

Greater Milwaukee Chapter of
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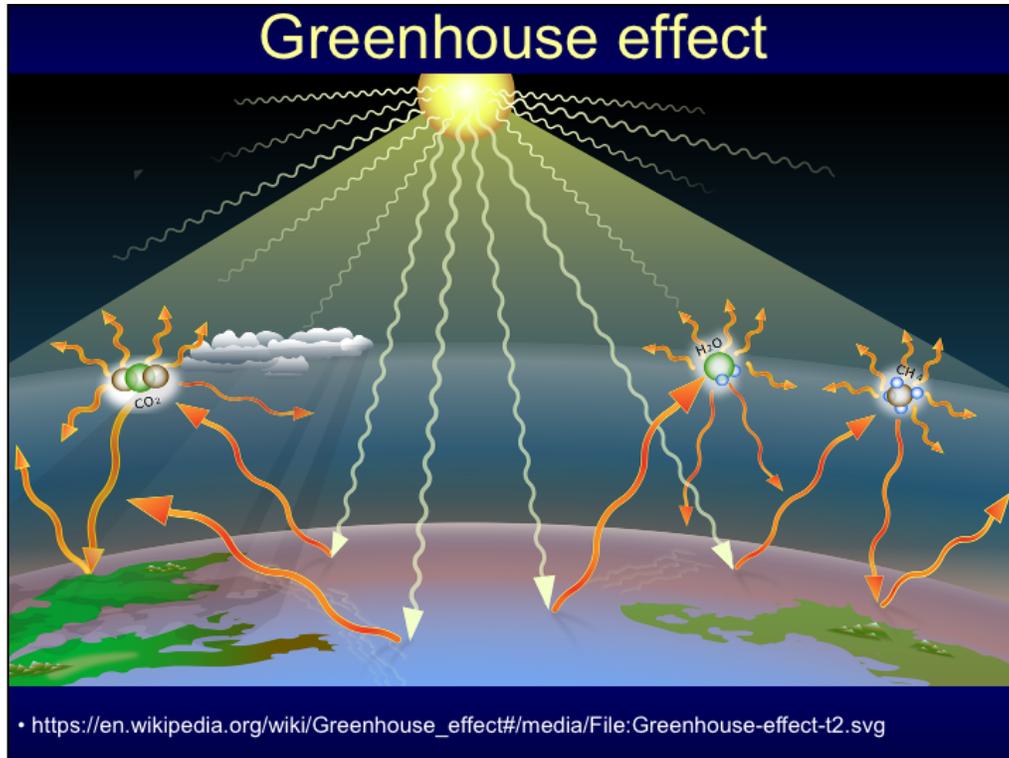
February 27, 2020

Long-term climate trends: What do we know? And how do we know?

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Invited presentation at the Greater Milwaukee Chapter of American
Meteorological Society meeting



Greenhouse gases transmit (most of) shortwave radiation and absorb long-wave back-radiation from the Earth's surface. This absorption warms the atmosphere, which then sends additional downward longwave radiation toward the Earth's surface. The net downward radiation flux in the presence of the greenhouse gases (solar + atmospheric downward radiation) is therefore larger than in the absence of greenhouse gasses (solar only), so the surface must warm to a larger temperature to achieve equilibrium.

Callendar, 1938(!)
 (QJRMS)

- 0.005 K/year warming “during the past half century” (~1890-1940)
- this is substantial when accumulated over a long-term period, especially wrt global-mean temp. variations

•<https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.49706427503>

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE 223

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THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR
 (Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. DOBSON, F.R.S.)
 [Manuscript received May 19, 1937—read February 16, 1938.]

SUMMARY

By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from the best available data that approximately three quarters of this has remained in the atmosphere.

The radiation absorption coefficients of carbon dioxide and water vapour are used to show the effect of carbon dioxide on “sky radiation.” From this the increase in mean temperature, due to the artificial production of carbon dioxide, is estimated to be at the rate of 0.003°C. per year at the present time.

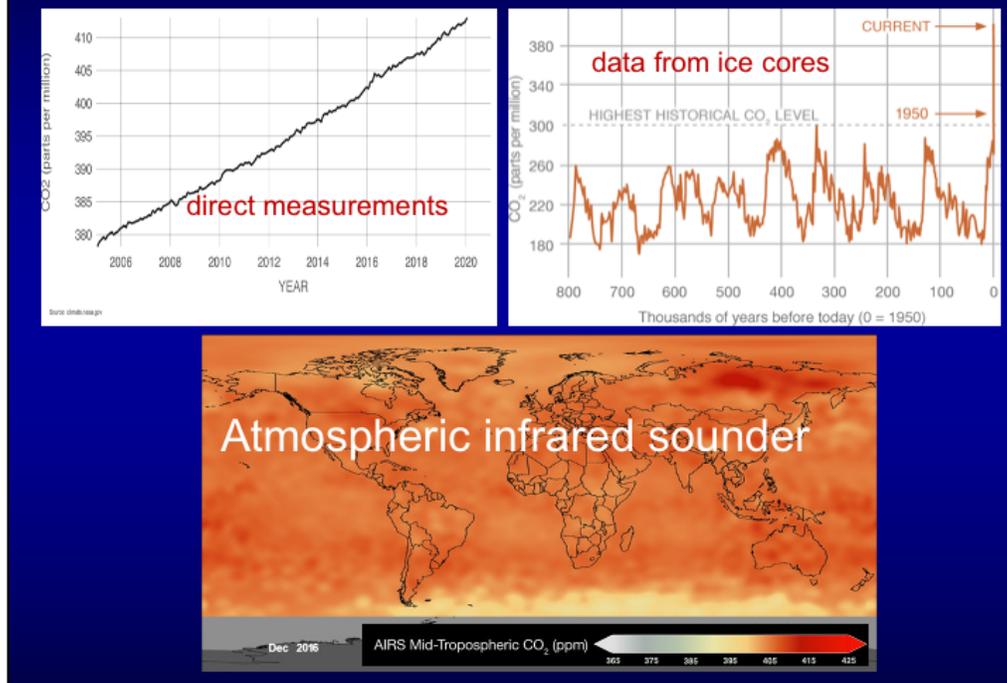
The temperature observations at 200 meteorological stations are used to show that world temperatures have actually increased at an average rate of 0.005°C. per year during the past half century.

Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale.

In the following paper I hope to show that such influence is not only possible, but is actually occurring at the present time.

This is a pioneering work using theoretical and observational analyses to suggest human-induced long-term climate trends. Note that the 0.005K number appears to be tiny compared to day-to-day or even year-to-year temperature variations at a single location, but it translates into a substantial temperature warming over long term, especially compared to spatially averaged (e.g. global-mean) variability.

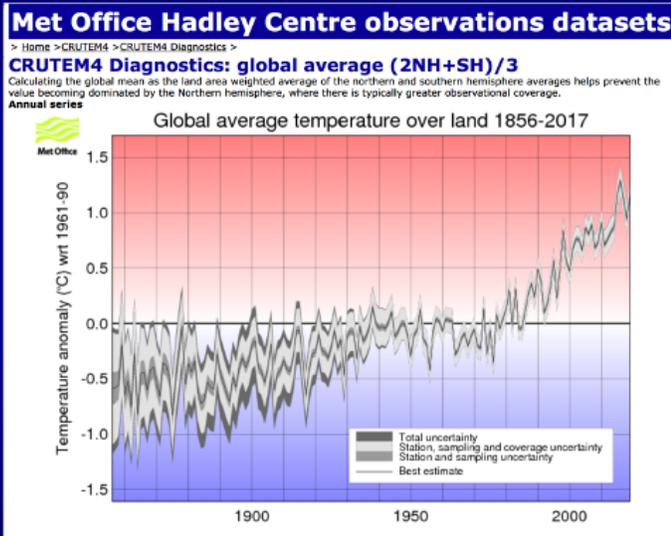
<https://climate.nasa.gov/vital-signs/carbon-dioxide/>



... and, indeed, CO₂ is increasing and is now way above the pre-industrial levels (based on proxy data). Also, it is pretty uniformly distributed horizontally (bottom panel), and it's a "good news" for our ability to detect temperature trends radiatively forced by the CO₂ increase, since we can do it for multiple stations all over the world. Why is it a good news? – because we can reduce signal contamination due to internal atmospheric "noise" (which is different for any two stations that are far apart) by averaging the temperature trends measured all over the world (cf. Callendar's paper above).

Temperature observations, in-situ, land stations

<https://www.metoffice.gov.uk/hadobs/crutem4/data/diagnostics/global/nh+sh/index.html>



1938 about here

- Estimate of global-mean temperature
- Different types of uncertainty
- Uncertainty decreases with time
- Data homogeneity
- cf. Callendar, 1938

This illustrates the analysis of global temperature using one of the state-of-the-art observational in-situ data sets. It currently streams information from about 5500 weather stations worldwide (much fewer stations in the beginning of the instrumental record, leading to large uncertainty in computing the global-mean). Each station also has gaps in data and errors associated with measurement accuracy. Data homogeneity is an important issue when addressing long-term trends (because different observational techniques can result in bogus climate “jumps”). Note the non-uniformity of warming, with global temperatures steady before 1880 and decreasing from about 1940 to 1970. This decrease was a major factor for Callendar’s work being under-appreciated at that time (apparently, his predictions failed to verify, right!) Why? – because CO₂ is only a part of the story, we’ll get to that later.

Marine instrumental observations

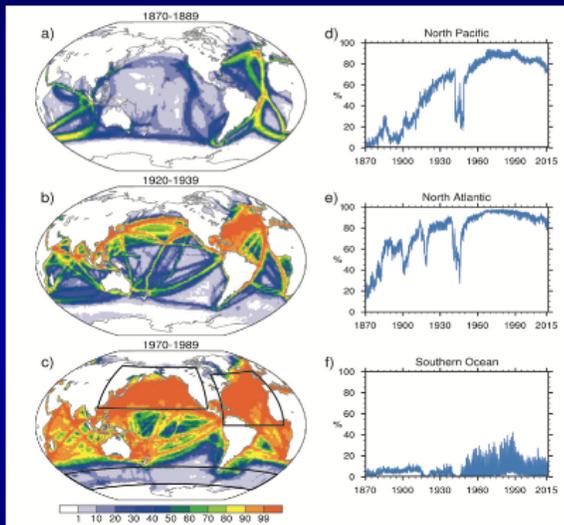


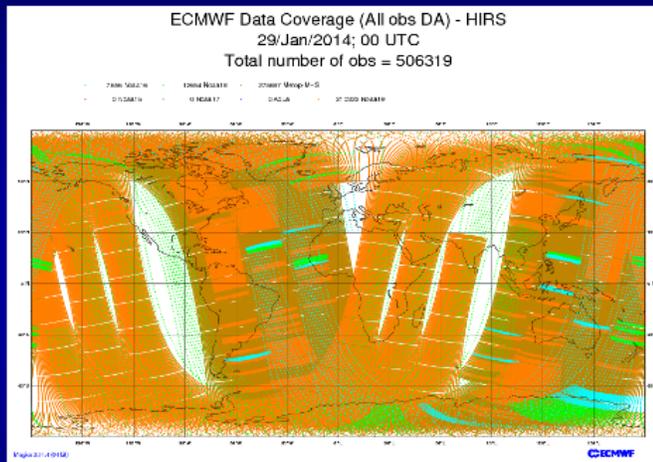
Figure 1: Distribution of sea surface temperature observations from the International Comprehensive Ocean Atmosphere Data Set. Maps show the percentage of months with at least one measurement in a 2 degree latitude by 2 degree longitude

- Incomplete coverage for sure, especially in the past
- Better coverage now, still poor over Southern Ocean
- Don't forget about data homogeneity!

Deser and Phillips, 2017, CLIVAR Exchanges, doi:10.22498/pages.25.1.2

Similar (or even more challenging!) issues exist with regards to instrumental data over the oceans!

Satellite observations

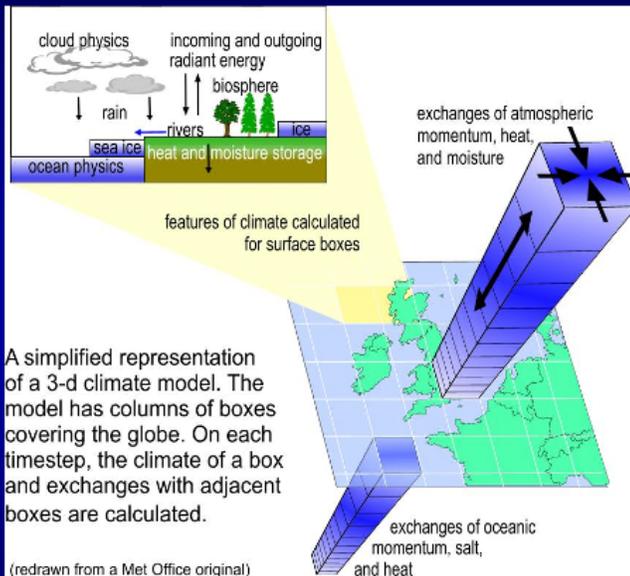


- started recently - in earnest, since late 20th century (so now we have ~50 yr of data)
- Lots of data!
- There exist various issues with space/time coverage, presence

<http://weather.mailasail.com/Franks-Weather/Weather-Observations-Nwp>

Satellite data provided observations with unprecedented coverage since about 1970s.

Climate models



- Coupled climate subsystems
- Relatively coarse resolution due to global coverage and need for long simulations
- Dynamical “first-principle” laws complemented by (often ad hoc) parameterizations of subgrid-scale processes

• This all leaves a lot of room for “model uncertainty”

State-of-the-art climate models are complex (yet incomplete!), but (and) prone to uncertainty due to ad hoc parameterizations of subgrid-scale (“unresolved”) processes (for example, the production of and effects of clouds on the climate of an individual atmospheric box). This uncertainty is not a small thing (e.g., see the next two slides).

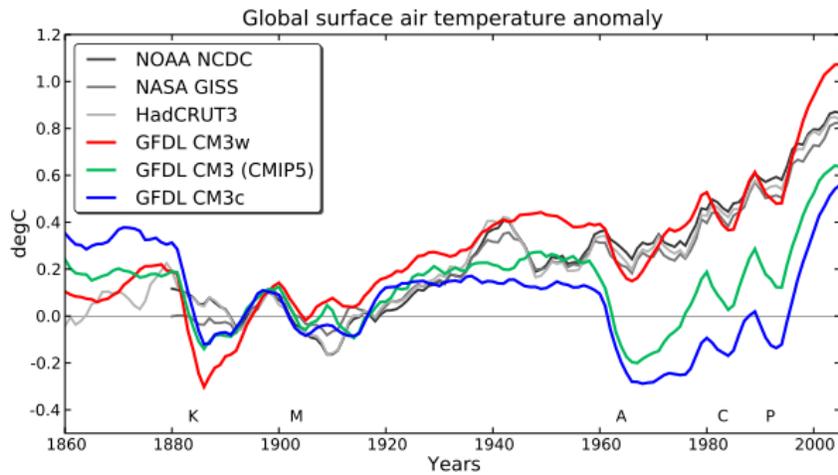
Cloud tuning in a coupled climate model: Impact on 20th century warming

Jean-Christophe Golaz,¹ Larry W. Horowitz,¹ and Hiram Levy II¹

[1] Climate models incorporate a number of adjustable parameters in their cloud formulations. They arise from uncertainties in cloud processes. These parameters are tuned to achieve a desired radiation balance and to best reproduce the observed climate. A given radiation balance can be achieved by multiple combinations of parameters. We investigate the impact of cloud tuning in the CMIP5 GFDL CM3 coupled climate model by constructing two alternate configurations. They achieve the desired radiation balance using different, but plausible, combinations of parameters. The present-day climate is nearly indistinguishable among all configurations. However, the magnitude of the aerosol indirect effects differs by as much as 1.2 Wm^{-2} , resulting in significantly different temperature evolution over the 20th century. **Citation:** Golaz, J.-C., L. W. Horowitz, and H. Levy II (2013), Cloud tuning in a coupled climate model: impact on 20th century warming, *Geophys. Res. Lett.*, 40, 2246–2251, doi:10.1002/grl.50232.

The process of choosing model parameters entering parameterization of subgrid-scale processes to make sure the model best matches the observed climate is called tuning. The problem is multiple combinations of model parameters may be used to achieve essentially the same model climate, but different responses to variable forcing.

GOLAZ ET AL.: CLOUD TUNING AND 20TH CENTURY WARMING



Here is how it looks! Changing, slightly, a couple of adjustable parameters in a model may result in major changes in the long-term climate trends simulated by the model (Black-to-gray: observational data sets; color lines – model simulations with different cloud-scheme parameters).

Coupled Model Intercomparison Project (CMIP)

AN OVERVIEW OF CMIP5 AND THE EXPERIMENT DESIGN

BY KARL E. TAYLOR, RONALD J. STOFFER, AND GERALD A. MEEHL

The fifth phase of the Climate Model Intercomparison Project (CMIP5), now underway, promises to produce a freely available state-of-the-art multimodel dataset designed to advance our knowledge of climate variability and climate change.

- Coordinated experiments using multiple coupled climate models using similar dynamical cores but, generally, different physical parameterizations
- Pre-industrial (PI) control simulations under constant forcings (e.g. CO₂ concentrations)
- Historical (20th century) simulations with variable in time “observed” forcings (GHG, aerosols, solar). Multiple climate “realizations” (ensemble) from different initial conditions.

One way of accounting for uncertainties in physical parameterizations within climate models is to use ensemble of models with different such parameterizations... Such models are developed and run by major climate research centers all over the world, producing a massive database for analyzing the dynamics of climate change.

Classification of climate variability in models (and observations...)

- **Forced**: variability caused by variations in the external forcing (GHG, aerosols, solar)
- **Internal**: variability generated by internal processes in the climate system; it is, therefore, present in the PI control runs
- **Note**: characteristics of internal variability may, in principle, be altered in the course of (and due to) forced climate change

Climate variations may be due to climate system's response due to variability in external forcing(s) or be internal to the climate system (and, hence, exist under constant-forcing conditions).

Forced climate model runs can be used to estimate the response of the climate system to forcing

- One can use **ensemble simulations** (started from perturbed initial conditions) using single (SM) or multiple (MM) climate models to estimate the climate's forced response over the 20th century (Kravtsov and Spannagle 2008; Knight 2009; Terray 2012, Steinman et al. 2015a)
- **SMEM (ensemble mean)** time series of a given climatic quantity would approximate an individual model's forced response. **MMEM** would characterize the average forced response of the MM ensemble
- We can **also interpret the forced responses from the models as estimates of the forced response in observations**

Ensemble simulations provide means to isolate forced signal by averaging over multiple forced runs of an individual model started from different initial conditions, since these runs would be characterized by the same forced signal, but uncorrelated realizations of internal variability.

Reanalysis products

- **Reanalysis is** a process of optimally combining available observations and climate-model forecasts to get the best estimates of the **climate state at all locations**
- Reanalysis procedure thus **objectively interpolates observed data** in space and time, while **also providing estimates of unobserved climate variables everywhere**
- Different reanalysis use different models in conjunction with different data sets to estimate climate states

Reanalysis products is our best guess(es) of the climate variability over the duration of the observational record, providing essentially continuous information in space and time. Different reanalyses combine different models with different observational data sets and may result in different estimates of climate states and their evolution. Note that the models used to produce reanalysis are also imperfect and model errors may be an issue as well.

Re-cap:

Observations of the climate state:

- **Direct measurements** available for ~past 150 years, with progressively better coverage and accuracy; **proxy data** can be used prior to that (large uncertainties though)
- Exponential growth of available **data** in the **satellite** era (1970+)

Numerical Climate Models:

- Couple **first-principle dynamics** of the climate-system components (ocean, atmosphere, ice, etc.) with **ad hoc parameterizations** of unresolved processes (e.g., clouds). The latter parameterizations result in **large model uncertainties**
- **Ensemble simulations** to isolate **forced and internal variability** and quantify model uncertainty

Reanalysis products:

- Best-guess **reconstructions (continuous in space and time)** of both observed and unobserved climate variables, **consistent with both model dynamics and available observations**

Climate science is a data-driven science, but numerical climate models is its main analysis tool!

Human-induced climate change?

Greenhouse-gas (GHG) emissions:

- CO₂ and others
- fairly uniform concentrations throughout the globe
- monotonic increase from 1900+
- theoretically, should result in **monotonic and uniform warming throughout the globe**

Particular matter pollution (aerosols):

- microscopic particles of matter suspended in the air
- can be of both natural and anthropogenic origin
- anthropogenic aerosols loadings are regionally intensified, as they tend to settle to the ground away from the source
- **expected to induce climate cooling** due to both direct effect of (sunlight dimming) and (**very uncertain**) indirect effect on clouds

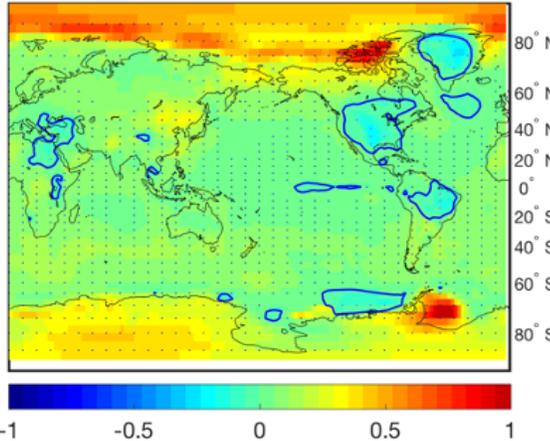
Others: Land use, agricultural activities

Human induced climate change is to be categorized as the response of the climate system to variability in the external (to climate system) forcing.

How global is the global warming?

- Has the planet warmed on average during past 150 years?
- Is this warming somehow associated with increasing CO₂?
- Is much of the recent CO₂ increase due to human activity?
- Is the warming uniform throughout the globe?

SAT trend 1900-2005, 20CR (K per decade)

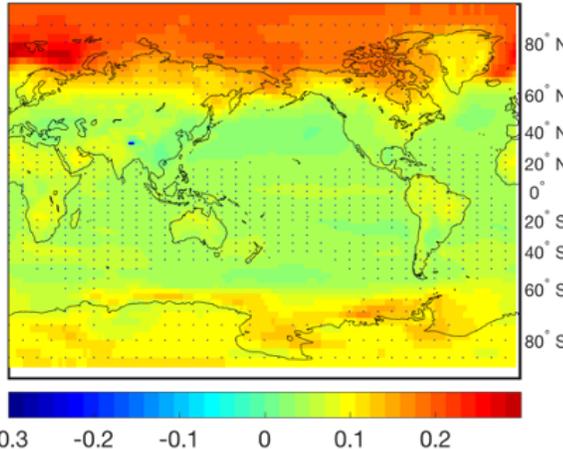


- Non-uniform warming rates throughout the world
- Polar amplification
- Regional warming “holes,” including Southeastern US

Using theories, observations and models, we can address various questions associated with the problem of global warming. Is there a warming of a planet on average over the past 150 years? – Sure, we saw the observational evidence before. Is it somehow associated with increasing carbon dioxide in the atmosphere? – Very likely: after all, the CO₂ concentration increased to levels unprecedented in at least several thousand centuries in the past and the net rate of warming is consistent with theoretical estimates based on greenhouse effect physics. Is much of this CO₂ increase due to human activity? – Perhaps: industrial revolution is the major phenomenon delineating the 20th century from the 19th. Is the warming uniform throughout the globe? For example, do you think Milwaukee warmed from 1900 to 2000? No! For example, polar regions warmed much faster than the rest of the world, and there are regional warming “holes.”

How are climate models doing?

SAT trend 1900-2005, CMIP5 (K per decade)

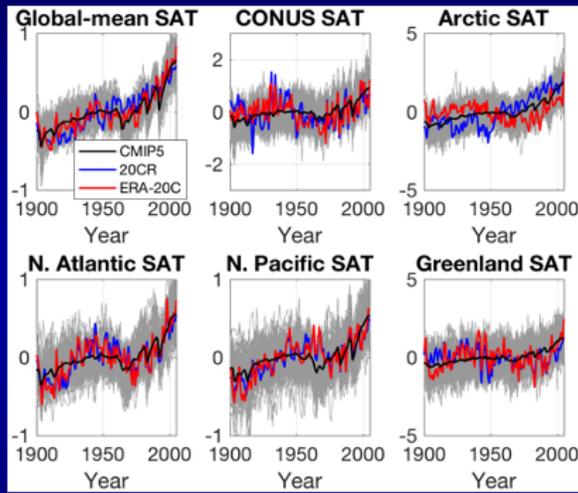


- Polar amplification? – Yes, but weaker.
- Warming holes? – Not really!
- Apparently, models don't reproduce some important aspects of the observed global warming, so

we should treat projections of the future warming obtained using current generation of climate models with caution.

While models do reproduce well the global-mean warming (next slide), they miss some important features of the observed regional dependence of the global warming.

Models vs. observations in time

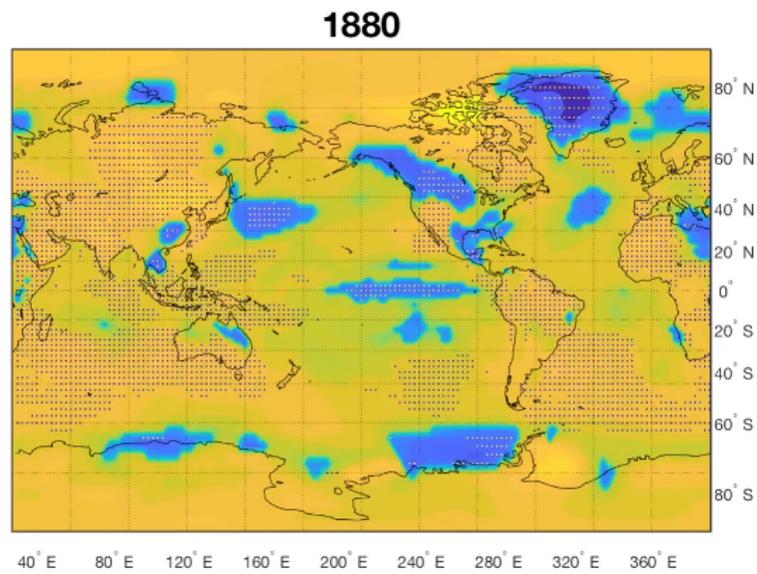


- Warming is non-uniform in time too, for both models and observations
- Ensemble-mean of model simulations — our best estimate of the forced climate response — is non-linear in time due to time dependence of prescribed forcings

- However, there are **persistent multidecadal deviations of the observed temperatures from the model simulated forced signal**; deviations of such duration and magnitude are **not present in any of the model simulations!**

The same applies to the apparent non-uniformities of global warming in time. Smoothed multidecadal deviations of individual CMIP5 runs from their forced signals are much smaller than the observed deviations, which exhibit an oscillatory-like globally propagating signal, the so-called stadium wave (Kravtsov et al. 2018, next slide).

Global “Stadium Wave” (Kravtsov et al. 2018)



Stadium wave originates as a temperature anomaly in the North Atlantic Ocean, and propagates to the North Pacific, Southern Ocean and Antarctica, and, finally, to the Arctic, requiring a few decades to complete half-cycle (from positive to negative phase). These spatial patterns and their sequence are absent from CMIP5 models (Kravtsov et al. 2018).

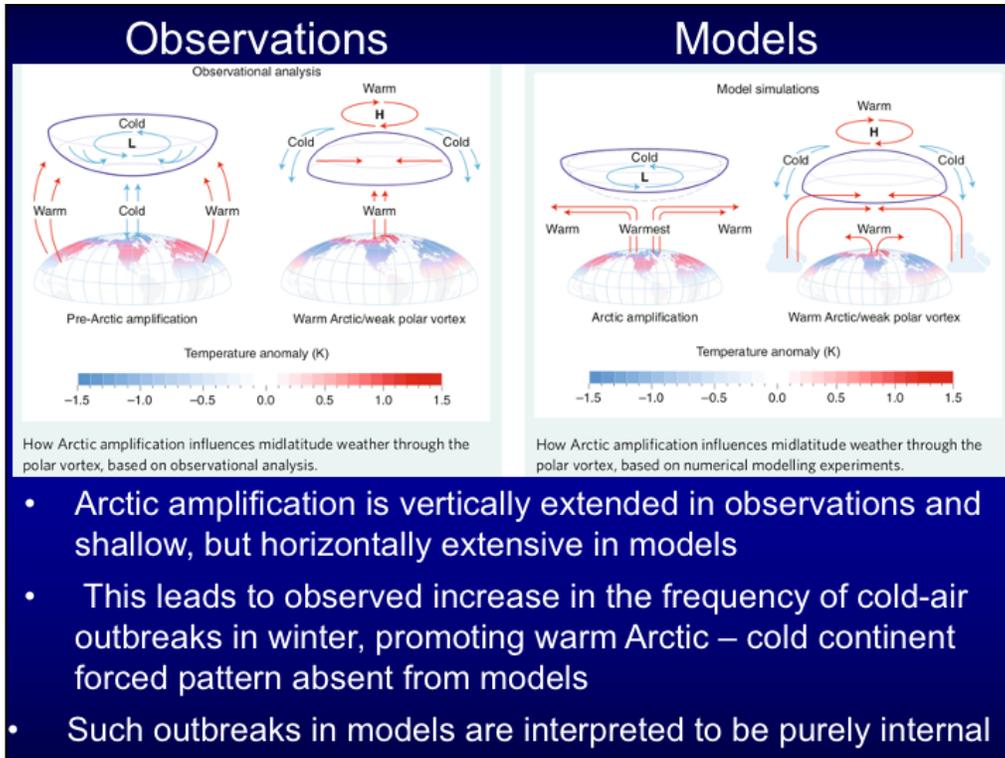
What causes multidecadal deviations of observed and model simulated climates?

- One possibility is that **the forced signals estimated by models are wrong**
- Indeed, **model uncertainties**, for example, those associated with parameterizations of indirect aerosol effects, are large
- Other **misrepresented dynamical mechanisms** may also be at work (see next slide)

Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather

J. Cohen^{1,2*}, X. Zhang³, J. Francis⁴, T. Jung^{5,6}, R. Kwok⁷, J. Overland⁸, T. J. Ballinger⁹,
U. S. Bhatt³, H. W. Chen^{10,11}, D. Coumou^{12,13}, S. Feldstein¹¹, H. Gu¹⁴, D. Handorf⁵, G. Henderson¹⁵,
M. Ionita⁵, M. Kretschmer¹³, F. Laliberte¹⁶, S. Lee¹¹, H. W. Linderholm^{17,18}, W. Maslowski¹⁹, Y. Peings²⁰,
K. Pfeiffer¹, I. Rigor²¹, T. Semmler⁵, J. Stroeve²², P. C. Taylor²³, S. Vavrus²⁴, T. Vihma²⁵,
S. Wang¹⁴, M. Wendisch²⁶, Y. Wu²⁷ and J. Yoon²⁸

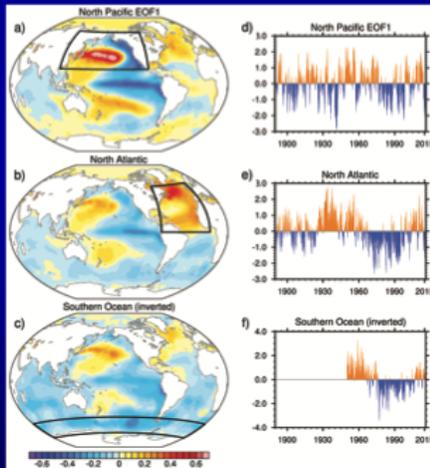
The Arctic has warmed more than twice as fast as the global average since the late twentieth century, a phenomenon known as Arctic amplification (AA). Recently, there have been considerable advances in understanding the physical contributions to AA, and progress has been made in understanding the mechanisms that link it to midlatitude weather variability. **Observational studies overwhelmingly support that AA is contributing to winter continental cooling. Although some model experiments support the observational evidence, most modelling results show little connection between AA and severe midlatitude weather or suggest the export of excess heating from the Arctic to lower latitudes. Divergent conclusions between model and observational studies, and even intramodel studies, continue to obfuscate a clear understanding of how AA is influencing midlatitude weather.**



One hypothesis of why the response of models to Arctic amplification of global warming is different from the observed response is misrepresentation, in models, of the interactions between the troposphere and stratosphere.

What causes multidecadal deviations of observed and model simulated climates?

- Another possibility is that these differences are due to model's lacking multidecadal internal variability rooted in slow ocean dynamics

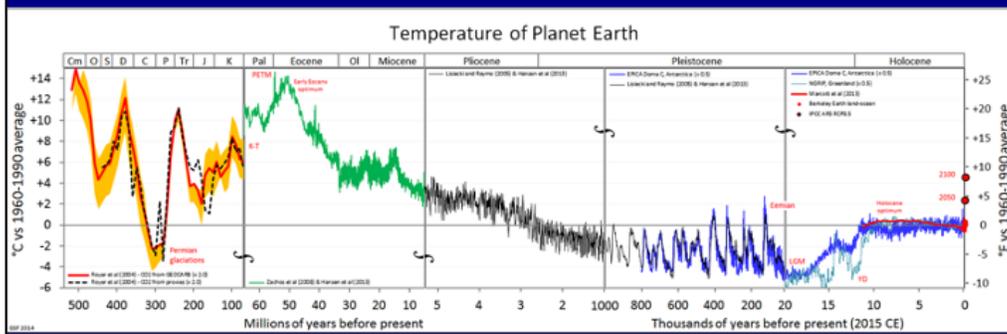


- Indeed, the coherence in time of the temperature deviations from the global-mean warming trend is striking. How can it be forced?
- This figure (from Deser and Phillips 2017) basically illustrates the stadium wave using different data set and different methodology of subtracting the forced signal

Conclusions

- CO₂ is increasing, overall climate is warming
- Warming rate is consistent with that expected, theoretically, from GH effect
- Warming is geographically non-uniform and, in some regions, negative (ha-ha:)
- The dynamics of these regional effects are complex
- State-of-the-art climate models are uncertain due to ad hoc parameterizations of unresolved processes and do not quite capture the geographical pattern of global warming
- The future GW projections using these models should be treated with caution, especially at regional level

... and just to put things into perspective



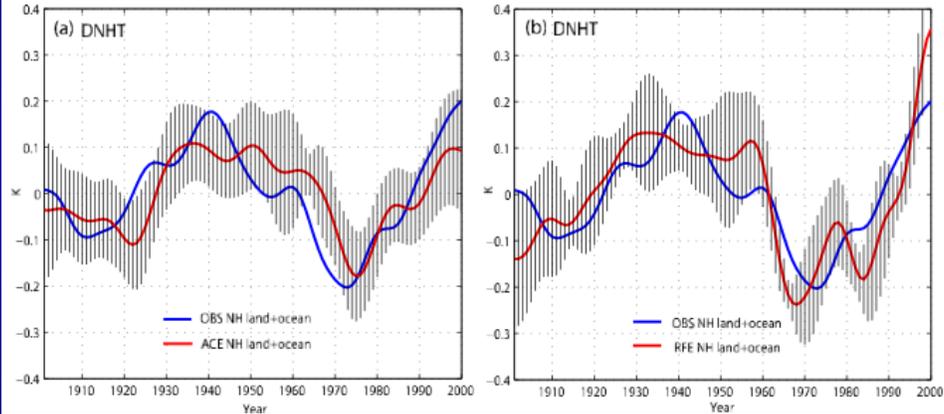
https://www.reddit.com/r/conspiracy/comments/55v4m1/the_truth_about_global_warming/

Climate variability in the past exhibited various regimes. Keep in mind though that the processes operating in the past could be very different from those dominating the present climate variability.

Back up slides

Establishing causes of multidecadal variability is tricky...

ZHANG ET AL.: NORTHERN HEMISPHERE MEAN TEMPERATURE



Slab-ocean mixed layer in the North Atlantic with time-dependent Q-flux, constant RF

Radiatively forced (RF) GFDL CM2.1 ensemble

...since the internally generated SST anomalies (e.g. due to variations in AMOC) and non-uniform (in time) radiative forcing may both be responsible for the observed non-uniformities in the NH warming!

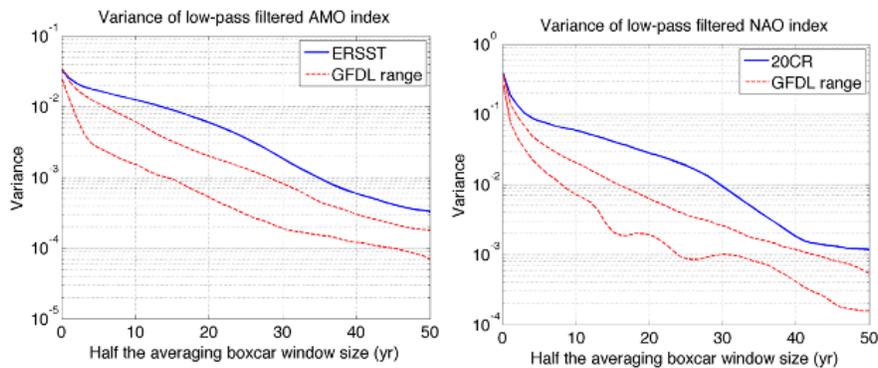
...so, multidecadal deviations of NH surface temperature from linear trend may well be rationalized as being either due to the climate's response to the ocean-driven heat-flux forcing from the North Atlantic SSTs, or due to the response to non-linear trends in the radiative forcing

Notes:

- in both setups, the climate response is forced
- the ensemble spreads (due to internal variability) are similar too, and are fairly narrow: this suggests that in the coupled setting, GFDL2.1's internally generated decadal-scale SST anomalies in the North Atlantic have a smaller magnitude than the observed SST anomalies

Two contrasting views of multidecadal climate variability in the twentieth century

Sergey Kravtsov¹, Marcia G. Wyatt², Judith A. Curry³, and Anastasios A. Tsonis¹

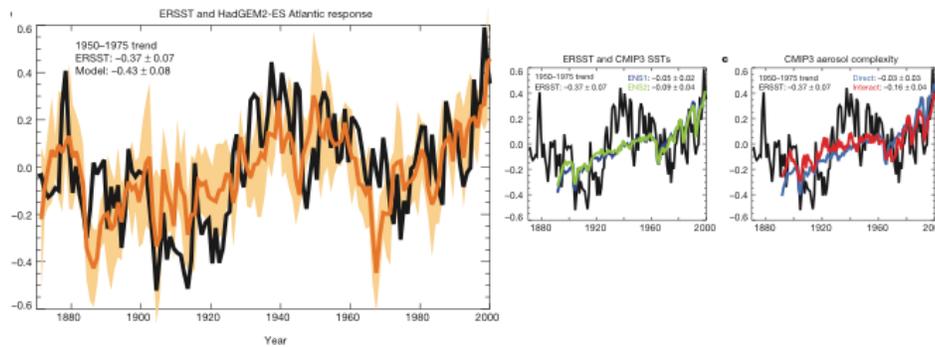


- Variance of linearly detrended 40-yr low-pass filtered AMO signal in GFDL is ~ factor of 5 smaller than observed; for NAO – order of magnitude smaller

The multidecadal deviations from the linear trend in GFDL2.1 simulated North Atlantic SSTs are indeed much smaller than observed, but this is even more so for NAO (which, incidentally, has essentially no forced component in the CMIP5 model simulations). Note that the linearly detrended NHT variance is similar to the observed, consistent with Zhang et al. (2007).

Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability

Ben B. Booth¹, Nick J. Dunstone^{1*}, Paul R. Halloran^{1*}, Timothy Andrews¹ & Nicolas Bellouin¹



- Lack of multidecadal SST variability in the North Atlantic was suggested to be due to underestimation of aerosol indirect effects in coupled climate models
- In this interpretation, multidecadal variations of the North Atlantic SSTs are forced (cf. Zhang et al. 2007)

Aerosols?

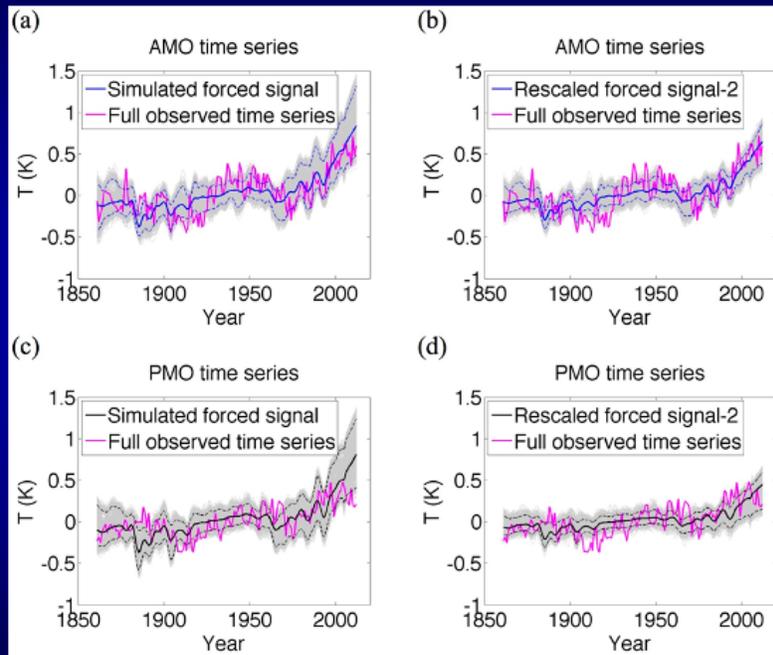
Have Aerosols Caused the Observed Atlantic Multidecadal Variability?

RONG ZHANG,* THOMAS L. DELWORTH,* ROWAN SUTTON,+ DANIEL L. R. HODSON,+ KEITH W. DIXON,*
ISAAC M. HELD,* YOCHANAN KUSHNIR,# JOHN MARSHALL,@ YI MING,* RYM MSADEK,* JON ROBSON,+
ANTHONY J. ROSATI,* MINGFANG TING,# AND GABRIEL A. VECCHI*

- major discrepancies between HadGEM2-ES simulations and observations in terms of the 3-D structure of multidecadal upper-ocean temperature and salinity in the North Atlantic, as well as in various fields outside of North Atlantic (we'll see some of that later in the talk)
- Still, if observed multidecadal deviations of North Atlantic SSTs from linear trend are internally generated, why is their magnitude so much larger than that in CMIP5 coupled runs?

Well, maybe not, but what would then be the explanation for the insufficient simulated amplitude of multidecadal variability?...

Estimates of the forced signal



Left – no rescaling; right – rescaled signals. Linear growth of uncertainty at the end of the record is due to linear extrapolation of model time series from 2005 through 2012.

Summary

- We used **Monte-Carlo approach to estimate forced signals** from multi-model ensemble of CMIP5 historical simulations
- These forced signals were subtracted from individual model runs and, after rescaling, from observed time series to **derive the internally generated component of the observed and simulated climate variability**
- Internal climate variability in models has **a smaller amplitude and different spatiotemporal structure** wrt the observed variability
- The differences between models and observations are dominated by **a low-dimensional multidecadal mode of the observed climate variability**, which is apparently absent from models