



Climate Change Science: what do we know?

Gerald Lehmacher

Department of Physics and Astronomy

15 March 2018



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Quote

It was a revelation, a liberation. Physicists, mathematicians, astronomers, logicians, biologists, all were here at the University, and they came to him or he went to them, and they talked, and new worlds were born of their talking. It is of the nature of idea to be communicated: written, spoken, done. The idea is like grass. It craves light, likes crowds, thrives on crossbreeding, grows better for being stepped on.

Ursula Le Guin (1929–2018), in: *The Dispossessed*, 1974



Climate Poll – 1 of 3

Do you think global warming is happening?

- A. Yes
- B. No
- C. Don't know



<http://climatecommunication.yale.edu>



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Climate Poll – 2 of 3

Assuming global warming is happening, do you think it is...

- A. Caused mostly by human activities
- B. Caused mostly by natural changes in the environment
- C. Other
- D. None of the above because global warming isn't happening



Climate Poll – 3 of 3

**To the best of your knowledge,
what percentage of climate scientists think
that human-caused global warming is happening?**

- A. 90-100 %
- B. 70-90 %
- C. 50-70%
- D. Less than 50%
- E. Don't know



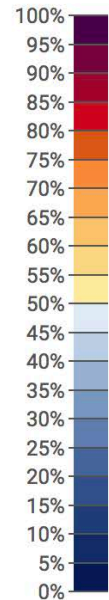
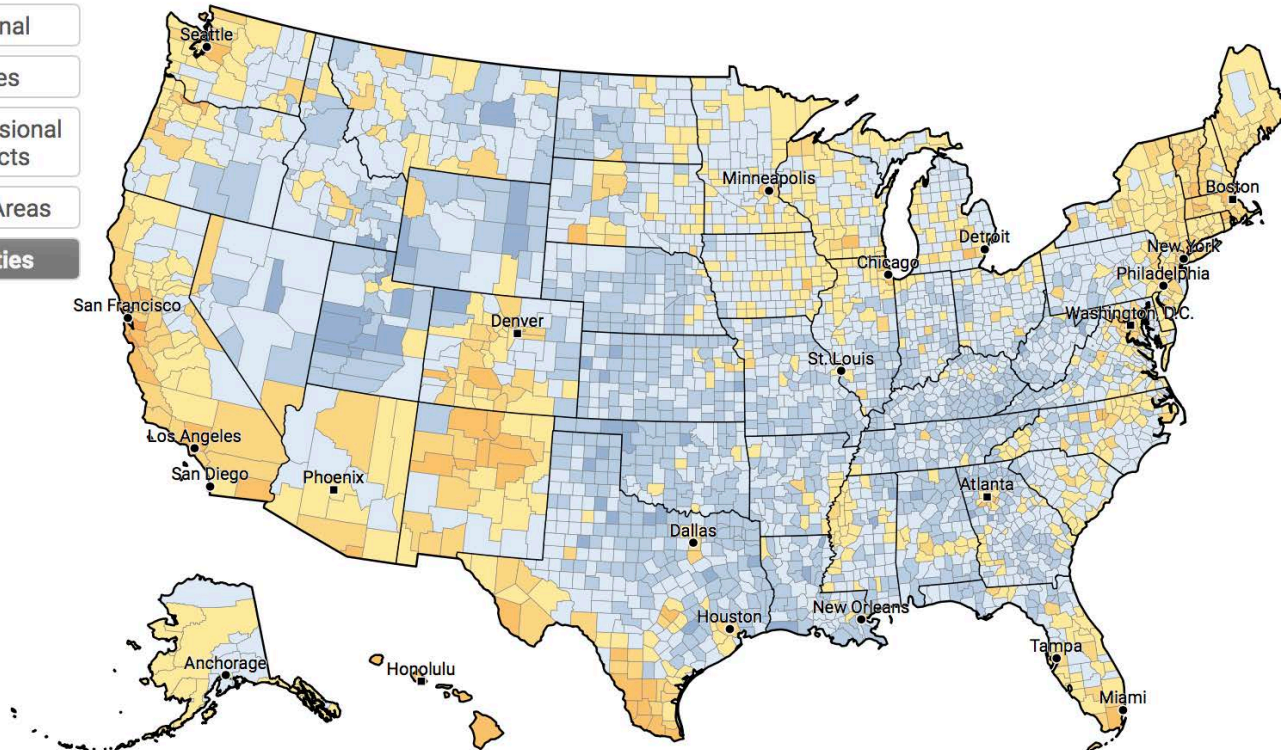
Estimated % of adults who think global warming is mostly caused by human activities, 2016

Display model output:

[Permalink](#)

Click on map to select geography, or:

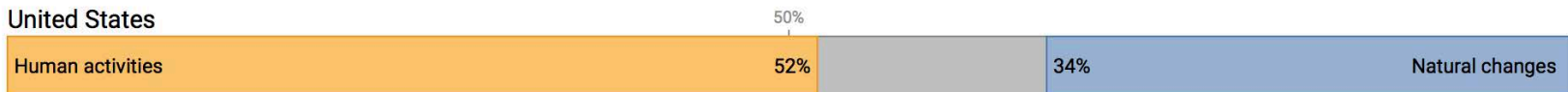
- National
- States
- Congressional Districts
- Metro Areas
- Counties**




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8
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United States

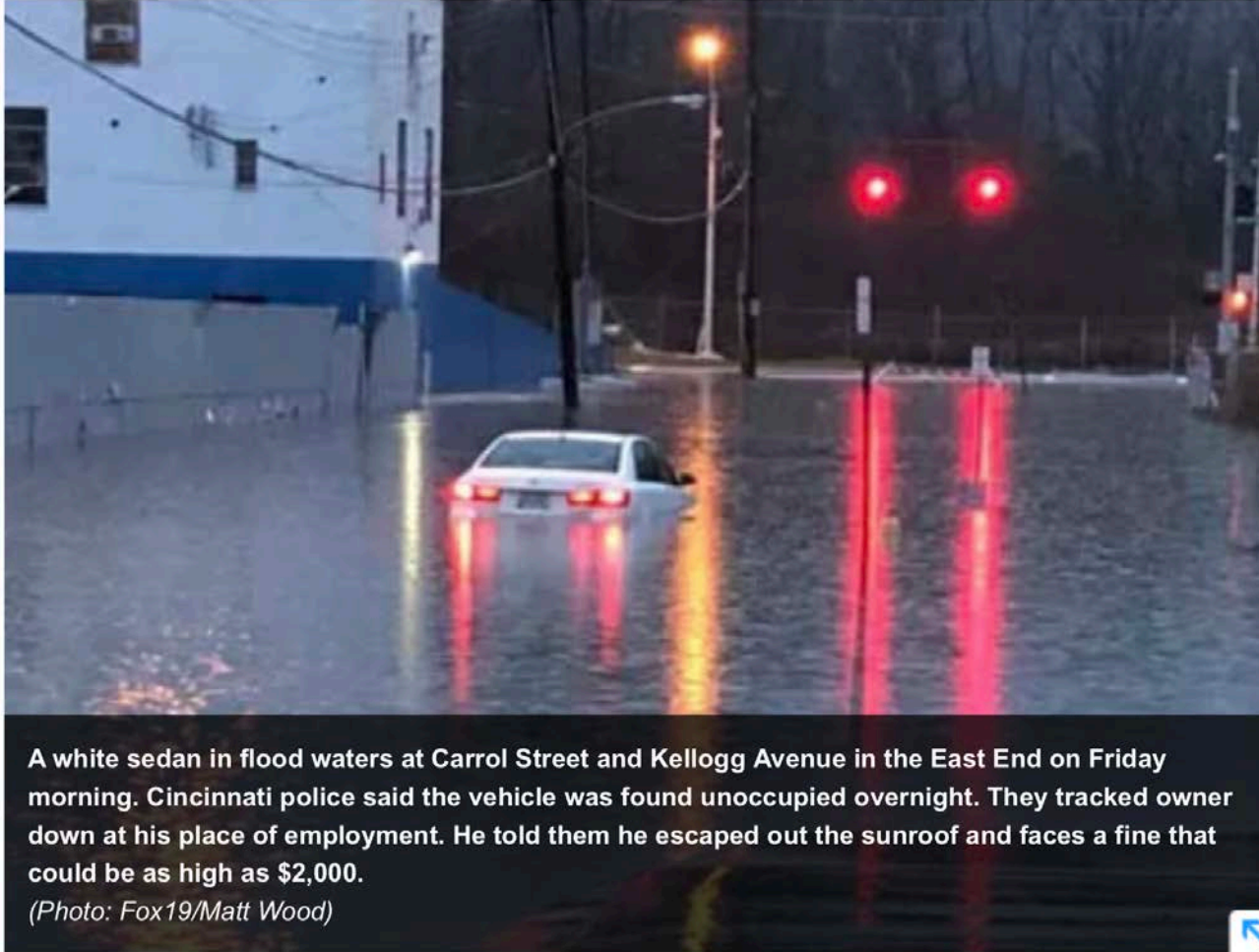




Is it just the weather,
is it the climate,
or is it climate change?



Is it weather, climate, or climate change?



A white sedan in flood waters at Carrol Street and Kellogg Avenue in the East End on Friday morning. Cincinnati police said the vehicle was found unoccupied overnight. They tracked owner down at his place of employment. He told them he escaped out the sunroof and faces a fine that could be as high as \$2,000.

(Photo: Fox19/Matt Wood)

Flash floods and
tornadoes in South
and Midwest, Feb 24,
2018



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Is it weather, climate, or climate change?

10 cm snow in Rome on
February 26, 2018.
Photo: AP



Is it weather, climate, or climate change?



Multi-year drought in
South Africa declared
National Disaster, 13
March 2018

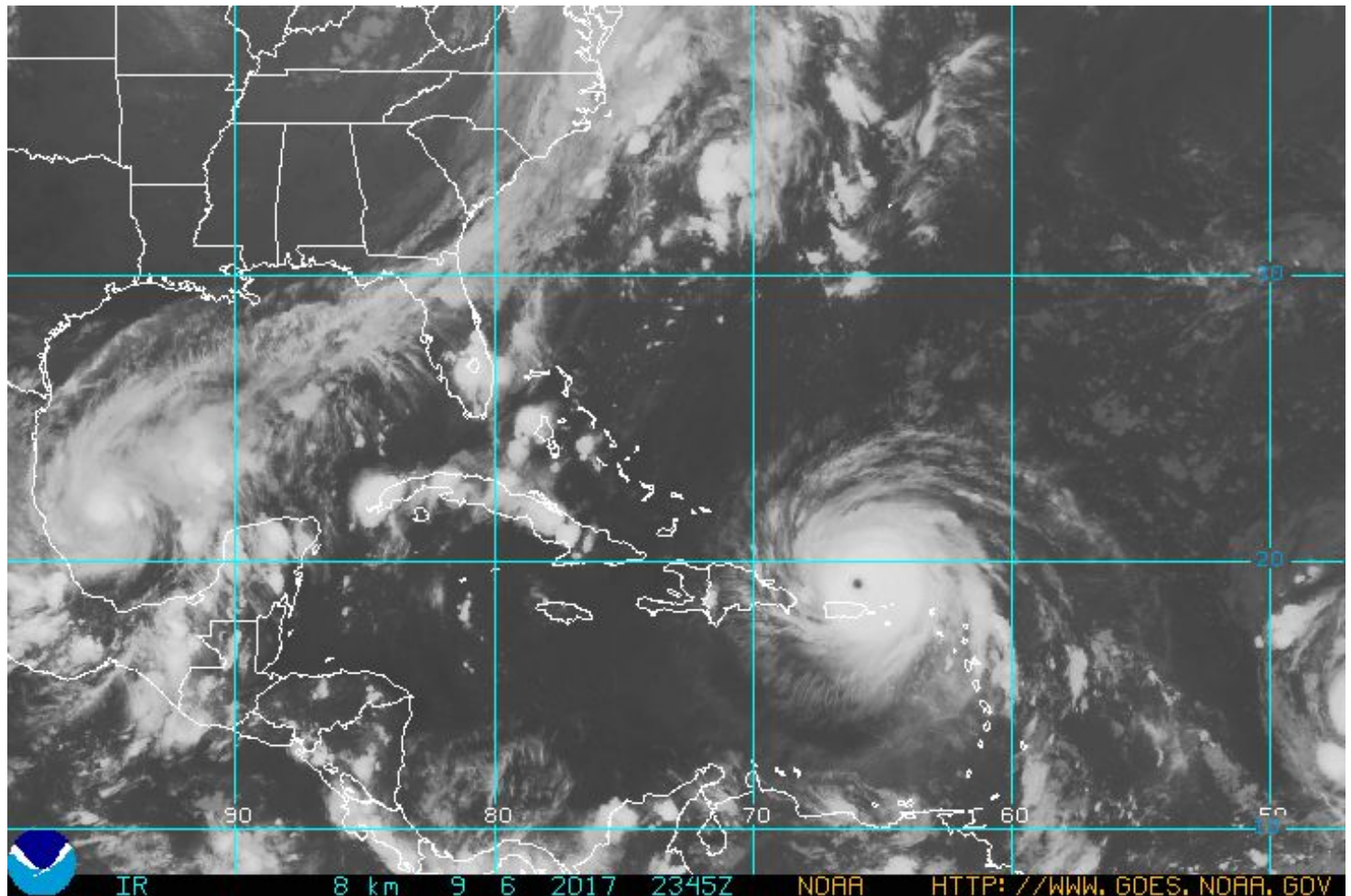
FILE PHOTO: Sand blows across a normally submerged area at Theewaterskloof dam near Cape Town, South Africa, January 20, 2018. REUTERS/Mike Hutchings/File Photo



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Is it weather, climate, or climate change?

Seventeen
named
storms, six
major
hurricanes in
Atlantic
season 2017



In one photo:
Irma, Jose, Katia

Is it weather, climate, or climate change?



Thermokarst, thaw ponds in N. Quebec,
<http://www.bethanydeshpande.com/wp/>



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Selected Significant Climate Anomalies and Events January 2018

GLOBAL AVERAGE TEMPERATURE

January 2018 average global land and ocean temperature was the fifth highest for January since records began in 1880.

ARCTIC SEA ICE EXTENT

January 2018 sea ice extent was 9.4 percent below the 1981–2010 average—the smallest January sea ice extent since satellite records began in 1979.

ASIA

Near- to -cooler-than-average conditions were observed across central Asia. The most notable cool temperature departures were -3.0°C (-5.4°C) or lower. Meanwhile, warmer-than-average conditions were present across northern Russia and southern Asia. As a whole, January 2018 tied with 1997 as the 26th warmest January in the 109-year record.

CONTIGUOUS UNITED STATES

Warmer-than-average conditions plagued much of the western half of the contiguous U.S., while the eastern half had near- to cooler-than-average conditions. Nine states across the West had a top 10 warm January.

EUROPE

Warmer- and wetter-than-average conditions affected much of Europe during January 2018. This was the second warmest January, behind 2007, since continental records began in 1910. Austria and France had their wettest January since 1982 and 1959, respectively.

SOUTH AMERICA

As a whole, South America had its 14th warmest January on record. January 2018 temperature departure from average was the lowest since 2011.

AUSTRALIA

Australia had its third highest January temperature since national records began in 1910. Regionally, Queensland, New South Wales, Victoria, Tasmania, and South Australia had a top eight warm January.

NEW ZEALAND

January 2018 was the warmest month for any month on record and the warmest January since national records began in 1909.

ANTARCTIC SEA ICE EXTENT

January 2018 sea ice extent was 17.4 percent below the 1981–2010 average—the second smallest January sea ice extent on record, behind 2017.

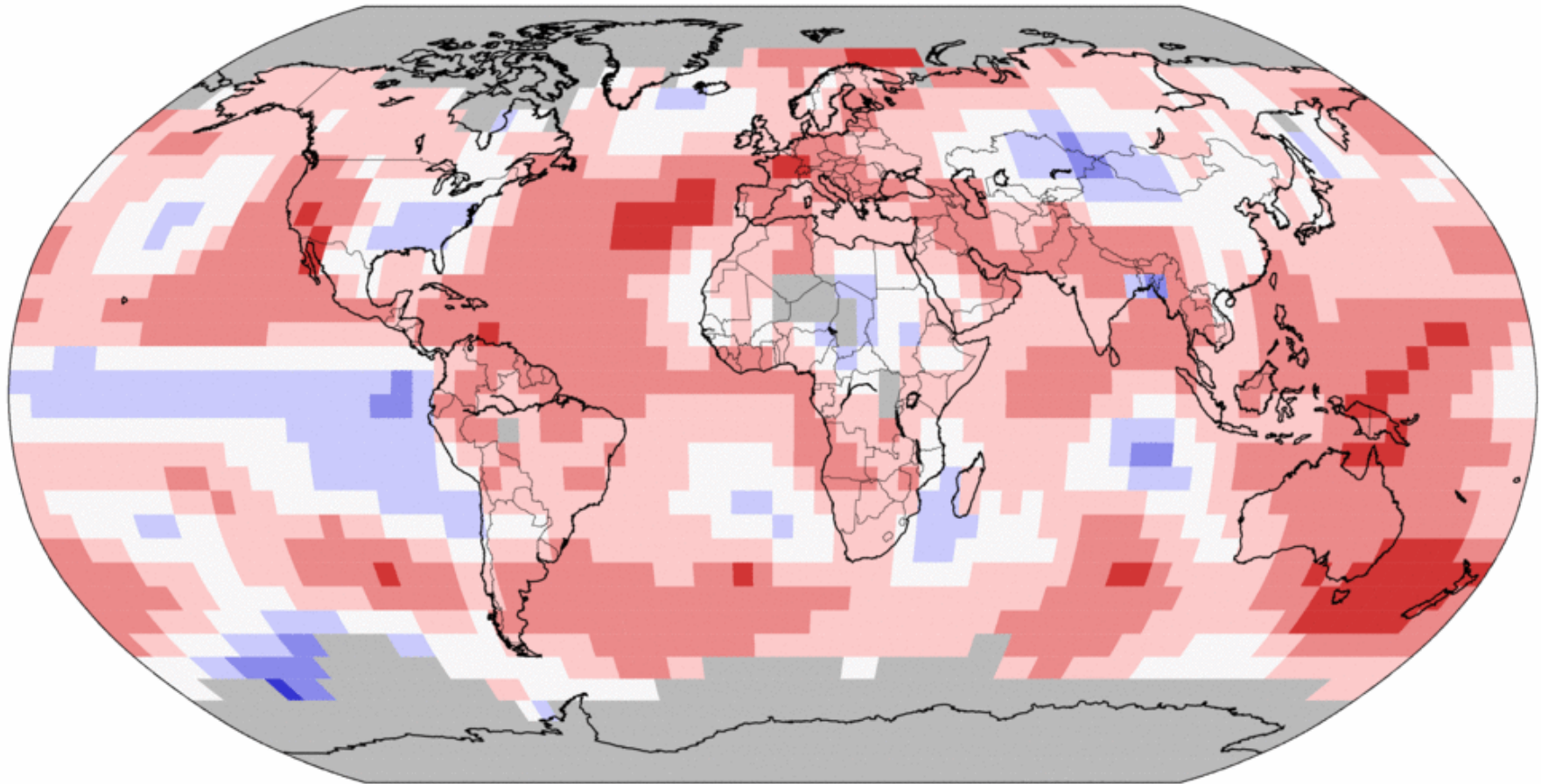
Please Note: Material provided in this map was compiled from NOAA's State of the Climate Reports. For more information please visit: <http://www.ncdc.noaa.gov/sotc>



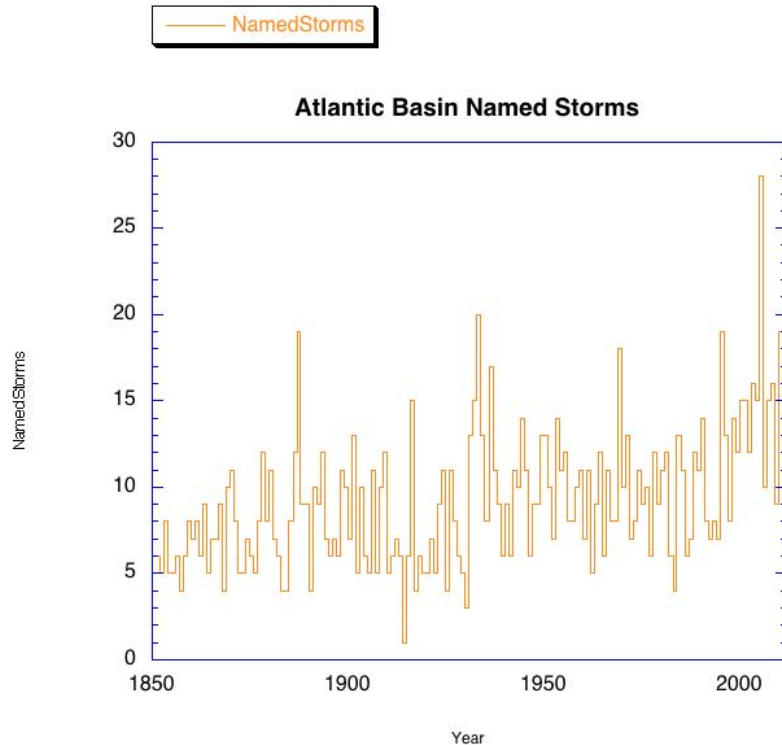
Land & Ocean Temperature Percentiles Jan 2018

NOAA's National Centers for Environmental Information

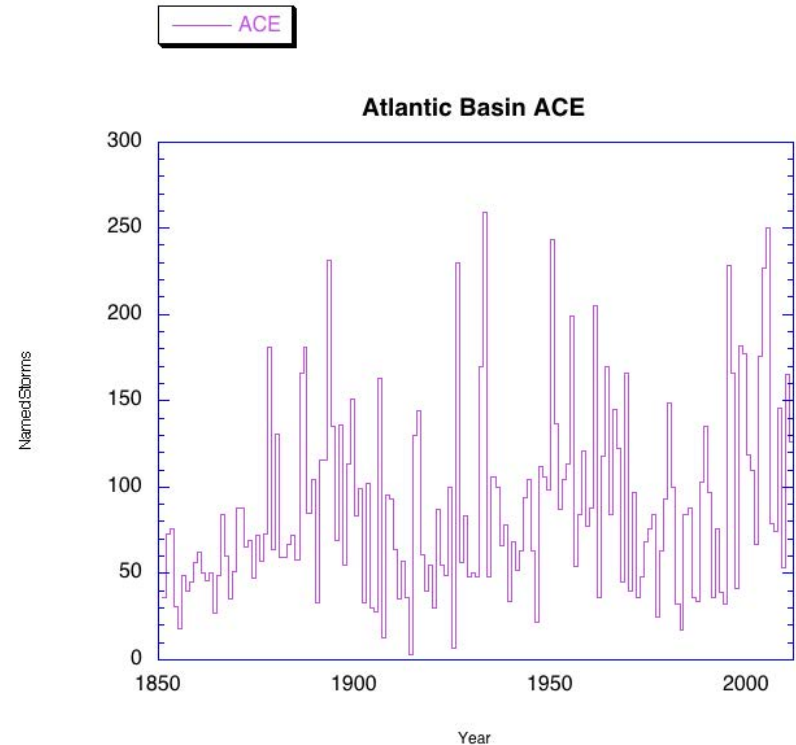
Data Source: GHCN-M version 3.3.0 & ERSST version 4.0.0



Frequently Asked Question: Are or will there be more hurricanes?



Years 1851-2016 (2017: 17)
<http://www.aoml.noaa.gov/hrd/tcfaq/E11.html>



ACE = Accumulated Cyclonic Energy
(2017: highest on record)

Rules of Thumb for a warmer world

(confirmed by observations and predicted by models with high certainty)

- more heat records
- less cold records

- more heat waves
- larger downpours, flash floods

- wet places get wetter
- dry places get drier

- less snow pack
- earlier snow melt

- prolonged droughts
- stronger tropical storms (not certain)



2017

CSSR

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Climate Science Special Report

Fourth National Climate Assessment (NCA4), Volume I

This report is an authoritative assessment of the science of climate change, with a focus on the United States. It represents the first of two volumes of the Fourth National Climate Assessment, mandated by the Global Change Research Act of 1990.

▣ Recommended Citation

This assessment concludes, based on extensive evidence, that it is extremely likely that **human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century.** For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.

<https://science2017.globalchange.gov/chapter/executive-summary/>



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2015



DEPARTMENT OF DEFENSE

[HOME](#) > [NEWS](#) > [ARTICLE](#)

DoD Releases Report on Security Implications of Climate Change

DoD News, Defense Media Activity

[PRINT](#) | [E-MAIL](#)



WASHINGTON, July 29, 2015 — Global climate change will aggravate problems such as poverty, social tensions, environmental degradation, ineffectual leadership and weak political institutions that threaten stability in a number of countries, according to a report the Defense Department sent to Congress yesterday.



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2018

https://www.nasa.gov/press-release/long-term-warming-tre

Yr - EUMI Northern Lig... Global Clima... hurricane sta... Executive Su... DoD Release... Long-Term... Long-Term...

NASA NASA TV Search

Climate

Jan. 18, 2018
RELEASE 18-003

Long-Term Warming Trend Continued in 2017:
NASA, NOAA

f t t p +

2017 Takes Second Place for Hottest Year

2017 was the second hottest year since 1880,
when global measurements first became possible.

1880 - 1884
2013 - 2017

Earth's long-term warming trend can be seen in this visualization of NASA's global temperature record, which shows how the planet's temperatures are changing over time, compared to a baseline average from 1951 to 1980. The record is shown as a running five-year average. Credit: NASA's Scientific Visualization Studio/Kathryn Mersmann
Credits: NASA's Scientific Visualization Studio/K. Mersmann
[Download high-definition video here.](#)

<https://www.nasa.gov/press-release/long-term-warming-trend-continued-in-2017-nasa-noaa>

A brief history of modern climate change



Jean-Baptiste Joseph Fourier (1768-1830)

develops a theory of “heat”
and discovers Earth’s “greenhouse effect”.

Earth’s surface is **warmer**
than heating from Sun alone would imply.



A brief history of modern climate change



John Tyndall (1820-1893)

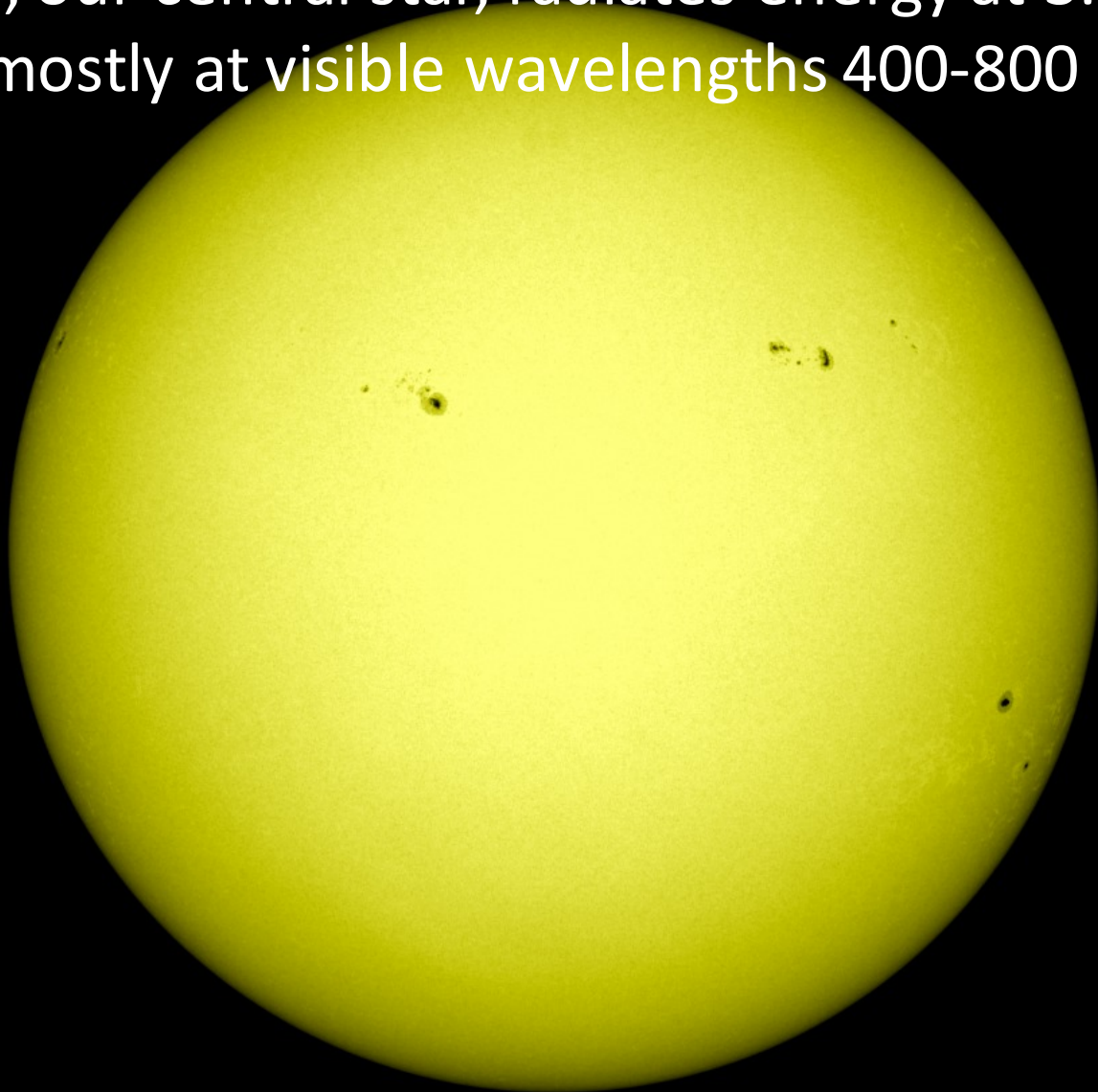
discovers the absorption of infrared radiation by molecules like CO_2 , H_2O , N_2O , CH_4 , O_3

These are the atmospheric
“greenhouse gases”



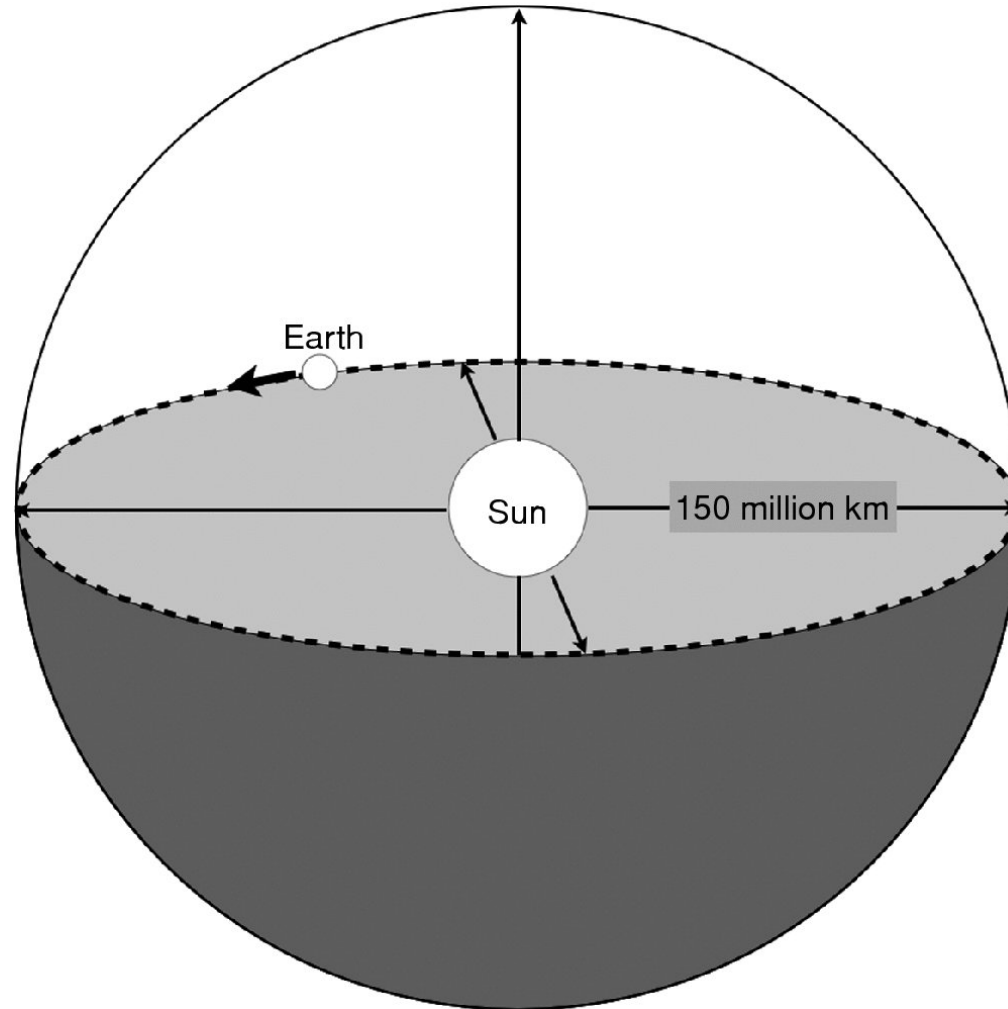
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The Sun, our central star, radiates energy at 3.8×10^{26} W,
mostly at visible wavelengths 400-800 nm

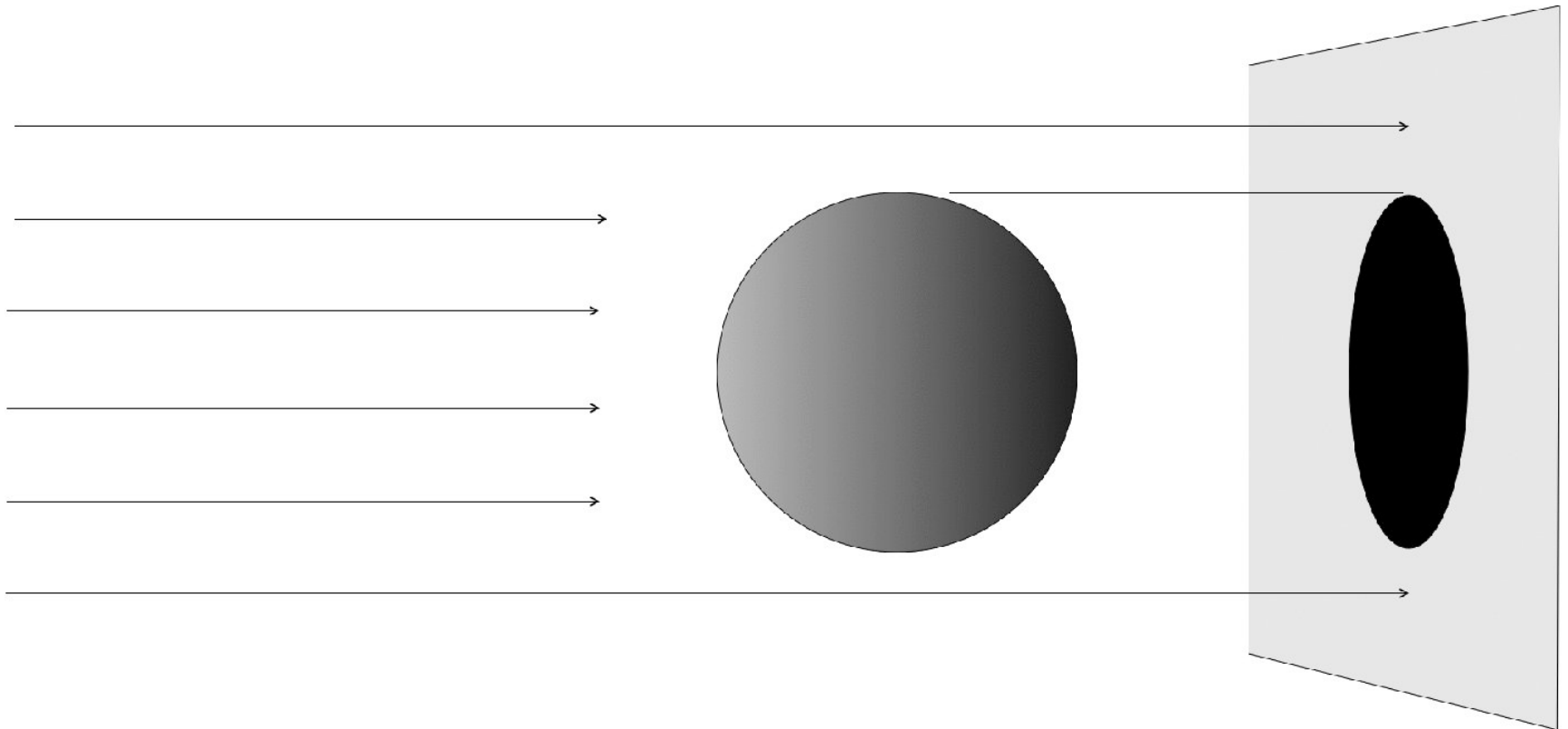


some as X rays, UV, and near IR

This power is diluted with the distance squared ($1/r^2$).
At the Earth, the “solar constant” is still **S = 1370 W/m²**



The Earth collects solar power across its “shadow area” of $S (\pi R^2)$ all the time at the “top of the atmosphere” (like in low-earth orbit)

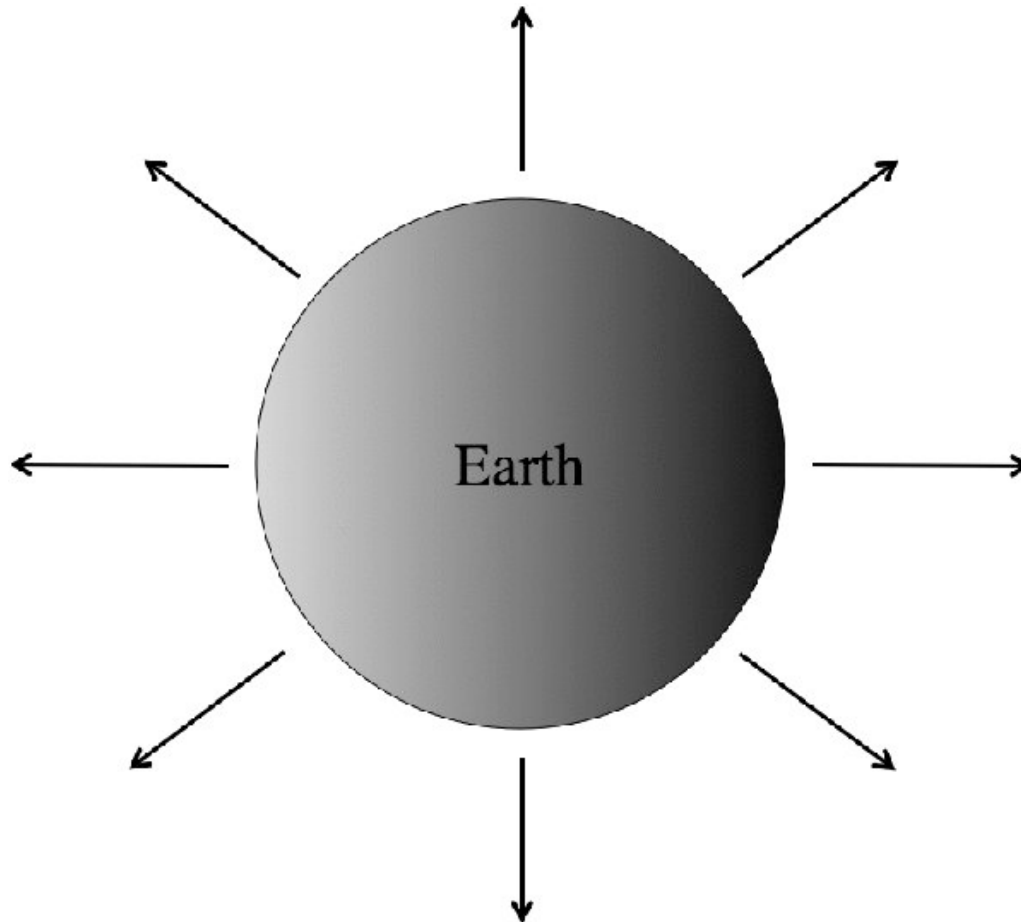


Clouds and ice on Earth reflect about 30% back to space
("albedo")



The sunlight reaches and **warms** the Earth's surface, since the atmosphere is **mostly transparent** for visible light.

The entire Earth's surface ($4 \pi R^2$) must **lose** the energy by thermal radiation to space.



If we balance

Energy (in) = Energy (out)

$S(1-\alpha) / 4 = \sigma T^4$, with

$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

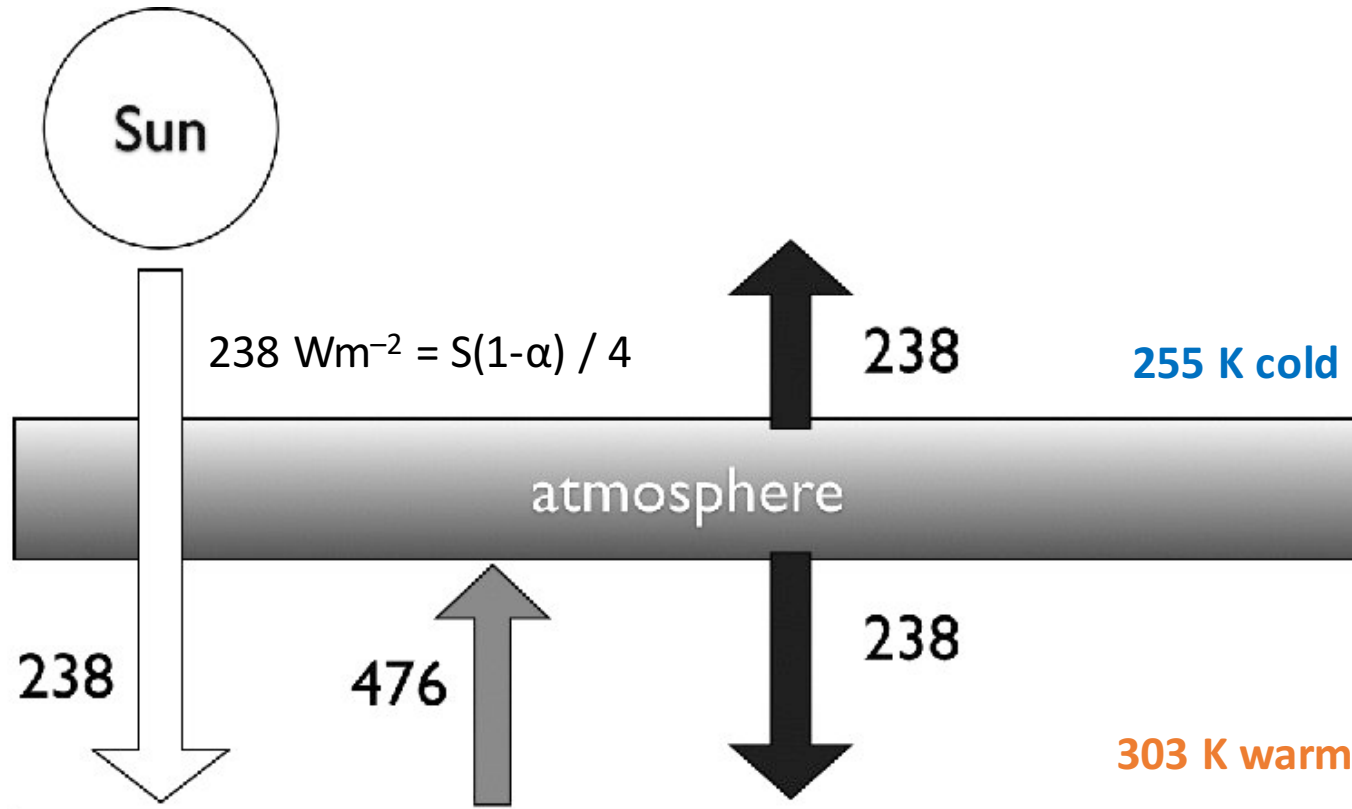
we find the
surface temperature as

$T = [S (1-\alpha) / (4 \sigma)]^{1/4}$

$T = 255 \text{ K } (-18 \text{ }^\circ\text{C})$

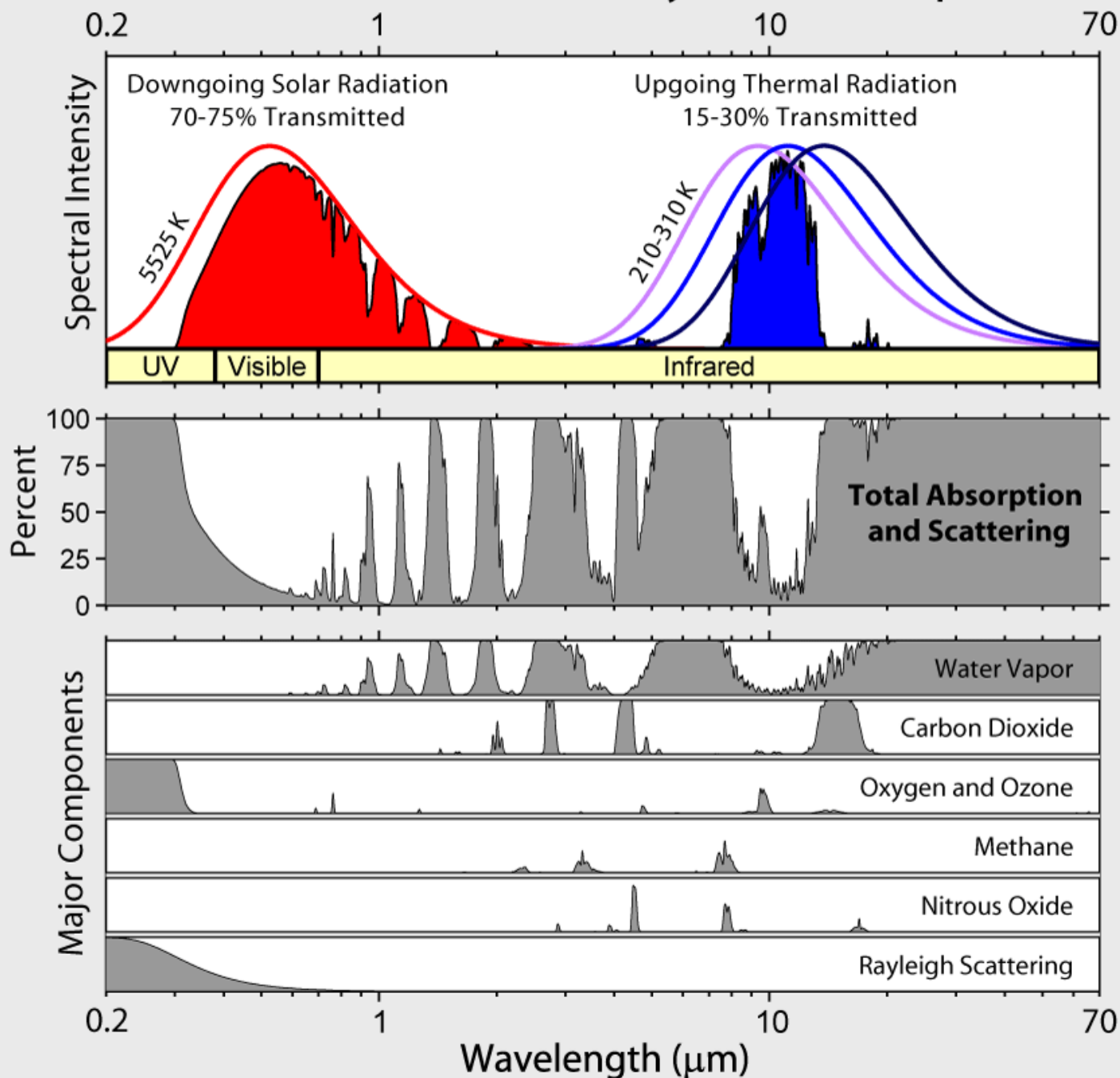
which is much colder than the
observed average temperature!

We need to consider an atmosphere **that is opaque** for the outgoing infrared radiation

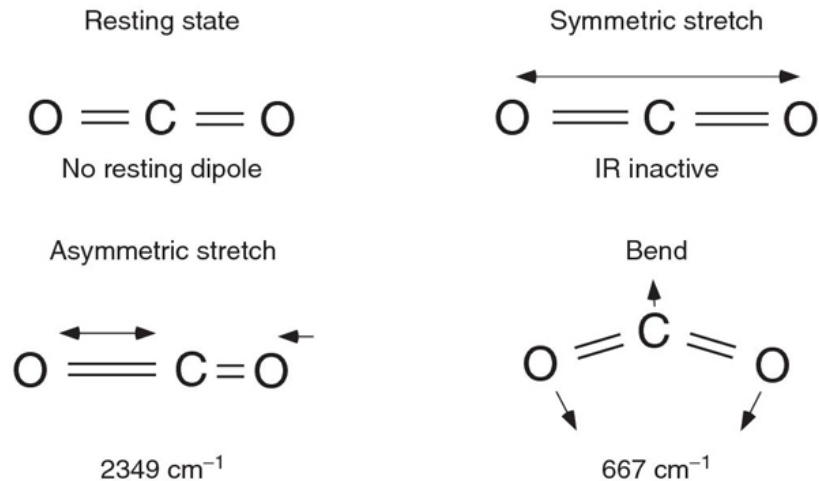


The surface receives solar radiation and “back radiation” from the atmosphere. The resulting surface temperature is 303 K (a bit too warm, real value 289 K = 16°C)

Radiation Transmitted by the Atmosphere



Infrared active molecules



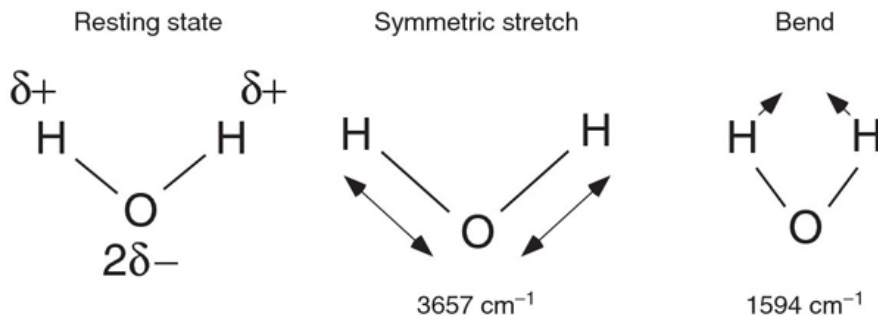
$\text{N} \equiv \text{N}$ $\text{O} = \text{O}$ are IR inactive

Its quantum physics!

Symmetric bend of CO_2 near 667 cm^{-1} ($15 \mu\text{m}$) is most important for greenhouse effect on Earth (despite its small mixing ratios of 400 ppm \uparrow). Also on Venus and Mars.

Water vapor (H_2O , 10000 ppm but variable) absorbs at many wavelengths in near and middle infrared.

The more bonds, the more absorption lines. Therefore, CH_4 (1.86 ppm \uparrow) and **CFCs** and **HFCs** are also important greenhouse gases that count.



This is an explanation of the “natural” greenhouse effect in its simplest form

It keeps oceans liquid for probably all¹ of Earth’s history of 4.6 Gy

Refinements:

Heat is also transported away from the surface by convection and latent heat. The temperature structure is therefore better described as **radiative-convective equilibrium** (Manabe and Weathersald, 1967).

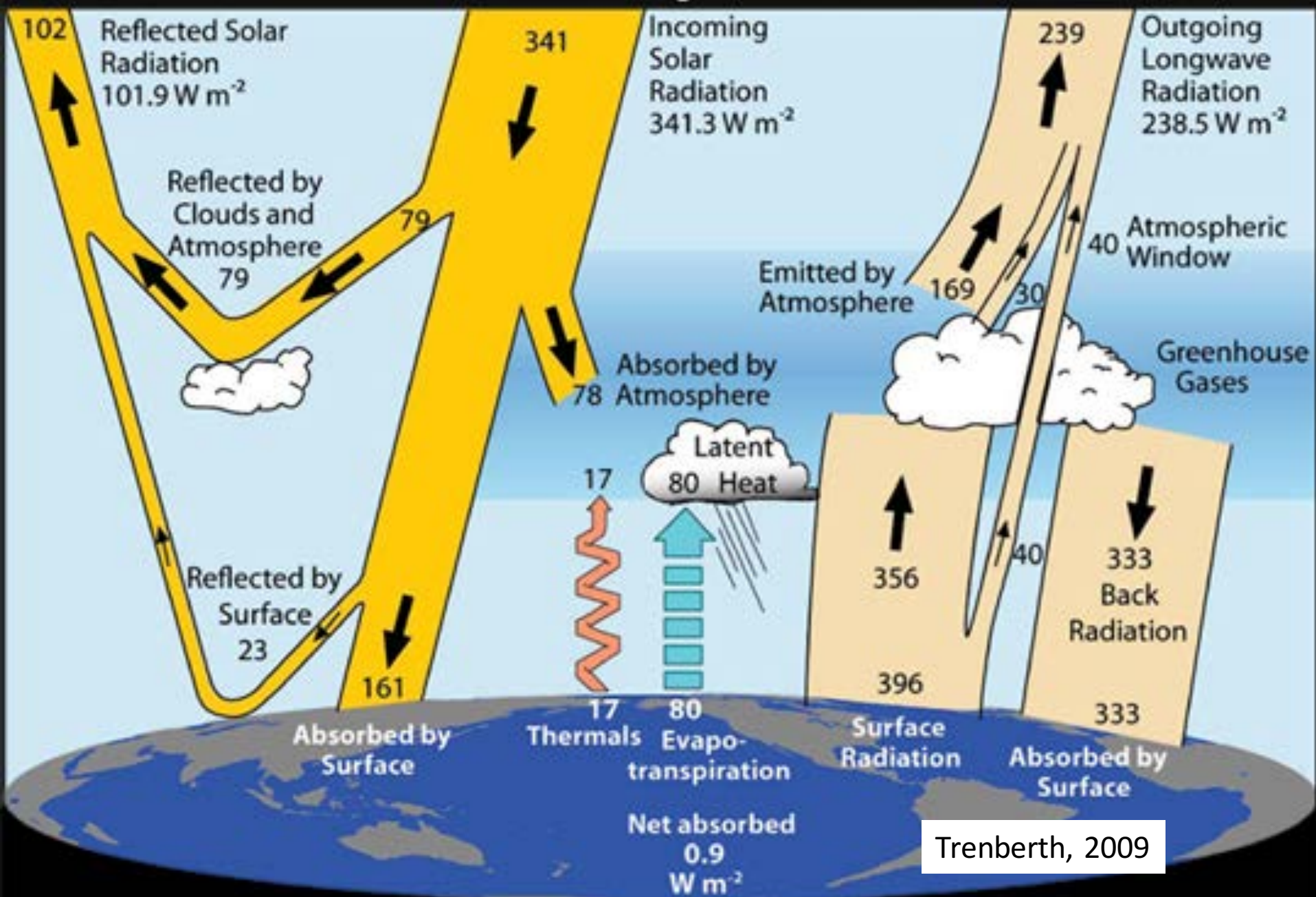
Most important greenhouse gases are water vapor, which is recycled in a few days, and carbon dioxide, which is **long-lived** with time scales of 100s to 10,000s of years.

Water vapor content increases with increasing temperature, which is the most important **positive climate feedback**.

¹ Snow Ball Earth, Faint Sun Paradox, very high CO₂ content in Carboniferous



Earth's Energy Balance



Trenberth, 2009

A brief history of modern climate change



Svante Arrhenius (1859-1927)

first speculated that humans fossil fuel burning and adding carbon dioxide may raise the temperature of the Earth

more greenhouse gases enhance the natural greenhouse effect and cause global warming



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A brief history of modern climate change

Charles David Keeling (1928-2005)



starts systematic measurements of carbon dioxide and shows that they are ever increasing

Global carbon dioxide levels are now higher than they were in the past million years and have increased from preindustrial levels of **280 ppm to over 406 ppm** due to human fossil-fuel burning, deforestation and changes in land use

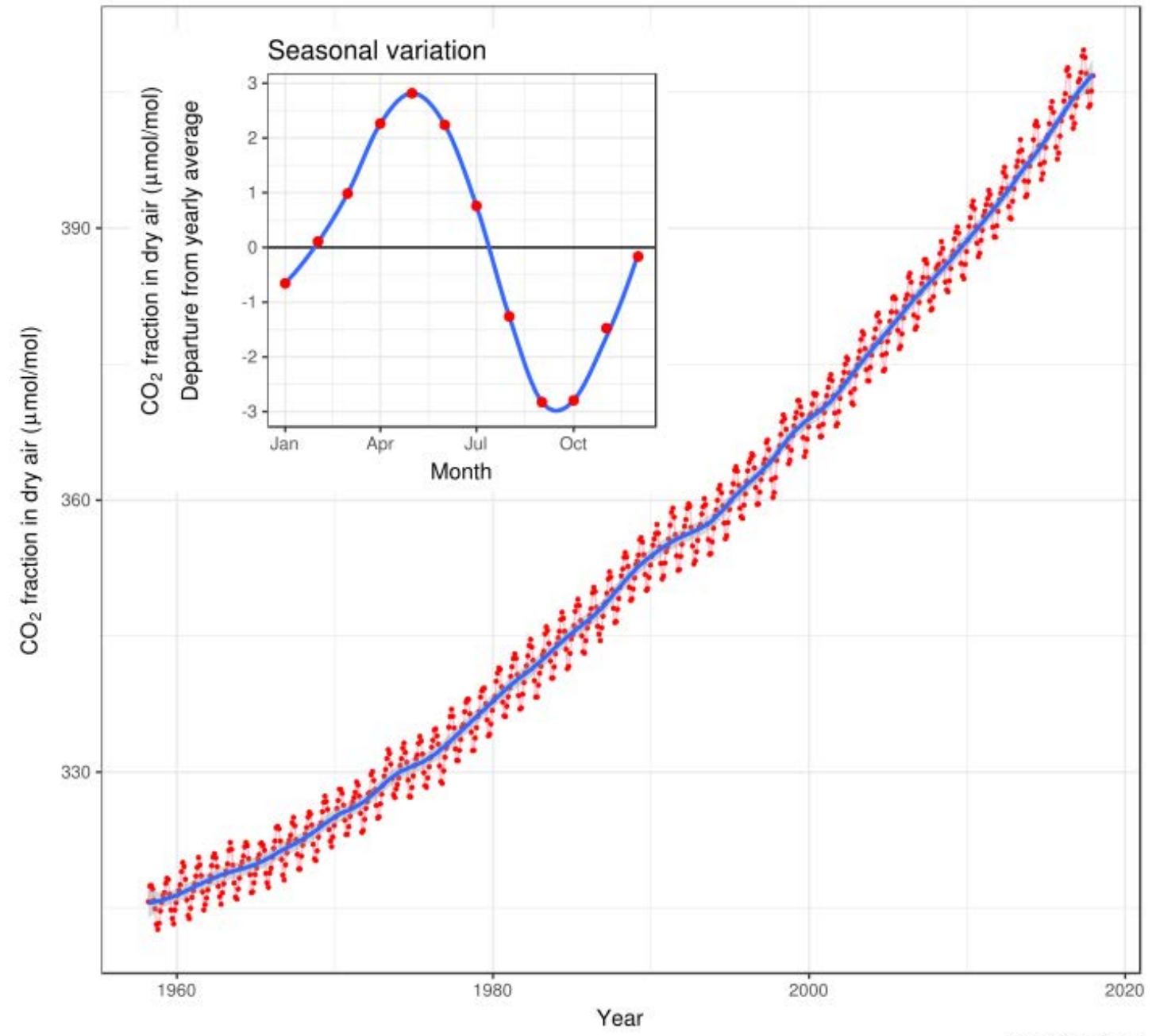
About half of the emitted CO₂ is being dissolved in the oceans (acidification), the other half **remains in the atmosphere for 100 years** and even much longer



Monthly mean CO₂ concentration

Mauna Loa 1958 - 2017

“Keeling curve”



A brief history of modern climate change



James Edward "Jim" Hansen (b. 1941)

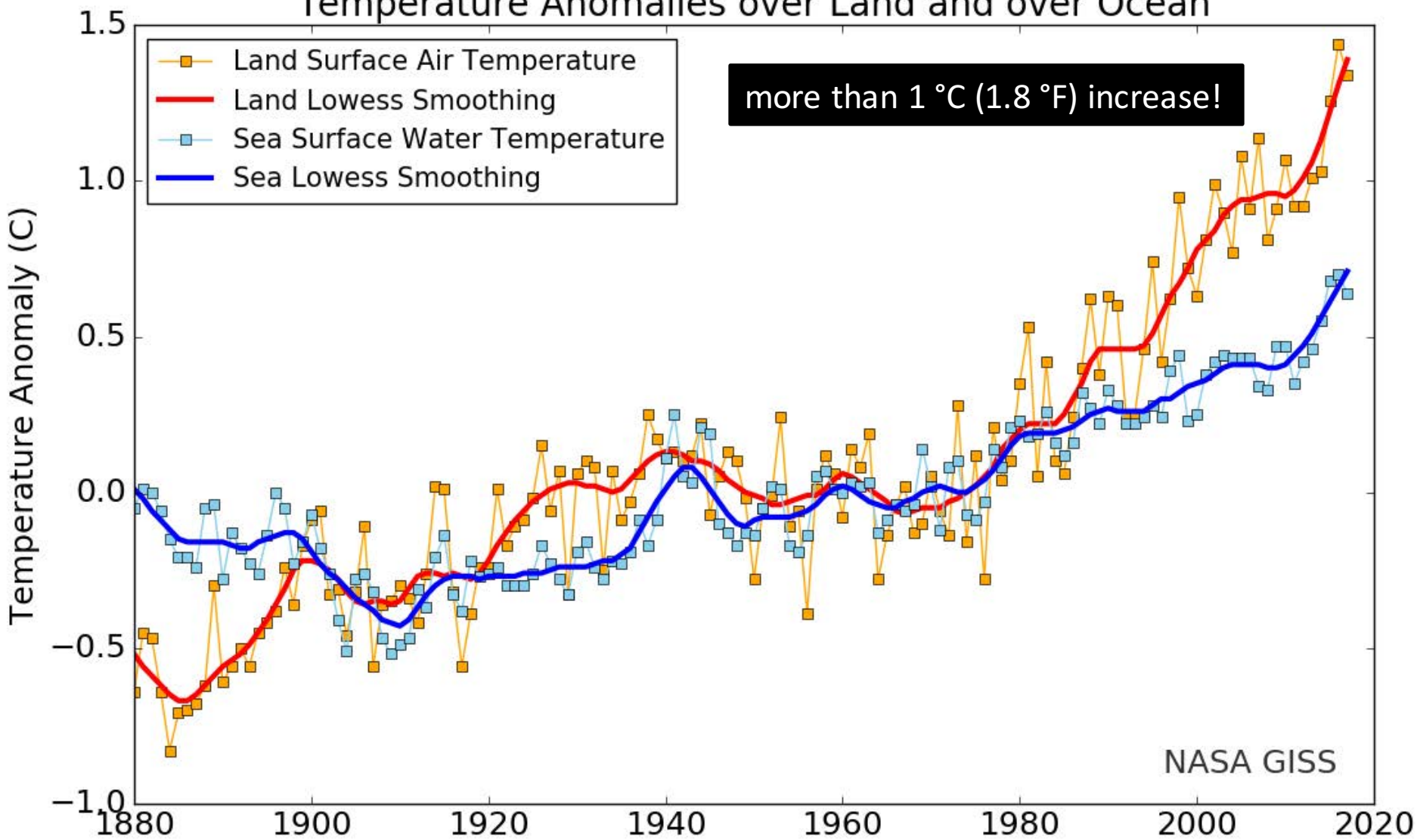
develops global temperature sets and global climate models at NASA since the early 1980s,

which show that the observed warming **can only be modeled and explained** by including the radiative forcing the human caused greenhouse emissions and associated feedbacks, such as ice-albedo decreases and water vapor increases

He testifies about his results before Congress first in 1988.

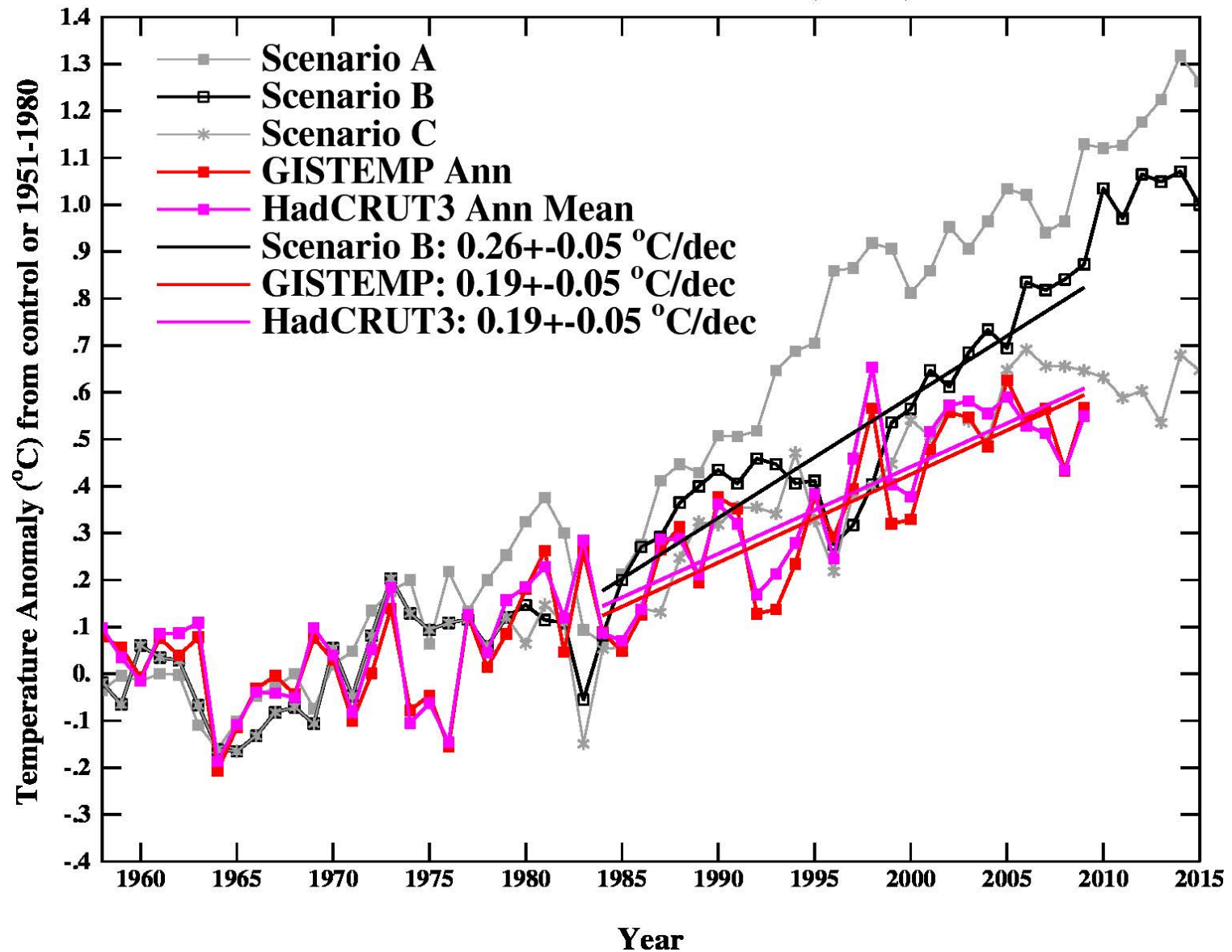
Average global temperatures are now warmer than ever in the past 400,000 years (during previous interglacials, warm periods between ice ages)

Temperature Anomalies over Land and over Ocean



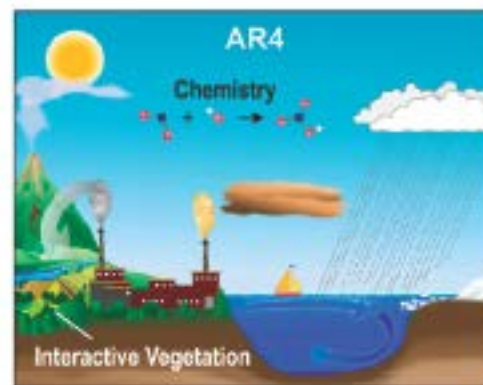
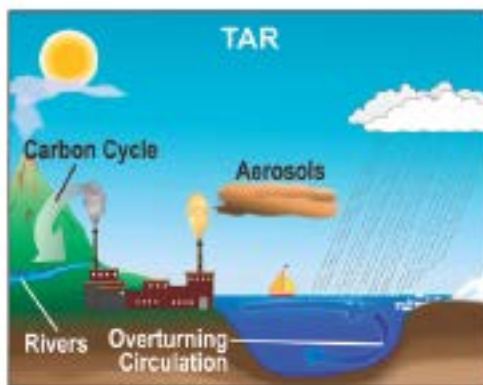
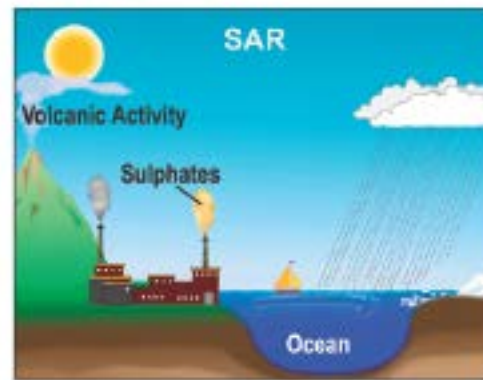
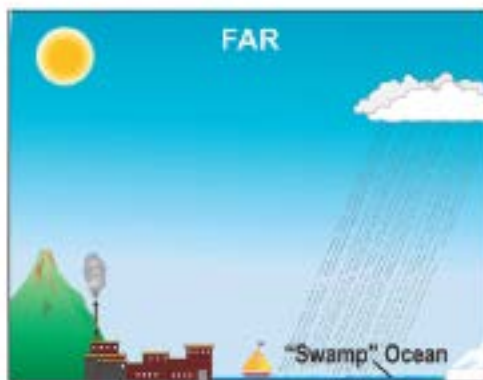
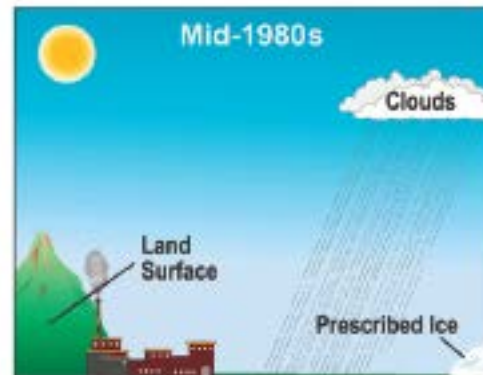
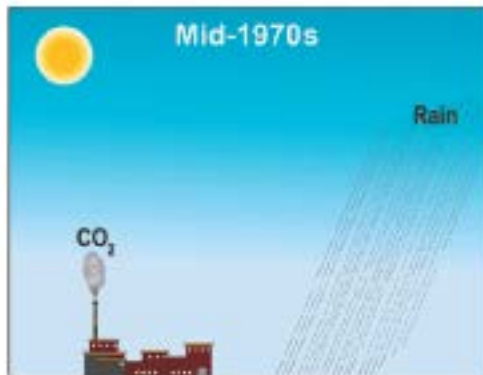
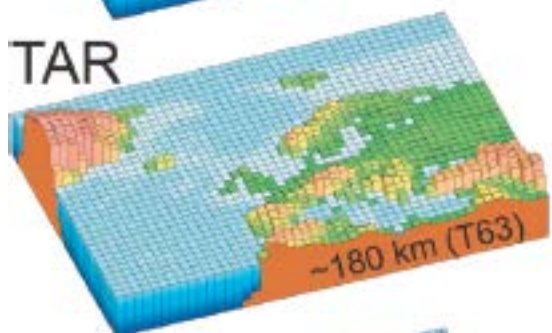
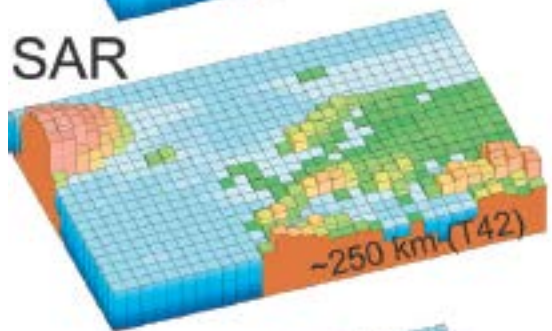
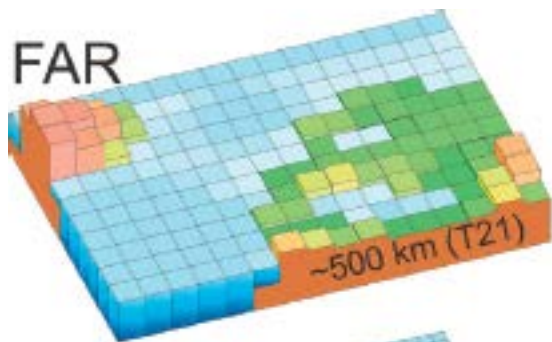
The land warms faster than the ocean; the ocean absorbs 98% of the extra warming, expands and causes **sea level rise**.

How well did Hansen et al (1988) do?



Surprisingly well (paper by Gavin Schmidt, 2009). A, B, C are different emission scenarios

The World in Global Climate Models



Other evidence for climate change

From the **2017 U.S. Climate Change Special Report**

“In addition to warming, many other aspects of global climate are changing, primarily in response to human activities. **Thousands of studies conducted by researchers around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor.**”



Debunking climate myths



Home Arguments Software Resources Comments The Consensus Project Translations About Donate

MOST USED Climate Myths

and what the science really says...

- 1 Climate's changed before
 - 2 It's the sun
 - 3 It's not bad
 - 4 There is no consensus
 - 5 It's cooling
 - 6 Models are unreliable
 - 7 Temp record is unreliable
 - 8 Animals and plants can adapt
 - 9 It hasn't warmed since 1998
 - 10 Antarctica is gaining ice
- [View All Arguments...](#)

<https://skepticalscience.com>

<https://insideclimatenews.org/news/22112017/thanksgiving-family-climate-denial-global-warming-science-answers>



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Debunking climate myths

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A banner image for RealClimate featuring a large, bright orange sun on the left and a blue ocean with white-capped waves on the right. The text 'RealClimate' is overlaid in a large, bold, yellow font, with the tagline 'Climate science from climate scientists' in a smaller, italicized yellow font below it.

RealClimate

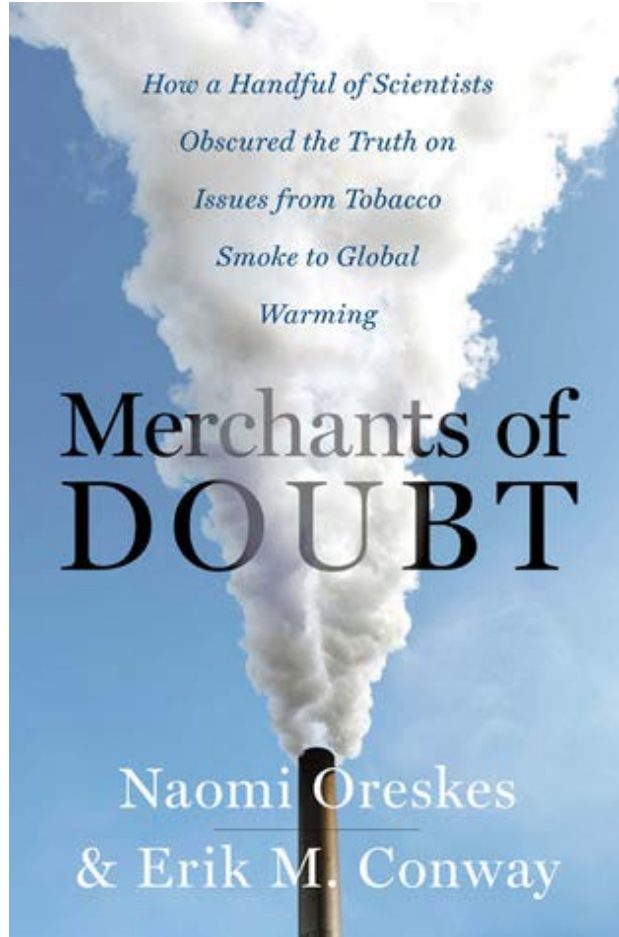
Climate science from climate scientists

<http://www.realclimate.org>



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Merchants of Doubt



Book (2010)

Movie (2014)

<https://www.youtube.com/watch?v=j8ii9zGFDtc>

repeat of the “tobacco strategy” of the 1960s



Current issues in climate science

MENU ▾

nature
climate change

A new climate for cities

Three new comments in Nature Climate Change deal with the adaptation and mitigation challenges that lie ahead for cities as the world becomes increasingly urbanised and climate change begins to bite.

<https://www.nature.com/nclimate/>



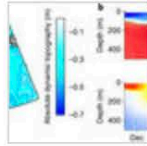
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Current issues in climate science

Latest Research

Letter | 14 March 2018

Increased risk of a shutdown of ocean convection posed by warm North Atlantic summers

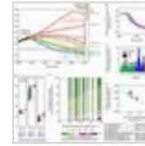


North Atlantic Ocean convection may be impeded by increased freshwater input or reduced surface heat losses. This... [show more](#)

Marilena Oltmanns, Johannes Karstensen & Jürgen Fischer

Article | 05 March 2018

Scenarios towards limiting global mean temperature increase below 1.5 °C



Scenarios that constrain end-of-century radiative forcing to 1.9 W m^{-2} , and thus global mean temperature increases to... [show more](#)

Joeri Rogelj, Alexander Popp [...] Massimo Tavoni

Perspective | 27 February 2018

Integrating human behaviour dynamics into flood disaster risk assessment

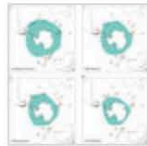


Flood impact and recovery is influenced by behavioural responses. This Perspective describes how integrating human... [show more](#)

J. C. J. H. Aerts, W. J. Botzen [...] H. Kunreuther

Article | 26 February 2018

Climate-driven range shifts of the king penguin in a fragmented ecosystem

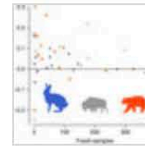


Ecological niche modelling of king penguins in the Southern Ocean, validated with population genomics and... [show more](#)

Robin Cristofari, Xiaoming Liu [...] Emiliano Trucchi

Article | 26 February 2018

Anthropogenic range contractions bias species climate change forecasts

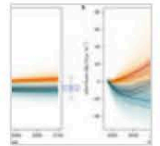


Models of the distribution of North American mammals show that estimated future diversity under climate change is... [show more](#)

Søren Faurby & Miguel B. Araújo

Letter | 26 February 2018

Mitigation potential of soil carbon management overestimated by neglecting N₂O emissions



Agricultural soils can be targeted for carbon (C) sequestration. Research considering C and nitrogen (N) dynamics... [show more](#)

Emanuele Lugato, Adrian Leip & Arwyn Jones

[More Latest Research >>](#)

Current issues in climate science

Science

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Now accepting applications for the
CZI Neurodegeneration Challenge Network

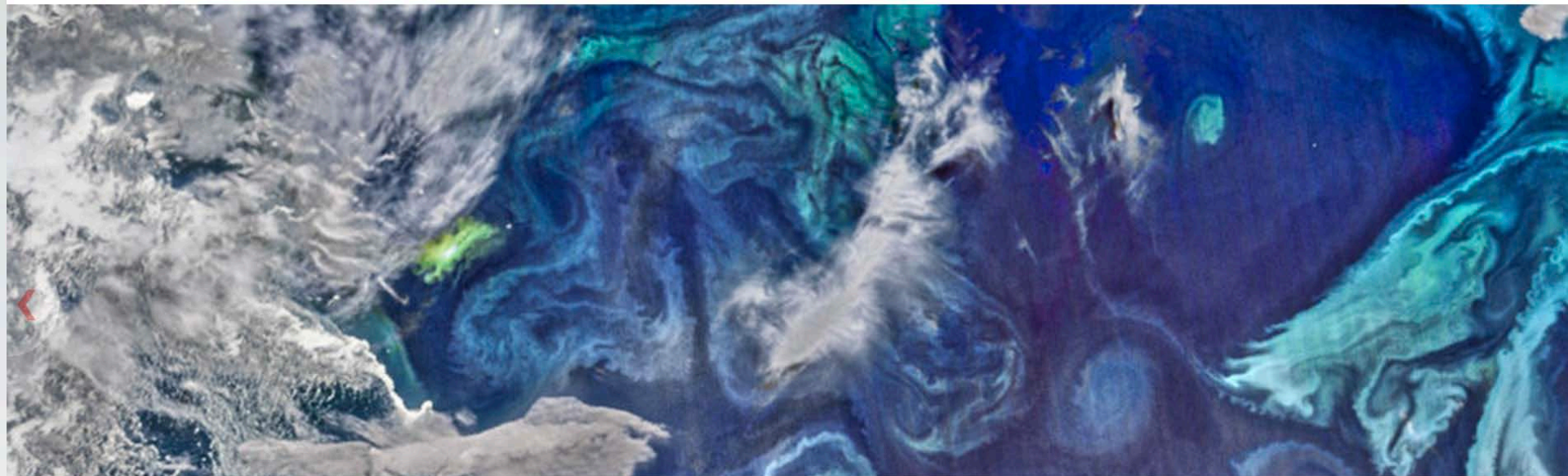
[Learn more](#)



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Will marine productivity wane?

Science | Mar. 7, 2018

Your search for "climate" in All Sources and Research and Reviews Articles returned 2,680 results.

RESEARCH AND REVIEWS

Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area

By Manoochehr Shirzaei, et al. | Mar 2nd, 2018

Storm intensity, associated rainfall, and storm surges affecting the coastal area were likely amplified by the elevated ocean temperature caused by ongoing global **climate** change (7). ... The spatial pattern of SLR in the northeast Pacific is generally affected by **climate** patterns (such as El Niño and La Niña), changes in gravitational pull due to large glaciers and ice melting, isostatic rebound caused by ice sheet loss, and tectonic processes, including interseismic land uplift and subsidence (8 , 9). ... Projections of SLR for the northeast Pacific suggested by the Intergovernmental Panel on **Climate** Change (IPCC) in 2007 (8 , 9) predict a rise of 4 to 30 cm by 2030, 12 to 61 cm by 2050, and 42 to 167 cm by 2100, relative to 2000.

DOI: 10.1126/sciadv.aap9234 Science Advances Vol. 4, No. 3

<http://www.sciencemag.org>

RESEARCH AND REVIEWS

Shark baselines and the conservation role of remote coral reef ecosystems

By Francesco Ferretti, et al. | Mar 2nd, 2018

INTRODUCTION **Climate** change and industrial exploitation are radically changing the structure and function of ocean ecosystems (1 , 2).

DOI: 10.1126/sciadv.aaq0333 Science Advances Vol. 4, No. 3

RESEARCH AND REVIEWS

Volatile chemical products emerging as largest petrochemical source of urban organic emissions

By Brian C. McDonald, et al. | Feb 14th, 2018

Volatile chemical products emerging as largest petrochemical source of urban organic emissions Brian C. McDonald 1 , 2 , *, Joost A. de Gouw 1 , 2 , Jessica B. Gilman 2 , Shantanu H.

DOI: 10.1126/science.aaq0524 Science Vol. 359, No. 6377

RESEARCH AND REVIEWS

Natural selection and the predictability of evolution in *Timema* stick insects

By Patrik Nosil, et al. | Feb 14th, 2018

Specifically, changes in color-morph frequencies are modestly predictable through time ($r^2 = 0.14$) and driven by complex selective regimes and yearly fluctuations in **climate**. ... However, the extent of predictability will depend on how NFDS interacts with other evolutionary processes (e.g., directional selection stemming from **climate** change) and on whether the ecological conditions that affect these other processes can themselves be predicted.

DOI: 10.1126/science.aap9125 Science Vol. 359, No. 6377



Solutions

If we want to limit the effects of global warming,

(for example, by +1.5 °C temperature increase over pre-industrial by 2100)

we must reduce global fossil fuel emissions as quickly as possible





possibly aided by

Carbon Capture and Storage (CCS)

THE
NEW YORKER

ANNALS OF SCIENCE NOVEMBER 20, 2017 ISSUE

CAN CARBON- DIOXIDE REMOVAL SAVE THE WORLD?

*CO₂ could soon reach levels that, it's widely agreed,
will lead to catastrophe.*

By Elizabeth Kolbert



CLEMSON
College of SCIENCE

as a last resort? Geoengineering

in particular, solar radiation management,
i.e. **dimming the Sun** with introducing stratospheric aerosols on a global scale,
like major volcanic eruptions do

must be continued indefinitely or until other solutions arise



<https://www.theguardian.com/environment/blog/2012/feb/06/artificial-volcano-cool-planet-sun>



Geoengineering: A "plan B" to curb climate change

Plan A is still to limit greenhouse gas emissions, but other solutions are being considered

Solar radiation management

To prevent some sun rays from reaching the Earth's surface



Giant mirrors in space to reflect 1 to 2% of the sun's rays

⊖ Danger of sudden warming if system fails, danger of changing rainfall patterns

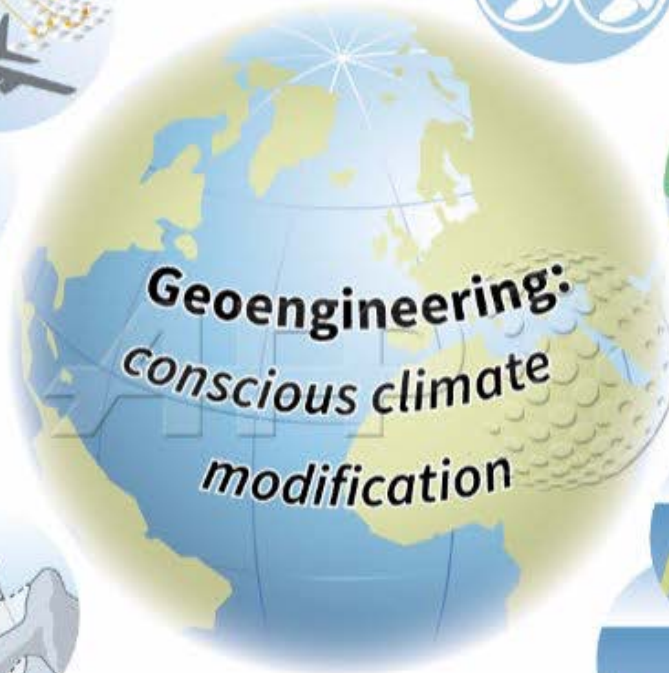
Enhanced weathering

Natural erosion consumes around 2% of global CO₂ emissions
Technology could accelerate that process

⊖ Feasibility and impact uncertain

⊖ Drawbacks

Injecting tiny reflective particles into the stratosphere or clouds



Direct CO₂ capture in atmosphere



⊖ Current technology is too expensive, global effect limited

Massive afforestation

Trees absorb CO₂

⊖ Number of trees needed would devour croplands, raising price of basic foodstuffs by 80% by mid-2000s



Ocean fertilisation

Nourish phytoplankton that absorb CO₂

⊖ Plankton die-offs consume oxygen in the oceans, creating massive "dead zones"




Bioenergy with carbon capture and storage (BECCS)

Plants used as biofuels absorb CO₂ as they grow, and when they are burned, the CO₂ produced can be sequestered. Net result is "negative emissions"

⊖ Upward of 40% of the planet's arable land could be needed





Thank you
for your attention