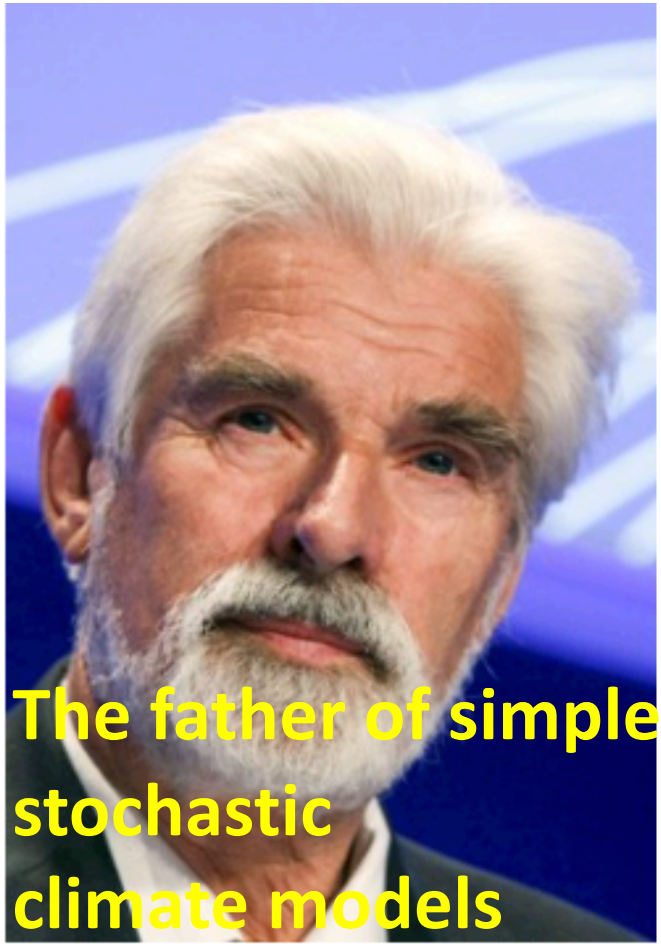
Sykuro Manabe
Geophysical Fluid Dynamics Laboratory
Princeton University

The unbearable simplicity of the climate system



Klaus Hasselmann
Max Planck Institute for Meteorology

Playing with catchy titles

Explicit and implicit approaches to complex systems

Front and back doors to complex system science

Frontal and flanking assaults on complex mysteries

Multi-mechanism interactions and random walks

Modeling the atmosphere vs. treating it as noise

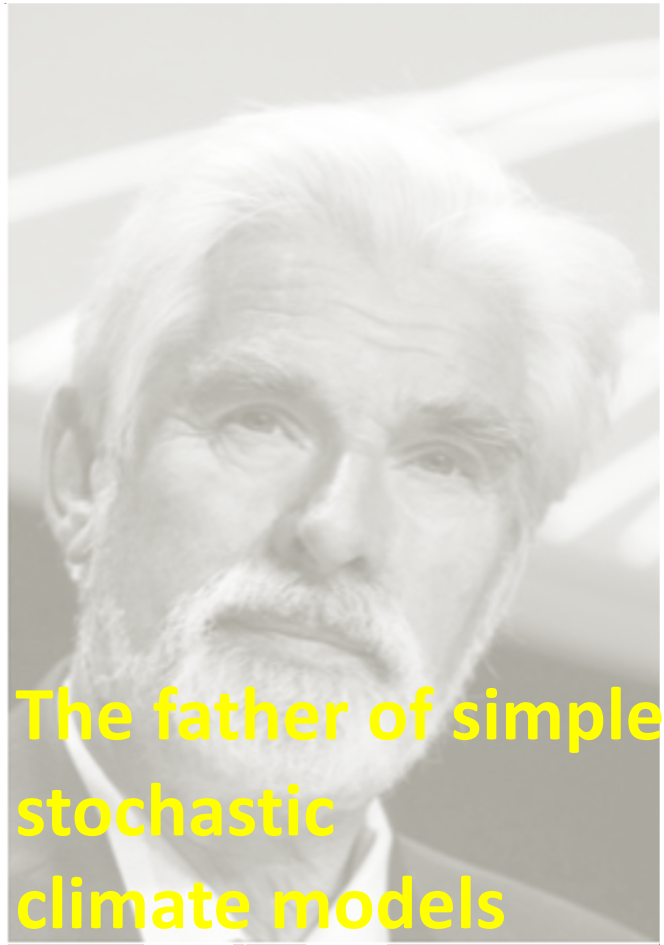
Exhaustive vs evasive models of the atmosphere

The atmosphere: a system or a noisemaker?

One person´s signal is another person´s noise

Sykuro Manabe
Princeton University

The unbearable simplicity of the climate system



Klaus Hasselman
University of Hamburg

First Physics Nobel Prize for Climate Science

Paul J. Crutzen
Facts


Photo from the Nobel Foundation archive.

Paul J. Crutzen
The Nobel Prize in Chemistry 1995

Born: 3 December 1933, Amsterdam, the Netherlands

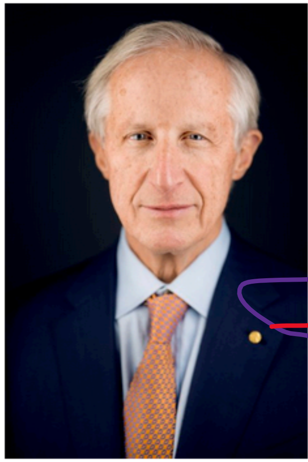
Died: 28 January 2021, Mainz, Germany

Affiliation at the time of the award: Max-Planck-Institut für Chemie, Mainz, Federal Republic of Germany

Prize motivation: "for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone."

Prize share: 1/3

William D. Nordhaus
Facts


© Nobel Media AB. Photo: A. Mahmoud

William D. Nordhaus
The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2018

Born: 31 May 1941, Albuquerque, NM, USA

Affiliation at the time of the award: Yale University, New Haven, CT, USA

Prize motivation: "for integrating climate change into long-run macroeconomic analysis."

Prize share: 1/2

First Physics Nobel Prize for Climate Science

IPCC
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
WMO UNEP

\-

Intergovernmental Panel on Climate Change (IPCC)

Prize share: 1/2

Photo: Ken Opprann

Albert Arnold (Al) Gore Jr.

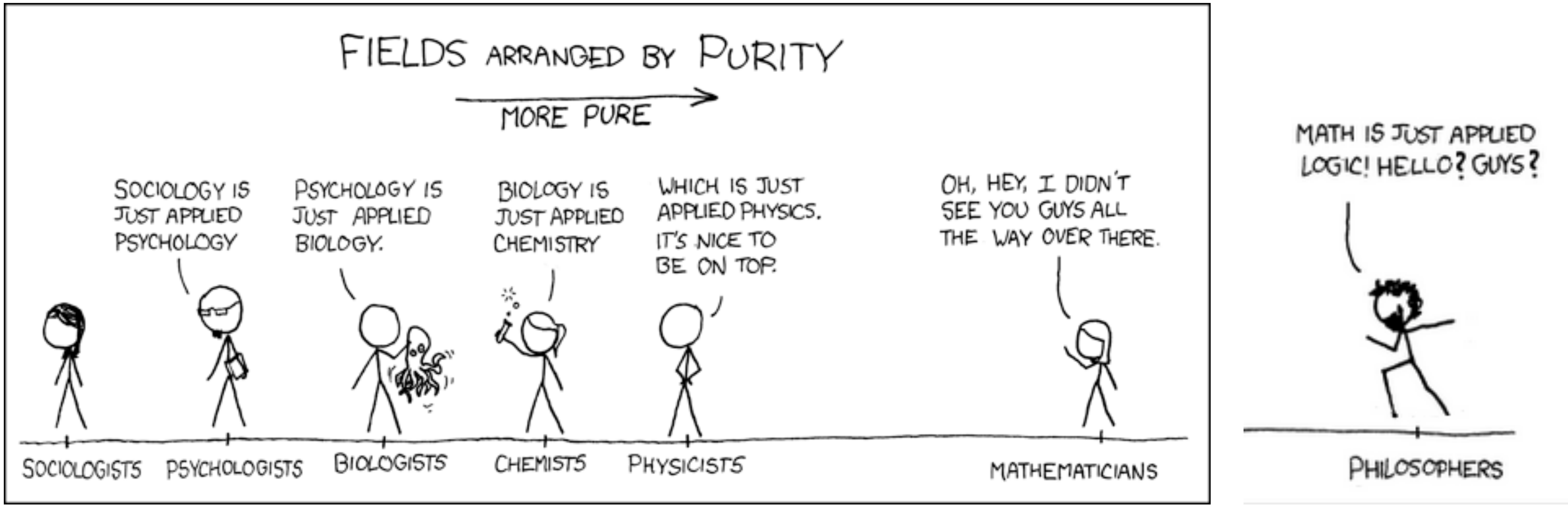
Prize share: 1/2

The Nobel Peace Prize 2007 was awarded jointly to Intergovernmental Panel on Climate Change (IPCC) and Albert Arnold (Al) Gore Jr. "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

The message behind Manabe and Hasselman’s Nobel prizes

- Despite the climate naysayers and “zombie theories”, the fundamental physics governing the atmosphere and climate system have been validated
- Global warming is resting on solid science
- Climate science is finally duly recognized

Abundance of biases, prejudices, feelings of superiority, myths, fallacies and "zombi theories" regarding meteorology and climate science.



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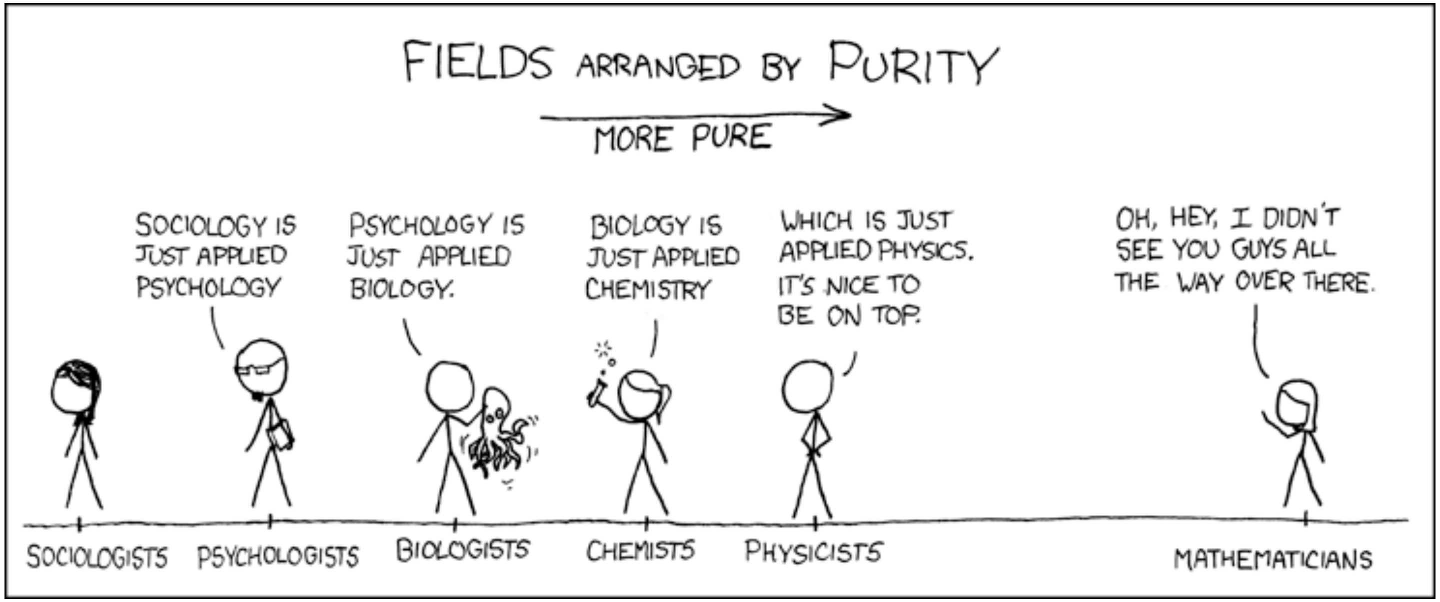


We should help Western culture rid itself...of the intellectual hierarchy in which “pure” is somehow better than “applied”, physics is better than chemistry, both are better than engineering, and the ...intellectual content of manufacturing is valued hardly at all.

J.A. Armstrong, “Research and competitiveness: the problems of a new rationale” Materials Research Society Bulletin, 18 (2), 4 (1993)

Meteorologists are sometimes confused with:

- Weather anchor (*)

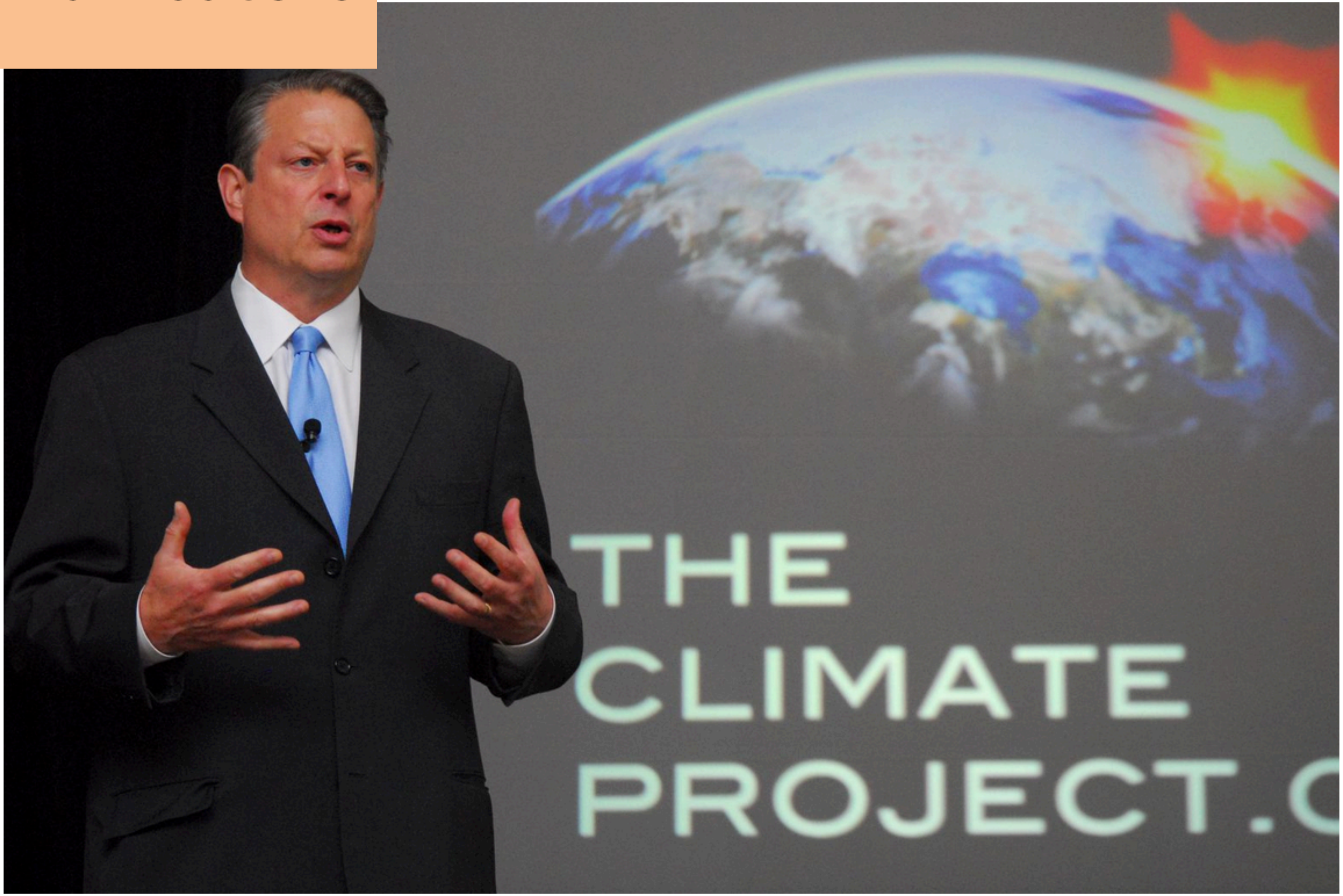
- Commmunicators

- Climate Activists

Weather anchor men/women (*)

(*): 50% of TV3 weather people are in fact physicists

Communicators



Climate activists

Deplorable ignorance? Arrogance? Thick-headedness?

Freeman Dyson, theoretical and mathematical physicist

"My first heresy says that all the fuss about global warming is grossly exaggerated. Here I am opposing the holy brotherhood of climate model experts and the crowd of deluded citizens who believe the numbers predicted by the computer models." [13]

[...] "There is no doubt that parts of the world are getting warmer, but the warming is not global." [13]

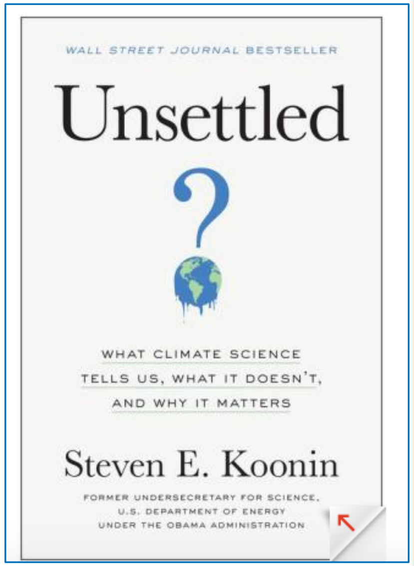
Steve Koonin, theoretical physicist

"Unsettled: the truth about climate science that you aren't getting elsewhere."

OPINION | THE WEEKEND INTERVIEW

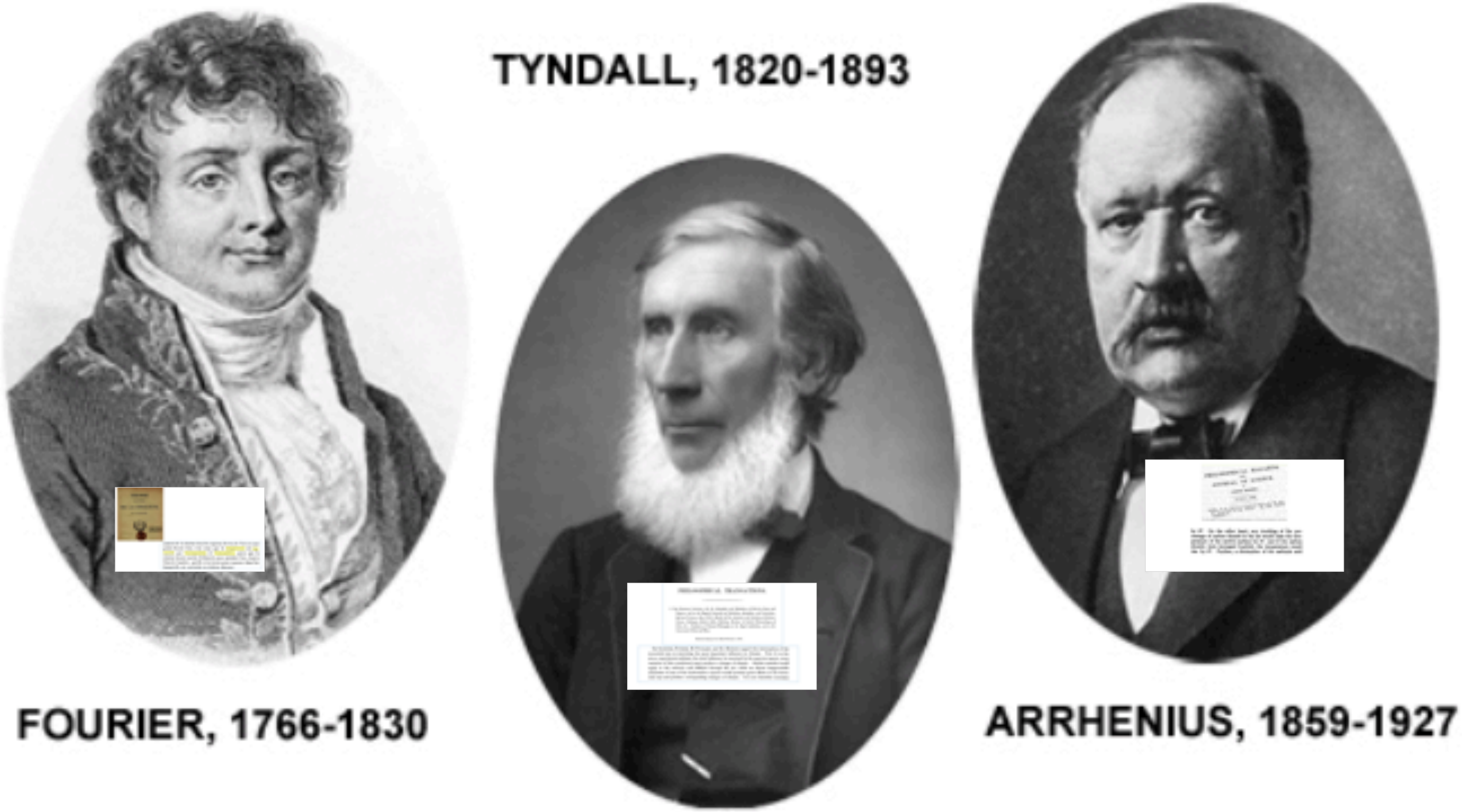
How a Physicist Became a Climate Truth Teller

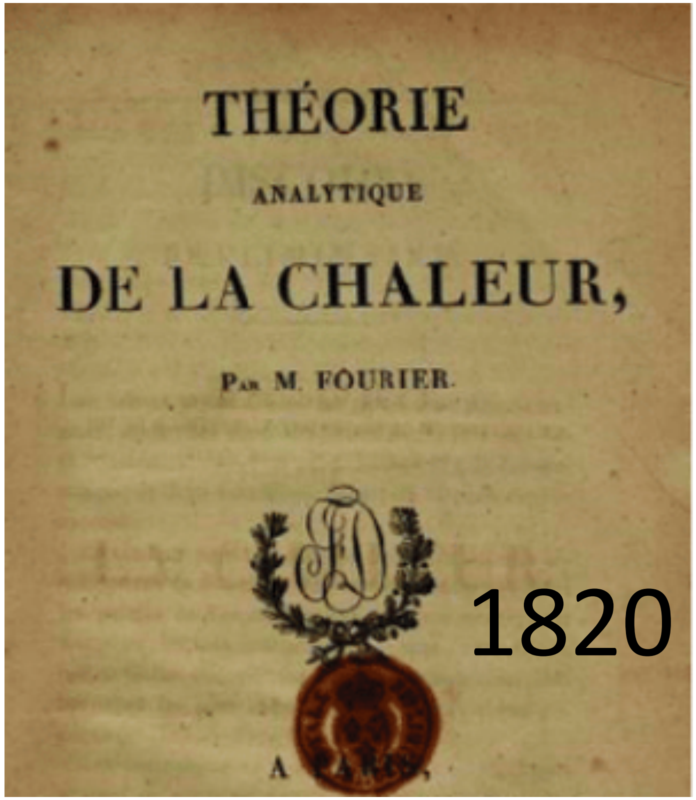
After a stint at the Obama Energy Department, Steven Koonin reclaims the science of a warming planet from the propaganda peddlers.



We´ve known about the greenhouse effect and CO_2 impact on climate for two centuries.
Really.

The Grandfathers of Climate Science ….




THÉORIE
ANALYTIQUE
DE LA CHALEUR,
PAR M. FOURIER.
A PARIS,

1820

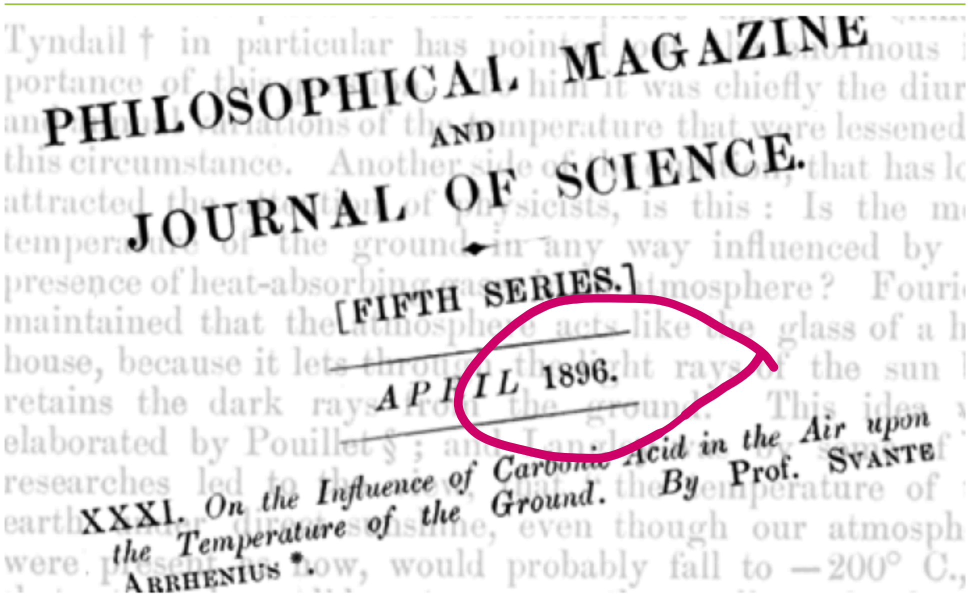
sement de la chaleur dans les régions élevées de l'air ne cesse point d'avoir lieu ; c'est ainsi que la température est augmentée par l'interposition de l'atmosphère, parce que la chaleur trouve moins d'obstacle pour pénétrer l'air, étant à l'état de lumière, qu'elle n'en trouve pour repasser dans l'air lorsqu'elle est convertie en chaleur obscure.

PHILOSOPHICAL TRANSACTIONS.

I. The Bakerian Lecture.—*On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction. By* John Tyndall, *Esq., F.R.S., Member of the Academies and Societies of Holland, Geneva, Göttingen, Zürich, Halle, Marburg, Breslau, la Société Philomathique of Paris, &c.; Professor of Natural Philosophy in the Royal Institution, and in the Government School of Mines.*

Received January 10,—Read February 7, 1861.

De Saussure, Fourier, M. Pouillet, and Mr. Hopkins regard this interception of the terrestrial rays as exercising the most important influence on climate. Now if, as the above experiments indicate, the chief influence be exercised by the aqueous vapour, every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid diffused through the air; while an almost inappreciable admixture of any of the hydrocarbon vapours would produce great effects on the terrestrial rays and produce corresponding changes of climate. It is not therefore necessary

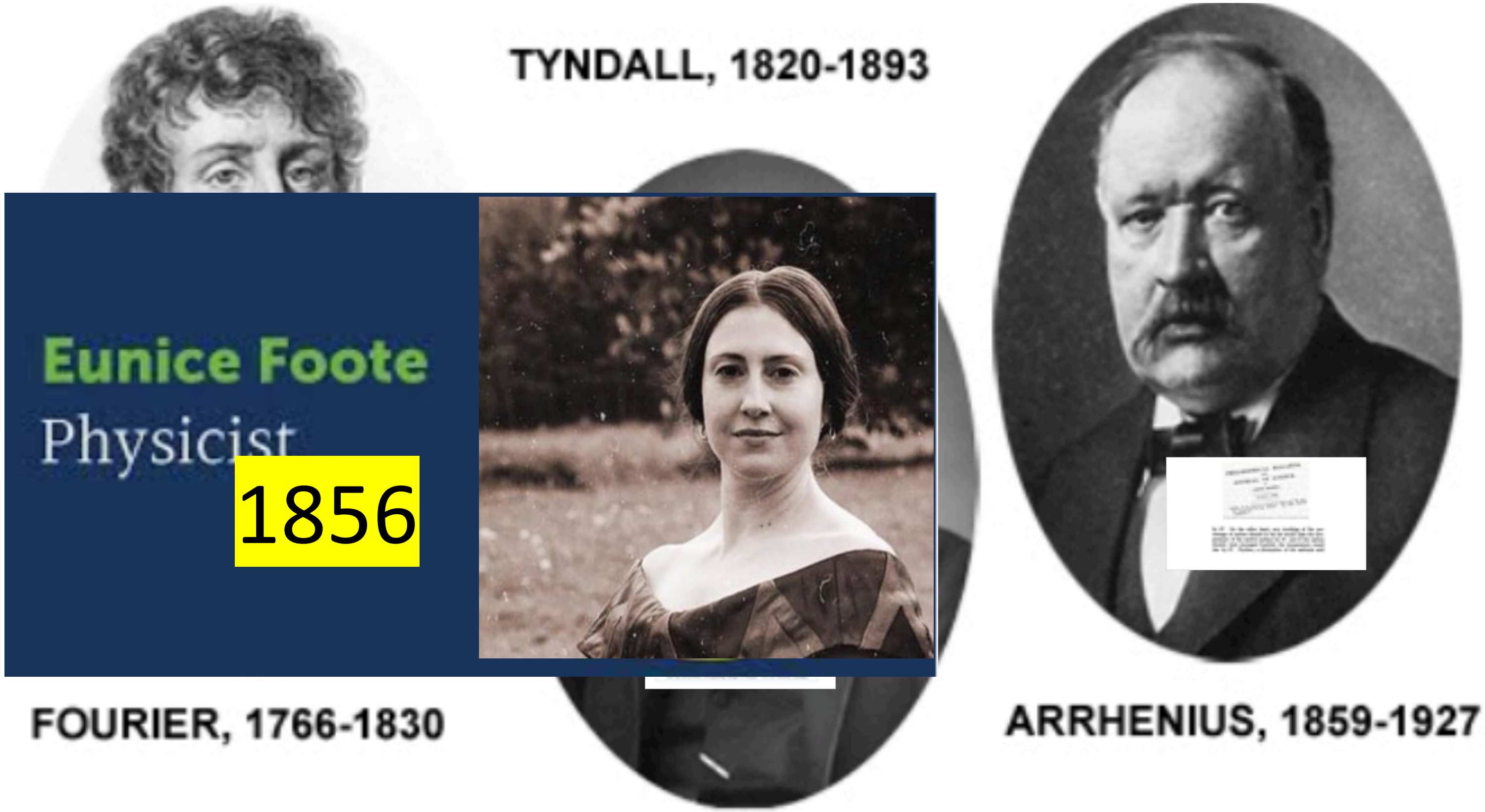


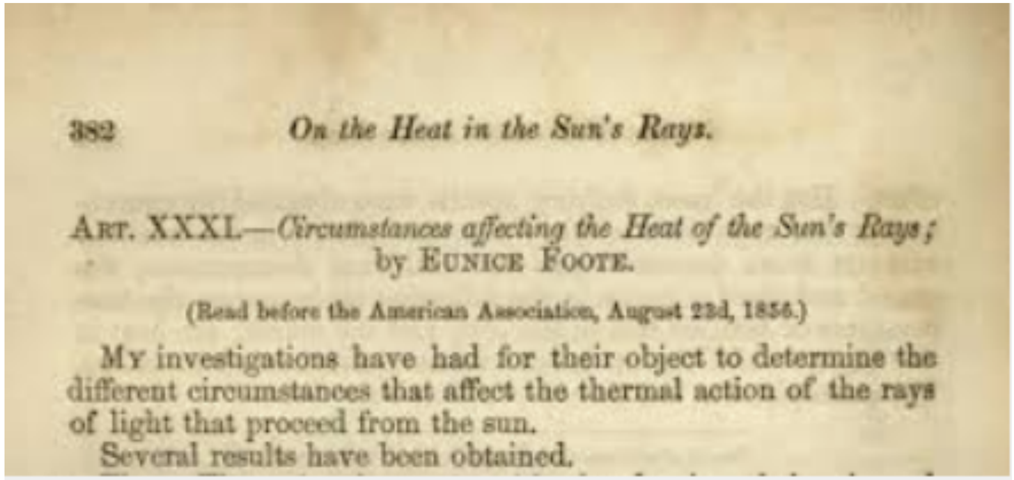
The title page of Arrhenius's groundbreaking paper on CO2 and atmospheric warming

by 8°. On the other hand, any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°. Further, a diminution of the carbonic acid

The Grandfathers of Climate Science ….

But the grand-mother is missing !!!





Art. XXXI.—*Circumstances affecting the Heat of the Sun's Rays;* by Eunice Foote.

(Read before the American Association, August 23d, 1856.)

My investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun.

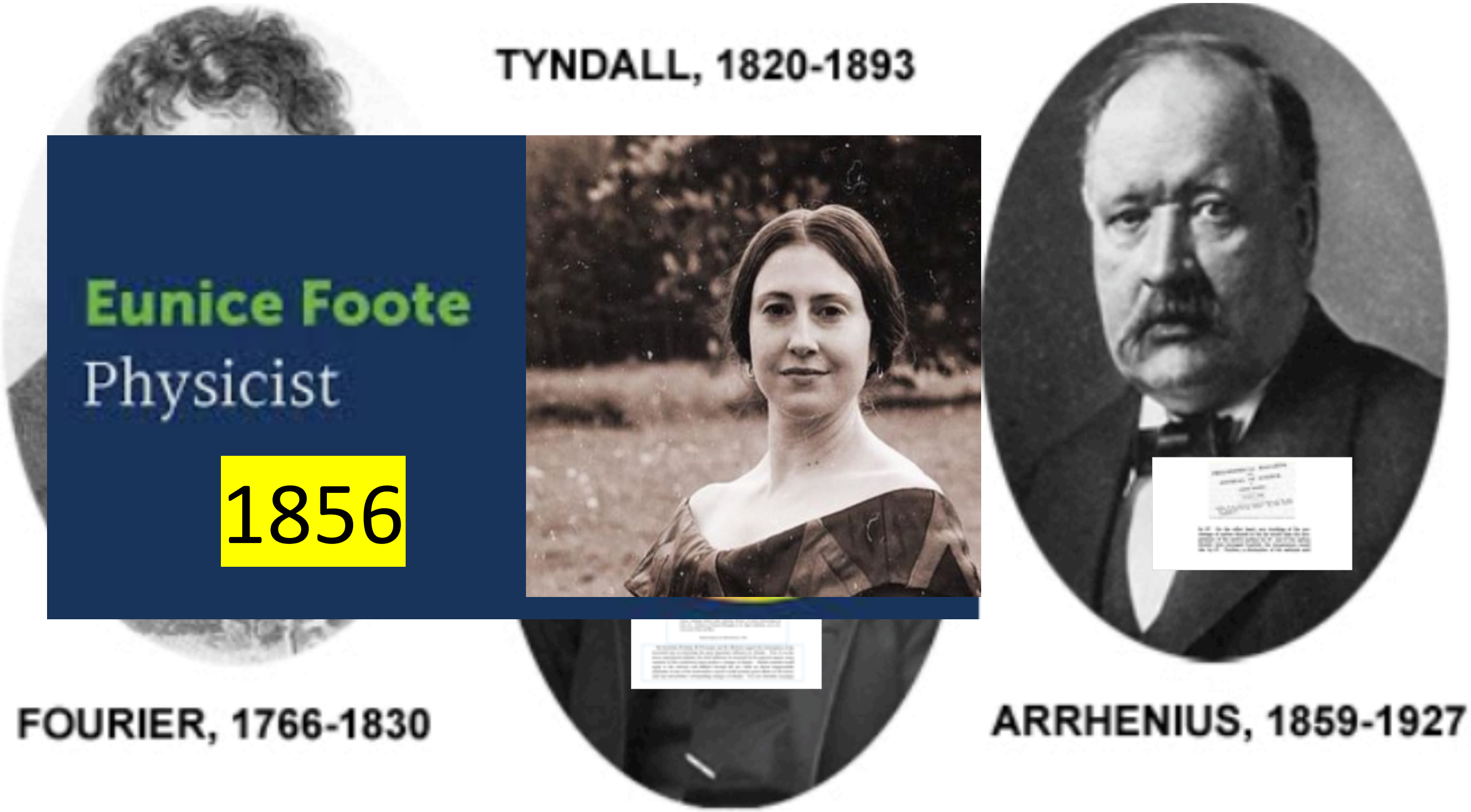
Several results have been obtained.

Thirdly. The highest effect of the sun's rays I have found to be in carbonic acid gas.

An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.

The Grandfathers of Climate Science ….

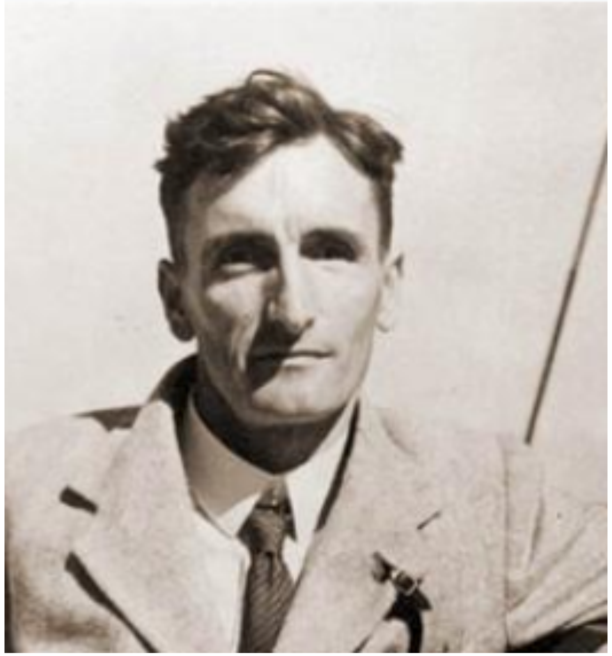
But the grand-mother is missing !!!



Science on the effect of the greenhouse effect progressed, albeit with gaps.
By the second half of the 20th century we also knew that:

1938: atmospheric temperature and CO_2 were increasing (Callendar)

Guy Stewart Callendar



Quarterly Journal of the Royal Meteorological Society

RMetS Royal Meteorological Society

Article

The artificial production of carbon dioxide and its influence on temperature

G. S. Callendar

First published: April 1938 | https://doi.org/10.1002/qj.49706427503 | Citations: 337

Science on the effect of the greenhouse effect progressed, albeit with gaps.

By the second half of the 20th century we also knew that:

1938: atmospheric temperature and CO_2 were increasing (Callendar)

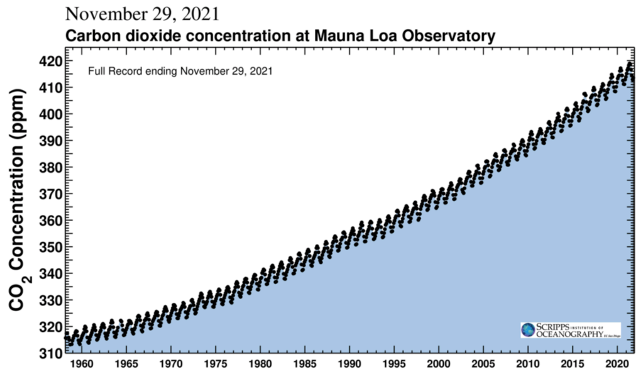
1931: adding more CO_2 would raise the effective emission height in the atmosphere to space and thus would warm the planet (Hulburt)

1958: confirmed via Keeling's monitoring program of CO2 concentration with infrared spectroscopy at Mauna Loa.

n

S. Callen

rst publis

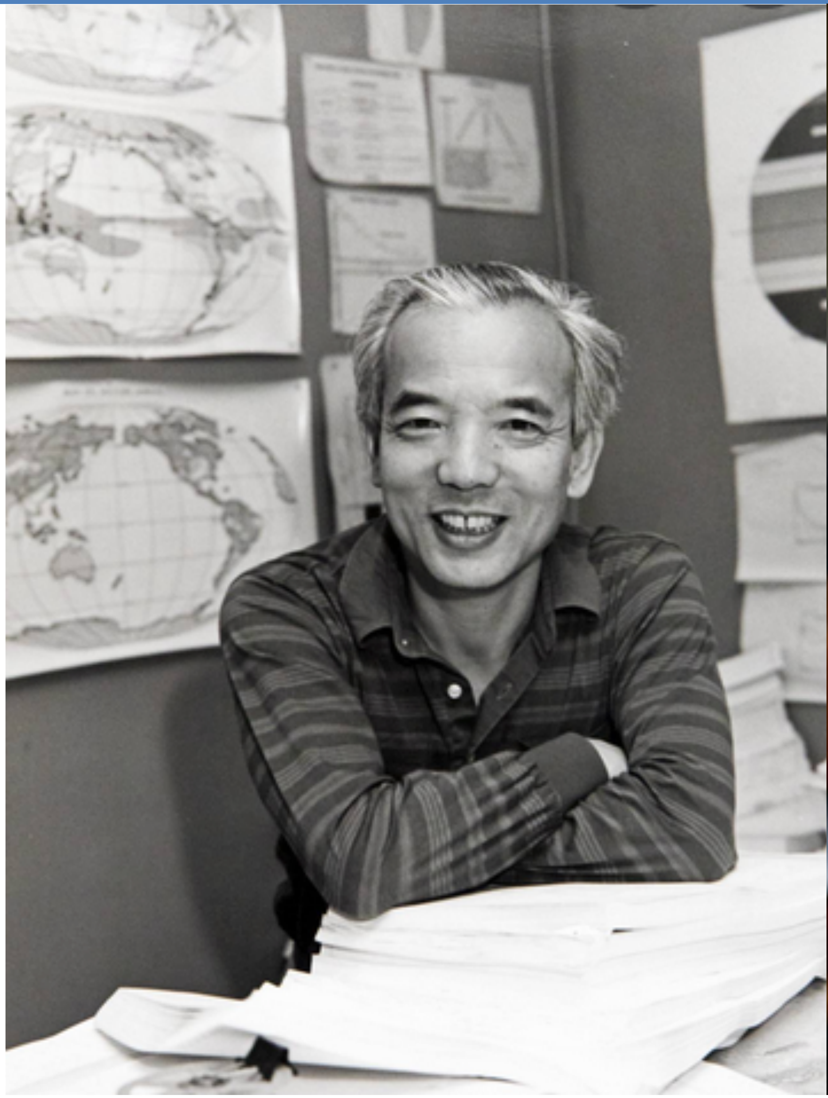


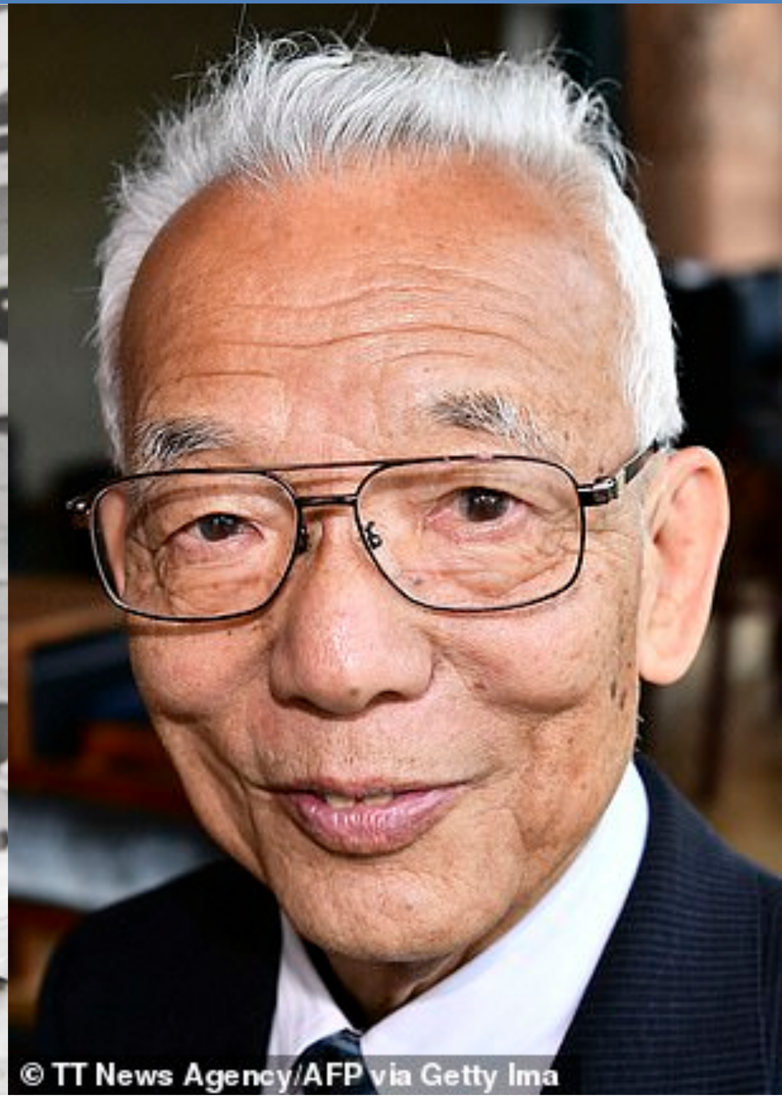
49706427

But **difficulties** remained:

- No solid mathematical framework to understand the finer details of the greenhouse effect
- No solid understanding of non-linear differential equations and how to solve them numerically
- No computational power to properly model the atmosphere in 3D.

Sykuro Manabe: a genius and a gentleman





"For the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming."

Sykuro Manabe:A pillar in the field of climate science

His work laid the foundation for the development of current climate models

BUT ALSO

He used simplified models

- To first explore the interaction between radiation balance and the vertical transport of air masses (RCE radiative-convective equilibrium).
- To first quantify the relative role of different greenhouse gases in earth´s climate, quantify the water vapor feedback and analyse what doubling carbon dioxide (CO_2) would do to global temperature.

Thermal Equilibrium of the Atmosphere with a Convective Adjustment

SYUKURO MANABE AND ROBERT F. STRICKLER

General Circulation Research Laboratory, U. S. Weather Bureau, Washington, D. C.

(Manuscript received 19 December 1963, in revised form 13 April 1964)

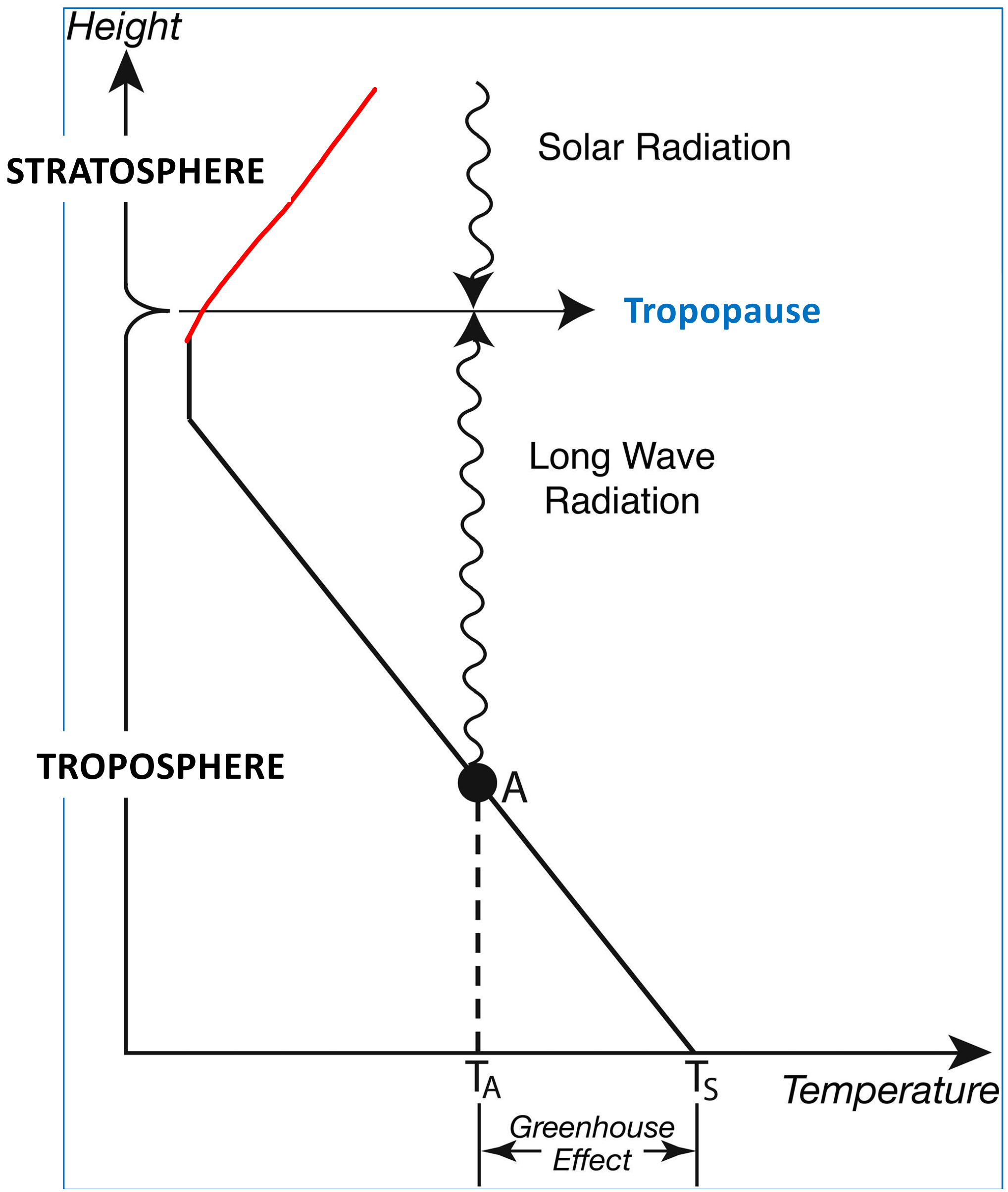
Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D. C.

(Manuscript received 2 November 1966)

Manabe and Wetherald (1967) has been described as the most influential climate paper ever.



Tropospheric layer is characterized by a decrease in temperature with height, i.e. a positive lapse rate:

$$\Gamma = -\frac{\partial T}{\partial z} \approx 6.5 \text{ K/km}$$

$$Ts \approx 15ºC$$

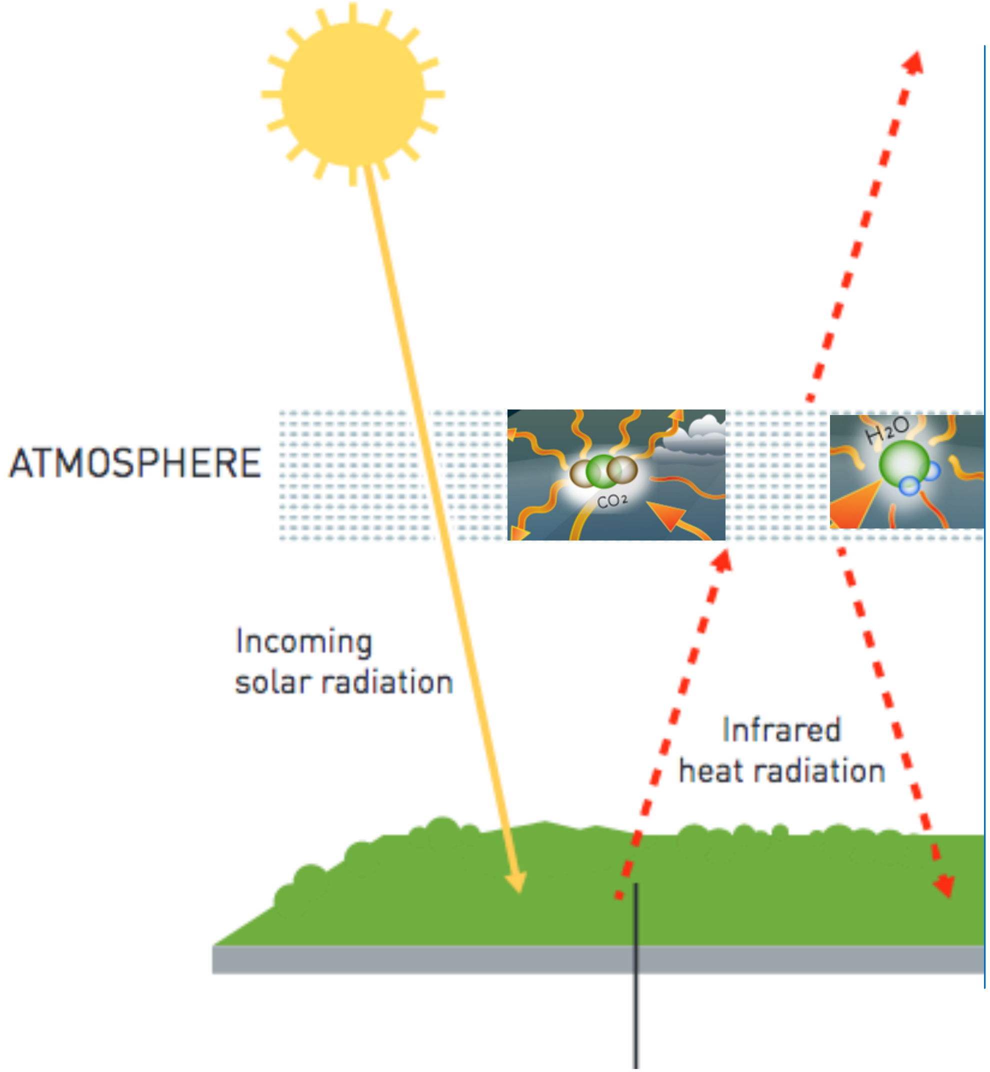
Before Manabe this profile was not well understood.

Pure radiative equilibrium: a recipe

- Consider a 1-D atmosphere
- Specify solar radiation at the top
- Specifiy short-wave and long-wave absortivity. for H_2O, CO_2 and O_3 (add absorbents to taste)

- Boundary conditions:
  - At the surface: net upward flux of long-wave radiation = net downward flux of solar radiation
  - At the top of the atmosphere: net upward flux of long-wave radiation = net downward flux of solar radiation

- Calculate radiative equilibrium temperature of each layer. Repeat calculation with new fluxes.
- **Solve for the asymptotic steady state solution of an initial value problem**



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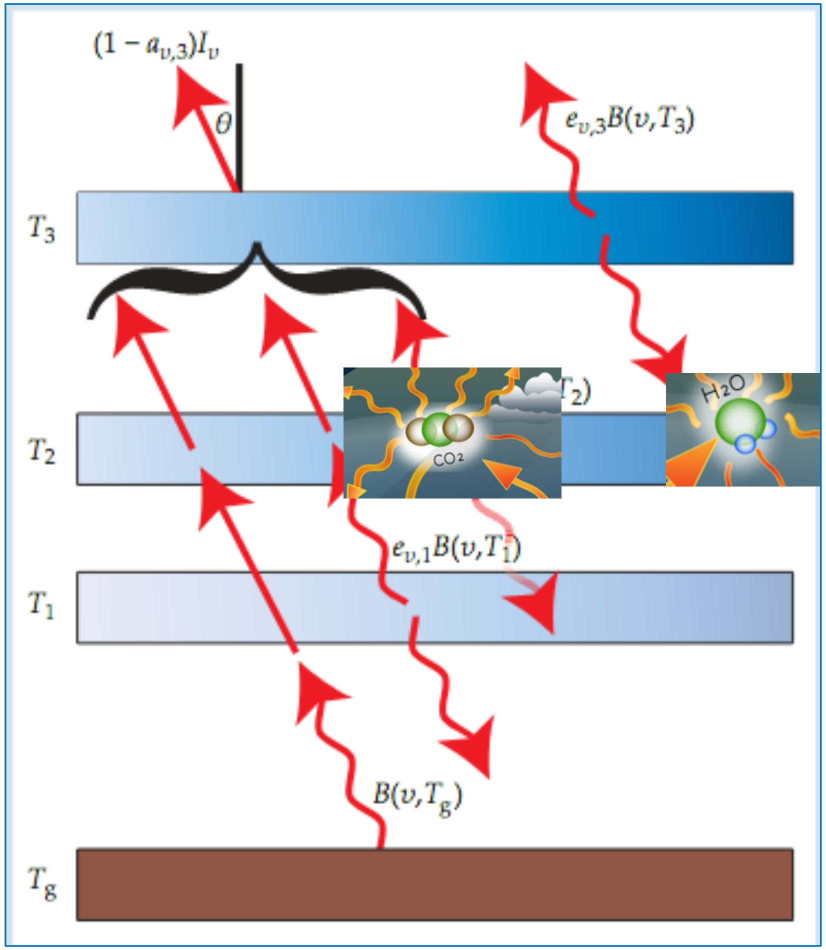

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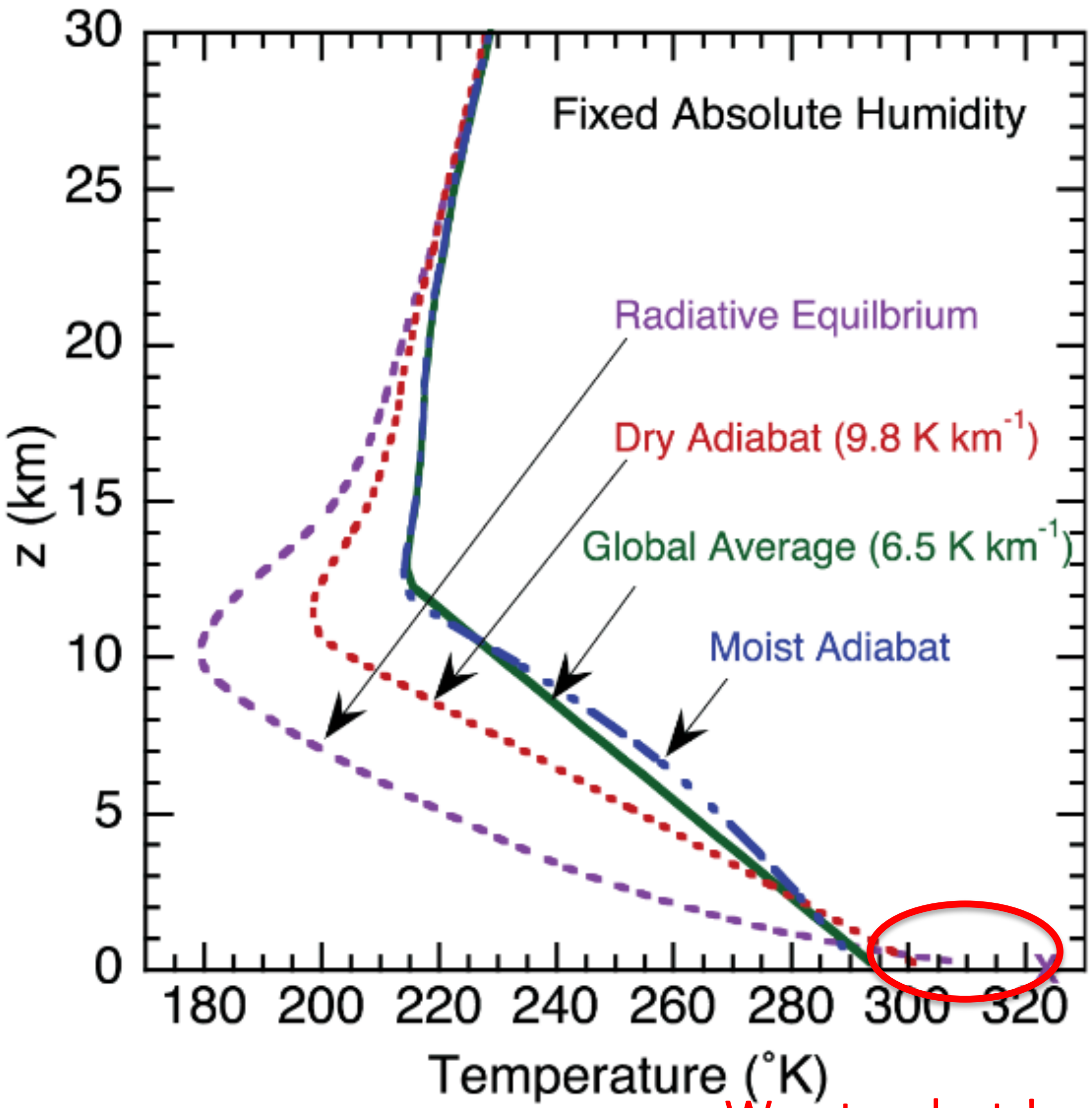


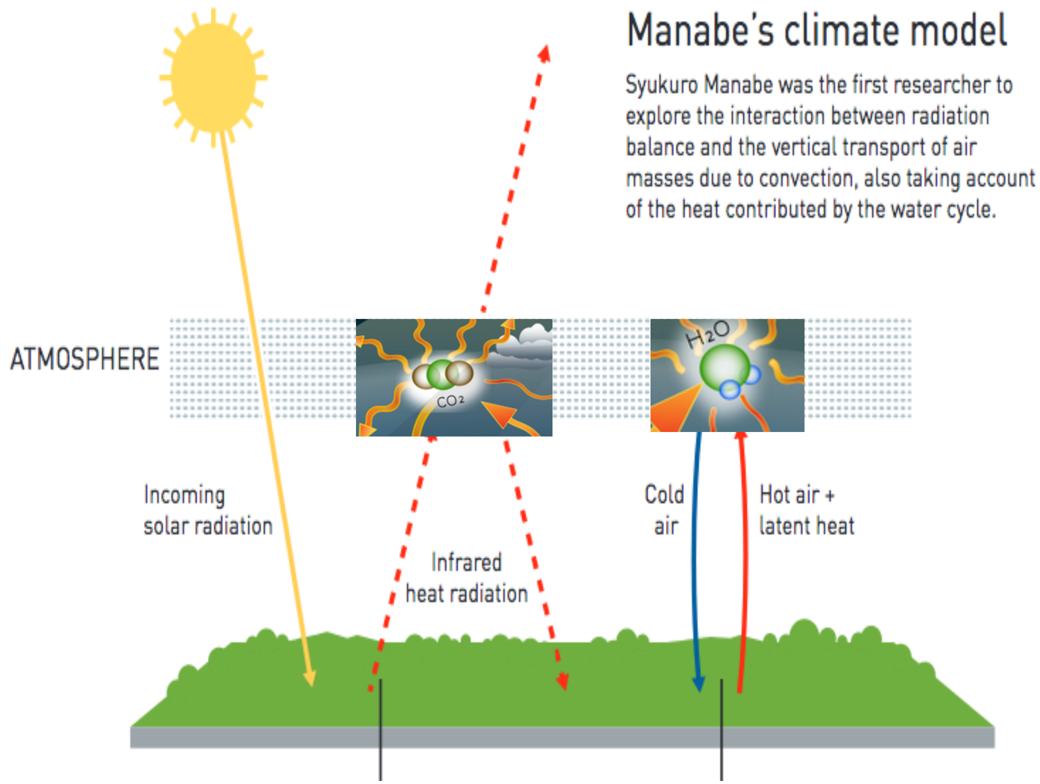
Way too hot !

Manabe's stroke of genius:

- Pure radiatitive equilibrium produces a surface that **is way too hot** the surface

- Manabe (and Stickler) deviced **a convective-adjustment scheme**, whereby the lapse rate is adjusted to the observed tropospheric lapse rate (6.5 K/km)

- The observed lapse rate (the result of competing complicted processes) is **accepted as an observed fact** and regarded as a critical threshold for convection.



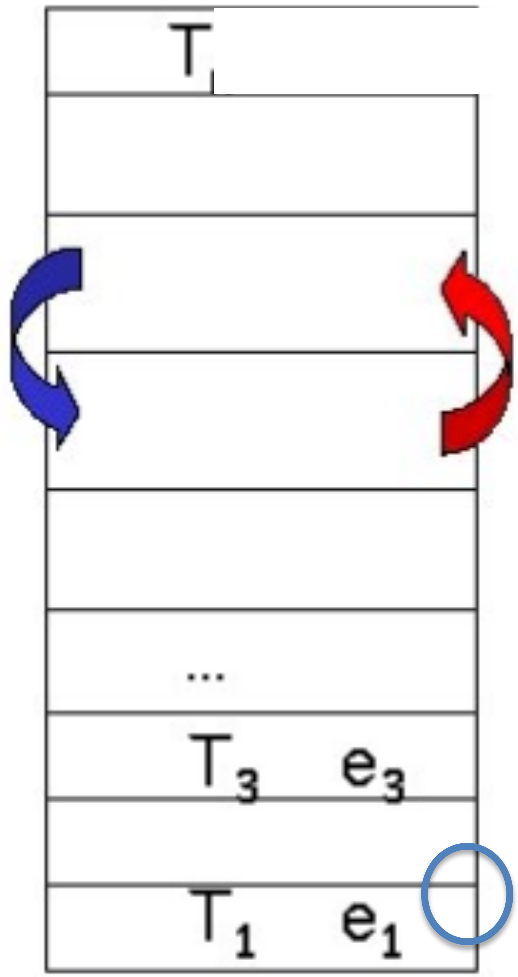
Radiative-convective equilibrium (RCE): a recipe

- Consider a 1-D atmosphere
- Specify solar radiation at the top
- Specifiy short-wave and long-wave absortivity for H_2O, CO_2 and O_3

- Calculate radiative equilibrium temperature of each layer
- Check for static stability
- If layers are unstable, mix them !
  (e.g. if $\Gamma > \Gamma_c$, set $\Gamma = \Gamma_c$)

- Solve for the asymptotic steady state solution of an initial value problem

- **This produces a fairly reasonable profile with a much colder surface**



Reasonable !

Radiative-convective equilibrium (RCE): a recipe

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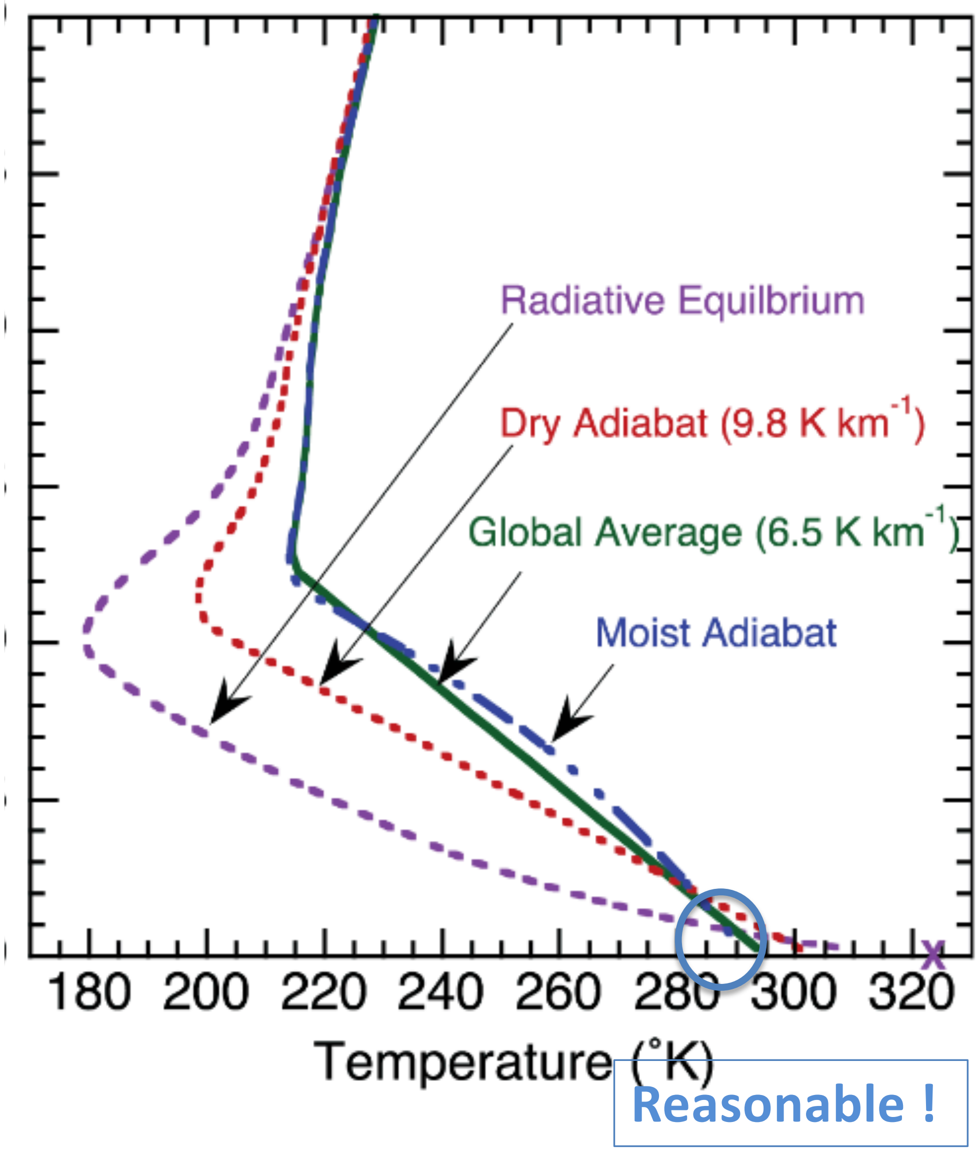
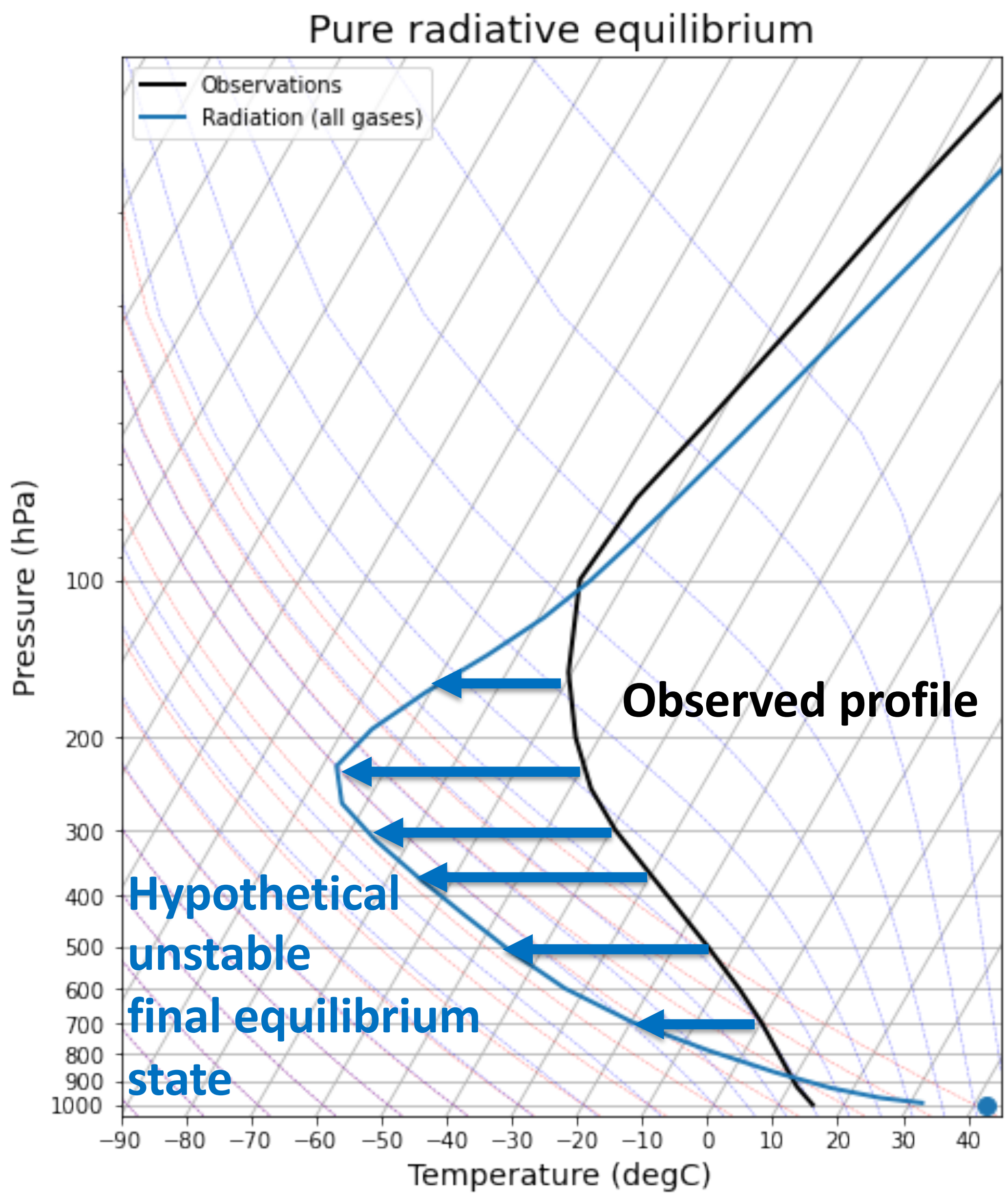


The concept of pure radiative equilibrium is still very useful because we can think of radiative emission (cooling) as a relaxation toward that target state **from a realistic noisy state.**

Analogy with Parisi´s work :

The radiative equilibrium profile could be viewed as a "frustrated unstable state", awaiting a "spontaneous symmetry breaking".

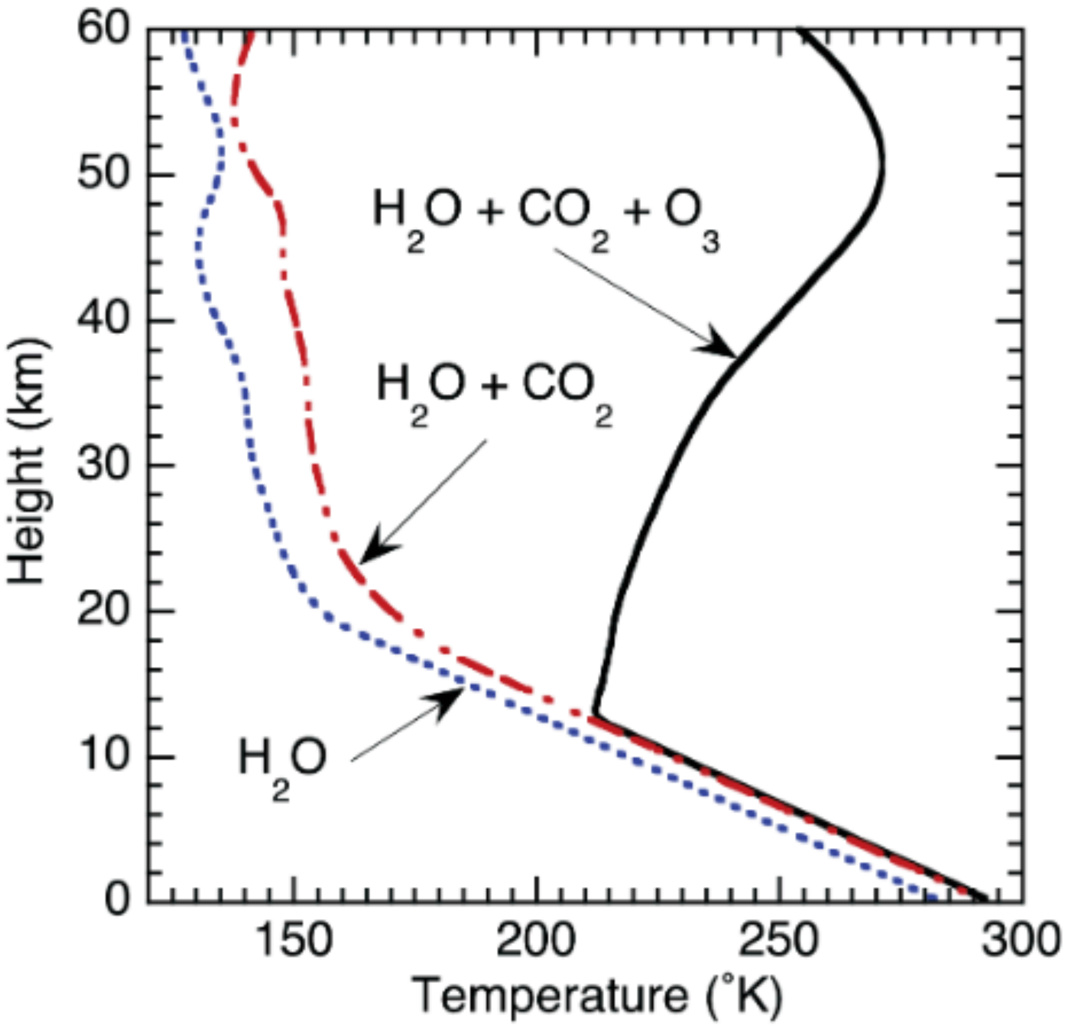
So maybe in the atmosphere we are concerned with the high-noise limit, whereas in spin-glass theory one is concerned with the low-noise limit (?)



Now the RCE model can be used for multiple purposes:

- Determine the role of each absorbent gas in maintaining the the thermal structure of the atmosphere and the surface temperature

Application of Manabe´s model



- Only water vapor: too cold and no stratosphere
- Add CO_2: 10ºC warmer but still no stratosphere
- Add O_3: sharp tropopause and a temperature increase with height in the stratosphere

Now the RCE model can be used for multiple purposes:

- Determine the role of each absorbent gas in maintaining the the thermal structure of the atmosphere and the surface temperature
- **Investigate the impact of doubling CO_2 or equilibrium climate sensitivity** (2.3°C close to current estimates)
- **Determine that the stratosphere** COOLS **upon increasing CO_2**

Carbon dioxide heats the atmosphere

Increased levels of carbon dioxide lead to higher temperatures in the lower atmosphere, while the upper atmosphere gets colder. Manabe thus confirmed that the variation in temperature is due to increased levels of carbon dioxide; if it was caused by increased solar radiation, the entire atmosphere should have warmed up.

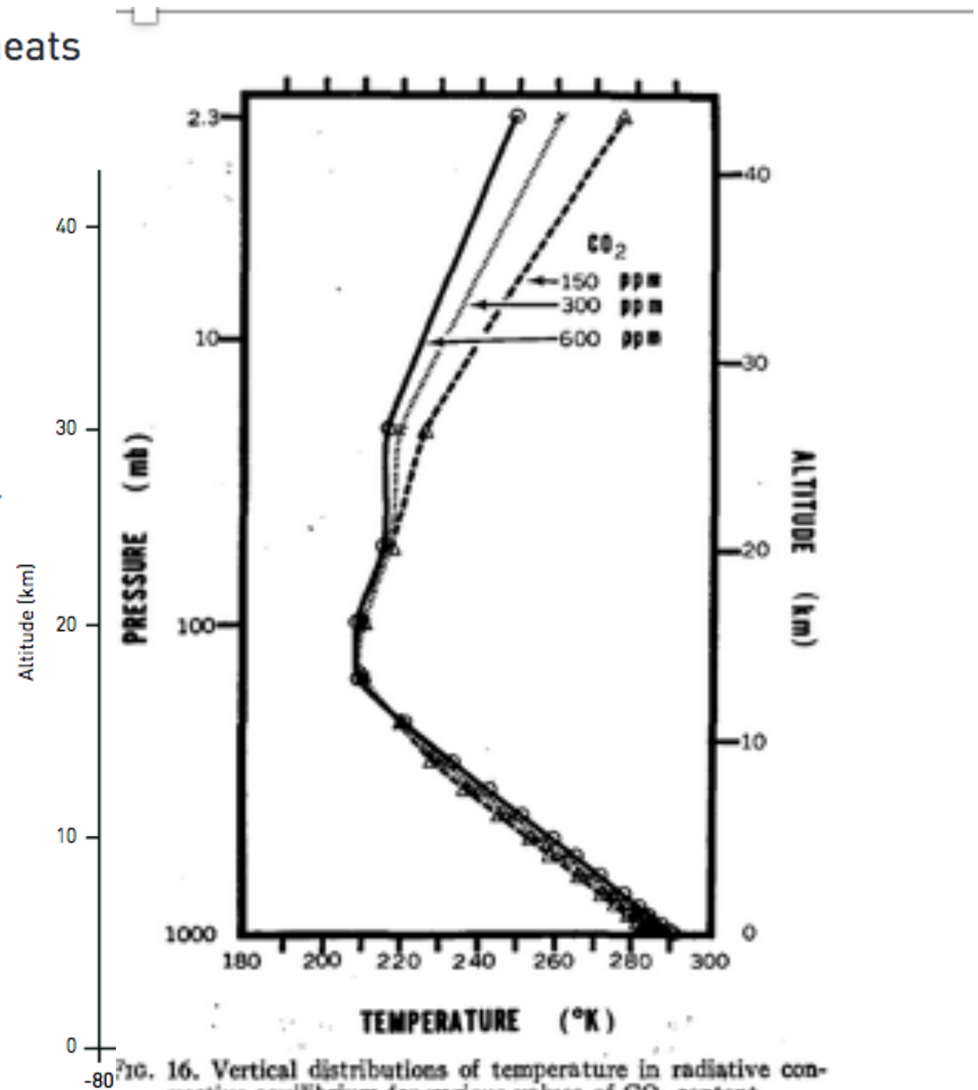


FIG. 16. Vertical distributions of temperature in radiative convective equilibrium for various values of CO_2 content.

Source: Manabe and Wetherald (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *Journal of the atmospheric sciences*, Vol. 24, Nr 3, May.

Equilibrium climate sensitivity (ECS) refers to the amount of global surface warming that will occur in response to a doubling of atmospheric CO2 concentrations .

- **1867: Manabe and Wetherald: ECS = 2**

- **2021**: IPCC AR6 (2021) reports assessed best estimate **is 3°C with a likely range of 2.5°C to 4°C**

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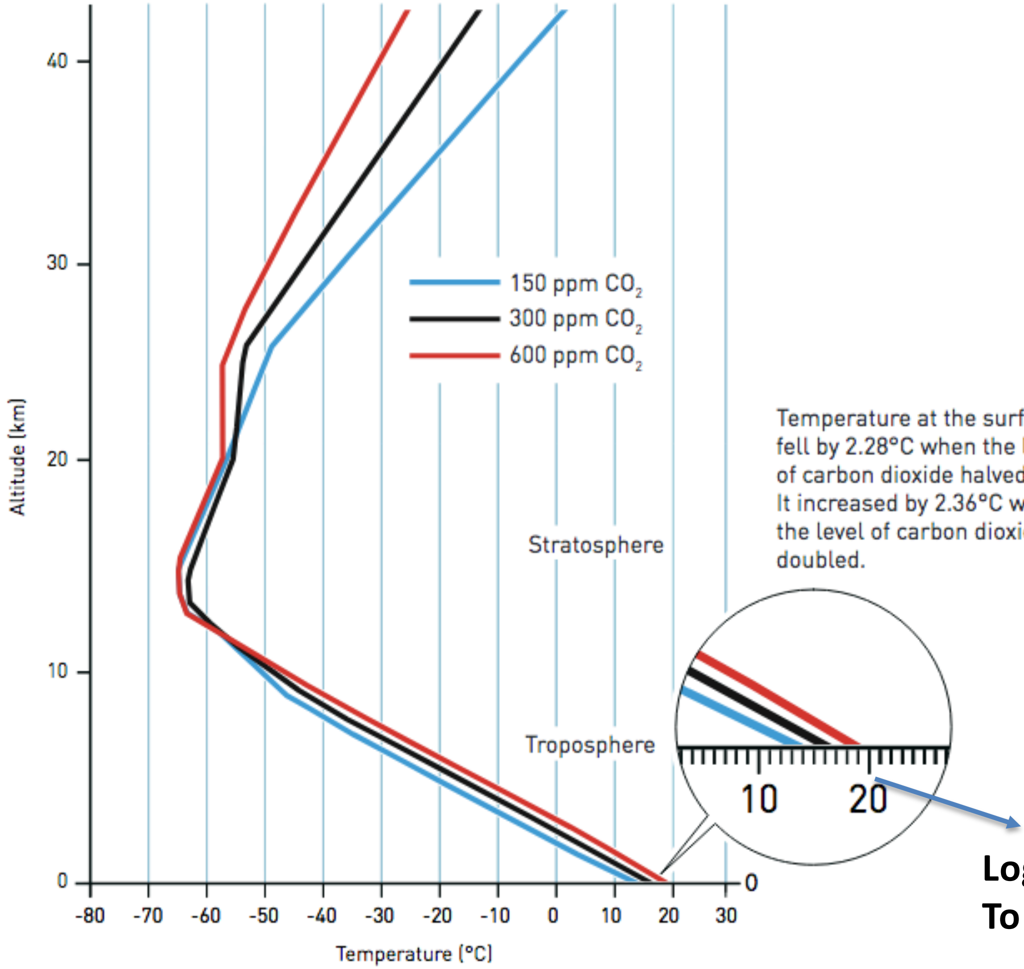

Temperature at the surface fell by 2.28°C when the level of carbon dioxide halved. It increased by 2.36°C when the level of carbon dioxide doubled.

Source: Manabe and Wetherald (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *Journal of the atmospheric sciences*, Vol. 24, Nr 3, May.

Logarithmic effect. Each doubling of CO_2 leads To the same temperature increase

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Change in the Radiative-convective equilibrium temperature profiles computed with a 1D model

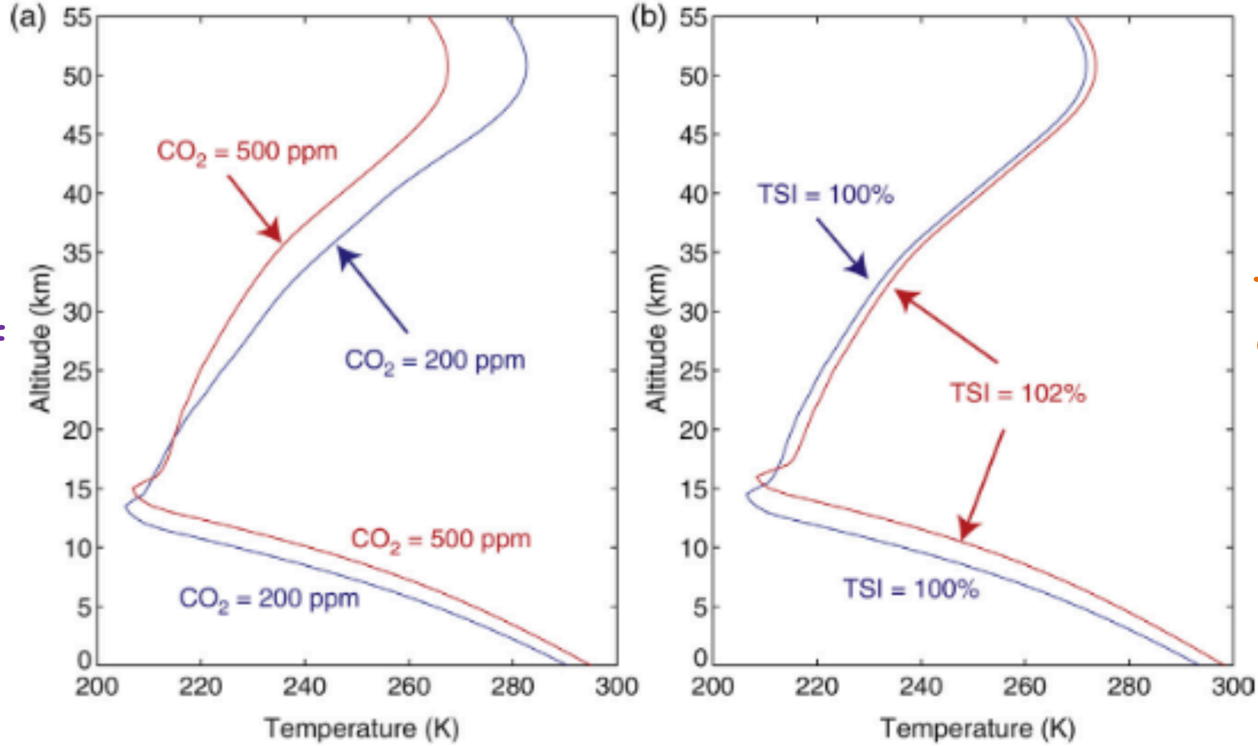
Distinct fingerprints of two kinds of forcing

Troposphere warms but stratosphere cools !

This the signature of the Greenhouse Effect

CO_2 increase

Solar constant increase



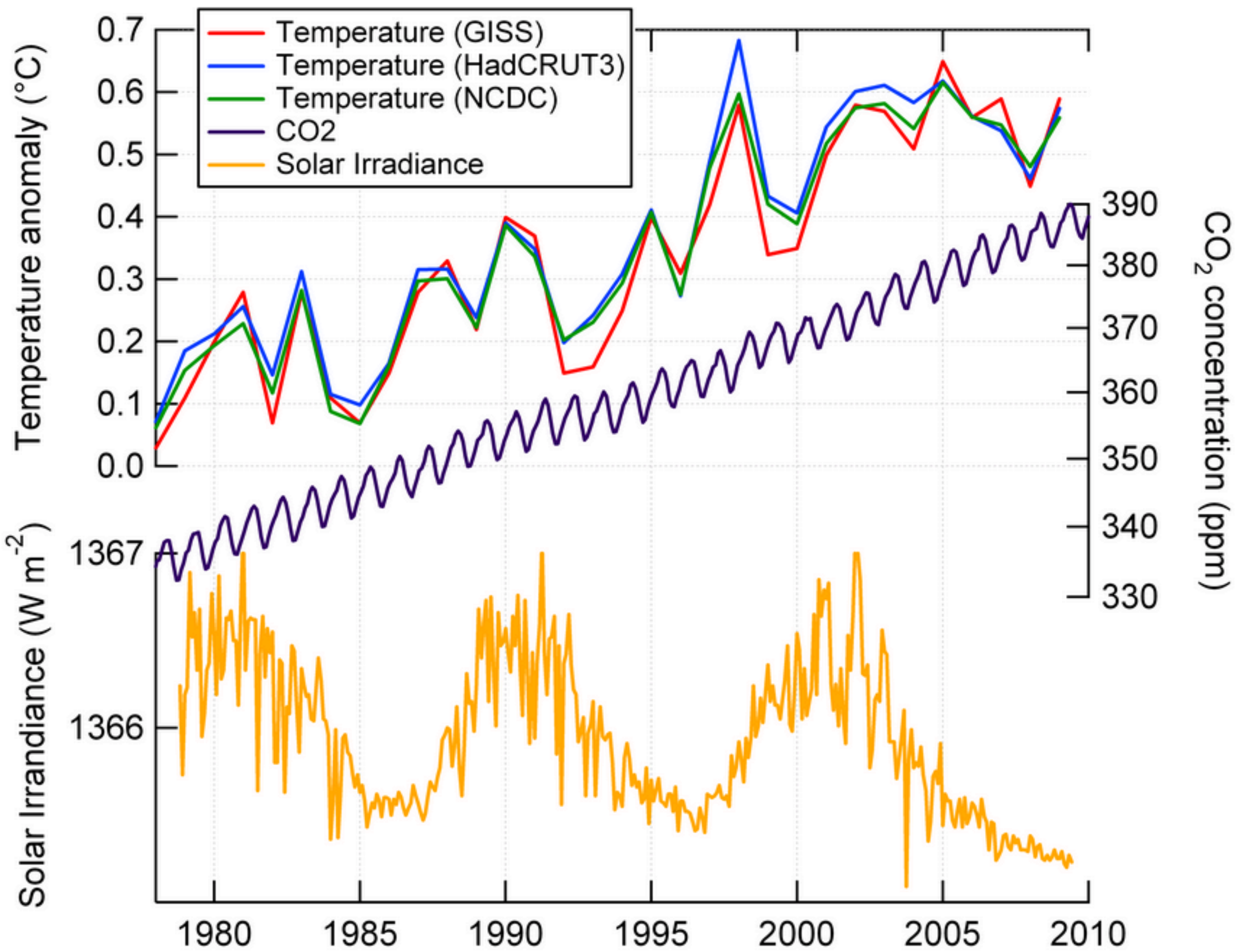
Both troposphere and stratosphere warm !

This is the fingerprint of an increase in solar output

Data from Manabe and Wetherald (1967)

Debunking zombie theories:

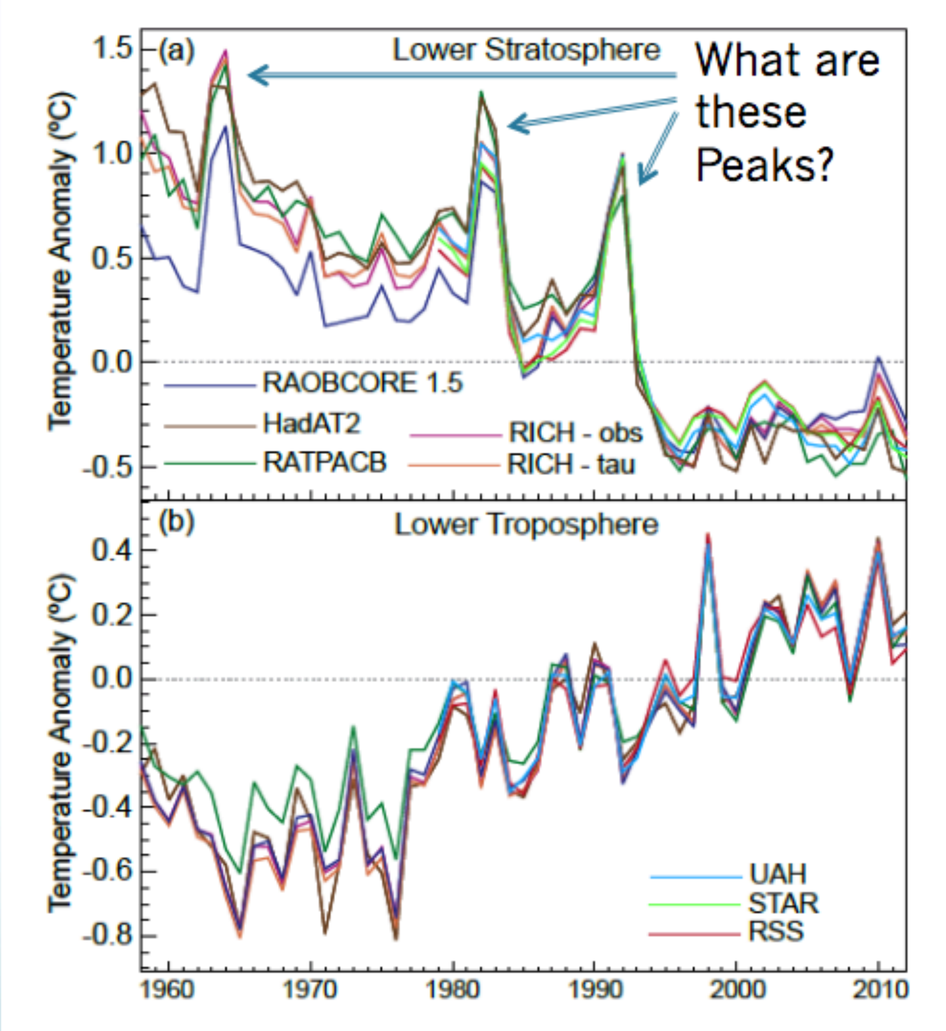
Not only does the solar irradiance not show any increasing trend in recent decades, unlike greenhouse gas concentrations ….



… but the vertical structure of the observed warming is NOT consistent with solar forcing !

Temperature Trends with Height

- We expect increasing CO_2 to warm the surface and troposphere and cool the stratosphere.
- We definitely see that



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- Determine the role of each absorbent gas in maintaining the the thermal structure of the atmosphere and the surface temperature

- Investigate the impact of doubling CO_2 or equilibrium climate sensitivity (2.3°C close to current estimates)

- Determine that the stratosphere COOLS upon increasing CO_2

- Investigate the role of the water vapor feedback (positive feedback that magnifies the surface temperature change by a factor of ~2)

- Investigate the role of clouds

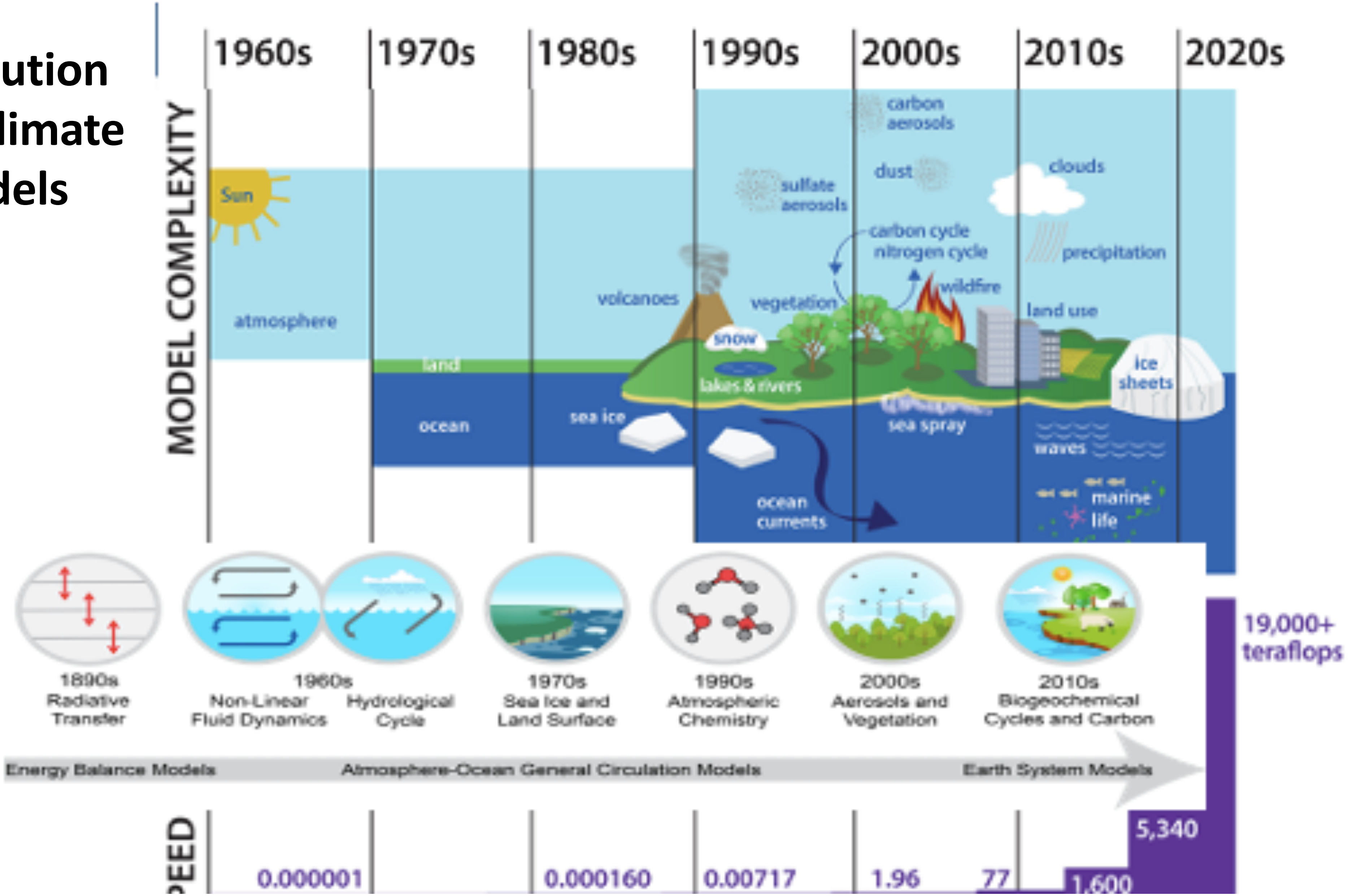
- **Test the method to incorporate radiative transfer into an advanced general circulation model of the atmosphere**

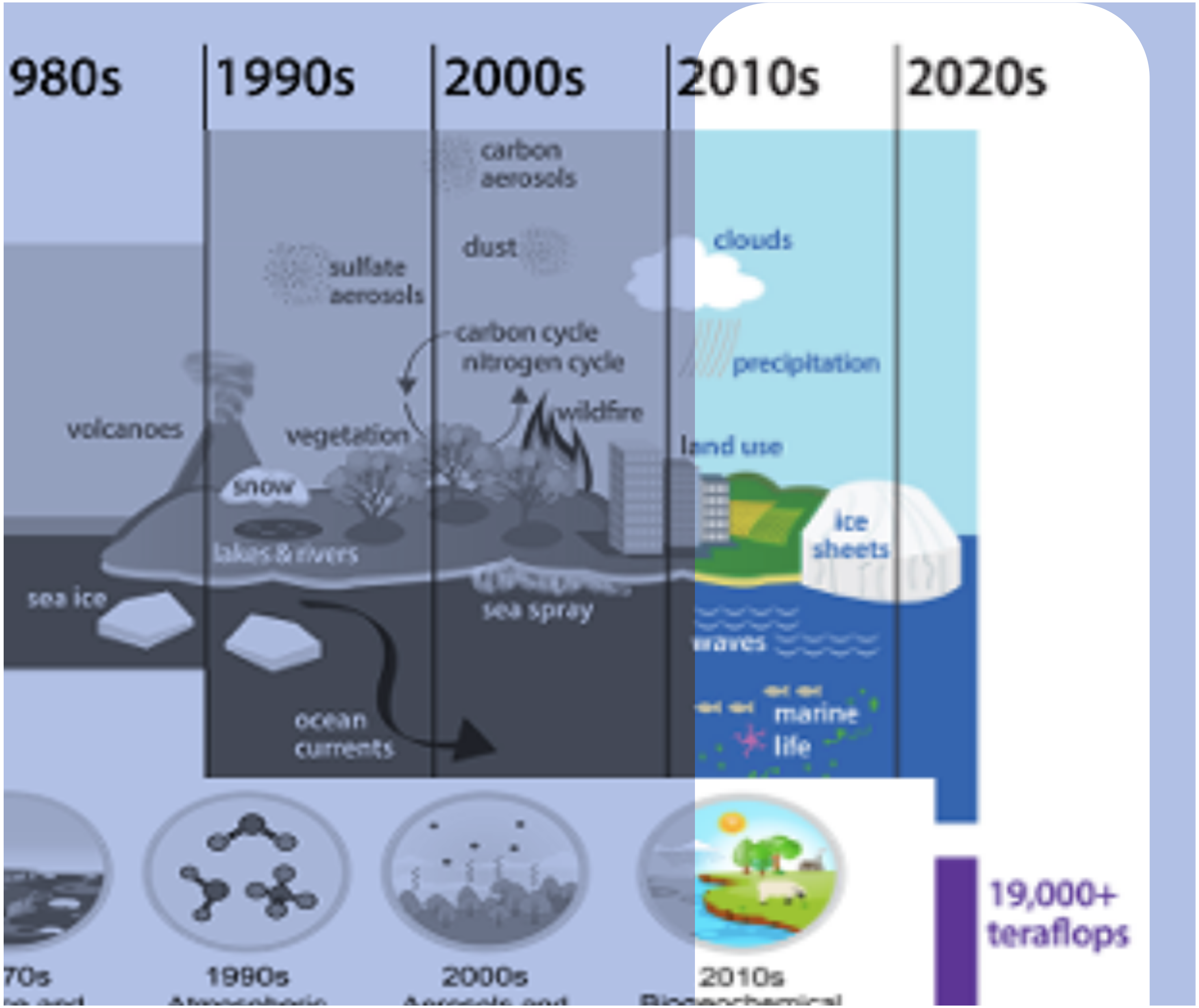
Suki Manabe: Father of Climate Modeling

- Manabe's subsequent work led to the development of the GFDL general circulation model (or global climate model), initially just including the atmosphere and eventually and ocean.

- For the first time, it was possible to take into account the complex interactions between the atmosphere and the oceans, including the dynamics of radiative heat transfer and carbon dioxide levels in driving global climate

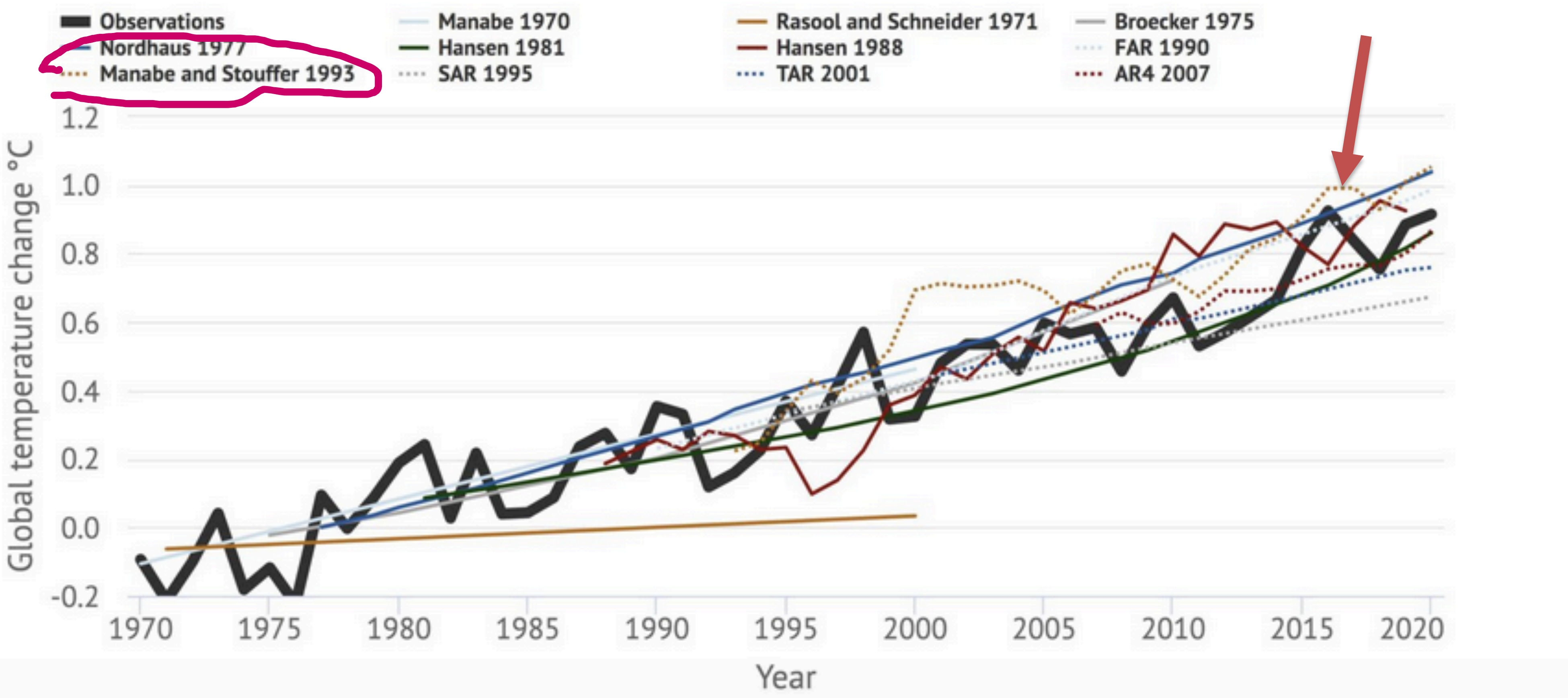
Evolution of Climate Models





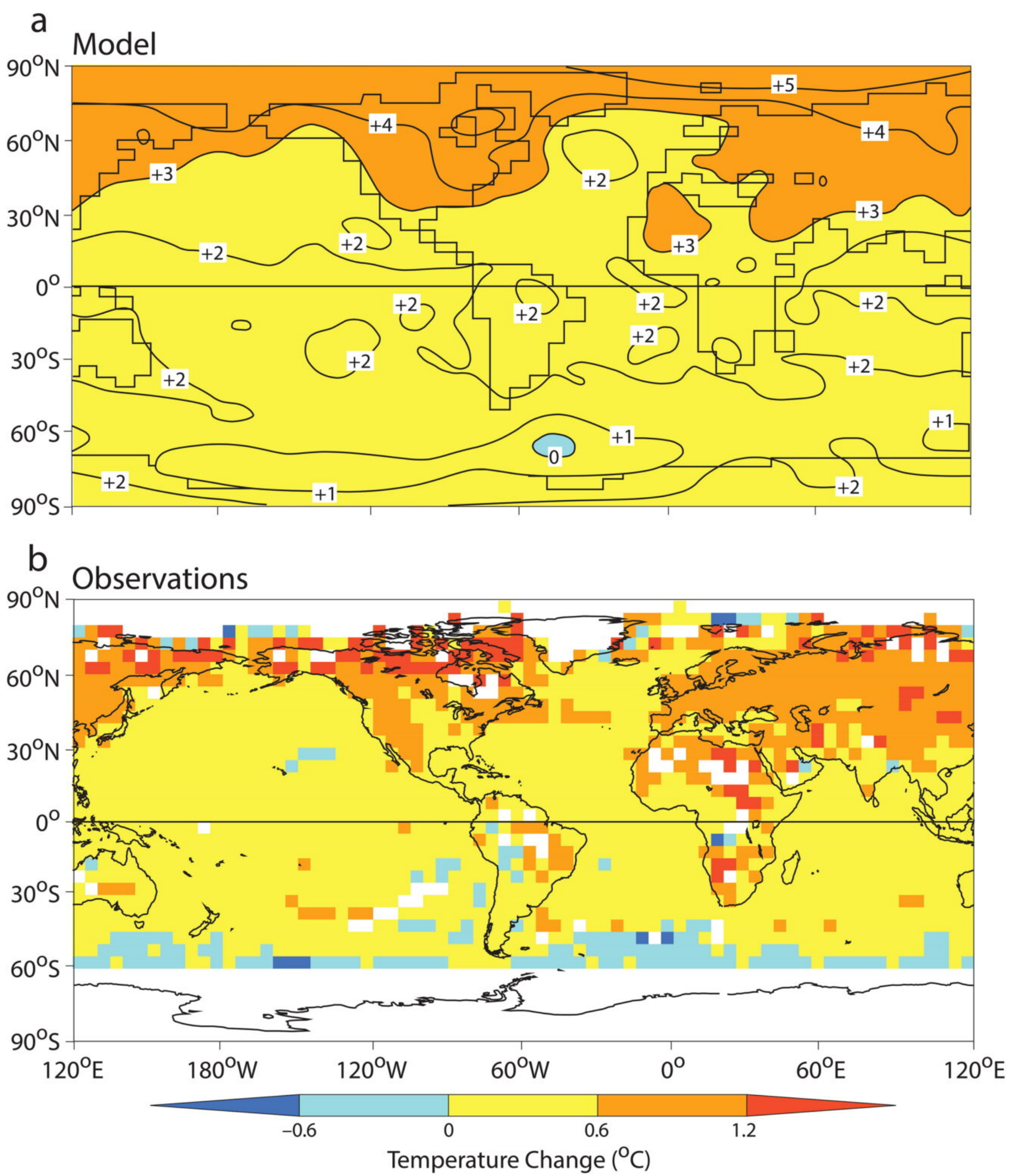
Climate models are now **Earth system models**

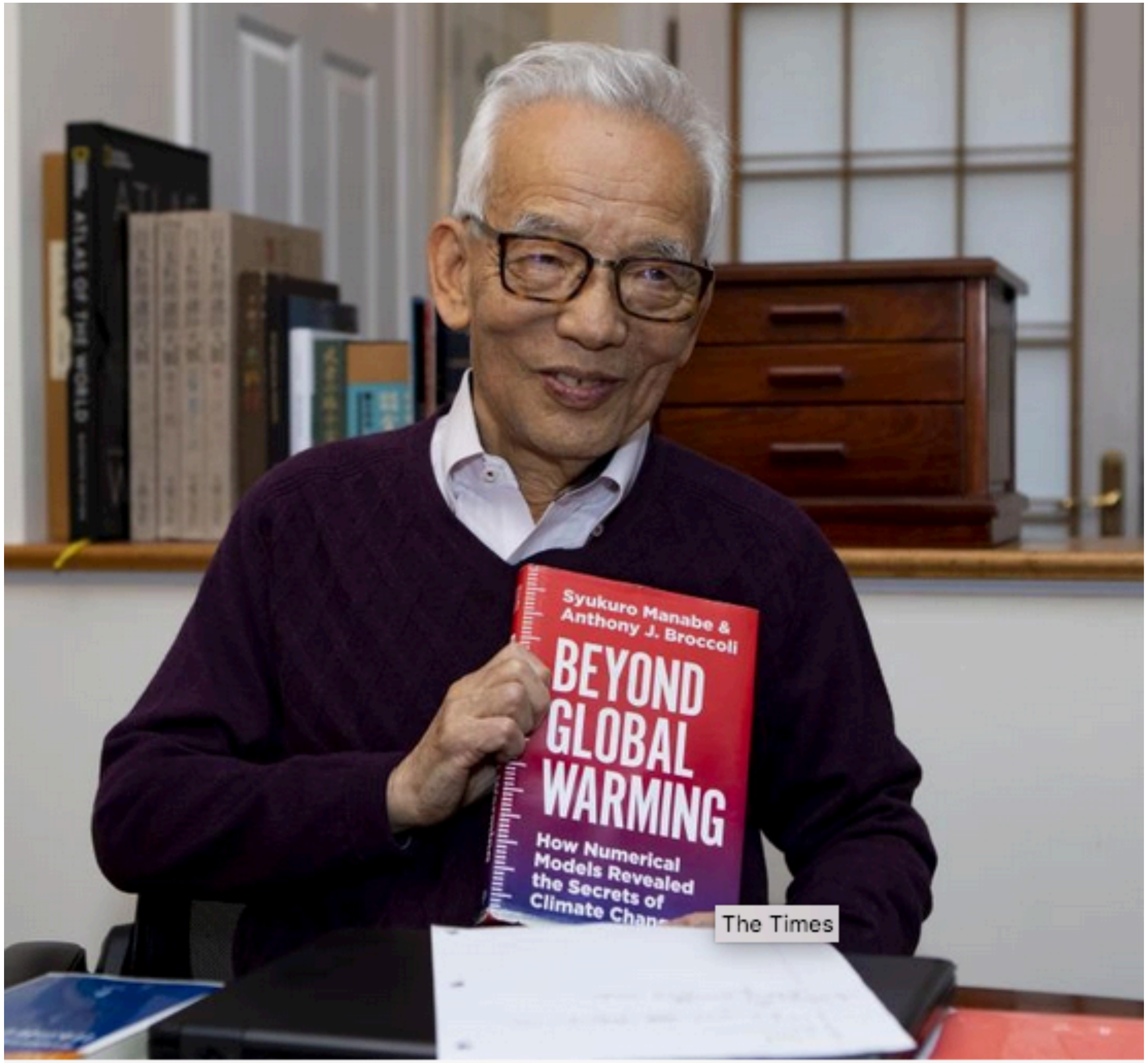
Manabe´s model projections have held up very well!



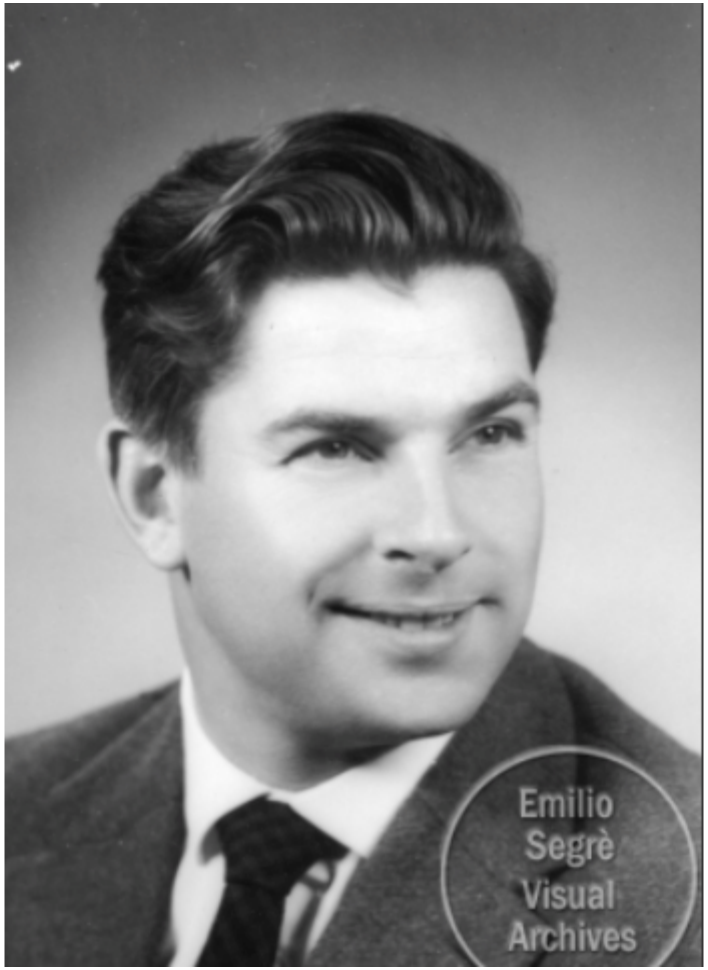
Comparison of the ***pattern*** of warming from Manabe and Stouffer (1989), assuming a transient doubling of CO_2, with subsequent observations of temperature change (1991-2015 minus 1961-1990)

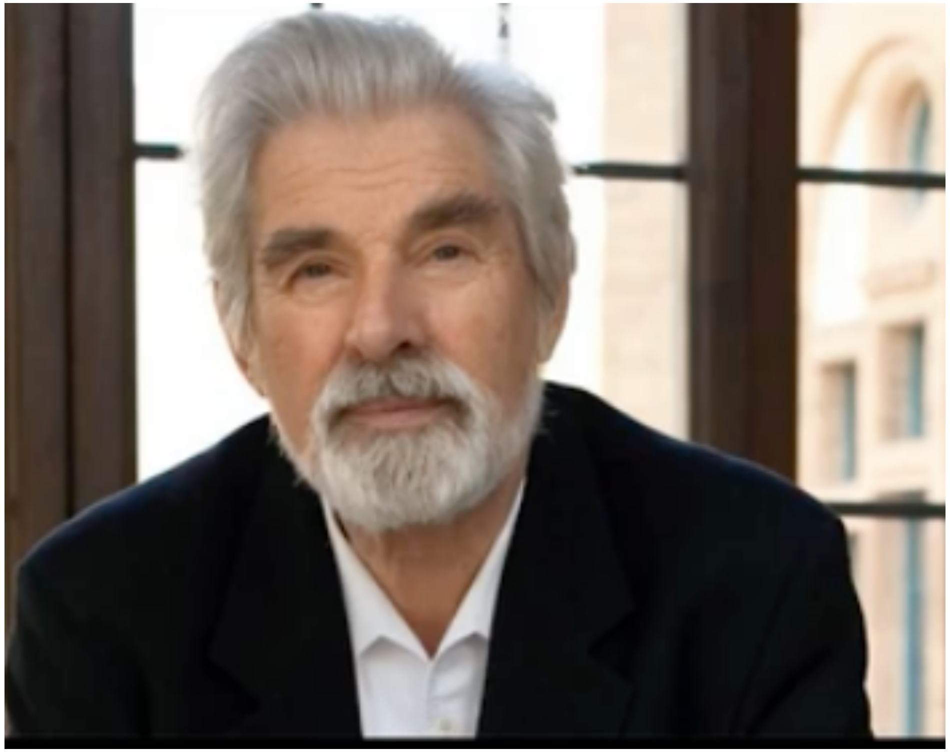
The projections shown here were made before the observations confirmed them as being correct, striking at the heart of the argument that modellers tune their models to yield the correct climate change results.




Syukuro Manabe &
Anthony J. Broccoli
BEYOND
GLOBAL
WARMING
How Numerical
Models Revealed
the Secrets of
ATLAS OF THE WORLD
The Times

Klaus Hasselman: an über-multidisciplinary scientist





"For the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming."

Hassellmann has produced excellent work on many different fields:

- Turbulence
- Ocean waves
- Seismic waves
- Remote sensing
- Stochastic forcing
- Climate Dynamics
- Climate Change, using insights from quantum and plasma physics

- Two great legacies:

The stochastic climate model

Fingerprinting

Stochastic climate models

Part I. Theory

By K. HASSELMANN, *Max-Planck-Institut für Meteorologie, Hamburg, FRG*

(Manuscript received January 19; in final form April 5, 1976)

Tellus (1977), 29, 289–305

Stochastic climate models, Part II Application to sea-surface temperature anomalies and thermocline variability

By CLAUDE FRANKIGNOUL[1] and KLAUS HASSELMANN, *Max-Planck-Institut für Meteorologie, Bundesstr. 55, 2000 Hamburg 13, FGR*

(Manuscript received December 10, 1976; in final form February 11, 1977)

Klaus Hasselmann and his colleague Frankignoul developed climate models that incorporated weather events instead of averaging over them, as had been done before.

He relied on the premise that the climate slowly evolves as an overall response to the fast random fluctuations we know as weather.

He derived a generalizable stochastic description of the ocean, in which the noise is associated with weather while the underlying trends indicate changes in climate.

In so doing, he advanced GCMs and our understanding of atmosphere-ocean interactions. We now have a a deeper appreciation for the base-line impacts of this interaction and the role the oceans play in modifying climate behaviour.

Basic idea :

The coupled ocean-atmosphere-cryosphere-land system is divided into

- **a rapidly varying "weather" component** (essentially the atmosphere)
- **a slowly responding "climate" component** (the ocean, cryosphere, land vegetation, etc.)

Traditional approach:

Average flux effects of the rapidly varying weather components are parameterised.

The resultant prognostic equations are deterministic, and **climate variability can normally arise only through variable external conditions.**

Stochastic approach:

The non-averaged "weather" components are also retained and appear formally as **random forcing** terms

The climate system acts as an integrator of these short-period fluctuations and exhibits a random-walk response.

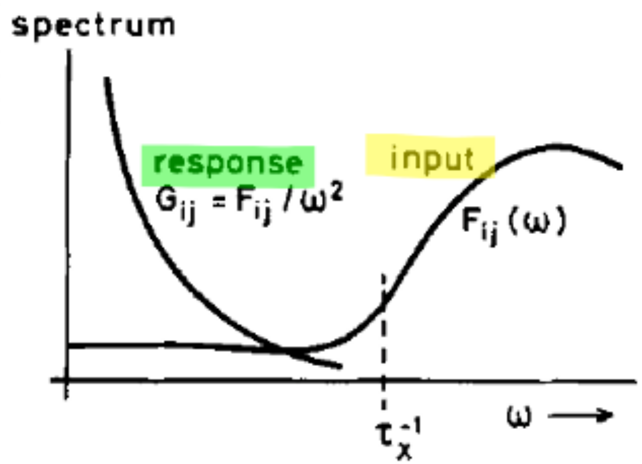
(analogy with the Brownian motion problem in which large particles interact with an ensemble of much smaller particles).

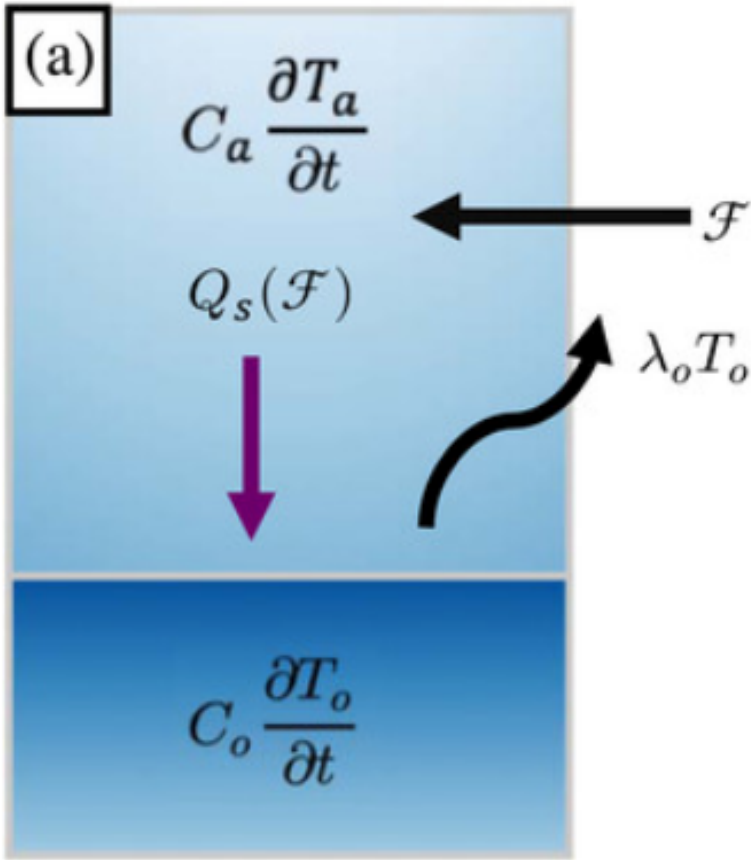
APPROACH: stochastic two-time scale climate model paradigm for climate (SST) variability

$$\tau_{atmosphere} \ll t \ll \tau_{ocean}$$

- Ocean mixed-layer temperature **anomalies are forced by high frequency random atmospheric variability** via surface energy fluxes and **decays by damping back to the atmosphere** via turbulent energy and longwave radiative fluxes, modelled as a negative linear feedback term).

$$\frac{dT}{dt} = \frac{f_1'}{h} - \lambda T$$

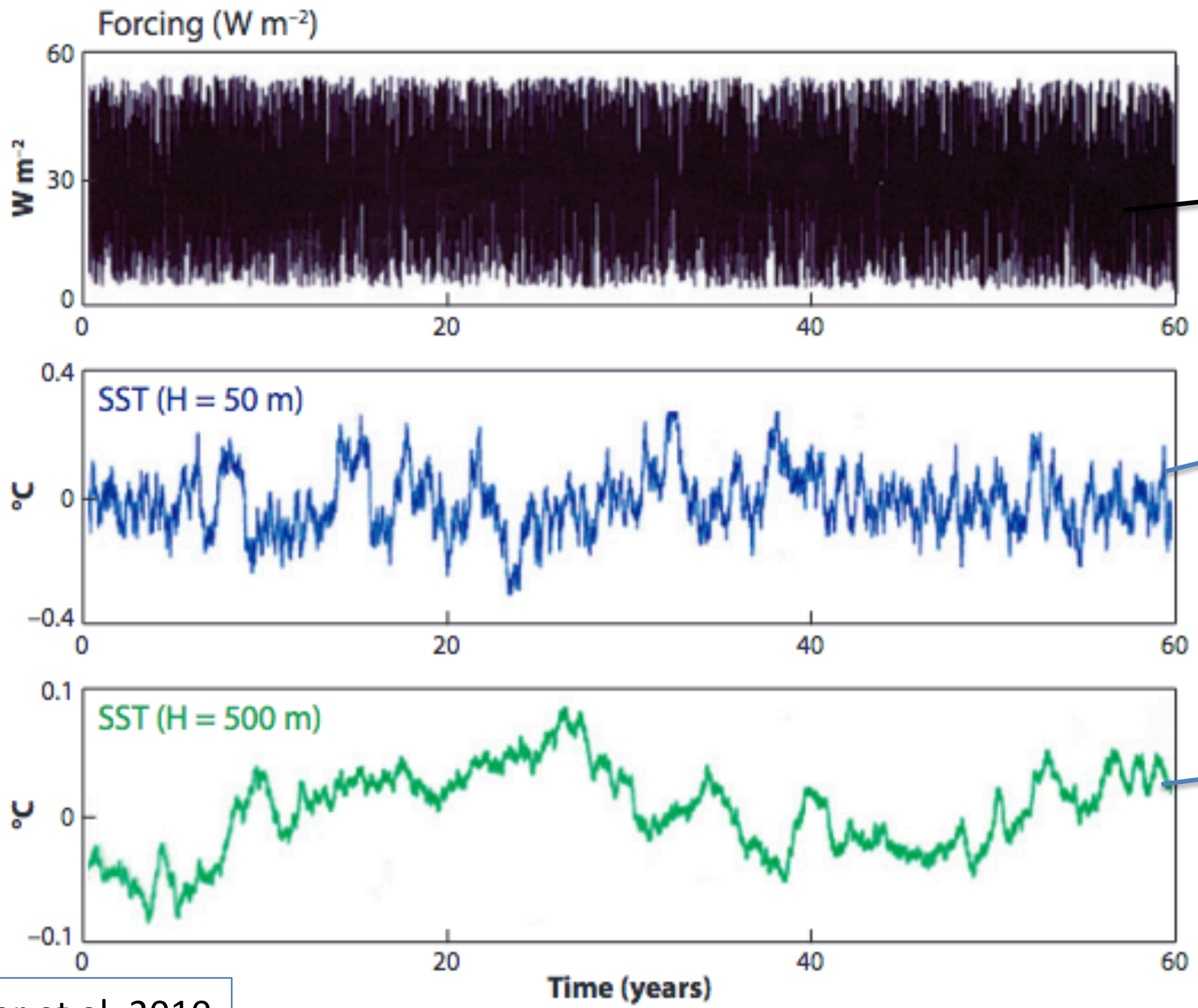




Thus, the ocean mixed layer integrates the "white noise" atmospheric forcing to yield a "red noise" SST response.

The predictability or persistence of SST anomalies is thus limited to the timescale associated with the thermal inertia of the mixed layer (depth of the mixed layer and damping time scale)

SST (mixed-layer) temperature response to random variations in surface heat flux forcing over a 60-year period for a shallow (winter North Pacific) and a deep (winter northern North Atlantic) mixed layer.



Same fast atmospheric forcing (weather)

Ocean response in a shallow mixed layer: year to year fluctuations

Ocean response in a deep mixed layer: Decade to decade fluctuations

This makes it difficult to separate the contributions of oceanic and atmospheric forcing solely on a timescale basis.

Deser et al. 2010

The white-noise spectrum of the atmospheric input produces a red response spectrum, with most of the variance concentrated in very long periods.
We need the negative feedback for the response to be stationary.

$$\frac{dT}{dt} = \frac{f_1'}{h} - \lambda T$$

SST spectra from Hasselmann´s stochastic model is a reasonable fit to observed SST spectra in the northern Pacific Ocean (a dynamically "quiet region")

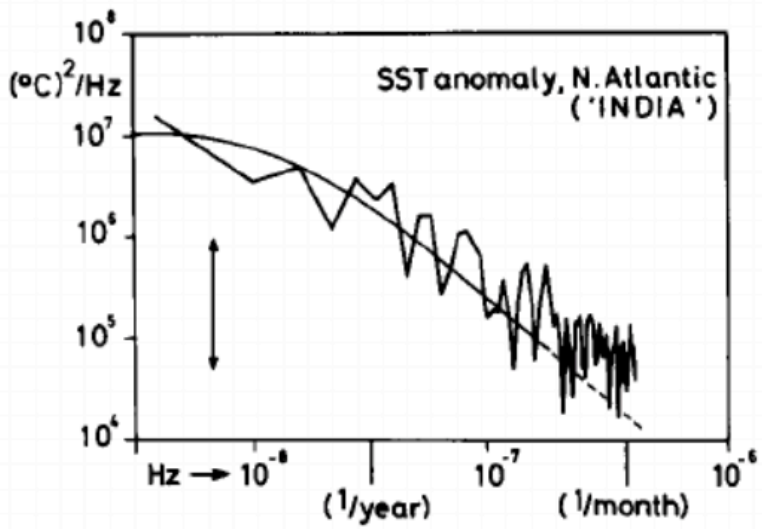


Fig. 5. Spectrum of SST anomaly at Ocean Weather Ship India for the period 1949–1964 (after Frost, 1975). The arrows indicate the 95% confidence interval. The smooth curve was calculated from relation (4.1) with $h =$ 100 m, $\lambda = (4.5 \text{ month})^{-1}$.

- **Hasselmann´s simple stochastic climate model has been widely adopted as the leading paradigm for the "null hypothesis" of SST variability in middle and high latitudes in regions where random atmospheric forcing is a good approximation and away from dynamically active regions.**

Hasselmann´s simple stochastic climate model has been widely adopted as the leading paradigm for the “**null hypothesis**” of SST variability in middle and high latitudes, in regions where random atmospheric forcing is a good approximation and away from dynamically active regions.

1979

Published: September 1997

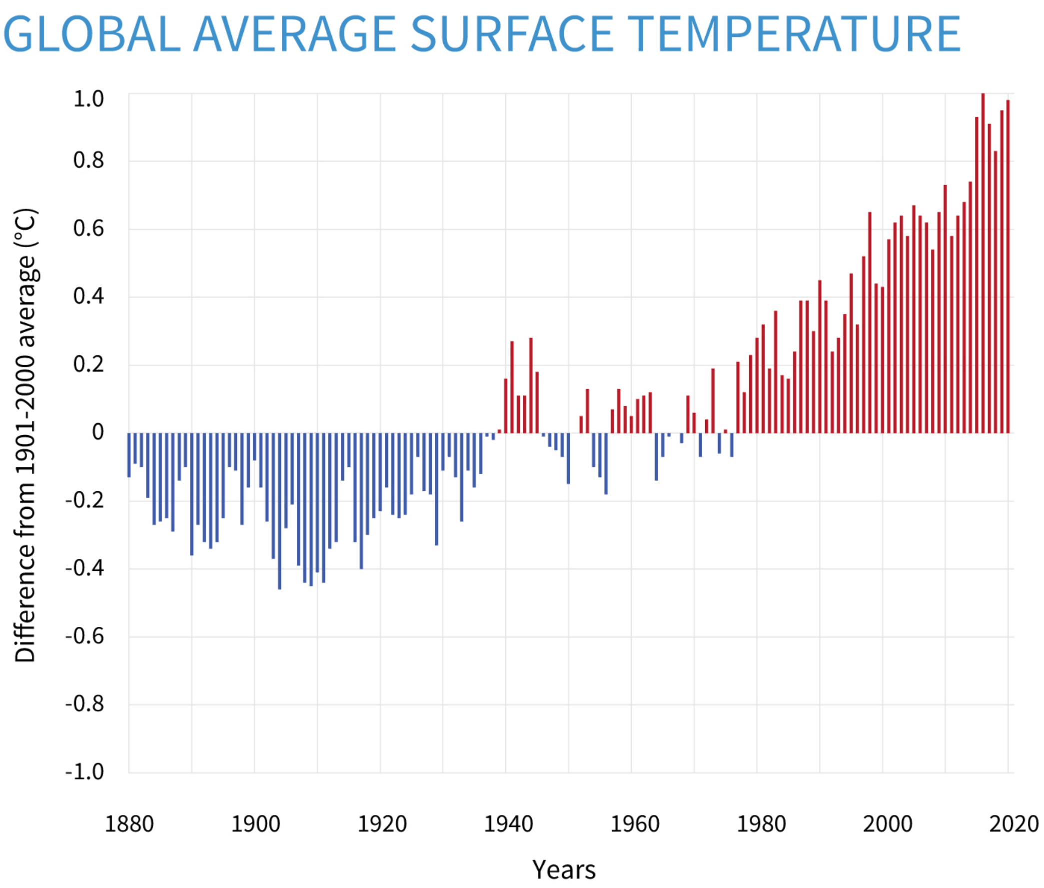
Multi-pattern fingerprint method for detection and attribution of climate change

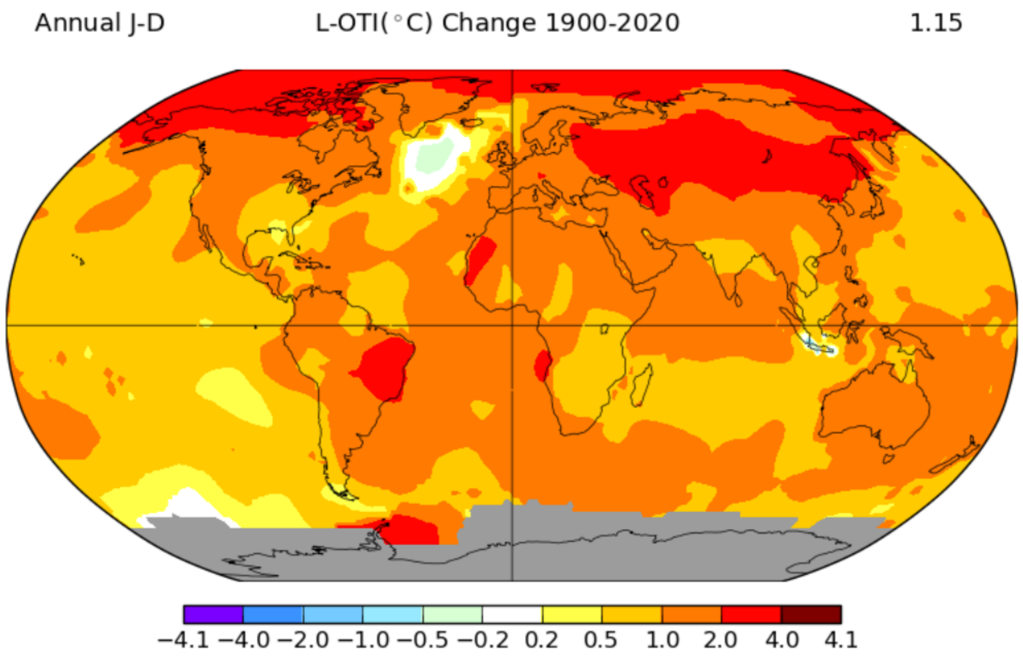
K. Hasselmann

Climate Dynamics **13**, 601–611 (1997) | Cite this article

The paper set the stage for formal methods of detection and attribution of climate change.

The problem in a nutshell:
can we attribute the observed warming to a human cause?





Source: GISS

Detection and attribution

- Detection: finding evidence in a record of observations for a contamination of the “natural variability“ by man-made signals
  → A statistical problem.

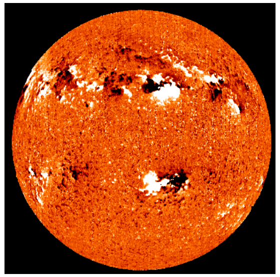
- Attribution: finding the most plausible explanation for the cause of the detected contamination
  → A plausibility argument.

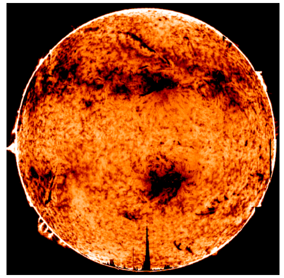
Klaus Hasselman big contribution: fingerprinting

Source: Ben Santer

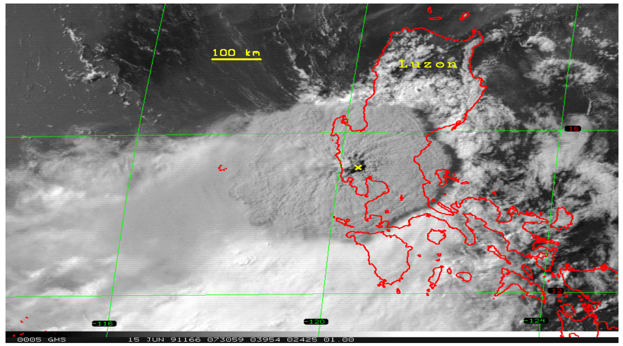
Natural mechanisms influencing climate

Changes in the Sun

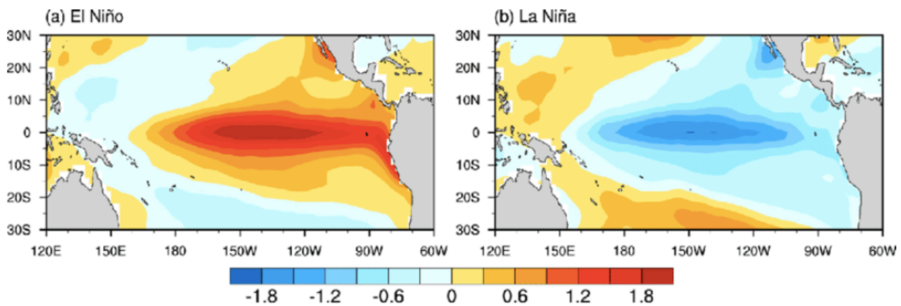




Changes in volcanic aerosols

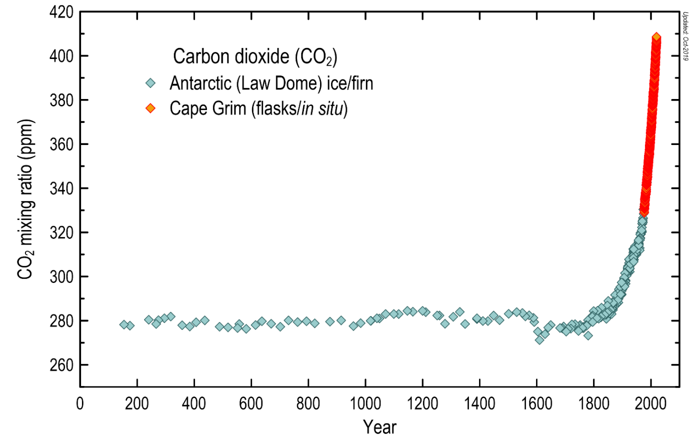


Internal variability of the coupled atmosphere-ocean system

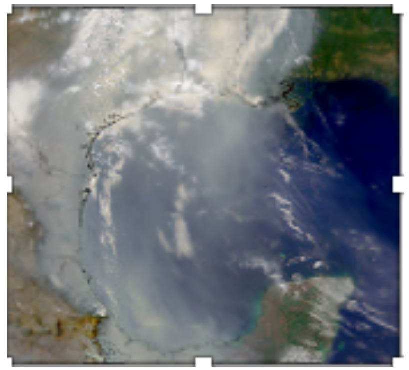


Human effects on climate

Changes in greenhouse gas concentrations

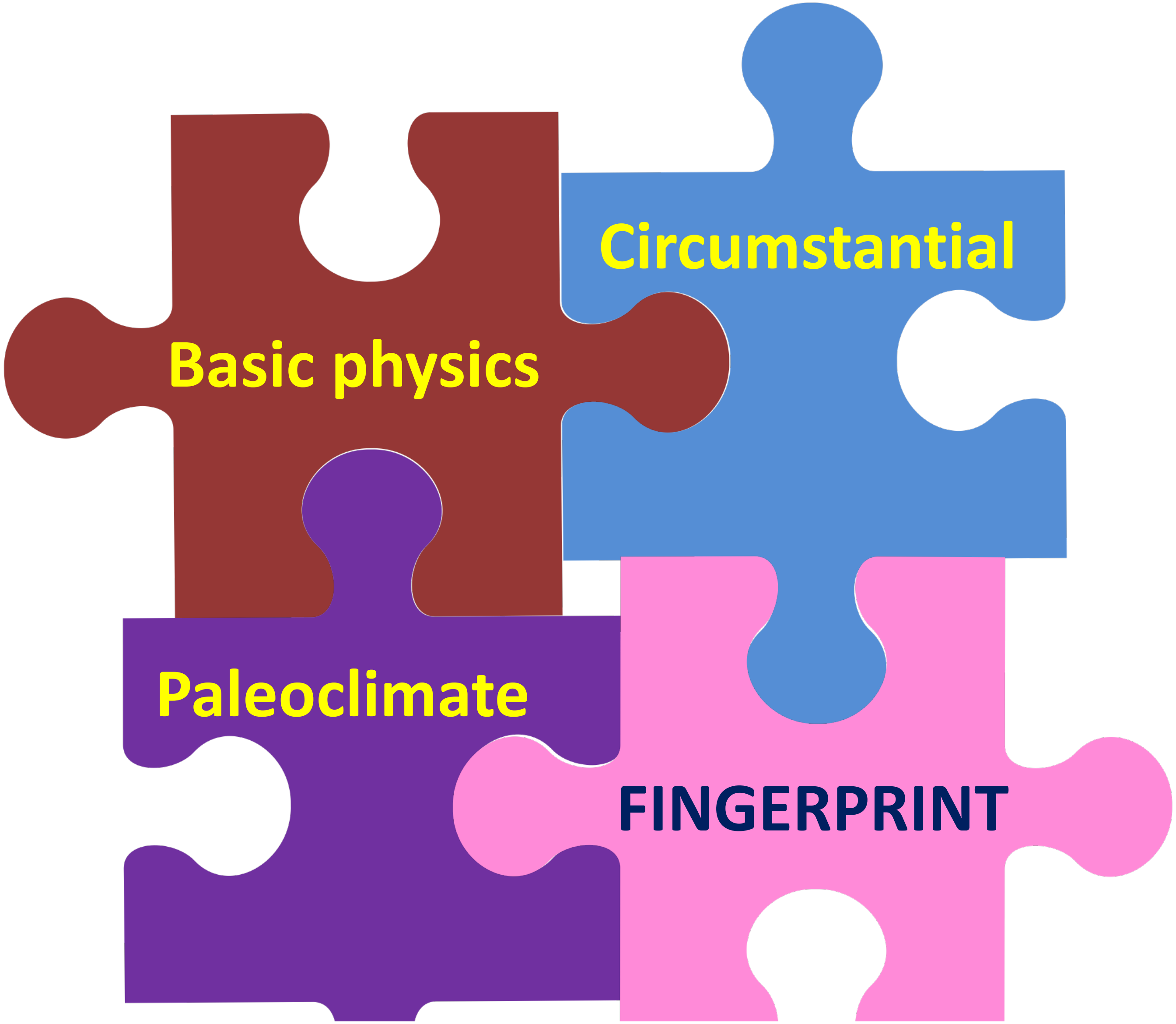


Changes in aerosol particles from fossil fuel burning and biomass burning



Changes in the reflectivity of the Earth's surface (albedo)

Multiple lines of evidence on which "discernible human influence" conclusions are based



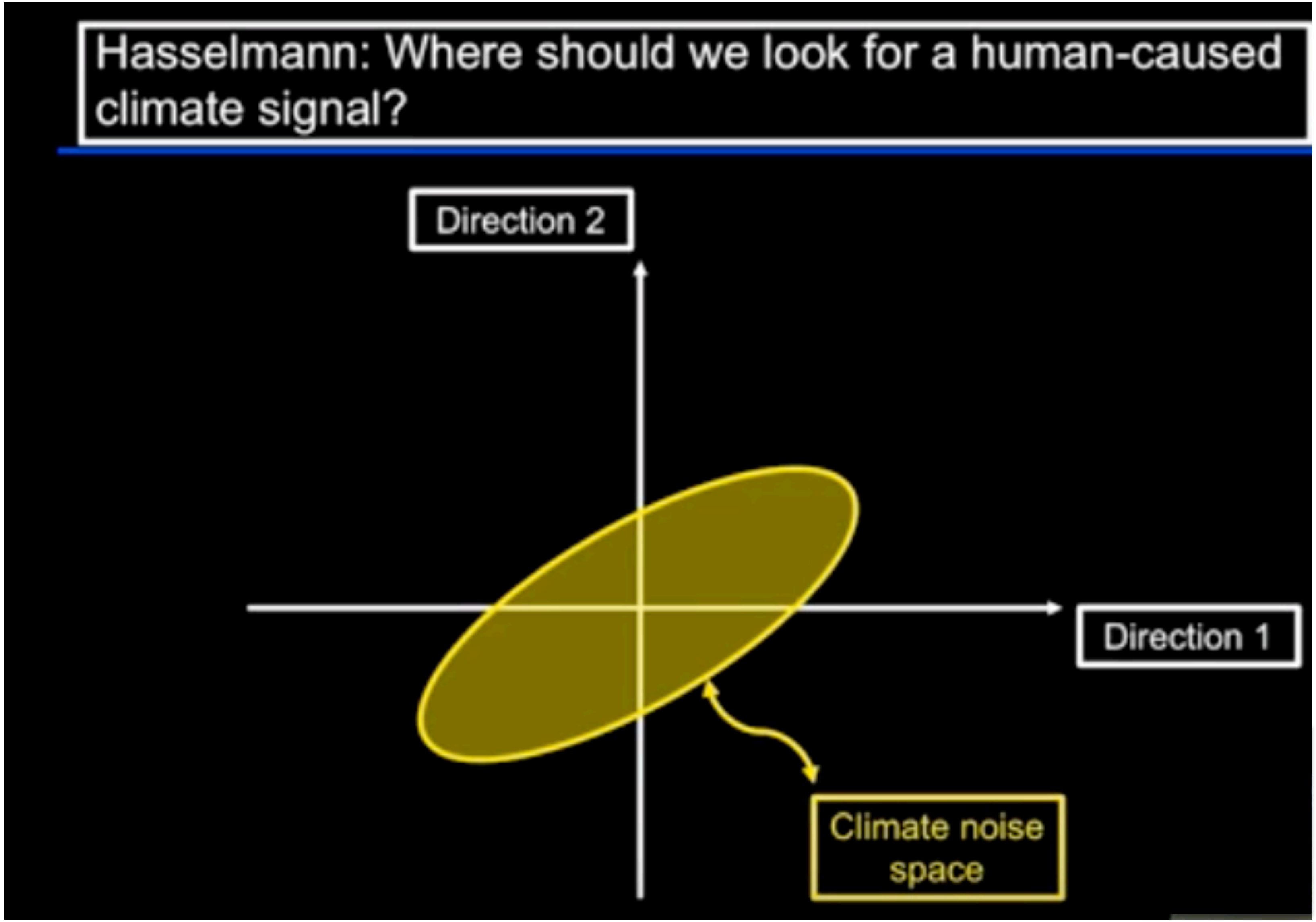
So what is fingerprinting ?

Strategy: Search for a computer model-predicted pattern of climate change (the “fingerprint”) in observed climate records

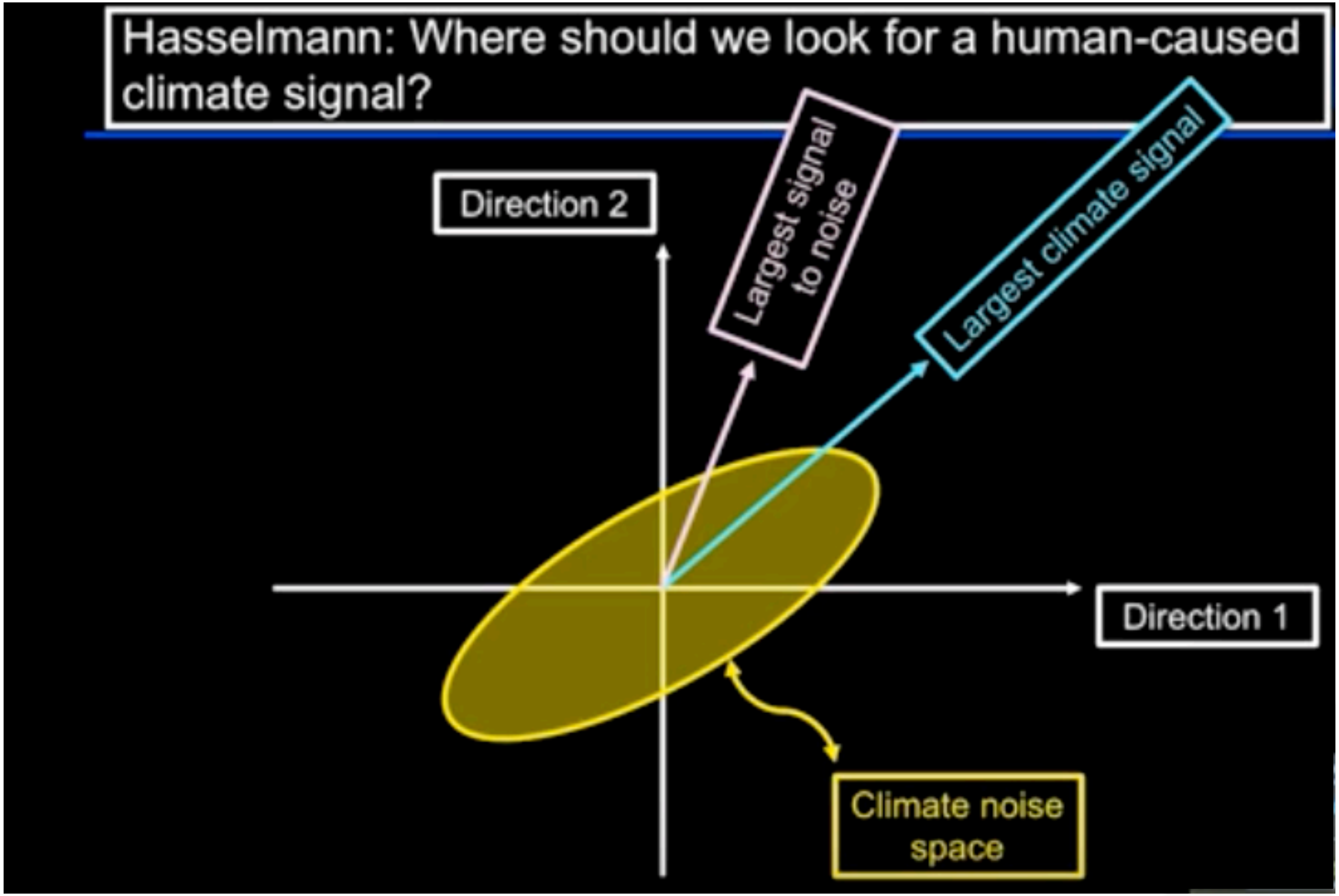
Assumption: Different influences on climate have different fingerprints

Method: Standard statistical techniques are used to estimate the level of agreement between the fingerprint and observations (and estimates of natural variations, or noise)

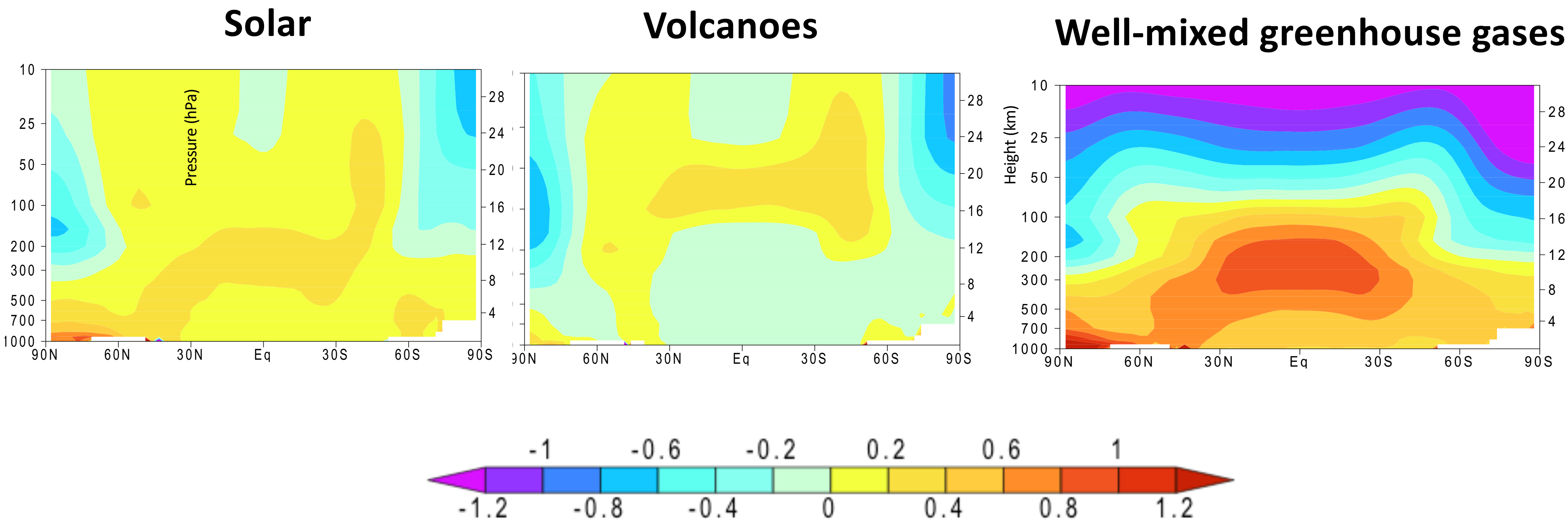
Advantage: Fingerprinting allows rigorous tests of competing hypotheses regarding the causes of recent climate change



Hasselmann: Where should we look for a human-caused climate signal?
Direction 2
Direction 1
Climate noise space

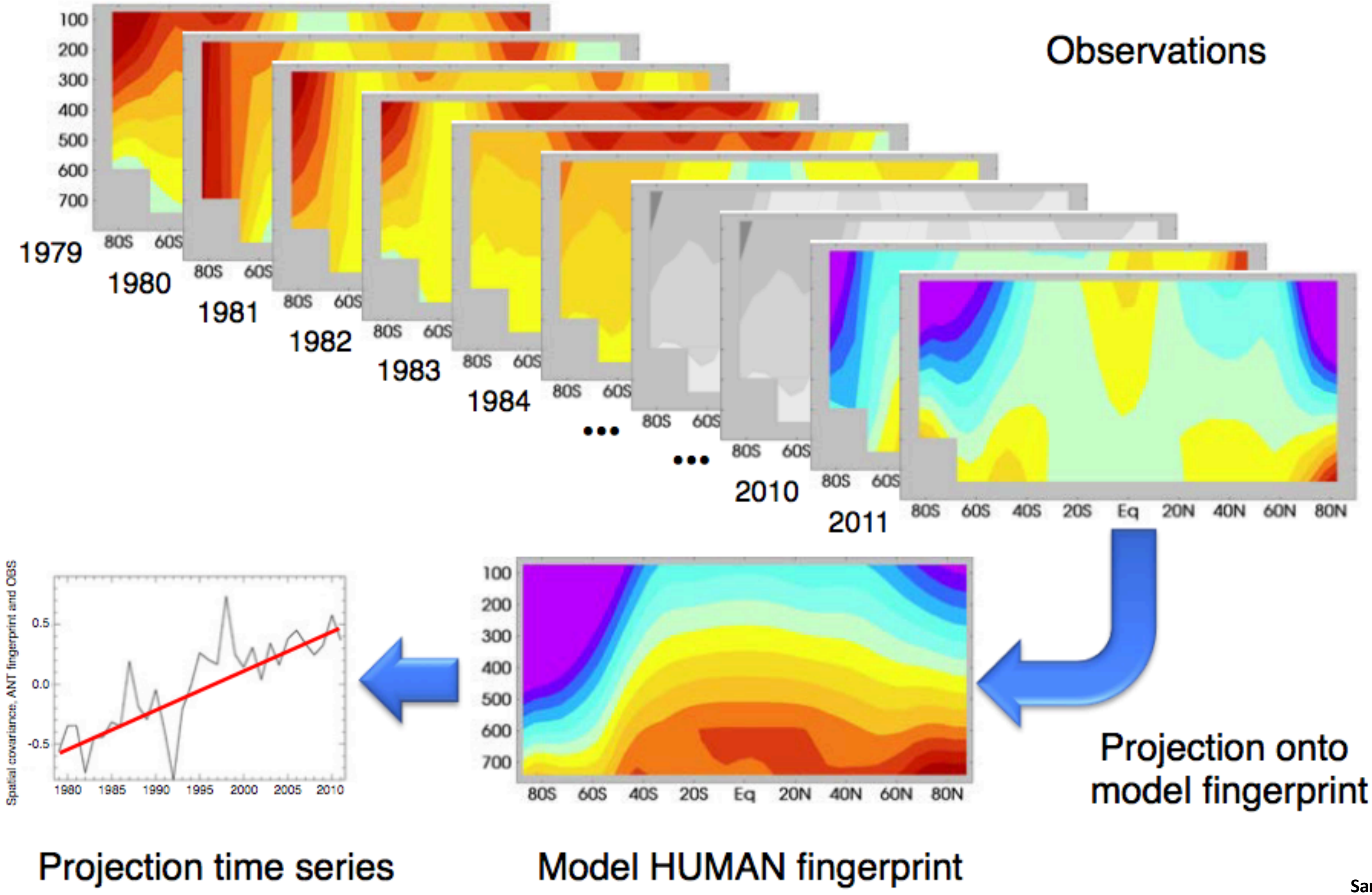

Hasselmann: Where should we look for a human-caused climate signal?
Direction 2
Largest signal to noise
Largest climate signal
Direction 1
Climate noise space

Different factors that influence climate have different "fingerprints"



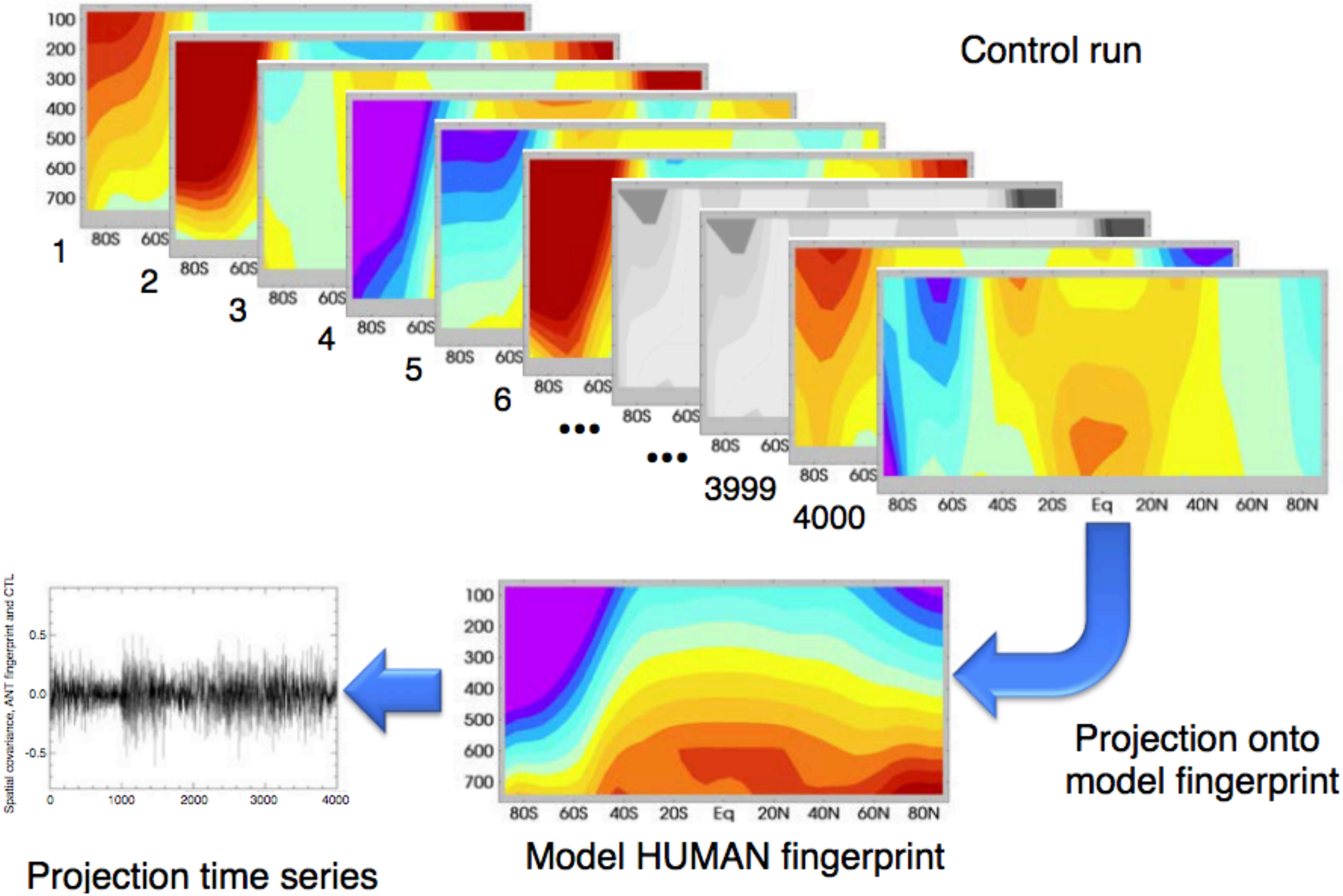
Santer *et al.*, CCSP, 2007

Fingerprint detection explained pictorially….



Santer *et al.*, CCSP, 2007

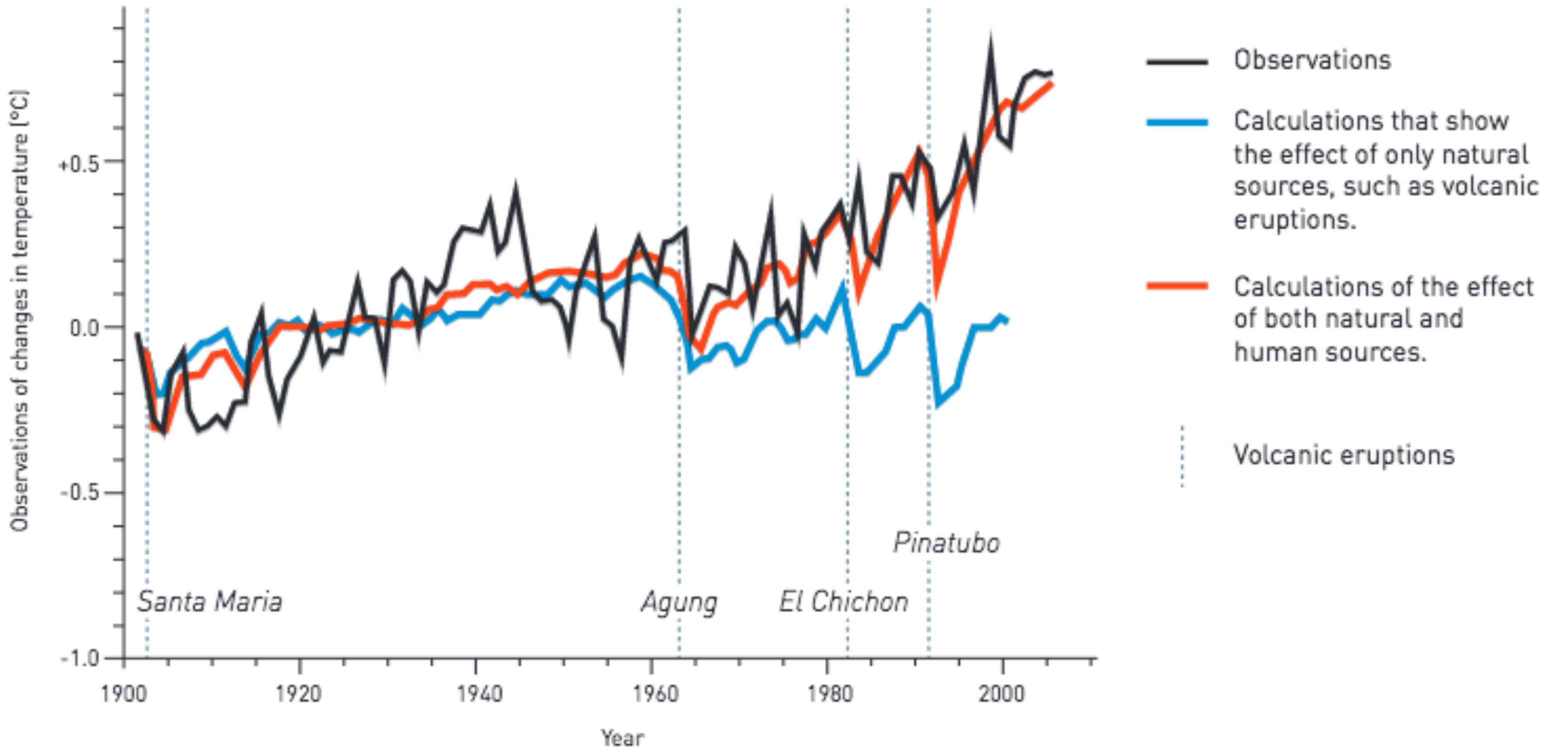
How do pattern similarity trends behave if there are no human effects on climate?



Santer *et al.*, CCSP, 2007

Identifying fingerprints in the climate

Klaus Hasselmann developed methods for distinguishing between natural and human causes (fingerprints) of atmospheric heating. Comparison between changes in the mean temperature in relation to the average for 1901–1950 (°C).



Source: Hegerl and Zweirs (2011) Use of models in detection & attribution of climate change, *WIREs Climate Change*.

CONCLUSIONS

- The climate system is telling us a physically and internally-consistent story: the planet is warming and this warming is only consistent with human-induced causes

- Many scientists at research institutions and universities around the world – and particularly **Suki Manabe and Klaus Hasselmann** – have helped to tell this story


JOEL PETT
LEXINGTON HERALD-LEADER
CLIMATE SCIENCE IS A HOAX!
YOU'RE IGNORING THE GRAVITY OF OUR SITUATION!
GRAVITY IS A HOAX!
CartoonArts International: www.nytsyn.com/cartoons