Climate Science

Life finds a way — Ian Malcolm.

Ivo Welch

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Basic Climate 101

- climate is *not* weather!
- humans can easily notice weather change
  - daily, weekly, monthly, yearly, multi-yearly
  - weather includes even multi-year el nino patterns
- humans cannot easily notice climate change:
  - especially in time (like frogs in warm water);
  - requires data and scientific measurement.

Extreme Temp Examples On Record

- 2016 was the warmest global year on record.
- winter 2021 in the antarctic was the coldest winter on record.
- 2022 (so far) has been the lowest atlantic hurricane season on record.

so what?

- for climate, we need global trends over decades

(ps: we will ignore that climate is more than just temp.)

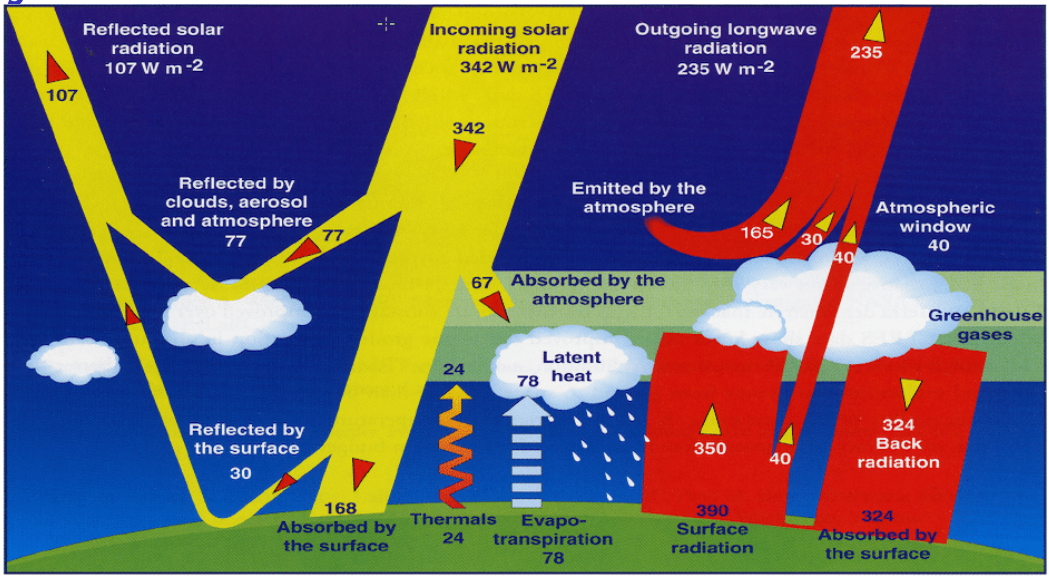
The Greenhouse Effect

- visible sunlight is absorbed or reflected.
  - often reflected in infrared
- GHGs oscillate at infrared frequencies.
- thus, they reemit energy upon capture in random directions, often back to Earth (a second time).

A Comprehensive Earth And GHG Balance

- next diagram is courtesy of gregory bothun.
- the radiation balance changes over time.
  - see gregory's explanation.

Physics GHG Basics



GHG Effect On Planet Earth

- today's life depends on presence of GHGs:
  - no GHGs: −18°C = 255°k = 0°f .
  - actual: +14°C = 287°k = 57°f .

what about venus?

Venus?

- venus: 460°C; 98% co_2.
  - water is required for stone weathering of co_2.
- Earth: 14°C; 0.0004% co_2.
  - fearing 0.0008% co_2.
  - humans are not ***that*** important! life on Earth will not end due to human co_2 emissions.
- mars: −65°C; 96% co_2.
  - can reach +20°C in summer on the equator

Earth's Past

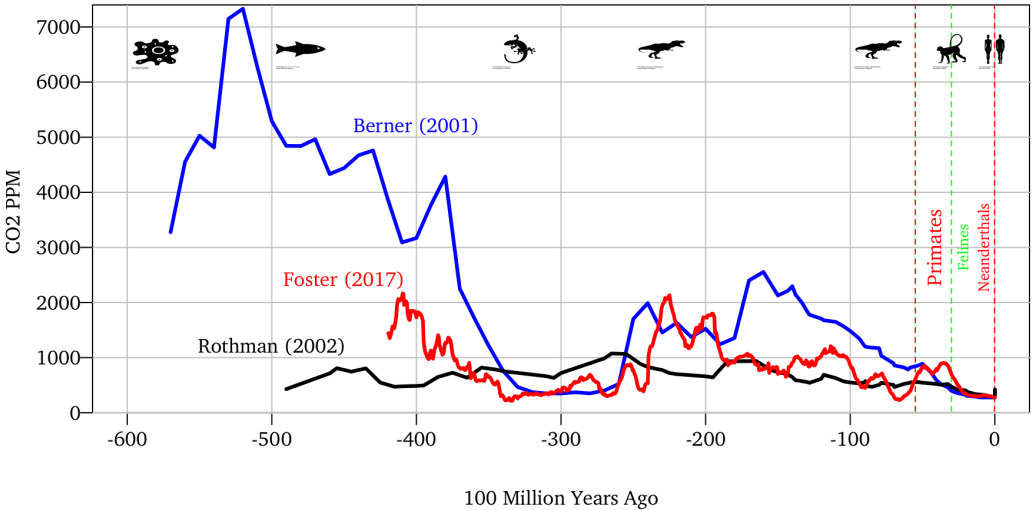
what do boffins know about the past?

Deep Time Introduction

- ***deep time***: ≈ 500 million years.
  - homo habilis: ≈ 2 million years ago.
  - homo sapiens: ≈ 0.3 million years.
- where/what can we measure exactly?
  - satellites were not as good then.
  - limited by data types (e.g., spores), and
  - limited by data spots (e.g., latitude).

darn planet is uncooperative. it also changed temp slope gradient across latitudes and even entire continents, too! *Animation of Continents*

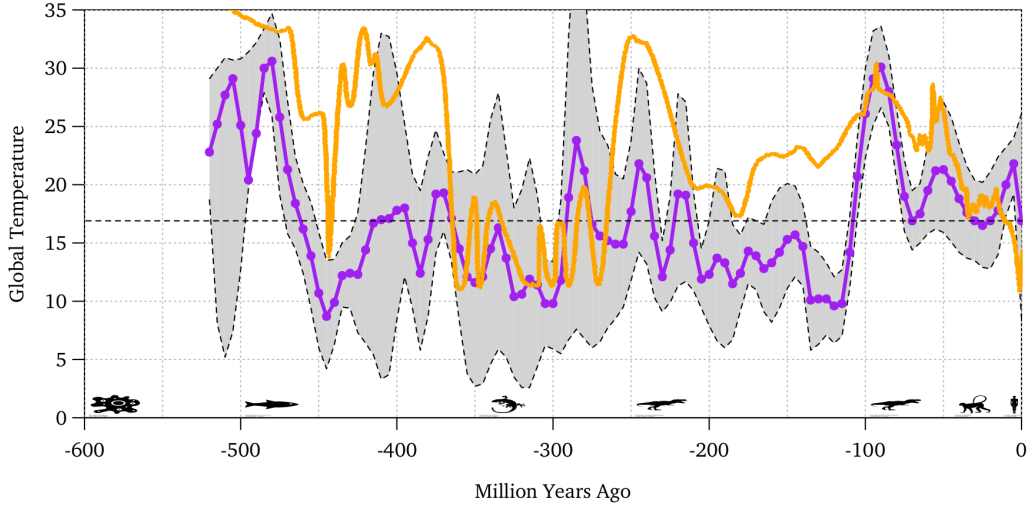
Deep Time Co_2 (Different Estimates)



Perspectives And Temperature?

- co_2 is planetwide.
  - 800 ppm was not unusual for 500 million years
  - 800 ppm was unusual for recent 50 million years
- temperature is highly geography dependent.
  - much harder to measure.

Deep Time Temperature (Different Estimates)



- Earth has experienced very large temperature changes even before humans arrived on the scene.
  - temperatures of 3°C higher than today were common over 500 million years;
  - but Earth and its creatures looked very different!

- (better get ready)

Ice Age Question

- is Earth in an *ice age*?
- what exactly is an *ice age*?

What Is An Ice Age?

- ice age = polar ice year round
  - 30% of last 2.5 billion years.
- *snowball Earth* < ice age < *greenhouse Earth*
- the *cambrian explosion* of life occurred after the last snowball Earth ended about 530 million years ago.

more fascinating background on Earth's ages

Current Ice Age

- current ice age
  - ongoing for 50 million years;
  - even primates (monkeys) have only known this ice age;
  - humans could plausibly see its end.
- within ice age
  - glacial = getting colder; glaciers advancing.
  - interglacial = getting warmer; glaciers retreating.

it is not novel to see glaciers retreating! it's the very definition of an interglacial period.

Deep-Time CO_2 ↔ Temp Association?

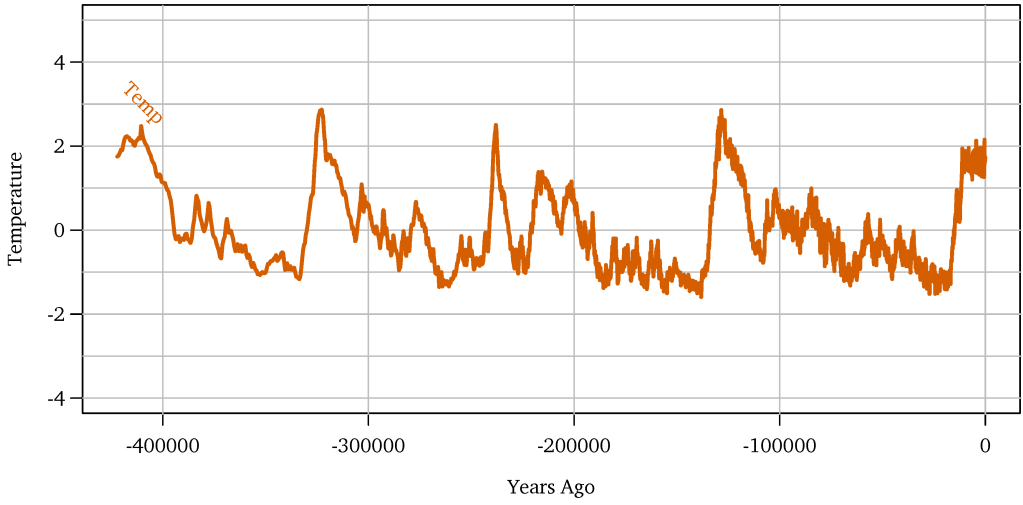
- do you see a relationship between co_2 and temperatures over the last 400 million years?

- I do not,
- but this is irrelevant for today, anyway:
  - sun was different,
  - continents were different,
  - rocks were different,
  - life was different,
  - and our measurements are highly uncertain, too.

Look Elsewhere For Evidence!

- we need to look at shorter time intervals
  - where we have better authoritative data, too!
- we need to look at more “human” times.
  - home sapiens sapiens exists for about 300,000 years.

Homo Sapiens' Temperature



You Are *Here*

- in the last glacial maximum (≈ 15,000 years ago):
  - it was ≈6°C colder!
  - sea level was about 150-200 feet (60 meters) lower.
  - nyc was under about 100 meters ice.
- we were near a glacial minimum = interglacial maximum.

Current Interglacial Maximum

- civilization has developed in this very warm 10,000-year interglacial period since the last glacial maximum.
  - it also seems unusually stable.
  - we are the top of the curve already.
  - … but also still going higher!
- don't count on remaining lucky in the future:
  - Earth temp will change again, up and down,
  - right now warmest in hundred-thousands and perhaps millions of years.

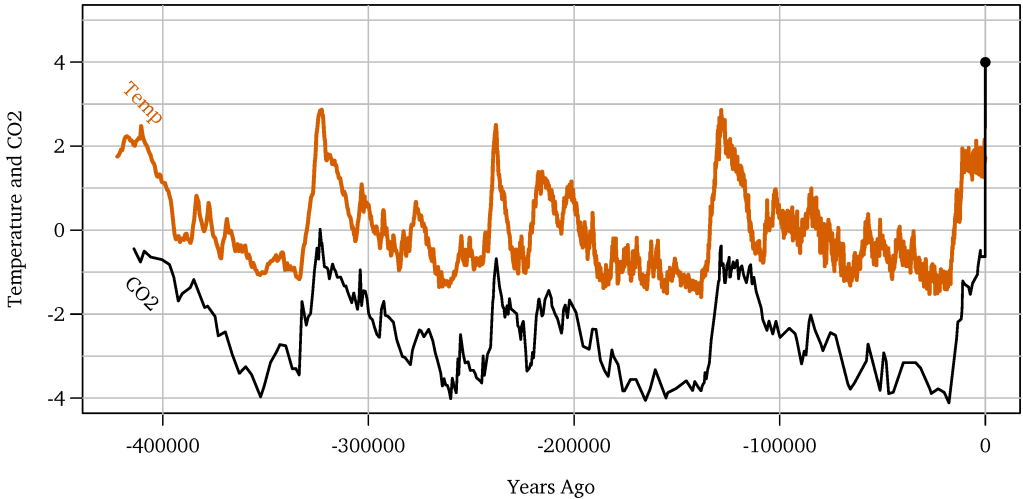
What Is The World's Optimal Temperature?

- are we at it?
- were we at it in 1980?
- is it even lower than 1980s?
- is it "whatever it is at the moment"?

Homo CO_2 ↔ Temp Association

sometimes a graph speaks louder than a thousand words!

smoking gun for co_2 → temp !?


Temp
CO2
Temperature and CO2
4
2
0
-2
-4
-400000
-300000
-200000
-100000
0
Years Ago

Smoking Gun?

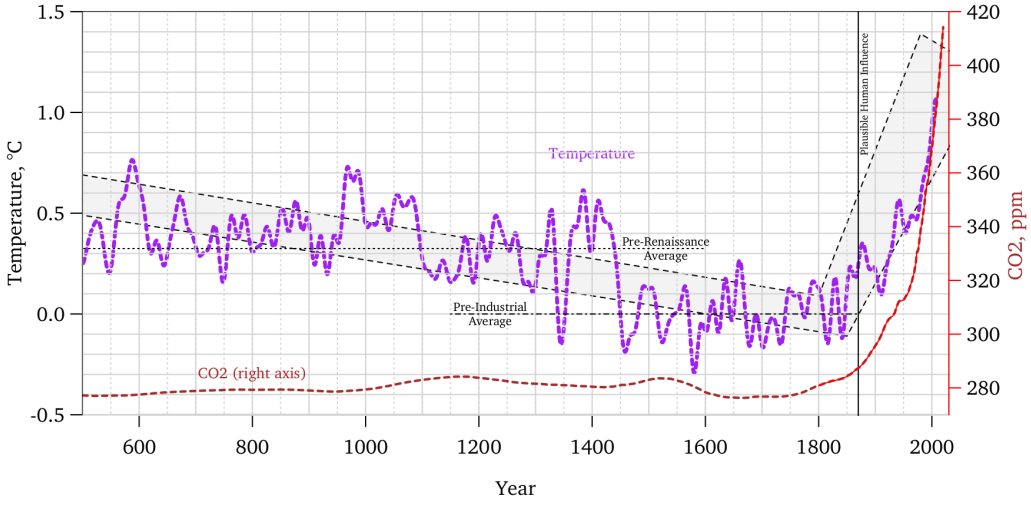
- ***no!*** this graph is often shown to deceive!
- many other factors could have caused this graph's association:
  - some factors influenced *not only* co_2 *but also* temperature.
  - boffins do not even know *all* factors.
  - temperature even influences plant/co_2 (cycle)!
  - and feedback is not mutually exclusive.

time precedence?: $(temp \rightarrow co_2) \gg (co_2 \rightarrow temp)$.

$CO_2 \leftrightarrow$ Temperature Association Evidence

- I would ignore above evidence as mostly irrelevant.
  - requires strong models that may or may not be true.
- I prefer to focus on more recent evidence,
  - for very good scientific reasons.
  - let me show you

Millenium Hockeystick



Great Evidence (I)

- global warming since about 1800 is indisputable!
  - since 1000s, still many organic records;
  - since 1880s, many global weather stations 24/7;
  - since 1980s, satellites measuring entire Earth 24/7.

ps: there was a coordinated fossil-fuel campaign to smear mann et al.

Great Evidence (II)

- this evidence is far more relevant:
  - in earlier figures, co_2 was endogenous.
  - here we know what caused *this* co_2 spike!
    - it was us humans!
  - this 'identification' is *a* **very big deal**!

Aligned CO_2 ↔ Temp Millenium

this evidence is as near-perfect as non-experimental science usually gets

- far less likely to be coincidental.
- boffins have good co_2-based explanations.
- alternatives are *far* more speculative.

But Is It 100% Certain?

- no. it's near-perfect, but not perfect.
- we would want to run an experiment where we stop and resume co_2 emissions a few times to see if anything else seems to matter, too, ideally starting from the same conditions.

- boffins are only humans, too.
- what if either/they are wrong? a lot is at stake.

Bias in Hypothesis Testing

a sequence of numbers has an order to it. for example, 1-2-3 is a different sequence from 3-2-1. some sequences of 3 numbers work, others do not. your goal is to figure out my rule—but you can't simply ask me for it. instead you can conduct experiments on me. you can make up a 3 number sequence and i'll tell you if fits. then you can make up another sequence, i'll tell you again, and we'll keep going until you're mostly (95%) confident you know the rule inside my head. let's do the first sequence together: 2-4-6 is good.

you pay $1 for each guess. you get $5 if you state the correct rule. you lose $5 if you state the wrong rule.

run online, then tell me how much I owe you.

Majority-Minority Agreement

boffins are in near-perfect agreement:

- Earth is warming *rapidly*.
- co_2 is the main GHG priming temperature.
- water vapor is the strongest GHG:
  - perhaps 97%;
  - perhaps 65-85%.
- $co_2 \rightarrow$ temp.
- $co_2 \rightarrow$ temp $\rightarrow$ water vapor $\rightarrow$ temp.

Majority-Minority *Dis*Agreement

- question: are GHGs 100% or just, say, 80%?
  - in GHG → temp → water vapor → temp .
- or also (in addition?):
  - x → temp → water vapor → temp ?
  - x → water vapor → temp ?

even if GHGs are capable of explaining warming, this is not proof that they committed the deed. where is the burden of proof? is reasonable doubt enough? boffins do not have exclusionary dna evidence here.

Should We Allow Disagreement??

- policy relevant! → controversial.
- science requires aggressive disagreement.
  - but some is beyond the pale now:
    - everyone distrusts other motives now.
    - climate boffins suspect (paid) trolls.
    - rightly so! there are many.
- does the end justify the means?
  - boffins are only (concerned) humans, too.
  - should “we” highlight unexplained phenomena?

Ideal Way To Resolve Disagreement

- we want 1,000 years of cloud data and reruns
  - and many other variables,
  - so boffins can try out alternative explanations for shocks to water vapor, that might not have been driven by co_2.
  - they simply don't have this data.
- in the land of the blind, the one-eyed man is king.

What Is Best Now?

today's debate is often about whether humanity should

1. spend *a lot of* money now?
   - (before the boffins are 100% sure)
2. or wait until boffins are certain?
   - (and perhaps milllions more of us will die?)

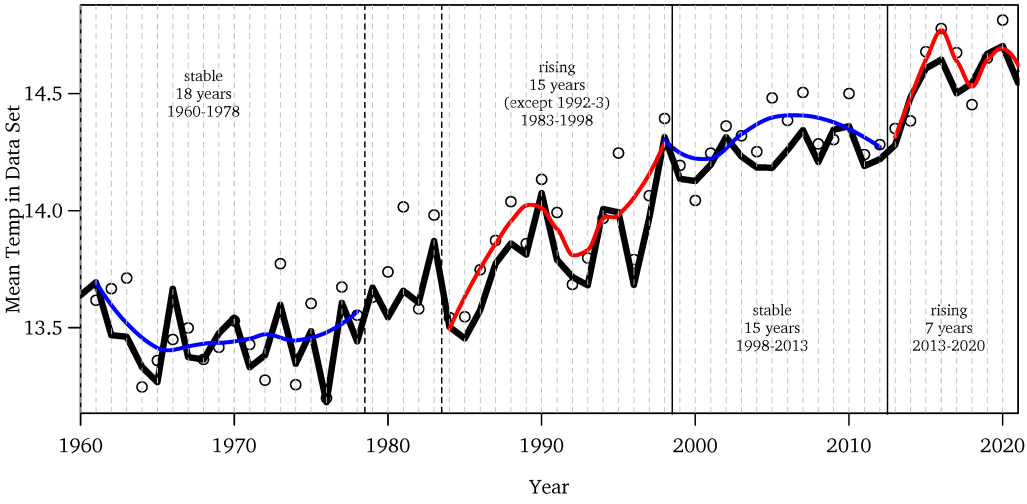
(cornell-welch posit that it's actually an irrelevant debate.)

Further Measurement Problems

- climate has natural variation.
- weather is chaotic in time and space.
- renaissance was warmer
  - ps: *little ice age* was **not** an ice age, and may have only been in northern hemisphere.
  - all primates only existed in an ice age,
  - but perhaps your grandchildren won't be.

Minor Clarification: Baseline Year

- start from renaissance or pre-industrial?
  - bottom of hockey stick is around 1800
  - 1500 was about 0.3-0.5°C warmer
  - 1°C vs 1.3°C warming?.
  - → 0.3°C difference in quoted warming.
- usually quoted from pre-industrial.
  - makes *increase-to-date* look bigger,
  - makes *percent-relative-to-future* look smaller.
- no right or wrong here baseline,
  - but it makes for many easy number confusions.


stable
18 years
1960-1978
rising
15 years
(except 1992-3)
1983-1998
stable
15 years
1998-2013
rising
7 years
2013-2020
Mean Temp in Data Set
14.5
14.0
13.5
1960
1970
1980
1990
2000
2010
2020
Year

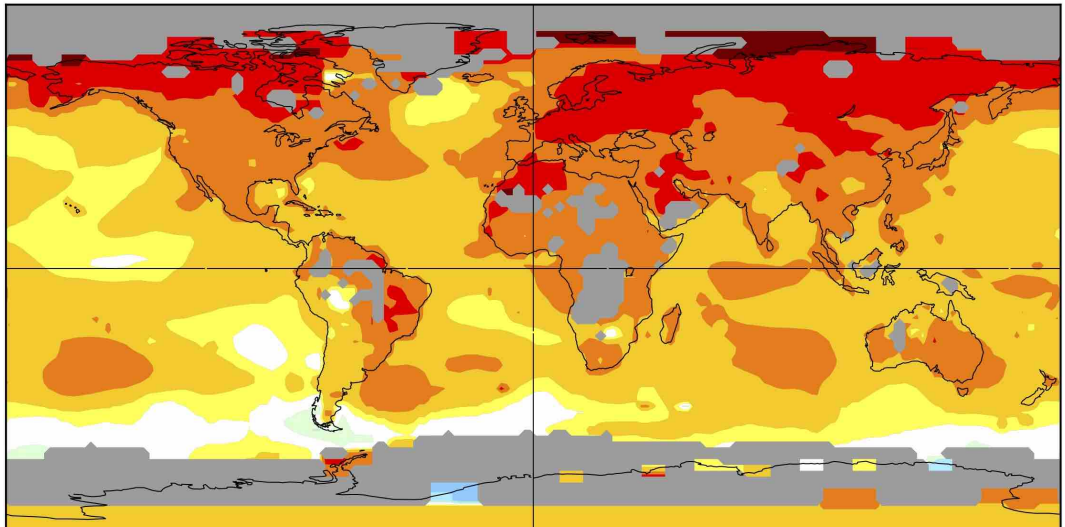
Some Remaining Little Puzzles

- post-2010 temp spike?
  - seems *too soon* for co_2 smooth increase.
  - or past seems too little?
  - possible cause: cleaner coal? so_2 peaked 1980.
- post-2000 hiatus?
  - el nino buffer responsible for 2000-2010?

- humanity before 1930 could not have done much, but warming began in 1800?!
  - some due to volcanoes, but not all.
- scientists often find (ex-post) reasons for deviations
  - e.g., phaseout of sulfur-laden coal
  - “cherry-picking” is possible because of “noise”
  - but what is “noise”?
  - there was ultimately some cause behind the hiatus, too

- and
  - why has it warmed more at night?
  - why has it warmed more at higher latitudes?
- interesting questions are not disputing main insight: global warming is continuing

Annual J-D L-OTI(°C) Change 1960-2021 1.01



Just Hold On

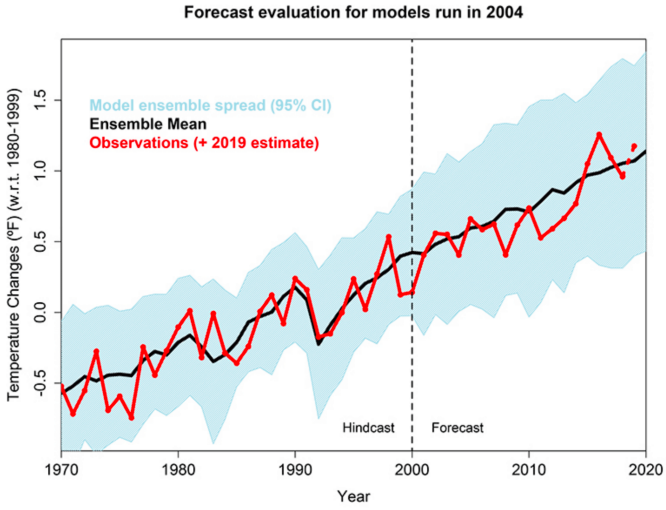
- we will learn more “soon”:
  - soon = think 50 years.
  - current temperature change is lightning fast by geological standards.

More Climate Science Slander

were past climate models wrong?

- not really!
- *urban myth*.

https://climate.nasa.gov/news/2943/study-confirms-climate-models-are-getting-future-warming-projections-right/



Models that were used in the IPCC 4th Assessment Report can be evaluated by comparing their approximately 20-year predictions with what actually happened. In this figure, the multi-model ensemble and the average of all the models are plotted alongside the NASA Goddard Institute for Space Studies (GISS) Surface Temperature Index (GISTEMP). Climate drivers were known for the 'hindcast' period (before 2000) and forecast for the period beyond. The temperatures are plotted with respect to a 1980-1999 baseline. Credit: Gavin Schmidt

Summary Of Undeniable Facts

- Earth has been warming (about 1°C since 1980).
- Earth will be warming a lot more (maybe another 2°C).
  - satellites can measure incoming and outgoing radiation (like a kettle on a stove).
  - Earth is *not* in thermal equilibrium.
  - only half of caused-by-already-emitted warming has occurred by now — maybe 0.7°C out of 1.4°C .
  - warming will be coming — unless something else (asteroid? super-volcano? nuclear war?) throws it off equilibrium.

- climate disasters will likely be more common:
  - slowly increasing.
  - yet, specific events are and will always be difficult to attribute.
    - if you strongly believe in fitted simulation models, then you can do some attribution relative to null hypothesis.
    - if you want the data to speak for themselves, then individual events are not attributable due to large system variances.
  - more energy injected into system Earth will eventually have an effect *on average*.
  - (this does not necessarily mean more damage)

Click-Bait

- attention is also increasing:
  - more people,
  - more media,
  - with a good alarming narrative for an interested clientele
- more impact and more notice.

Unarguable Conclusions

- Earth has been warming for 200 years.
- warming has recently been accelerating.
- anthropogenic GHGs (co_2) are major contributors:
  - basic physics demands it.
  - long-lived GHGs prime a water vapor amplifier, although the role of clouds is not fully understood.
- deniers are ignorant or disingenuous.

Arguable Conclusions

- a minority wonders
  - could something other than human GHGs also play a role?
  - could human GHGs be only one part of the puzzle?
  - would be important if continuing (like GHG emissions)