Global Warming
The Persuasive Physics

Mitchell Golden

Why this talk?

This talk is aimed at two kinds of people:

1) People who don't believe that human-caused global warming exists.

2) People who do believe that human-caused global warming exists, but who feel that they don't have a good handle on the science.

There is lots and lots of stuff on the internet and elsewhere about global warming, but I have found most of it dissatisfying with respect to physical explanations...

… and the physical explanations are quite persuasive.

Physics is persuasive

One reason that the public discussion on global warming generates so much heat and so little light is that

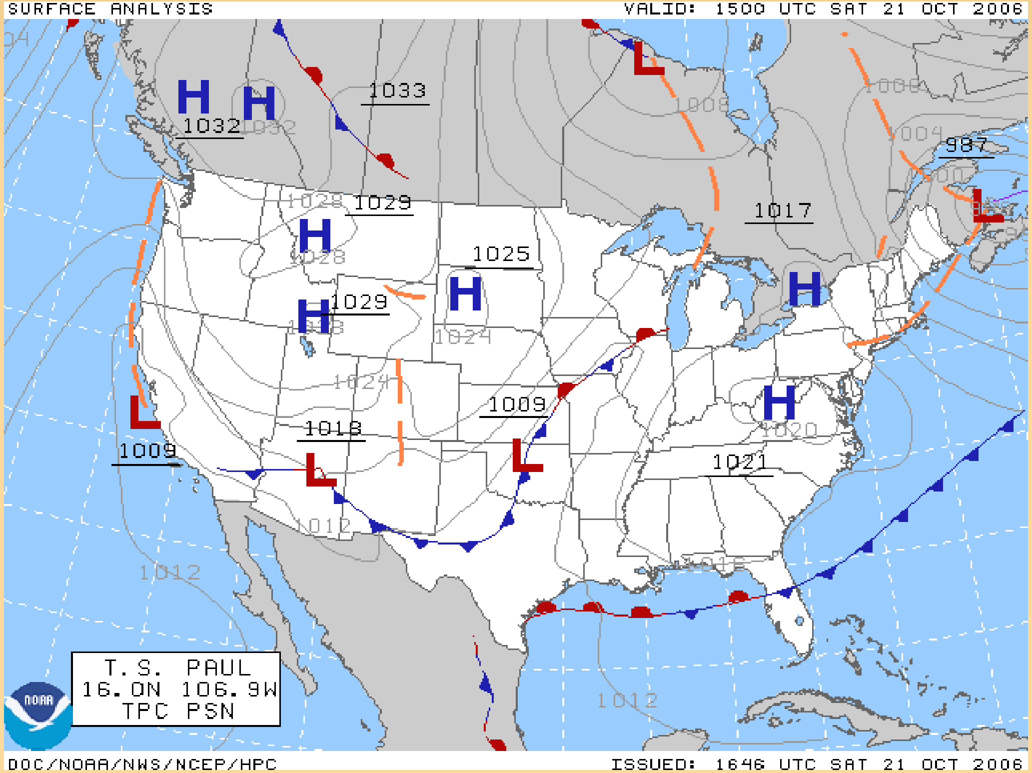
there is not enough physics in the public discussion!

The physics of global warming is not hard to understand.

My hope is to bring the science to the public in a way that is can be understood by the layman.

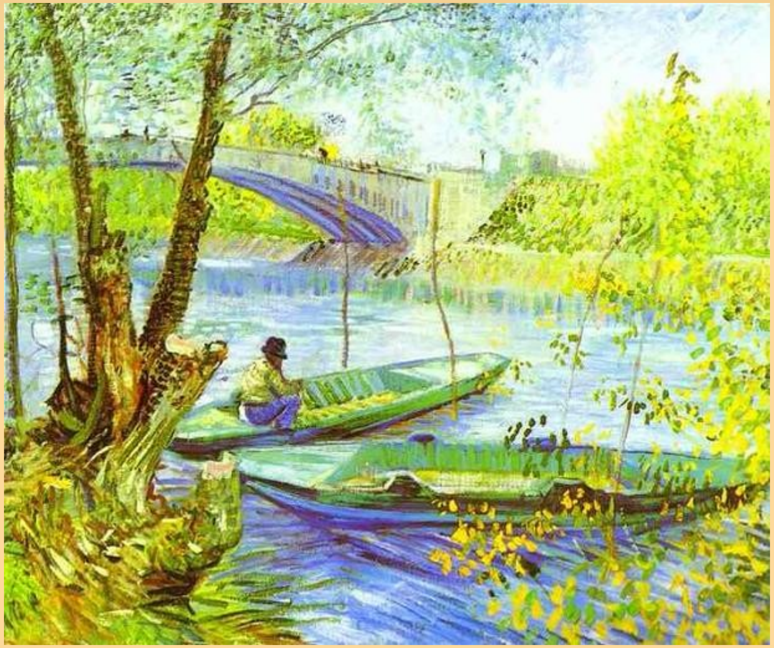
Why so much confusion about this subject?

People think that the climate system is too big and complicated for us to make statements about. “How can we say anything about the year 2100? After all, we can't even predict next week's weather!”



But...

But *weather* is not *climate* – climate is much easier to understand. Predicting climate is akin to understanding why the average temperature in May is higher than it was in December.



Complexity R Us

Science *does* get the complexity of the world around us under control.

How else would we be able to...

Build good highways?

(You have to understand how human drivers behave in all sorts of conditions!)

We *can* understand complex systems!

or...

Fly airplanes?

(Aerodynamics is very, very complicated!)

We *can* understand complex systems!

or...

Practice medicine?

(Is anything more complex than the human body?)

What is a model?

Not that kind!

In science we find that there are actually *no* systems we can analyze exactly – we *always* have to simplify. We just throw out the complexity by making approximations, yielding a simpler system, called a “model”.

Because models are approximations, we will have to check them to see if they are capturing the required behavior. We will often construct a series of models of greater complexity if we need more details.

An Example Model!

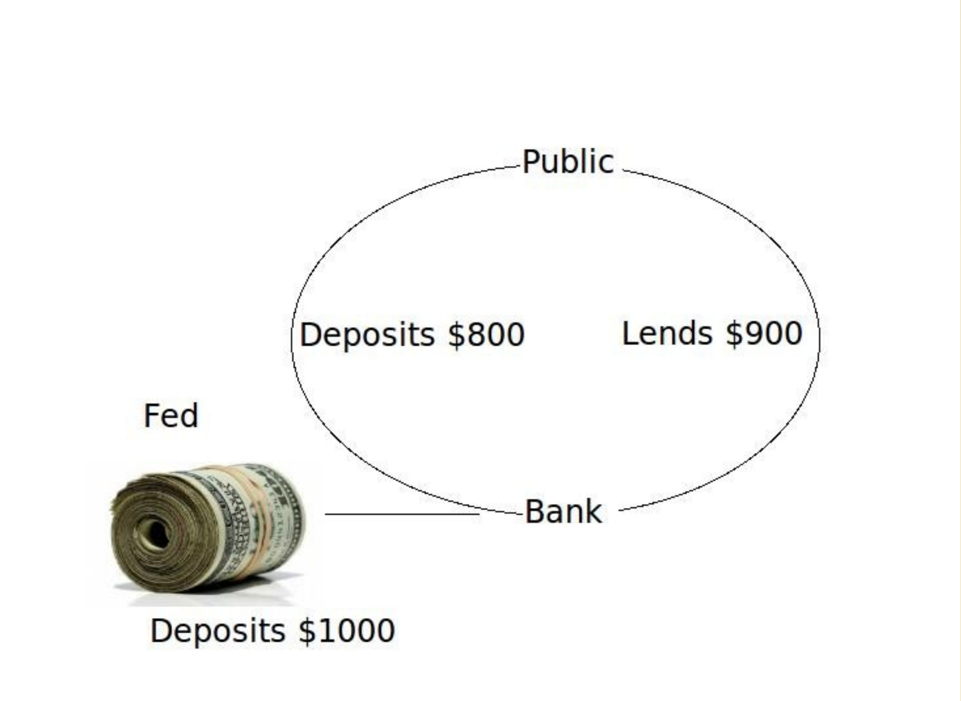
Q: What happens when the Federal Reserve deposits $1000 in a bank?

The economy consists of hundreds of millions of people making decisions about what sorts of transactions to engage in, subject to all the complexities of the human psyche. What could we possibly say about anything?

Actually, in all of this unruly chaos, we can still answer this question!

A simple economic model

Simplify the world: there are three players: The Fed, “The Banks”, and “The Public”



The total increase in bank deposits is $1000 + $800 + $640 + $512 + …
an infinite number of terms!

Economic model, continued

… but the series is not infinite.

Since each term gets smaller than the one before it actually adds up to a finite result – in this case $5000.

This sort of behavior is called a “positive feedback”. A system changes itself in response to an external push, and amplifies the effect of the push.

Some systems have “negative feedbacks”, in which the system responds *less* than the effect of the push. Negative feedbacks stabilize the system.

Our model has limits...

There are a lot of things our model did **not** tell us:

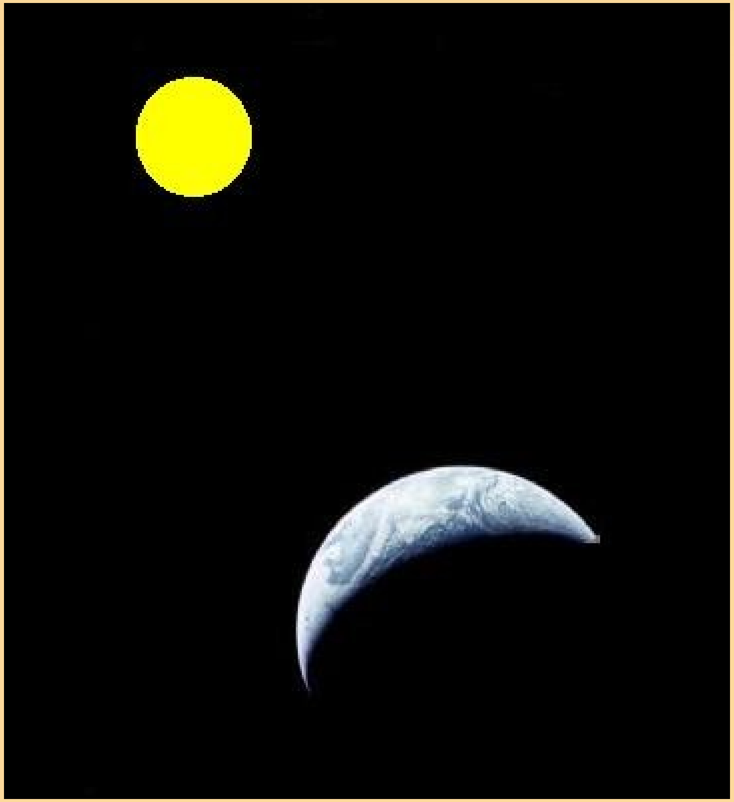
- Which banks get the deposits?
- How long does the process take?
- How do The Banks and The Public decide how much to lend out and deposit? (We simply put these things in as input parameters.)

If we want to answer to these questions, we need a more complex model. We may or may not be able to explain everything we want.

The fact that a model is limited doesn't mean that it is wrong or useless. Such a model is ***right*** – and highly conceptually useful – because it predicts the correct results and for the right reasons.

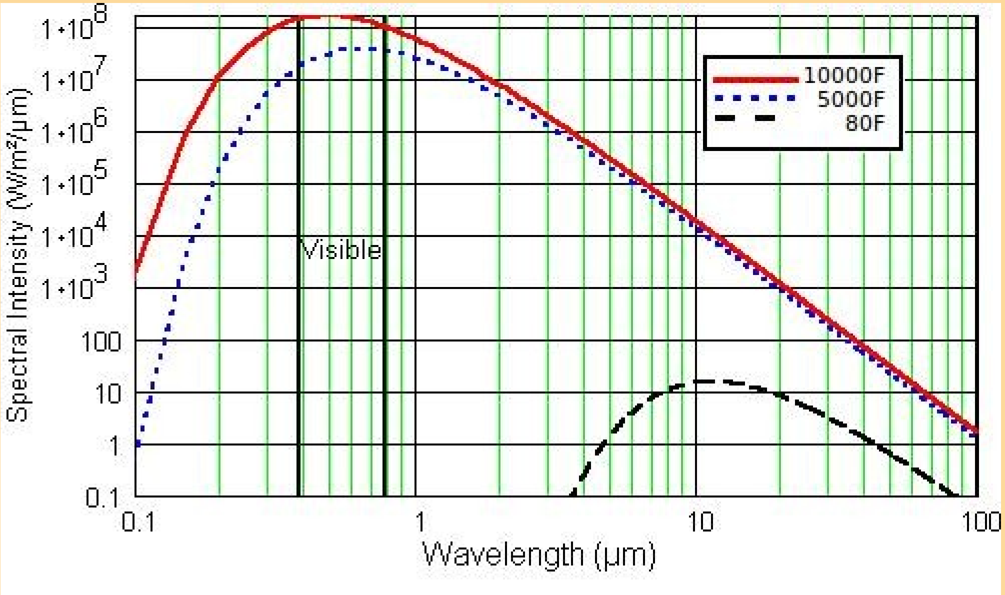
Constructing a model of climate, physical considerations

- The earth is an isolated system in space.
- It gets energy in one way only: by absorbing sunlight
- It releases energy in one way only: by radiating infrared to space. If it didn't radiate as much as it absorbed, the earth would keep getting hotter, so radiation out must equal radiation in.



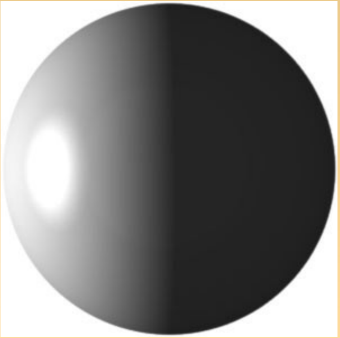
How do bodies emit radiation?

The so-called “black body” spectrum describes how a hot body emits radiation. Hotter bodies emit more radiation, and they emit it at shorter (bluer) wavelengths. Earth absorbs visible radiation from the sun and radiates it back to space as infrared.



Climate model 0: Earth with no atmosphere

The gray ball model: Assume that earth has no atmosphere and is a simple ball all at one temperature.



- Sunlight is about 1366 W/m^2 at earth's orbit
- Earth's albedo (reflectivity) is about 30%
- Earth is therefore absorbing about 950 W/m^2

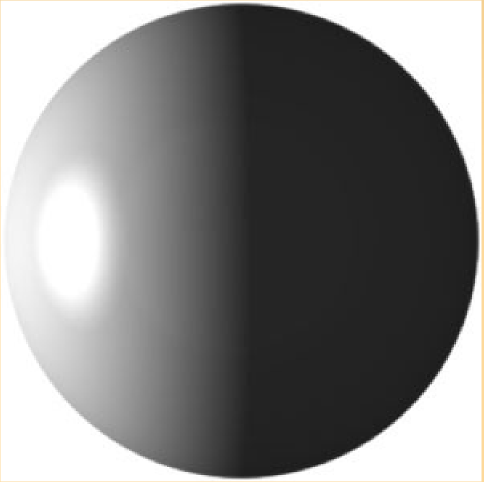
What temperature does a body have to be to emit the amount of energy the earth is absorbing?

Answer 0°F

Climate model 0: Earth with no atmosphere

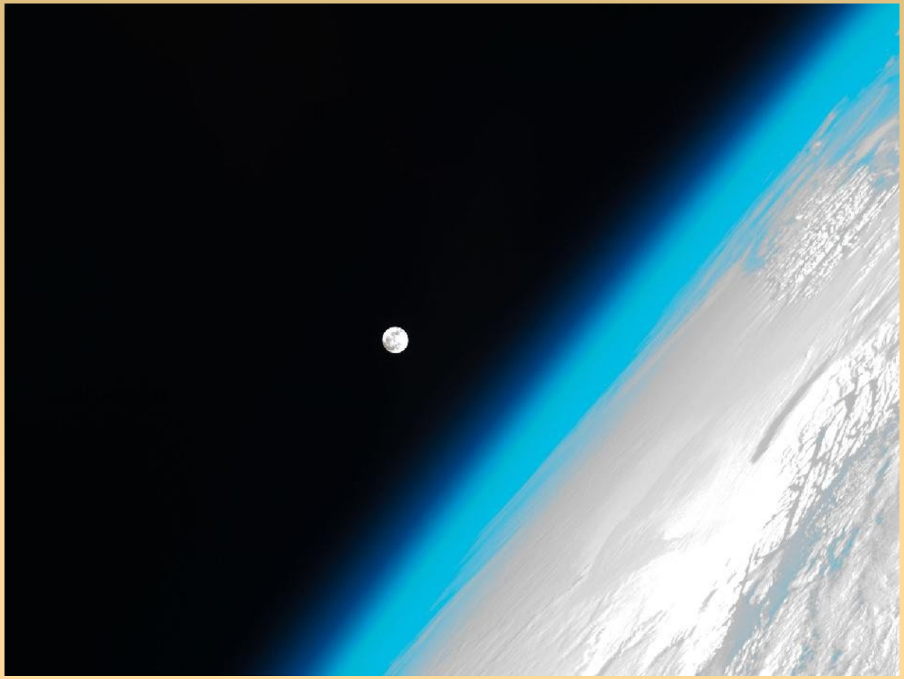
This model is too simple – actual average temperature of earth is about 56°F.

However – it illustrates that we can get to the right ballpark (compare to 10,000°F for the sun or -455°F for space), with very simple considerations.



We need to add in more detail!

Model 1: Add in an atmosphere



Physical properties of the atmosphere:

1) It's a gas!

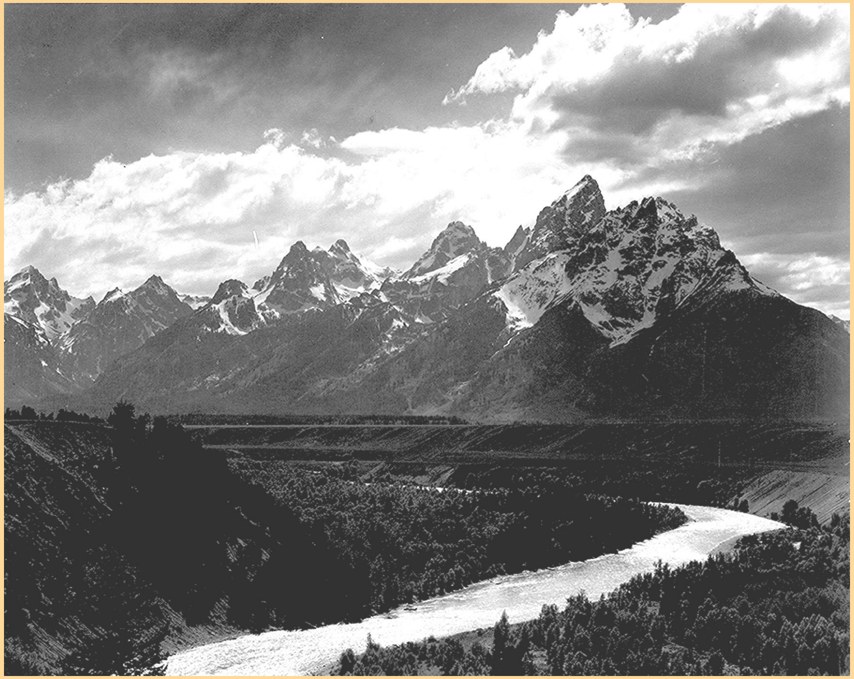
2) It's held down by gravity, and it holds itself up by its internal pressure.

3) It moves around and mixes itself vertically, fairly quickly, due to winds.

Model 1: Add in an atmosphere

So...

- Because of gravity (2) air is at a lower pressure at high altitudes.
- Air cools as it expands, so as wind carries air up (3), it will cool off. It's simple to show that dry atmosphere is 5.4F cooler each 1000 ft up (the so-called “lapse rate”)



A refinement

The earth's surface is ¾ water, so the dry lapse rate isn't going to be right

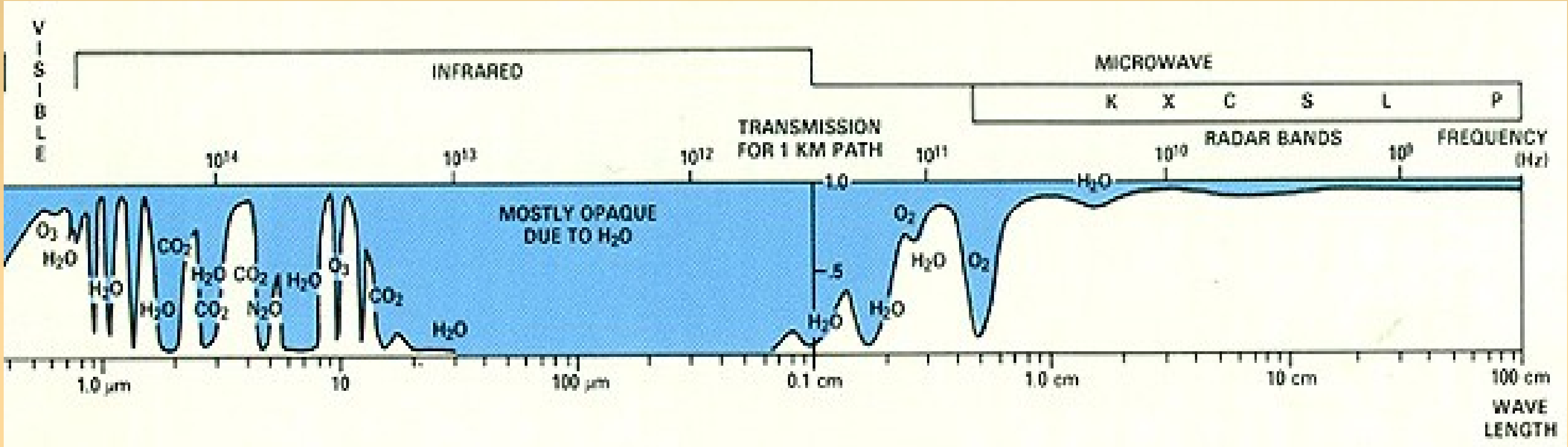
- As the air gets cooler, at some point water will condense out (forming fog/clouds), which releases heat into the remaining air.

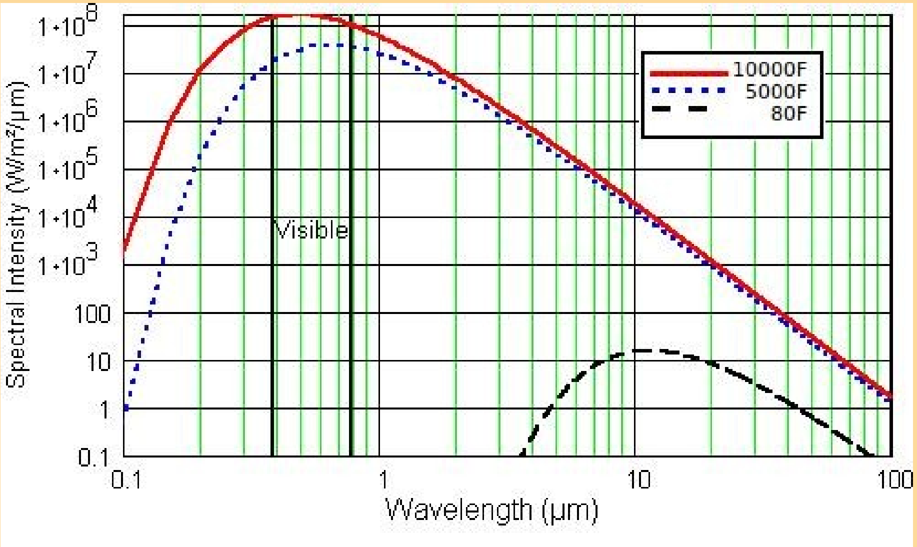
Blue Ridge Scenic Byway

- This yields the so-called “Moist adiabat”: the temperature goes down more slowly with height than if no water were present.
- The effect of moisture is greater when the surface is warm than cold.
- The actual lapse rate of the atmosphere averages about 3.5F/1000 ft.

Model 1: The atmosphere, continued

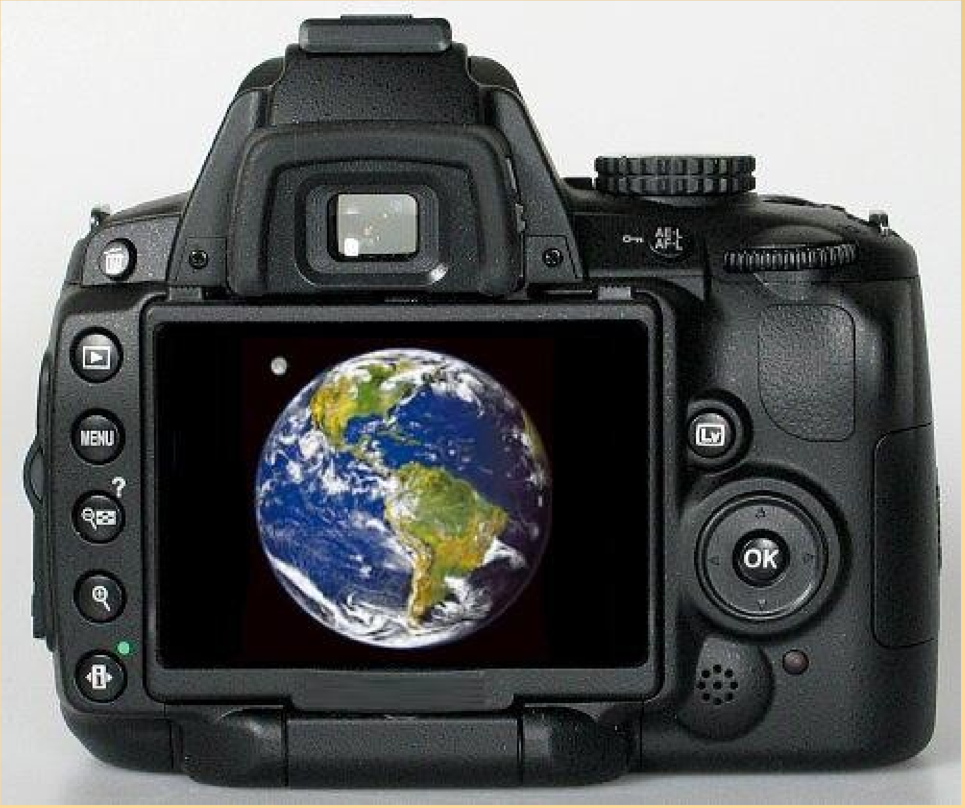
Next: the atmosphere is opaque to many infrared frequencies





Model 1: Earth from space 1

If we take a picture of earth from space



Model 1: Earth from space 2

But if we use a camera sensitive at 20 microns (infrared):

We cannot see the surface!

Model 1: Temperature, finally!

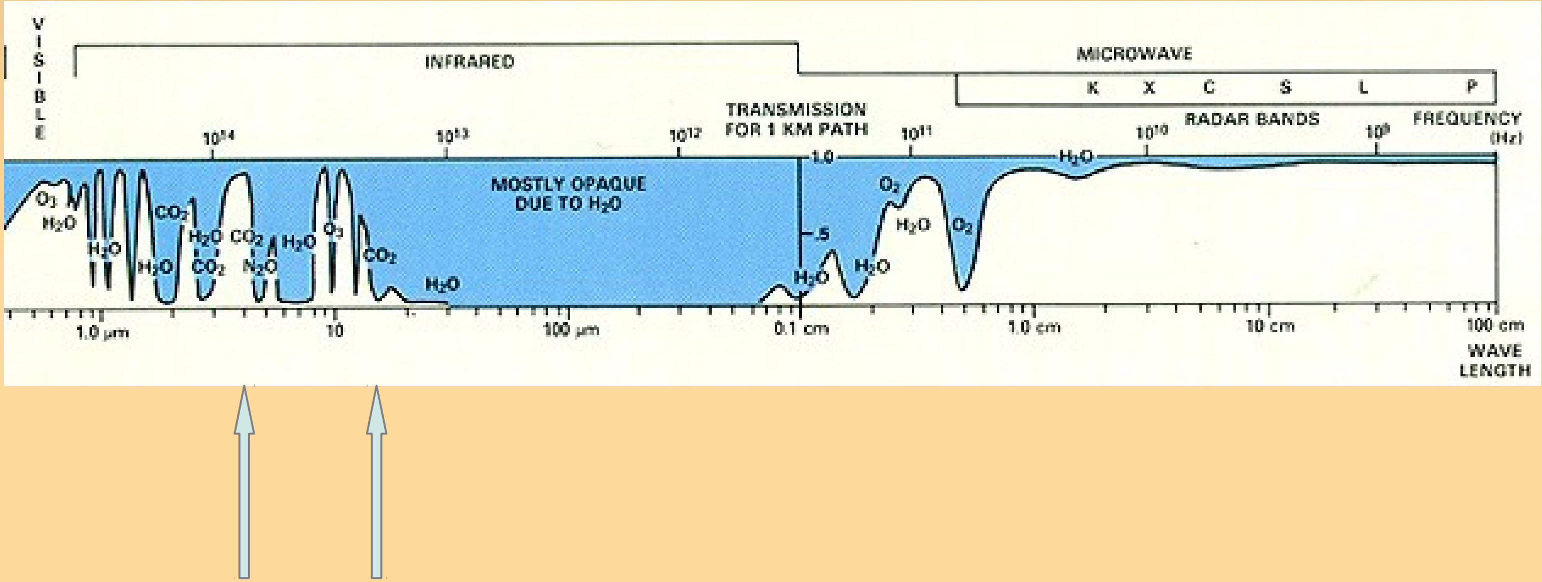
Because the atmosphere is transparent to the sun's rays, adding the atmosphere *does not change* the amount radiation that must be radiated to keep the earth in balance with the sun,

But looking down from space, it is not the surface you see radiating, since infrared radiation from the surface can't reach space. Instead, it is the atmosphere.

To be in balance, the place that is radiating should be about 0F. The lapse rate dictates that the surface is warmer than this point in the atmosphere. Therefore, the surface is warmer than it would have been.

What does CO2 do?

CO_2 is transparent in the visible part of the spectrum, but *not* in the infrared.

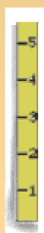


As we have seen, adding CO_2 will make the atmosphere more opaque to infrared, and so *raise* the emission height of the radiation going from earth seen to space, resulting in surface warming.

Even so little CO2?

CO2 is only is only 0.039% of the atmosphere!

This is not very much:



5 ¾ inches

As a fraction of

Height of Empire State Building

BUT...

CO2 can have a big effect while being a small part of the atmosphere because Nitrogen, Oxygen, and Argon (over 99% of the dry atmosphere) are neutral – very transparent to both infrared and visible light.

What's relevant isn't CO2's fraction of the atmosphere, but its fraction of the opacity in the infrared - this is why humanity can have an effect!

Simple, right?

That is all there is to the greenhouse effect -

It is based entirely on familiar concepts!

Can we attach some numbers to this?

The preindustrial atmosphere was 0.0275% CO_2.

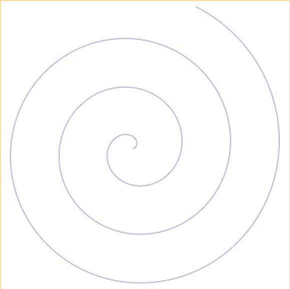
If you double CO_2 to 0.055% CO_2, one would expect the temperature of the surface to rise about 2°F (1.2°C).

Maybe that's not too much of a problem...

BUT!

The earth and atmosphere change as you warm them.

This induces *feedbacks* that enhance or reduce the original effect... just like our economic system had a feedback that enhanced the original $1000 deposit from the Fed.



So what changes if the earth warms?

What about the earth and atmosphere would change if you made them warmer?

There would be more water vapor in the atmosphere. (Warm air holds more moisture)

Ouch! As we've seen, water vapor is quite opaque to IR itself, so this will make the surface even hotter.

It is a strong *positive feedback.*

So what changes if the earth warms? (2)

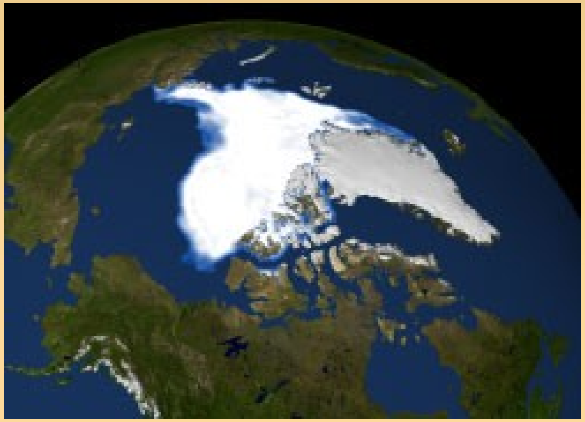
More water vapor and higher temperature means a smaller lapse rate (because of the moist adiabat).

Whew! This will lower the difference in temperature between the surface and the upper atmosphere, cooling the surface.

It is a *negative feedback*.

So what changes if the earth warms? (3)

As the earth warms, ice melts.



Ouch! Ice is quite reflective, but land, and especially ocean, is dark. Melting therefore makes the earth absorb more sunlight.

This is a *positive feedback.*

Climate Sensitivity

There are many more feedbacks...

(see http://en.wikipedia.org/wiki/Climate_change_feedback)

… and the goal of climate science is to figure them out and see how big they are and how fast they operate.

The term **climate sensitivity** refers to what you get if you add all of them up.

Some of the feedbacks are better understood than others, which is why there is still a lot to learn about the earth.

What do we need to know?

However...

The water vapor and lapse rate feedbacks are very big and fast acting, and reasonably well understood. What other things could play that big a role?

What about clouds?

Clouds have a *very large* effect on climate. If there were no clouds, the earth would be considerably darker (= hotter) than it is.

Plenty of white!

So more humidity = more clouds. More clouds = negative feedback, right?

Clouds are complex

Actually, no! Cloud formation is also very complex. It depends on the level of water vapor, the amount of dust in the air, and possibly even the level of cosmic rays! And there are different kinds of clouds:

- Puffy white ones (*cumulus)* and thin scraggly ones (*cirrus*), and ones between.
- The puffy white ones reflect sunlight – so lower the temperature during the day.
- But all clouds reflect infrared down to the surface, so raise temperature at night.
- The thin scraggly ones don't reflect much sunlight, so they raise temperature day and night.

Clouds as feedback

But all we really need to know is how clouds *change* if the earth warms, not everything about how they're formed.

If the earth warms, do more clouds form, and if so, what kinds? Are they high or low? Do they remove water vapor from the air?

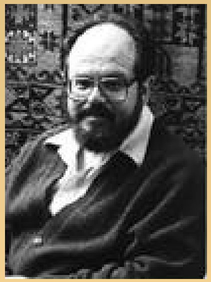
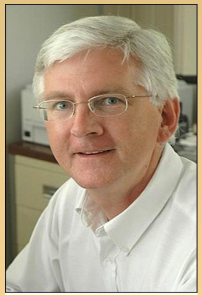
Do they function as a positive or negative feedback, and how large?

In fact, the role of clouds was one of the biggest uncertainties preventing consensus until the 1990s or so.

While the theoretical understanding of clouds is still incomplete for clouds over the past 30 years, *direct* measurements, some with satellites, have shown that the simple approximations used in climate models work pretty well.

Clouds are either a positive or small negative feedback.

The most famous men in climate science!

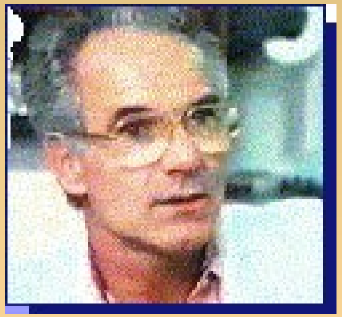
Richard Lindzen (MIT), John Christy (University of Alabama/Huntsville) and Roy Spencer (University of Alabama/Huntsville), Patrick Michaels (George Mason U., Cato Institute)

Lindzen and Spencer think that clouds will form a strong negative feedback that cancels out the water vapor and albedo feedbacks. (They don't actually agree with each other in detail.)

Their work has been refuted in the literature and their predictions haven't held up.

Yet the media need for “balance” means that they are quoted in virtually every article on climate science.

The most famous man in medicine?



If AIDS were covered the way that climate science is, Peter Duesberg would be the most famous man in medicine:

Professor at U.C. Berkeley and member of the National Academy of Sciences, who says that AIDS is caused by recreational drugs, not a virus.

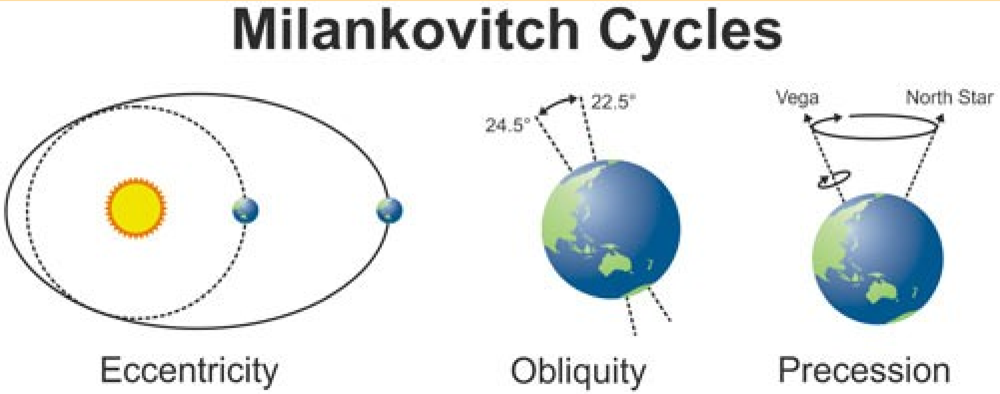
How do we know that we know what we're talking about?

As formulated by James Hansen (NASA), in DECREASING order of persuasiveness:

1) Paleoclimate: The ice ages are caused by small shifts in the orientation of the earth's axis with respect to the sun.

If the climate sensitivity were small, it would not possible to explain the ice ages.

You can actually evaluate how big the forcing effects of the orbital changes are, and estimate the climate sensitivity. It comes out quite similar from that of the climate models or other estimates.



www.skepticalscience.com

(An aside)

The fact that the climate has varied in the past without a human cause is often cited as a reason to believe that changes we are seeing today are not human-caused.

“Yes, our climates change. They’ve been changing ever since the earth was formed.”

- Rick Perry

This is PRECISELY BACKWARDS.

The past changes in climate did not happen by magic. Our analysis of what happened in the past is part of what we use to validate our understanding of climate in general.

How do we know...? (2)

2) Ongoing direct measurements

The temperature can be directly measured, as can the lapse rate, clouds, heat content of the ocean, icecaps and glaciers... and these all fit together and confirm the overall picture of what is happening.

How do we know...? (3)

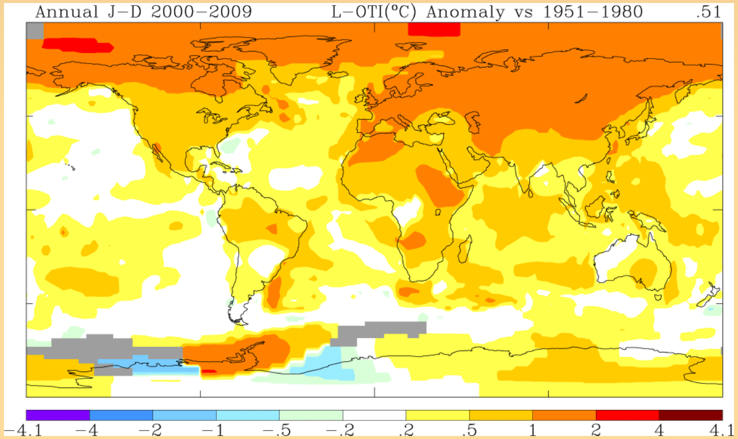
Computer calculations of climate models agree with observations!

Climate models are big and complicated, but many groups have worked on them and derive similar results. Models can be validated, for example, when a volcano erupts and puts sulfate dust into the air. (Mt. Pinatubo, 1991) climate models correctly predicted the cooling effects seen.

Other confirmations...

Aside from overall warming, the greenhouse gas model predicts some other changes as well:

- Cooling of the stratosphere.
- More heating at the poles than in the tropics (*aka* “polar amplification”).



- More nighttime warming than daytime warming.

All of which have been observed. (And all of which are the opposite of what would be expected if, for example, the currently observed warming were caused by the sun.)

The consensus value of climate sensitivity

Intergovernmental Panel on Climate Change (2007):

“Analysis of models together with constraints from observations suggest that the equilibrium climate sensitivity [to raising CO_2 to 0.055% from 0.028%] is likely to be in the range 2°C [3.6°F] to 4.5°C [8.1°F], with a best estimate value of about 3°C [5.4°F]. It is very unlikely to be less than 1.5°C [2.7°F]. Values substantially higher than 4.5°C [8.1°F] cannot be excluded, but agreement with observations is not as good for those values.”

Basically unchanged since 1979!

But why do I care?

“OK, so I am with you. The earth will warm by 3°C by the latter part of this century. Why do I care? Anyway, I hate cold weather!”

The secondary effects of climate change are worse than the temperature rise itself.

Effects of warming (brief!)

There are many many effects of warming, many are not much fun...

- Melting ice... leading to sea level rise...

- Ocean acidification... species extinction... tropical diseases...

But let's stay focused on physics!

The Water Cycle

Clearly there will be immediate effects if the air is warmer:

1. Water will evaporate faster

Therefore, in places where it is not raining, it will be drier.

Unless there is *more* rain in a given location than there was before, it will dry out. There will be long, intense droughts.

The Water Cycle (2)

2. There will be more water in the atmosphere, so there will be more precipitation. (But not necessarily in the same places as before!)

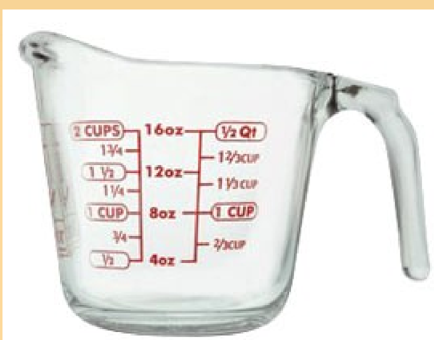
3. Storms will be more intense

Bidgee - Wikipedia

Why is water in the atmosphere dangerous?

This is DEEP, man: The so-called mechanical equivalent of heat is ENORMOUS:

1 BTU - the amount of energy it takes to raise the temperature of a pound of water (about a pint) by 1^{o}F - would make a car go 3mph!



Raise temp just 1^{o}F

Same energy as to get this going 3 mph!

To *evaporate* all the water in the cup, the same energy is required as to get the car going nearly 100 mph!

Why is water in the atmosphere dangerous?

More water vapor in the atmosphere means more energy available to convert into high and low pressure regions, and into strong winds. This is just a plausibility argument, but based on it you'd expect more intense deluges. (Including blizzards, BTW).

The bad news: There is about 4% more water vapor in the atmosphere than there was 30 years ago.

Why is water in the atmosphere dangerous?

As for the future:

“And so when you start talking about three, four, five degrees [Celsius of temperature rise] then you’re talking about twenty percent increases in the water vapor in the atmosphere… [T]he intervals between storms will be longer, but then when you do have the storms they are apt to be a doozie. … So you can really get deluges, and there are times when you have longer dry spells in between so there’s the risk of drought if you happen to miss these storms... But then when you do get hit by them suddenly you’ve got a deluge.”

– Kevin Trenberth, climate scientist, National Center for Atmospheric Research

Even physicists know enough about agriculture to tell you that droughts followed by deluges is not good for farming!

Conclusion: whom should I believe?

There are a lot of shrill voices – the press loves them – and it's hard to tell whom you should be paying attention to.

Who is the most reliable on this subject? Whose statements should I trust?

Not politicians!

Not editorials!

THE WALL STREET JOURNAL.

The New York Times

THE HUFFINGTON POST

The Washington Post

Not Individual Scientists, Scientific Organizations!

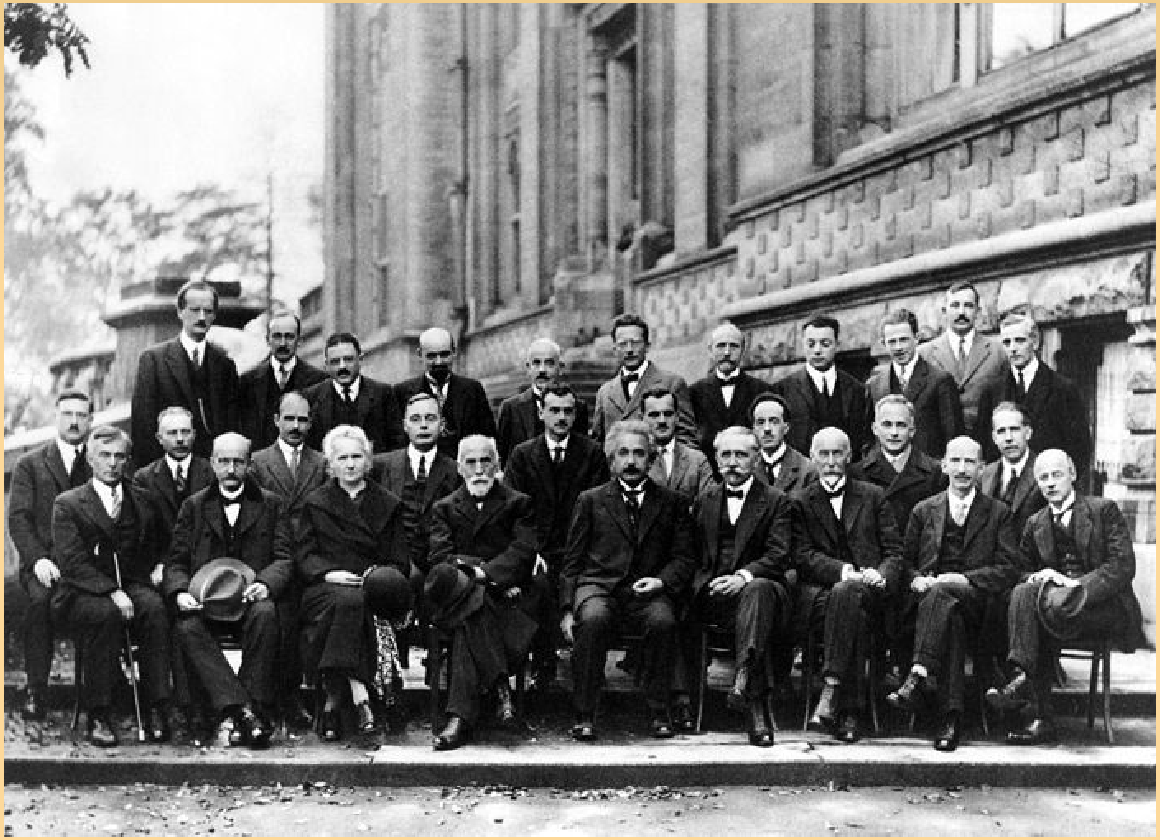
There is an impressive list of scientific organizations on record:

- National academies of Science of Australia, Belgium, Brazil, Cameroon, Canada, Caribbean, China, France, Ghana, Germany, Indonesia, Ireland, Italy, India, Japan, Kenya, Madagascar, Malaysia, Mexico, Nigeria, New Zealand, Poland, Russia, Senegal, South Africa, Sudan, Sweden, Tanzania, Turkey, Uganda, United Kingdom, United States, Zambia, Zimbabwe
- National Research Council (US)
- American Association for the Advancement of Science
- American Chemical Society
- American Institute of Physics
- American Physical Society
- Australian Institute of Physics
- European Physical Society
- European Science Foundation
- Federation of Australian Scientific and Technological Societies

- Earth sciences: American Geophysical Union, European Federation of Geologists, European Geosciences Union, Geological Society of America, Geological Society of Australia, Geological Society of London, International Union of Geodesy and Geophysics, National Association of Geoscience Teachers
- Meteorology and oceanography: American Meteorological Society, Australian Meteorological and Oceanographic Society, Canadian Foundation for Climate and Atmospheric Sciences, Canadian Meteorological and Oceanographic Society, Royal Meteorological Society (UK), World Meteorological Organization
- Paleoclimatology: American Quaternary Association, International Union for Quaternary Research
- Biology and life sciences: American Association of Wildlife Veterinarians, American Institute of Biological Sciences, American Society for Microbiology, Australian Coral Reef Society, Institute of Biology (UK), Society of American Foresters, The Wildlife Society (international)
- Human health: American Academy of Pediatrics, American College of Preventive Medicine, American Medical Association, American Public Health Association, Australian Medical Association, World Federation of Public Health Associations, World Health Organization
- Miscellaneous: American Astronomical Society, American Statistical Association

Why?

NOT because they are filled with eminences, smarter than mere mortals.



Anyone can be right about science, anyone can be wrong.

OK, so why?

Scientific organizations are slow moving and *conservative*. (In the *real* sense of that word!)

They have *processes* that require all points of view to be carefully considered and all statements to be refereed.

Conclusion: now you know what to ask!

If someone tells you “Global Warming is a hoax” your polite response to him should be this:

I understand your point of view. But let's not talk about stolen e-mail or claims of fraudulent data – these are distractions. The greenhouse effect is based on simple effects, such as the opacity of CO_2 to infrared rays and the fact that the atmosphere is colder higher up.

- Please tell me what you think is the strong negative feedback that cancels out the well understood positive feedback caused by water vapor.
- Please explain how, in the presence of your climate-stabilizing negative feedback, there have been ice ages in the past.
- Tell me why none of the scientific organizations have been persuaded by your arguments.