The Physics of Climate Change

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The Physics of Climate Change

- Basic principles
- Theoretical Climate Models
- The Zero-Dimensional EBM
- Applications
The Physics of Climate Change

• Basic principles
• Theoretical Climate Models
• The Zero-Dimensional EBM
• Applications
Svante Arrhenius (1896)
Performed numerical calculations that suggested that doubling the amount of carbon dioxide in the atmosphere could raise global mean surface temperatures by 5-6°C.

Joseph Fourier (1827)
Recognized that gases in the atmosphere might trap the heat received from the Sun.

James Tyndall (1859)
Careful laboratory experiments demonstrated that several gases could trap infrared radiation. The most important was simple water vapor. Also effective was carbon dioxide, although in the atmosphere the gas is only a few parts in ten thousand.

Svante Arrhenius (1896)
Performed numerical calculations that suggested that doubling the amount of carbon dioxide in the atmosphere could raise global mean surface temperatures by 5-6°C.

Guy Callendar (1939)
Argued that rising levels of carbon dioxide were responsible for measurable increases in Earth surface temperatures. Estimated that doubling the amount of CO2 in the atmosphere could raise global mean surface temperatures by 2°C.
GREENHOUSE EFFECT?
The Greenhouse Effect

Some solar radiation is reflected by the Earth and the atmosphere.

Solar radiation passes through the clear atmosphere.

Most radiation is absorbed by the Earth's surface and warms it.
Feedbacks

Initial climate forcing → Initial climate response

Response amplified by climate system

Positive feedback
Feedbacks

Initial climate forcing → Initial climate response

Response reduced by climate system

Negative feedback
Water Vapor Feedback
Ice-Albedo Feedback

Initial change

Climate warming

Increased warming

Decreased snow and ice; less reflectivity

More solar radiation absorbed at surface

Ice-Albedo Feedback
Initial Change

Climate warming

Reduced Warming

Uncertain

Increased clouds

Greater reflected radiation

Cloud Radiative Feedbacks
Doubling of atmospheric CO₂
FEEDBACKS INVOLVED IN GLOBAL WARMING

Doubling of atmospheric CO₂
FEEDBACKS INVOLVED IN GLOBAL WARMING

- Doubling of atmospheric CO₂
  - Increased CO₂ trapping of radiation in clear sky
  - Additional warming due to feedbacks

Water vapor
- Positive and negative feedbacks
- +2.5°C
  - +0.6°C Snow and ice albedo
  - ?? Clouds
  - -1.85°C

Impact of doubling CO₂: +1.25°C
OBSERVATIONS
Atmospheric Carbon Dioxide

Measured at Mauna Loa, Hawaii
Surface Temperature Changes

Graph showing Temperature Anomaly (°C) over the years from 1900 to 2020.
TALIBAN ATTACK PAKISTAN SCHOOL, RENEWING FEARS

AT LEAST 20 ARE KILLED NEW BRUTALITY BY GROUP MARGINALIZED AFTER 2014 MASSACRE

This article is by Deeksha Seth, Correspondence to The New York Times.

CAIRO—Attacks on education have long been a signature tactic of the Pakistan Taliban, whose militants have set schools on fire, burned girls from classrooms and gunned down students and teachers at their desks in a quest to impose an extremist ideology on Pakistani society.

The height of the attacks seemed to come in December 2014 when gunmen swarmed through a school in Peshawar, massacring dozens of schoolchildren in an assault that propagated widespread repression and a fierce military crackdown on militants.

But on Wednesday, Pakistanis were drawn back into their national nightmare. At least four Taliban attackers stormed a university campus in another northwestern town, gunning down at least 28 people, most of them students and teachers.

After a year in which the Pakistani Taliban had finally seemed to be on the run, the assault was a stark reminder of the group's continued threat.

2015 Far Eclipsed 2014 As World’s Hottest Year, Climate Scientists Say

A System ‘Warming Up, Relentlessly’ — Greenhouse Gases Are Blamed

BY JUSTIN GILLES

Scientists reported Wednesday that 2015 was the hottest year in the historical record for breaking the mark set only a year before—a burst of heat that has continued into this summer and is rolling weather patterns all over the world.

In the contiguous United States, the year was the second-warmest on record, punctuated by a December that was both the hottest and the wettest since record-keeping began. One result has been a wave of unusual winter floods coursing down the Mississippi River watershed.

Scientists started predicting a global warming trend months ago, in part because an El Nino weather pattern, one of the largest in years, will be releasing an immense amount of heat from the Pacific Ocean into the atmosphere. But the bulk of the record-setting heat, they say, is a consequence of the long-term planetary warming caused by human emissions of greenhouse gases.

“The whole system is warming up, relentlessly,” said Gerald Meehl, a scientist at the National Center for Atmospheric Research in Boulder, Colo.

A flag-hacking same-sex marriage, at the Supreme Court.

Crises in Two Cities Test Michigan’s Governor

Dire Conditions in Public Schools Threaten Detroit’s Recovery

As Water Problems Grew, Officials Belittled Complaints From Flint

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Surface Temperature Changes
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Climate Models

- Atmosphere is divided into 3-D grid boxes, each with its own local climate.
- Air in grid boxes interacts horizontally and vertically with other boxes.
- Influence of vegetation and terrain is included.
- Water in oceanic grid boxes interacts horizontally and vertically with other boxes.
- Oceanic grid boxes model currents, temperature, and salinity.

- 48% of solar radiation is absorbed by land and sea.
- 3% is reflected by clouds.
- 8% is absorbed by Earth's surface.
- 20% is absorbed by clouds.
- 19% is absorbed by water vapor.
General Circulation Models (GCMs) take into account the full three-dimensional structure of the atmosphere & ocean.
Hansen’s 1988 Predictions

Annual Mean Global Temperature Change (°C)

Model Simulation of Past

Model Predictions of Future (in 1988)

OBSERVED WEATHER STATION DATA

SCENARIO A

SCENARIO B

SCENARIO C
Hansen’s 1988 Predictions

Annual Mean Global Temperature Change (°C)

Model Simulation of Past

Model Predictions of Future (in 1988)

SCENARIO B

OBSERVED WEATHER STATION DATA
Projected Future Warming
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Theoretical Climate Models

The Zero-Dimensional EBM

Applications

Basic principles

The Physics of Climate Change

These mangoes exist in a reality that theoretical physicists have yet to fully comprehend. pic.twitter.com/YdQiEhnsbu
\[ \alpha = 0.3 \]
\[ S = 1370 \text{ W/m}^2 \]
\[ T_e = 255K! \]

\[ \sigma T_e^4 = (1 - \alpha)S/4 \]
(1- $\alpha$)S/4 = $\lambda$A + (1-$\lambda$)G

(1-$\lambda$/2)$\sigma T_s^4$ = (1- $\alpha$)S/4

G = (1-$\alpha$)S/[4(1-$\lambda$/2)]

ZERO-DIMENSIONAL EBM

\[ \sigma T_e^4 = (1 - \alpha)S/4 \]

\[ \lambda = 0.77 \]

\[ T_e = 288K! \]
ZERO-DIMENSIONAL EBM

(Equilibrium) \( (1-\lambda/2)\sigma T_s^4 = (1- \alpha)S/4 \)

What about non-equilibrium?

\[ CdT_s/dt = (1- \alpha)S/4 - (1-\lambda/2)\sigma T_s^4 \]

Account for stochastic weather forcing,

\[ CdT_s/dt = (1- \alpha)S/4 - (1-\lambda/2)\sigma T_s^4 + w(t) \]

linearize the quartic term, \( \sigma T_s^4 = a+bT \)

\[ CdT/dt = F - BT + w(t) \]

\( F \equiv (1- \alpha)S/4 - a(1-\lambda/2) \)

\( B \equiv (1-\lambda/2)b \)
ZERO-DIMENSIONAL EBM

Take:

\[ C = 2.08 \times 10^8 \text{ J K}^{-1}\text{m}^{-2} \] (effective heat capacity associated with 70 m depth mixed-layer ocean covering 70% of Earth surface.

In equilibrium, we have:

\[ \Delta F = B \Delta T \]

\[ \Delta T / \Delta F = 1 / B \]

\[ \Delta F_{2xCO_2} = 3.74 \text{ Wm}^{-2} \]

Equilibrium climate sensitivity (ECS) \( \Delta T_{2xCO_2} \)

For \( B = 1.25 \text{ Wm}^{-2}\text{K}^{-1} \), \( \Delta T_{2xCO_2} = 3.0^\circ \text{C} \)

\[ CdT/dt = F - BT + w(t) \]

\[ F \equiv (1 - \alpha)S/4 - a(1 - \lambda/2) \]

\[ B \equiv (1 - \lambda/2)b \]
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False Hope

The rate of global temperature rise may have hit a plateau, but a climate crisis still looms in the near future

By Michael E. Mann

“Temperatures have been flat for 15 years,” Wall Street Journal says. “Global warming, Arctic sea ice has already started to recede claims about climate change in the air.”

Global warming continues unabated. The misunderstanding stems from data showing that during the past decade there was a slowing in the rate at which the earth’s average surface temperature had been increasing. The event is commonly referred to as “the plateau,” but that is a misnomer: temperatures still rose, just not as fast as during the prior decade. The important question is, what does the short-term slowdown portend for how the world may warm in the future?

The Intergovernmental Panel on Climate Change (IPCC) is charged with answering such questions. In response to the data, the IPCC’s September 2013 report lowered the ease of its prediction for future warming. Its forecasts, released every few years, drive climate policy worldwide, so even the small change raised debate over how fast the planet is warming and how much time we have to stop it. The IPCC has not yet weighed in on the impacts of the warming or how to mitigate it.

Level of additional risk due to climate change

Undetectable  Moderate  High  Very high

Danger Zone in 22 Years

If the Northern Hemisphere’s surface temperatures rise more than two degrees Celsius above preindustrial levels (baseline), human civilization will suffer dangerous harm, scientists say. When will that occur if the world keeps burning fossil fuels at current rates? The answer comes from estimating greenhouse gas emissions or other sources of climate forcing (e.g., reduced energy use, increased use of carbon sequestration technologies), then projecting how much increase in temperature that adds up to over the next 50 years. The estimate that best agrees with recorded data reflecting the sensitivity of the earth’s climate is 1.5°C. The estimated warming is an average of 0.8°C to 1.1°C. The warming is greater in the northern hemisphere, a discrepancy that can be explained by the way the atmosphere’s temperature is measured. The warming is a “danger zone” because rising temperatures are expected to increase the frequency and severity of extreme weather events, causing mass displacement of people, and impacts on food and water availability.
\[ \frac{CdT}{dt} = F - BT \]

\[ F \equiv (1-\alpha)S/4 - a(1-\lambda/2) \]

\[ B \equiv (1-\lambda/2)b \]
\[ \frac{CdT}{dt} = F - BT \]

\[ F \equiv (1 - \alpha)S/4 - a(1-\lambda/2) \]

\[ B \equiv (1-\lambda/2)b \]
Refining ECS estimates with paleodata


*Climate Sensitivity underestimated?*
D'Arrigo et al. tree-ring based NH reconstruction (blue) along with the climate model (NCAR CSM 1.4) simulated NH mean temperatures (red) and the “simulated tree-ring” NH temperature series based on driving the biological growth model with the climate model simulated temperatures (green). The two insets focus on the response to the AD 1258 and AD 1809+1815 volcanic eruption sequences.
Refining ECS estimates with paleodata

PDF of ECS using decadally smoothed data between AD 1300–1849 (red = simulated actual temperature series; green = synthetic tree ring temperature series). Shown by dashed vertical lines are mean of the ESC distribution for simulated temperature series (red), mean of ECS distribution for synthetic tree ring temperature series (green), ECS estimate using MFR12 simulated tree ring temperature series where chronological error accumulation due to inferred missing rings is taken into account (cyan), and sensitivity estimate for D06 tree ring temperature reconstruction (blue). True value of ESC is 3.0 in both cases.
Climate Signal Detection

Observe and simulated multidecadal variability in the Northern Hemisphere

The “AMO”
Climate Signal Detection

![Graph showing temperature anomaly over time](Image)

**Geophysical Research Letters**

FRONTIER ARTICLE

On forced temperature changes, internal variability, and the AMO

Key Points:
- Certain common procedures fail to isolate internal variability in climate
- AMO appears to have been in a cool phase in recent decades
- 'Stadium wave' patterns are likely an artifact of flawed assessment procedures

Michael E. Mann', Byron A. Steinman', and Sonya K. Miller'
CMIP5-All ensemble mean of Northern Hemisphere SST+SAT, North Atlantic SST, and North Pacific SST (black curves) shown with individual model means (colored curves). Thin black line depicts the 95% confidence limits of the model mean determined via bootstrap resampling. Blue line depicts observed temperatures.
Climate Signal Detection

(A-C) CMIP5-all mean (black lines) and 24 individual realizations (colored lines) of AMO, PMO and NMO determined using target region regression. Predicted 1 sigma limits for mean series are shown by two horizontal dashed lines. (D-F) Mean (solid lines) and 1 sigma limits determined using detrending (blue) global SST regression (red) target region regression (black), target region differencing (green), and rescaled target region differencing (purple).

Atlantic and Pacific multidecadal oscillations and Northern Hemisphere temperatures
Byron A. Steinman, Michael E. Mann, Sonya K. Miller
Climate Signal Detection

Semi-empirical estimate of AMO (blue), PMO (green), and NMO (black) based on target region regression using (A) CMIP5-GISS, (B) CMIP5-AIE, and (C) CMIP-All historical climate model realizations. Bivariate regression-based approximation of NMO (red) strongly correlates (R²=0.86/0.88/0.91 for CMIP5-All/CMIP5-GISS, CMIP5-AIE, respectively) with semi-empirical NMO estimate (black). 95% confidence limits of the AMO, PMO, and NMO CMIP5-All means (determined using bootstrap resampling) are shown as colored shading.
Humans ARE to blame for record temperatures: Global warming caused by greenhouse gas emissions has led to 13 of the world's hottest years, study claims

- Scientists said it is 'extremely likely' humans caused soaring temperatures
- 13 of the 15 warmest years on record have occurred since the millennium
- Researchers say the odds of this happening naturally are one in 170,000
- It comes just days after data revealed 2015 was the hottest year on record

New calculations shows there is just a 0.01% chance that recent run of global heat records could have happened due to natural climate variations

recent record temperature years 'extremely unlikely' without global warming, scientists say
The Likelihood of Recent Record Warmth

Michael E. Mann¹, Stefan Rahmstorf², Byron A. Steinman³, Martin Tingley⁴ & Sonya K. Miller⁵

2014 was nominally the warmest year on record for both the globe and northern hemisphere based on historical records spanning the past one and a half centuries⁶,⁷. It was the latest in a recent run of record temperatures spanning the past decade and a half. Press accounts reported odds as low as one-in-650 million that the observed run of global temperature records would be expected to occur in the absence of human-caused global warming. Press reports notwithstanding, the question of how likely observed temperature records may have been both with and without human influence is interesting in its own right. Here we attempt to address that question using a semi-empirical approach that combines the latest CMIP5 climate model simulations with observations of global and hemispheric mean temperature. We find that individual record years and the observed runs of record-setting temperatures were extremely unlikely to have occurred in the absence of human-caused climate change, though not nearly as unlikely as press reports have suggested. These same record temperatures were, by contrast, quite likely to have occurred in the presence of anthropogenic climate forcing.
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Conclusions

• The 0d EBM is useful for exploring a broad range of climate change issues.

• Uncertainty in ECS unlikely to buy significant time in avoiding 2C warming under business-as-usual carbon emissions.

• Very low-end sensitivity (~2.0C) in some paleoclimate studies likely an artifact of biases in estimated volcanic cooling.

• Recent temperature records very unlikely to have happened in absence of human-caused climate change.