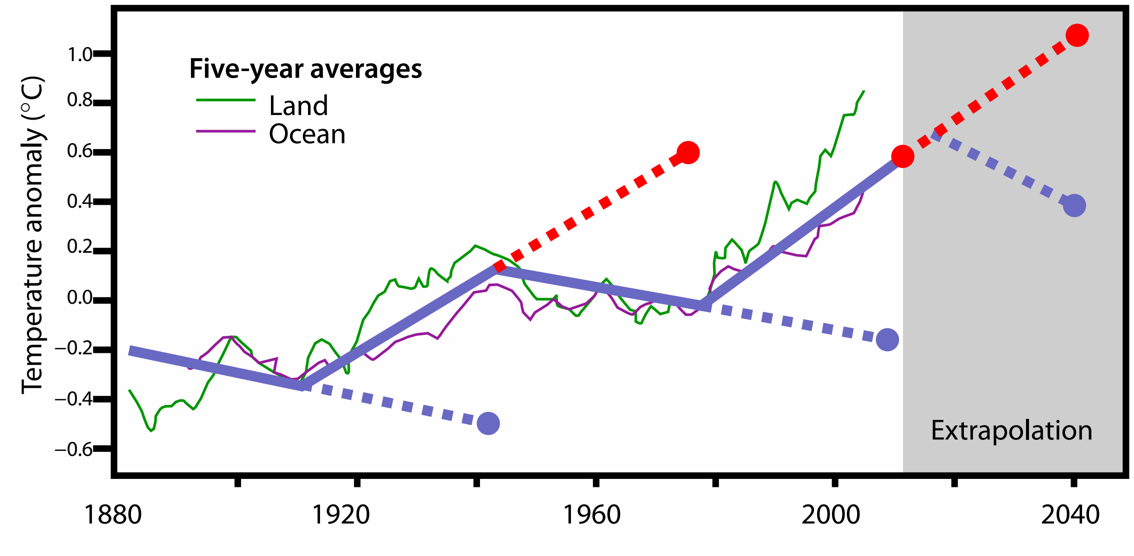


Figure 14: Global surface temperature change since 1880.
The dotted blue and dotted red lines illustrate how much error one would have made by extrapolating a multi-decadal cooling or warming trend beyond a typical 25-35 year period. Note the recent 1975-2000 warming trend has not continued, and the global temperature remained relatively constant until 2014.

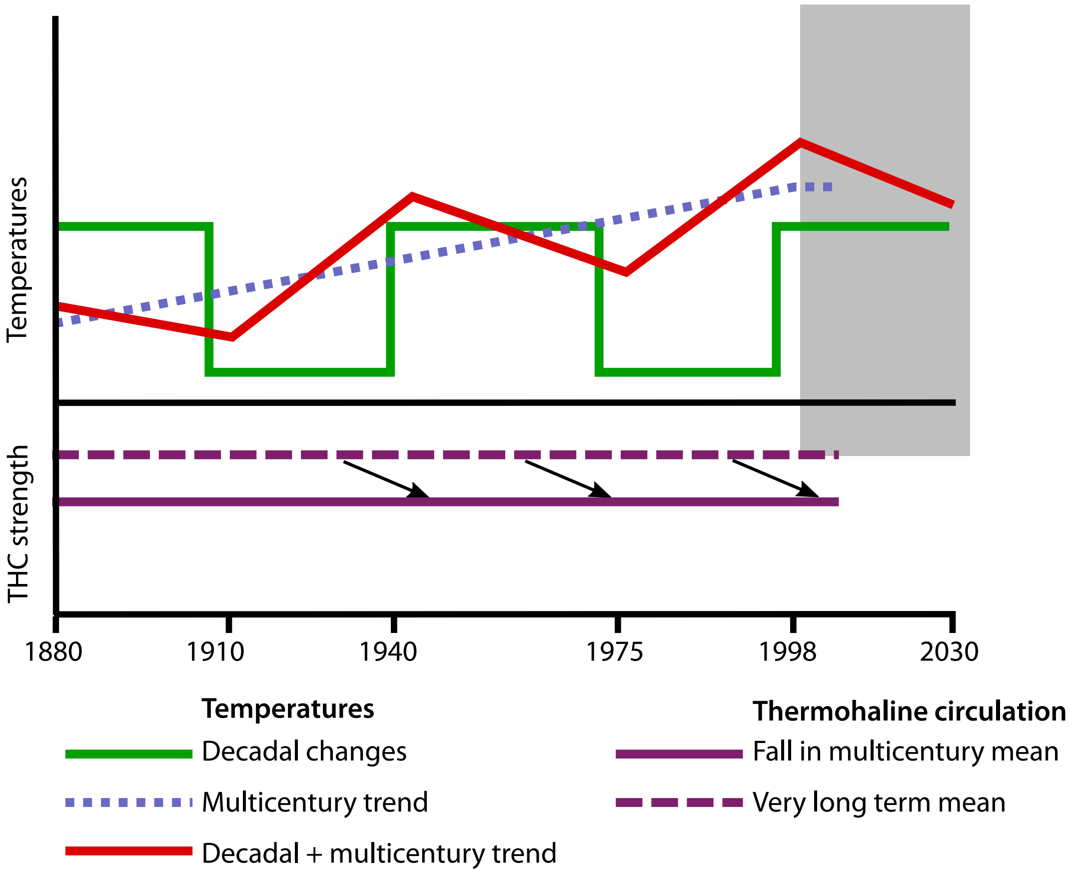


Figure 15: Impact on temperatures of negative long-term multicentury THC.
Short-term THC variations are also highlighted with associated changes in global temperature.

the hydrologic cycle is thus the primary regulator of the globe's surface temperature. Variations in global precipitation are linked to long-term changes in the MOC (or THC).

I have proposed that any additional warming from an increase in CO_2 added to the atmosphere is offset by an increase in surface evaporation and increased precipitation (an increase in the water cycle). My prediction seems to be supported by evidence of upper-tropospheric drying since 1979 and the increase in global precipitation seen in reanalysis data. I have shown that the additional heating that may be caused by an increase in CO_2 results in a drying, *not a moistening*, of the upper troposphere, resulting in an increase of outgoing radiation to space, not a decrease as proposed by the most recent application of the greenhouse theory.

Deficiencies in the ability of GCMs to adequately represent variations in global cloudiness, the water cycle, the carbon cycle, long-term changes in deep-ocean circulation, and other important mechanisms that control the climate reduce our confidence in the ability of these models to adequately forecast future global temperatures. It seems that the models do not correctly handle what happens to the added energy from CO_2 IR blocking.

Solar variations, sunspots, volcanic eruptions and cosmic ray changes are energy-wise too small to play a significant role in the large energy changes that occur during important multi-decadal and multi-century temperature changes. It is the Earth's internal fluctuations that are the most important cause of climate and temperature change. These internal fluctuations are driven primarily by deep multi-decadal and multi-century ocean circulation changes, of which naturally varying upper-ocean salinity content is hypothesized to be the primary driving mechanism. Salinity controls ocean density at cold temperatures and at high latitudes where the potential deep-water formation sites of the THC and SAS are located. North Atlantic upper ocean salinity changes are brought about by both multi-decadal and multi-century induced North Atlantic salinity variability.

Notes

1. PJ Klotzbach, JCL Chan, PJ Fitzpatrick, WM Frank, CW Landsea, and JL McBride (2017) The science of William M. Gray: His contributions to the knowledge of tropical meteorology and tropical cyclones. *Bull. Amer. Meteor. Soc,* 98, 2311-2336, doi: 10.1175/BAMS-D-16-0116.1.
2. JA Church, NJ White, T Aarup, WS Wilson, PL Woodworth, CM Domingues, JR Hunter and K Lambeck (2008) Understanding global sea levels: past, present and future. *Sustain. Sci.,* 3, 9-22.
3. Charney, JG *et al.* (1979) Carbon dioxide and climate: A scientific assessment. *National Academy of Science*.
4. MG Bosilovich, R Lucchesi and M Suarez (2015) MERRA-2: File specification. NASA GMAO Office Note 9
5. E Kalnay *et al.* (1996) The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, 77, 437–471.
6. DH Douglass, JR Christy, BD Pearson and SF Singer, 2007: A comparison of tropical temperature trends with model predictions. *Int. J. Climatol.,* 28, 1693–1701.
7. KE Trenberth and JT Fasullo (2013) An apparent hiatus in global warming? *Earth's Future*, 1, 19–32.
8. KE Trenberth, JT Fasullo and J Kiehl (2009) Earth's global energy budget. *Bull. Amer. Meteor. Soc.,* 90, 311–323.
9. WM Gray and B. Schwartz (2010) The association of outgoing radiation with variations of precipitation – implications for global warming. Presented at the 29th Conference on Hurricanes and Tropical Meteorology (AMS), Tucson, AZ, May 10–14, 2010.
10. WM Gray and B Schwartz (2011) The association of albedo and OLR radiation with variations of precipitation – implications for AGW. Presented at the 91st meeting of the AMS Conference, Seattle, WA, January 23–27, 2011.
11. C Wang, C Deser, J-Y Yu, P DiNezio and A Clement (2012) El Niño–Southern Oscillation (ENSO): A review. In: *Coral Reefs of the Eastern Pacific,* P Glynn, D Manzello and I Enochs (eds), Springer Science.
12. T Delworth, R Zhang and ME Mann (2007) Decadal to centennial variability of the Atlantic from observations and models. *Ocean Circulation: Mechanisms and Impacts, Geophys. Monogr.*, vol. 173, American Geophysical Union, pp. 131–148.
13. I Grossmann and PJ Klotzbach (2009) A review of North Atlantic modes of natural variability and their driving mechanisms. *J. Geophys. Res.*, 114, D24107.
14. SB Goldenberg, CW Landsea, AM Mestas-Nuñez and WM Gray (2001) The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, 293, 474–479.
15. S. Rahmstorf, JE Box, G Feulner, ME Mann, A Robinson, S Rutherford and EJ Schaffernicht (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, 5, 475–480.
16. MJ McPhaden and D Zhang (2002) Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, 415, 603–608
17. WS Broecker, S Sutherland and T-H Peng (1999) A possible 20th-century slowdown of Southern Ocean deep water formation. *Science*, 286, 1132–1135.
18. WM Gray, JD Sheaffer and CW Landsea (1997) Climate trends associated with multidecadal variability of Atlantic hurricane activity. In: *Hurricanes, Climate and Socioeconomic Impacts,* HF Diaz and RS Pulwarty (eds), Springer, pp. 15–53.

About the Global Warming Policy Foundation

The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

Views expressed in the publications of the Global Warming Policy Foundation are those of the authors, not those of the GWPF, its trustees, its Academic Advisory Council members or its directors.

GWPF BRIEFINGS

1	Andrew Turnbull	The Really Inconvenient Truth or 'It Ain't Necessarily So'
2	Philipp Mueller	The Greening of the Sahel
3	William Happer	The Truth about Greenhouse Gases
4	Gordon Hughes	The Impact of Wind Power on Household Energy Bills
5	Matt Ridley	The Perils of Confirmation Bias
6	Philipp Mueller	The Abundance of Fossil Fuels
7	Indur Goklany	Is Global Warming the Number One Threat to Humanity?
8	Andrew Montford	The Climate Model and the Public Purse
9	Philipp Mueller	UK Energy Security: Myth and Reality
10	Andrew Montford	Precipitation, Deluge and Flood
11	Susan Crockford	On the Beach
12	Madhav Khandekar	Floods and Droughts in the Indian Monsoon
13	Indur Goklany	Unhealthy Exaggeration
14	Susan Crockford	Twenty Good Reasons not to Worry about Polar Bears
15	Various	The Small Print
16	Susan Crockford	The Arctic Fallacy
17	Indur Goklany	The Many Benefits of Carbon Dioxide
18	Judith Curry	The Climate Debate in the USA
19	Indur Goklany	The Papal Academies' Broken Moral Compass
20	Donoughue and Forster	The Papal Encyclical: a Critical Christian Response
21	Andrew Montford	Parched Earth Policy: Drought, Heatwave and Conflict
22	David Campbell	The Paris Agreement and the Fifth Carbon Budget
23	Various	The Stern Review: Ten Years of Harm
24	Judith Curry	Climate Models for the Layman
25	Fritz Vahrenholt	Germany's *Energiewende*: a Disaster in the Making
26	Hughes, Aris, Constable	Offshore Wind Strike Prices
27	Michael Miersch	Truly Green?
28	Susan Crockford	20 Good Reasons not to Worry About Polar Bears: Update
29	Mikko Paunio	Sacrificing the Poor: *The Lancet* on 'pollution'
30	Mikko Paunio	Kicking Away the Energy Ladder
31	Bill Gray	Flaws in Applying Greenhouse Warming to Climate Variability

For further information about the Global Warming Policy Foundation, please visit our website at www.thegwpf.org. The GWPF is a registered charity, number 1131448.