THE NATIONAL JUDICIAL COLLEGE

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INTRODUCTION TO CLIMATE SCIENCE: PARTS 1 AND 2

DIVIDER 4

Ben Santer, Ph.D.

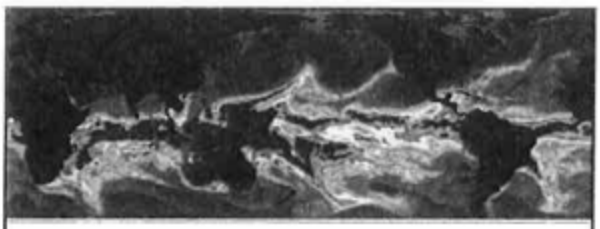
OBJECTIVES:

At the end of the session, the participants will be able to:

1. Summarize the human influences on the earth's climate as opposed to natural influences;
2. Describe how scientists can differentiate between human and natural signatures ("fingerprints") using statistical pattern recognition; and
3. State with clarity that satellite temperature measurements provide compelling evidence of human fingerprints on the climate.

REQUIRED READING:

PAGE



Introduction to Climate Science: Part 1

Ben Santer
Visiting Researcher, UCLA

My Background

- My **job**: Atmospheric **scientist**
- My **educa**tion: U.K. and Ger**many**
- My research: Climate fingerprinting
- My **hobby**: Rock-**climbing**

The arc of history...

The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more

The balance of evidence suggests a discernible human influence on global climate

It is unequivocal that human influence has warmed the atmosphere, ocean, and land

1995

2007

2013

IPCC, 1988

What this presentation will cover

Natural effects on climate

- Changes in the Sun's energy output
- Changes in volcanic activity
- Natural internal variability (El Niños, La Niñas)

What this presentation will cover

Human effects on climate

- Changes in greenhouse gases
- Changes in particulate pollution (sulfates, soot)
- Changes in land surface properties

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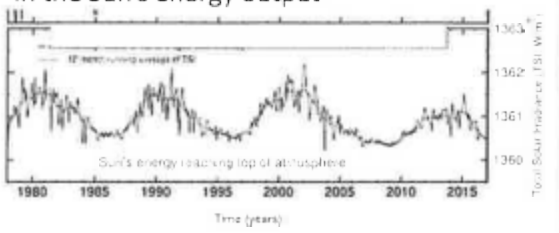
Studying changes in the Sun

- Direct measurements (since 1979)
- Sunspot numbers
- Cosmogenic isotopes

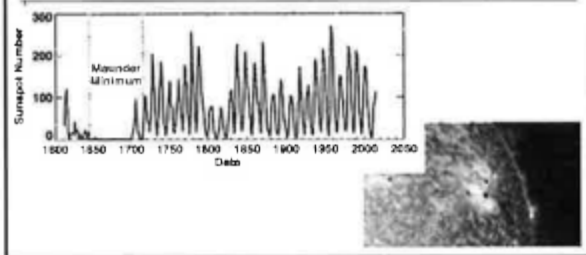
Satellite measurements of changes in the Sun's energy output



Sunspots

- First spotted by telescope in 1611
- Sunspot numbers increase and decrease in a cycle of roughly 11 years
  - Can be as short as 8 years and as long as 14 years
- Highest number of sunspots in any cycle = Solar Maximum
- Lowest number of sunspots in any cycle = Solar Minimum

Sunspots



Sunspots

- Maunder Minimum in sunspots between 1645 and 1715
- Sunspot numbers dropped dramatically during that time
- The Maunder Minimum was a colder time in Europe
  - Prolonged Solar Minimum may have decreased solar energy and cooled parts of the Earth during Maunder Minimum
  - "Little Ice Age"

Sunspots

https://www.nasa.gov/mission_pages/sunearth/news/solarcycle-primer.html

Painting: The Castle of Muiden in Winter by Jan Abrahamsz Beerstraten, 1658

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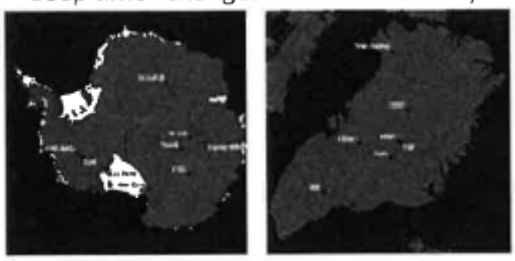
Close encounters of the eruptive kind...

Climbing Mt. St. Helens, April 1980

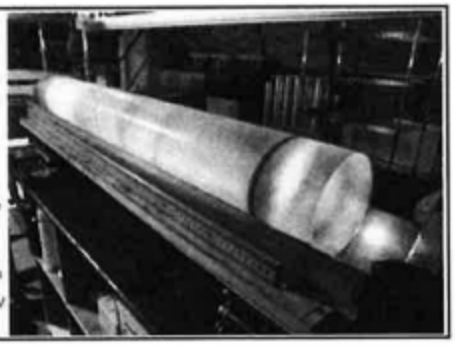
Studying changes in volcanic activity

- Using ice cores
- From space
- From the ground

Ice cores provide one way of studying "deep time" changes in volcanic activity

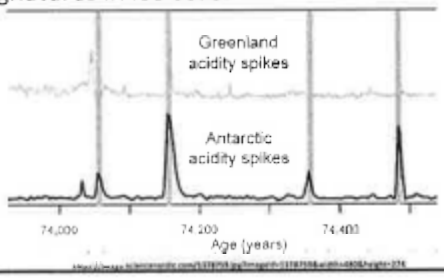


Studying volcanic activity with ice cores

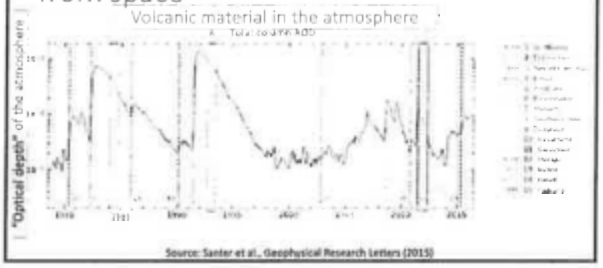


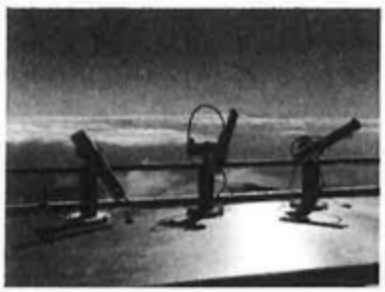
The dark band in this ice core from the West Antarctic Ice Sheet Divide is a layer of volcanic ash that settled on the ice sheet roughly 21,000 years ago. Photo credit: Heidi Roop, NSF. https://icecores.org/icecores/

Many volcanic eruptions have "bipolar" signatures in ice cores



Studying changes in volcanic activity from space





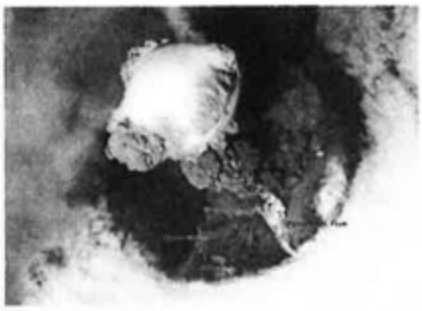
Studying changes in volcanic activity from the ground

Photometers at Izaña Observatory, Mt. Teide, Tenerife

Photo: Ben Santer

Early 21st century eruptions

Tarvurvur (2006)



Early 21st century eruptions

Sarychev (2009)

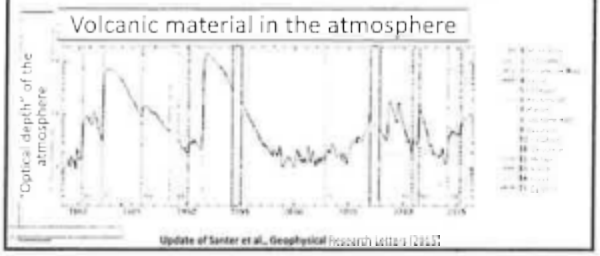
Early 21st century eruptions

Nabro (2011)

Early 21st century eruptions

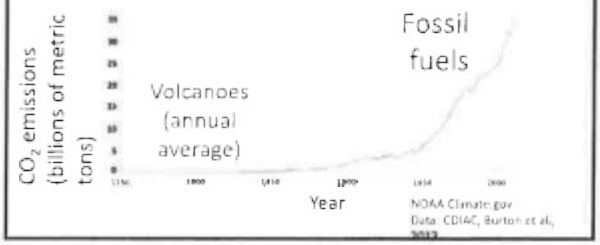
Calbuco (2015)

Recent changes in volcanic activity have detectable changes in temperature



Update of Santer et al., Geophysical Research Letters [2013]

SIDEBAR: Do volcanoes produce more CO_2 than human activities?



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- Changes in the Sun's energy output
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What is internal variability of the climate system?

Cyclical changes in global or regional climate

- Purely natural!
- Primarily due to interactions between atmosphere and ocean
- They happen on a range of timescales (months to centuries)
- Unclear how human-caused warming will affect these cycles

Some commonly studied modes of internal climate variability

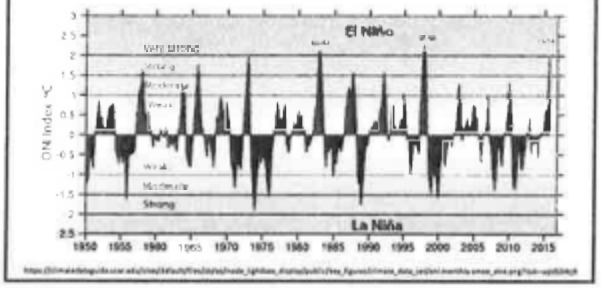
- El Niños and La Niñas
- Atlantic Multidecadal Oscillation
- Pacific Decadal Oscillation
- Quasi-Biennial Oscillation

What are El Niños and La Niñas?

Animation of El Niños and La Niñas https://oceanservice.noaa.gov/facts/ninonina.html

https://oceanservice.noaa.gov/facts/ninonina.html

How have El Niños and La Niñas varied?

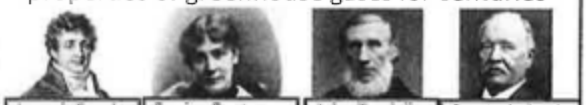


What this presentation will cover

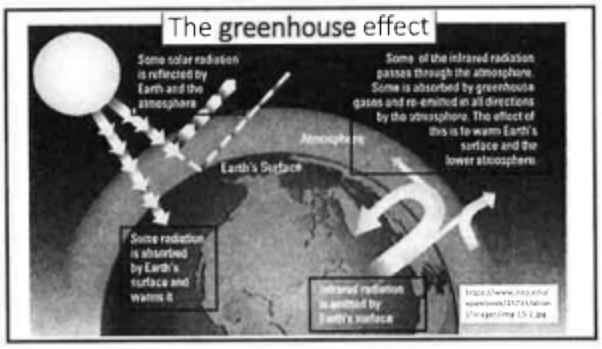
Human effects on climate

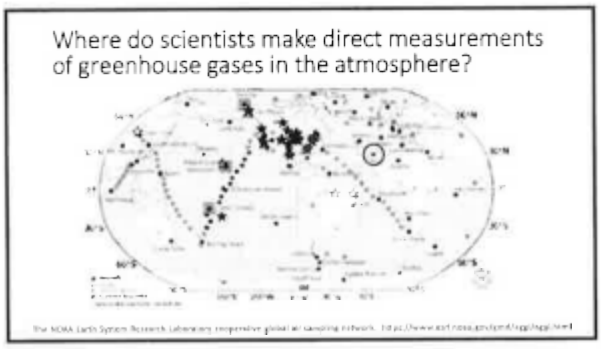
- Changes in greenhouse gases
- Changes in particulate pollution (sulfates, soot)
- Changes in land surface properties

Scientists have studied the heat-trapping properties of greenhouse gases for centuries



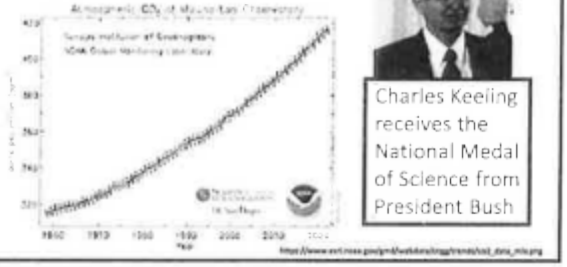
Joseph Fourier (1768-1830). Often credited with the discovery of the greenhouse effect	Eunice Foote (1819-1888). In 1856, presented paper predicting that increases in atmospheric CO_2 would increase temperature	John Tyndall (1820-1893). First to measure the infrared absorptive power of CO_2 & other gases	Svante Arrhenius (1859-1927). 1st to calculate the impact of increasing **atmospheric CO_2 on Earth's** surface temperature


The greenhouse effect
Some solar radiation is reflected by Earth and the atmosphere
Some of the infrared radiation passes through the atmosphere. Some is absorbed by greenhouse gases and re-emitted in all directions by the atmosphere. The effect of this is to warm Earth's surface and the lower atmosphere
Atmosphere
Earth's Surface
Some radiation is absorbed by Earth's surface and warms it
Infrared radiation is emitted by Earth's surface


Where do scientists make direct measurements of greenhouse gases in the atmosphere?

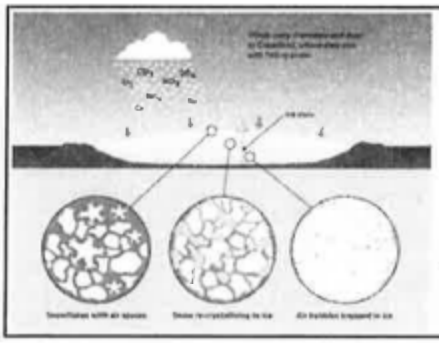

Measuring greenhouse gas changes in the atmosphere
Mauna Loa Observatory (Hawaii)
https://www.esrl.noaa.gov/gmd/obop/mlo/gallery/

Direct measurements of CO_2 in the atmosphere

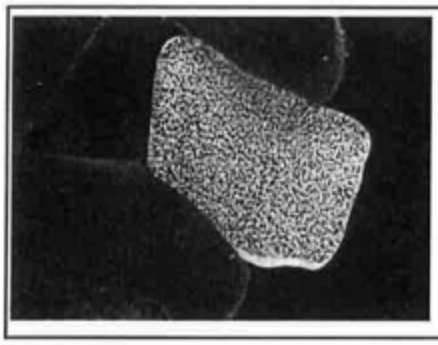


Charles Keeling receives the National Medal of Science from President Bush

We also measure CO_2 in ice cores

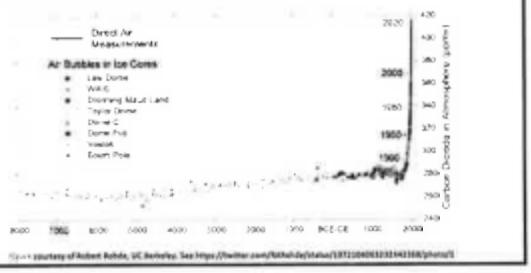


Air bubbles in Antarctic ice



By CSIRO, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=35439336

10,000 years of atmospheric CO_2 levels: Combined data from direct air measurements and ice cores



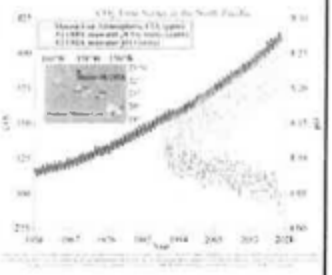
800,000 years of atmospheric CO_2 levels: Combined data from direct air measurements and ice cores

How do we know that most of the recent increase in atmospheric CO_2 is due to human activities?

- Oceans are acidifying
- Atmospheric oxygen is decreasing
- Isotopic carbon ratios are changing

Oceans are acidifying

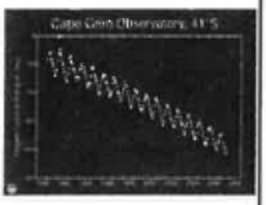
- The oceans store the largest amount of the Earth's carbon, so if the atmospheric CO_2 increase were "natural", it would likely be coming from the oceans – ocean pH would rise
- But we know the CO_2 increase is not coming from the oceans because the pH of the oceans is dropping



https://www.skepticalscience.com/co2-increase-is-natural-not-human-caused.htm

Atmospheric oxygen is decreasing

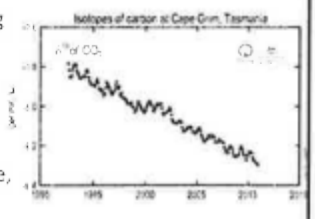
- Burning carbon requires oxygen; when we burn an atom of carbon, the required oxygen becomes part of the CO_2 molecule
- The CO_2 increase from burning fossil fuels should be accompanied by a decrease in atmospheric oxygen – which is what has been observed



https://www.skepticalscience.com/co2-increase-is-natural-not-human-caused.htm

Isotopic carbon ratios are changing

- CO_2 produced from burning fossil fuels has a different isotopic signature from natural CO_2 in the atmosphere
- As CO_2 from burning fossil fuels is released into (and mixes with) the atmosphere, the average ratio of Carbon^{13} to Carbon^{12} decreases



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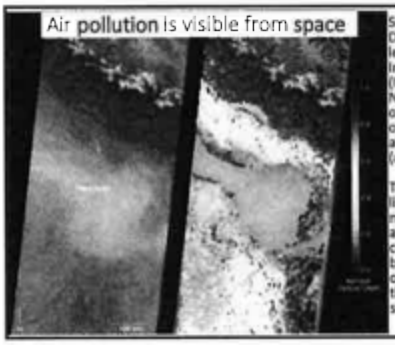
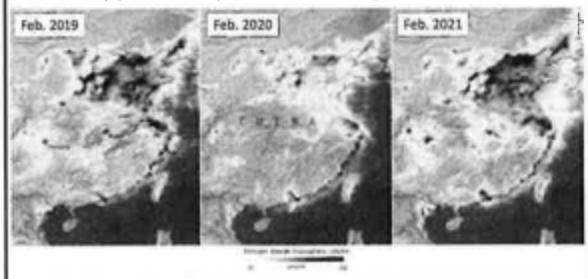
Air pollution is visible from space



Severe air pollution over New **Delhi** in Nov. 2016. **Image** on **left** is from **Multi-angle Imaging Spectro-Radiometer (MISR) instrument** aboard **NASA's** Terra satellite. Image **on** right is map of aerosol **optical** depth – a measure of **abundance** of tiny particles **(aerosols)** in atmosphere.

The extreme air pollution was **likely due** to combination of **nearby** agricultural burning **after harvest,** urban **construction & solid-waste burning,** & other factors. An **optical depth** of 1.0 **means that only about 37% of direct sunlight reaches the surface.**

What happened to pollution during lockdown?



https://cdn.cnn.com/cnnnext/dam/assets/210315165946-pollution-air-covid-19-rise-trnd-exlarge-169.jpg

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Deforestation in Cambodia

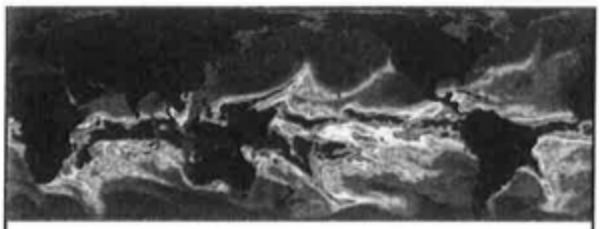
Land surface changes through urbanization

Animation of changes in areal extent of Los Angeles over time
http://www.atlasofurbanexpansion.org/historical-data

Changes in urban extents were identified using a combination of historical maps and satellite imagery
Source: http://www.atlasofurbanexpansion.org/historical-data

Summary of Part 1

- Climate is influenced by:
  - Natural factors (the Sun, volcanoes, internal variability)
  - Human factors (greenhouse gases, particulate pollution, land surface changes)
- How we separate natural and human influences on climate is the subject of Part 2



Introduction to Climate Science: Part 2

Ben Santer
Visiting Researcher, UCLA

What Part 2 will cover

- Climate fingerprinting 101
- Fingerprinting and the 2021 Nobel Physics Prize
- Fingerprinting examples
- Looking at the causes of changes in extreme events
- Satellite temperature data
- Conclusions

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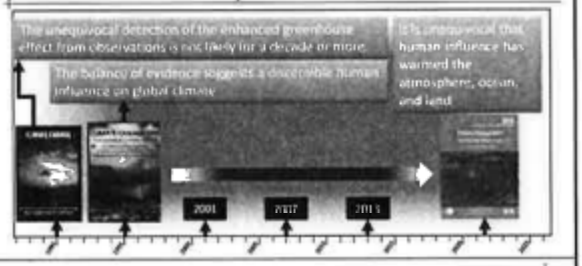
The arc of history...



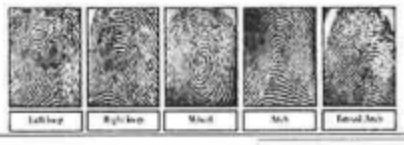
How was scientific progress made?

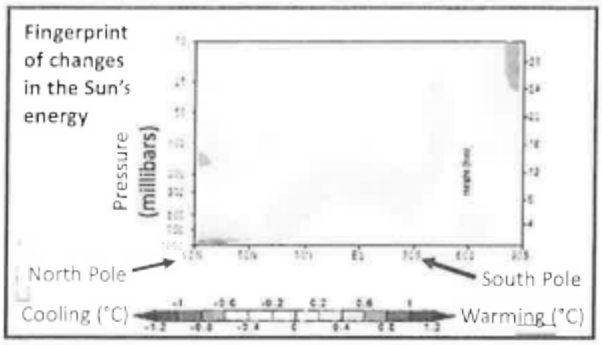
- Improved (and more) climate models
- Better understanding of factors that affect climate
- Improved (and longer) observed climate records
- Community-wide analysis of climate model results
- Infrastructure for sharing climate model output
- "Climate fingerprinting"

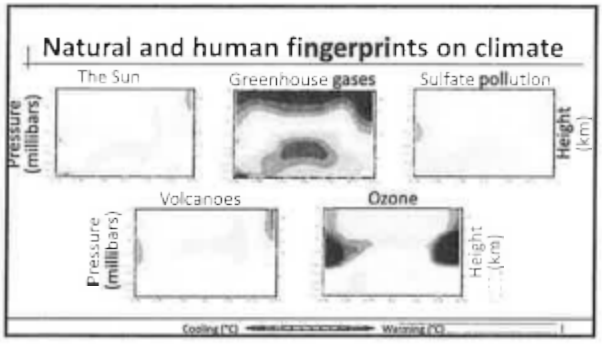
What is "climate fingerprinting"?

Basic idea:

- Different influences on climate have different signatures
- Signatures are easier to discern in patterns ("fingerprints")







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Hasselmann: The power of patterns


Klaus Hasselmann

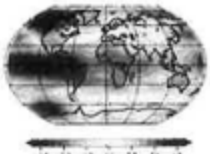
2021 Nobel Physics Prize
Awarded for developing:
"...methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in the climate"

Using patterns to discriminate between human and natural effects on climate

Human fingerprint


Pattern amplitude

Natural climate variability


Pattern **amplitude**

Manabe: Using models to understand the real-world climate **system**


Syukuro Manabe

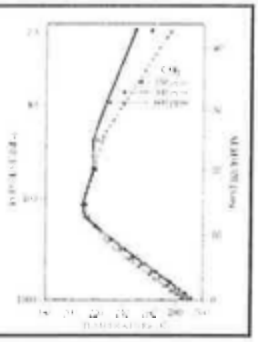
2021 Nobel Physics Prize
Awarded for:
"...the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

Manabe and Wetherald, 1967

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

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

(Manuscript received 2 November 1966)



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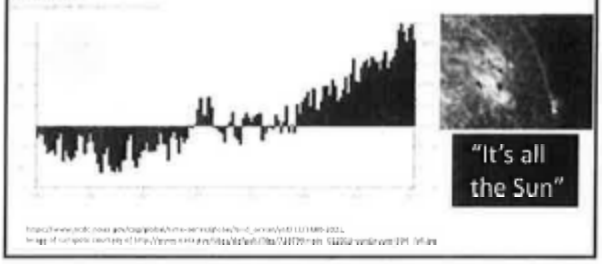
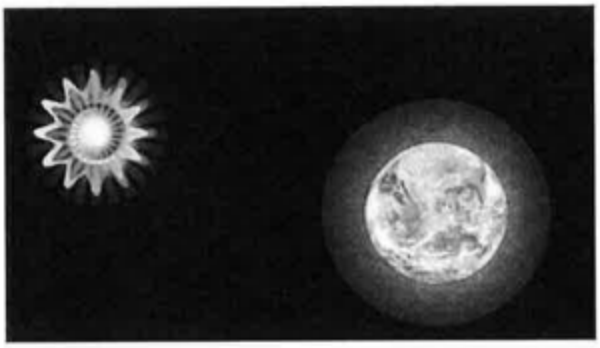
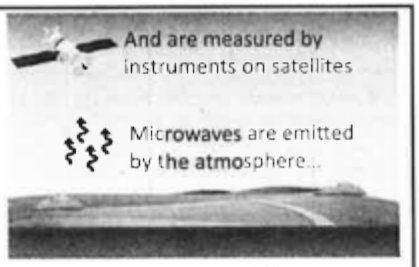
Example 1





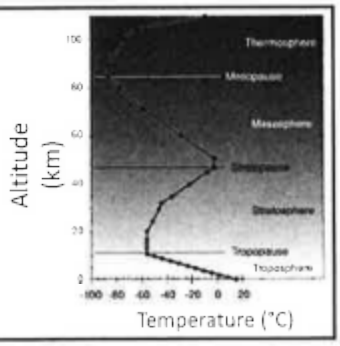
Measuring atmospheric temperature from space

- Higher temperatures = More microwave emissions from oxygen molecules



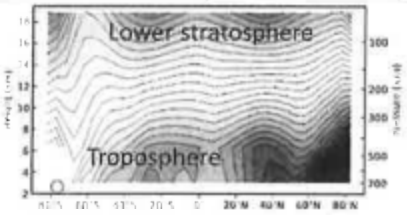
- By choosing different microwave frequencies, different atmospheric layers can be measured

Different layers of Earth's atmosphere



Satellite temperature data show the atmospheric temperature fingerprint predicted by Manabe

Satellite observations (Santa Rosa, CA)

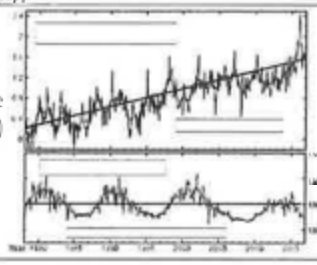


Temp. trend over 1979 to 2020 °C/decade

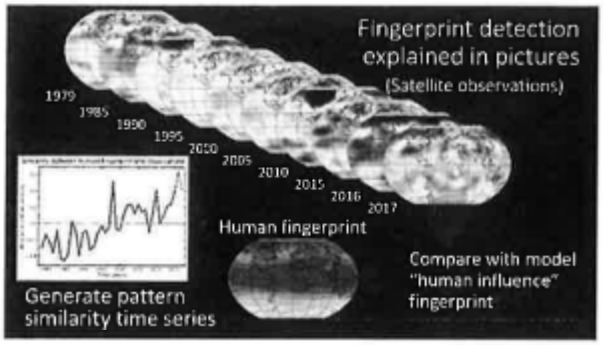
Santer et al., *Proceedings of U.S. National Academy of Sciences*, 2013 (updated)

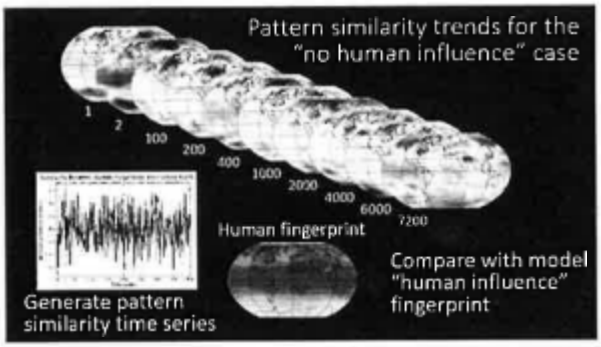
Other evidence against "the Sun explains all surface **warming" hypothesis**

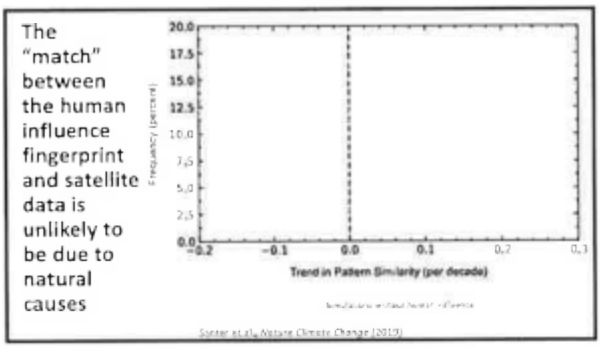
Surface Temperature Anomaly (°F)

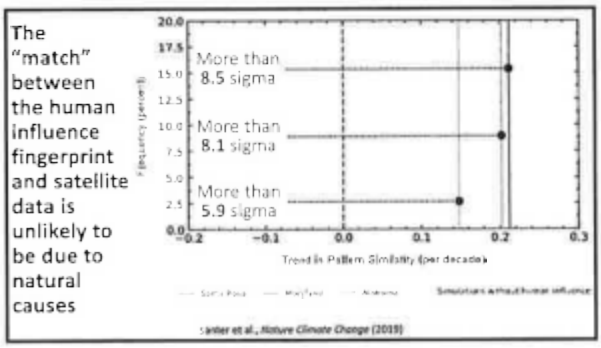


Total Solar Irradiance (TSI; W/m²)




Pattern similarity trends for the "no human influence" case
1
2
100
200
400
1000
2000
4000
6000
7200
Human fingerprint
Compare with model "human influence" fingerprint
Generate pattern similarity time series


The "match" between the human influence fingerprint and satellite data is unlikely to be due to natural causes
Trend in Pattern Similarity (per decade)


The "match" between the human influence fingerprint and satellite data is unlikely to be due to natural causes
More than 8.5 sigma
More than 8.1 sigma
More than 5.9 sigma
Trend in Pattern Similarity (per decade)

Fingerprinting has moved beyond "temperature only" studies

- Climate scientists have identified human "fingerprints" in many different aspects of the climate system – not just in temperature

- Changes in different climate variables are physically and internally consistent, and are independently monitored with a wide range of instruments

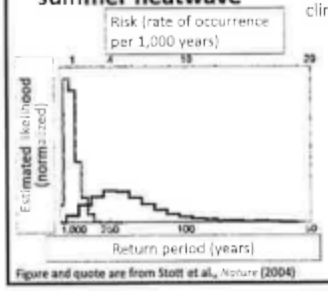
What Part 2 will cover

- Climate fingerprinting 101
- Fingerprinting and the 2021 Nobel Physics Prize
- Fingerprinting examples
- Looking at the causes of changes in extreme events
- Satellite temperature data
- Conclusions

The 2003 European summer heatwave

- July and August 2003
- Health crises in several countries
- Estimated death toll: 72,000*

The 2003 European summer heatwave



Histogram of return periods without human-caused climate change

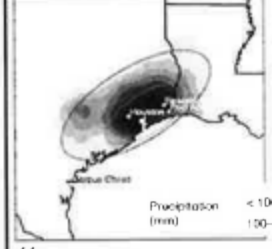
Histogram of return periods with human-caused climate change

"We estimate it is very likely (confidence level >90%) that human influence has at least doubled the risk of a heatwave exceeding this threshold magnitude."

Figure and quote are from Stott et al., Nature (2004)

Hurricane Harvey (2017)

- Category 4 hurricane
- Landfall: August 2017
- $125 billion in damages
- More than 100 deaths
- Peak rainfall: > 60 inches in 4 days



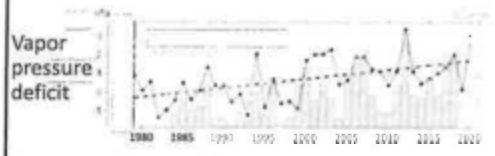
Event attribution: Hurricane Harvey

Precipitation total for Houston region from 25 to 31 August (2017)

"...Anthropogenic climate change likely increased Hurricane Harvey's total rainfall by at least 19% with a best estimate of **38%**."

Figure and quote from Risser and Wehner, Geophysical Research Letters (2017)

Changes in wildfire weather



Fingerprinting with changes in vapor pressure deficit

Zhuang et al., *Proceedings of U.S. National Academy of Sciences*, 2021

Event attribution: Legal issues and questions

- Can we reliably estimate the human contribution to the extreme event's likelihood?
- In estimating this contribution, are the key uncertainties well-quantified?
- Are there reliable damage estimates for the extreme event?

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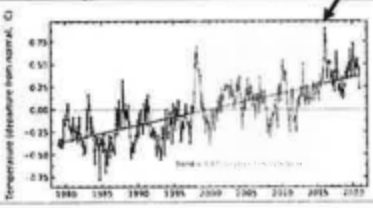
Satellite temperature data: Technical issues

- Satellite orbit drift
- Satellite altitude decay
- Drift in calibration of microwave sounder on the satellite
- Change in type of instrument

Satellite temperature data

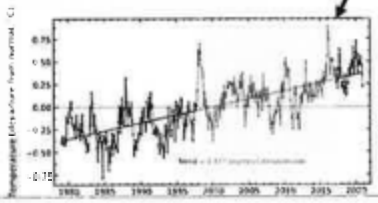
Dec. 2015



"No significant global warming for the past 18 years" Senator Ted Cruz on Dec. 8, 2015 (see also earlier claim by Senator Cruz on Late Night with Seth Meyers, Mar. 16, 2015)

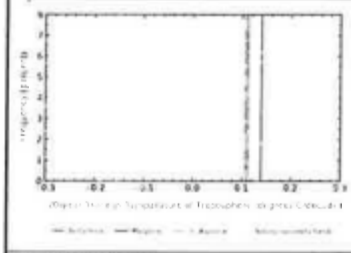
Satellite temperature data

Jan. 2017



"Satellite data show leveling off of warming over the past two decades" EPA Administrator Scott Pruitt, Jan. 18, 2017

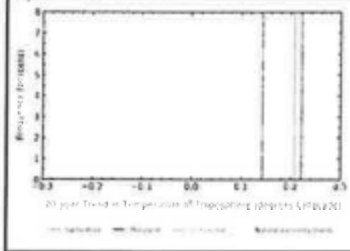
Testing the "leveling off of warming claim"



Probability that final 20-year warming trend in satellite data could be natural

Santa Rosa	1.6%
Maryland	3.1%
Alabama	6.3%

Testing the "leveling off of warming claim"



Probability that average of all possible 20-year trends in satellite data could be natural

Santa Rosa	0.007%
Maryland	0.006%
Alabama	1.7%

Summary

- "Climate fingerprinting" uses pattern information to separate human and natural effects on climate
- It was developed in the late 1970s
- Human fingerprints on climate are unequivocal and ubiquitous
- Today, scientists routinely estimate the impacts of climate change on extreme events
- Satellite temperatures show significant global warming

Resources

- https://www.nap.edu/catalog/25733/climate-change-evidence-and-causes-update-2020
- https://www.nap.edu/catalog/21852/attribution-of-extreme-weather-events-in-the-context-of-climate-change
- https://www.nap.edu/catalog/12781/americas-climate-choices
- https://www.nap.edu/catalog/12181/carbon-dioxide-and-climate-a-scientific-assessment