Energy Balance and its Discontents: Fundamentals of Climate and Issues with Solar GeoEngineering

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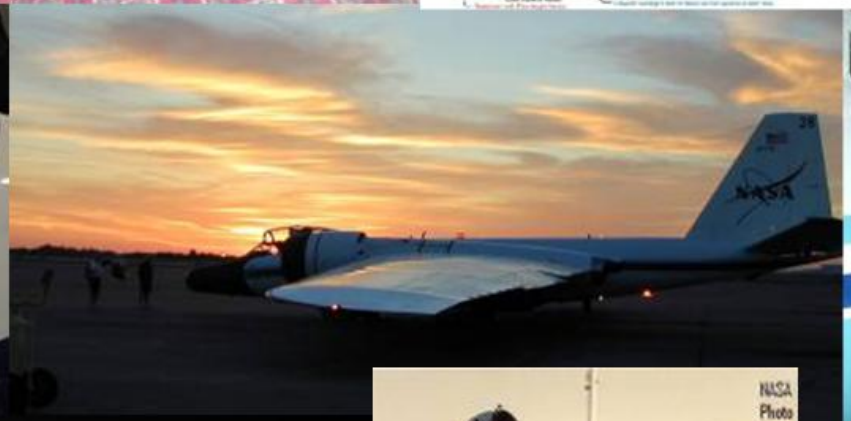
- **University of Denver, Mechanical and Materials Engineering**

- **Research Interests:**
  - **Aerosol sampling and measurement from aircraft**
  - **Stratospheric aerosol characterization**
  - **Stratospheric ozone depetion**
  - **Air quality**
  - **Climate Change**
- **Research Tools**
  - **Instruments to sample, collect and characterize size and abundance of aerosol particles from nanometers to microns in size. Collected samples analyzed with X-ray fluorescence and electron microscopy**
  - **Aircraft operated by NASA, NOAA, NCAR, UK operating drom the surface to 22 km altidude depending on topic (See next slide for a sample). Instruments had to meet requirements and pass flight readiness reviews**



Nixon thru Trump 1st

Assessed Science

- Montreal Protocol 1987. 198 Parties. Universally ratified. Succeeded in arresting stratospheric ozone depletion.
  - Quadrennial science reports under auspicies of the Protocol
  - Hundreds of scientist authors from dozens of countries, >100 expert reviewers
  - https://csl.noaa.gov/assessments/ozone/2022/executivesummary/

- IPCC set up in 1988 by the WMO and UNEP to provide assessments to UNFCCC (195 Members). UNFCCC is the United Nations Framework Convention on Climate Change. Every country on the planet belongs to the UNFCCC and the IPCC. Maybe its every country but one. Have to check.
  - Hundreds of scientists act as authors, reviewers and editors.
  - Defined rules and roles.
  - Climate Change 2021 was 6th science report of the IPCC. 7th underway.

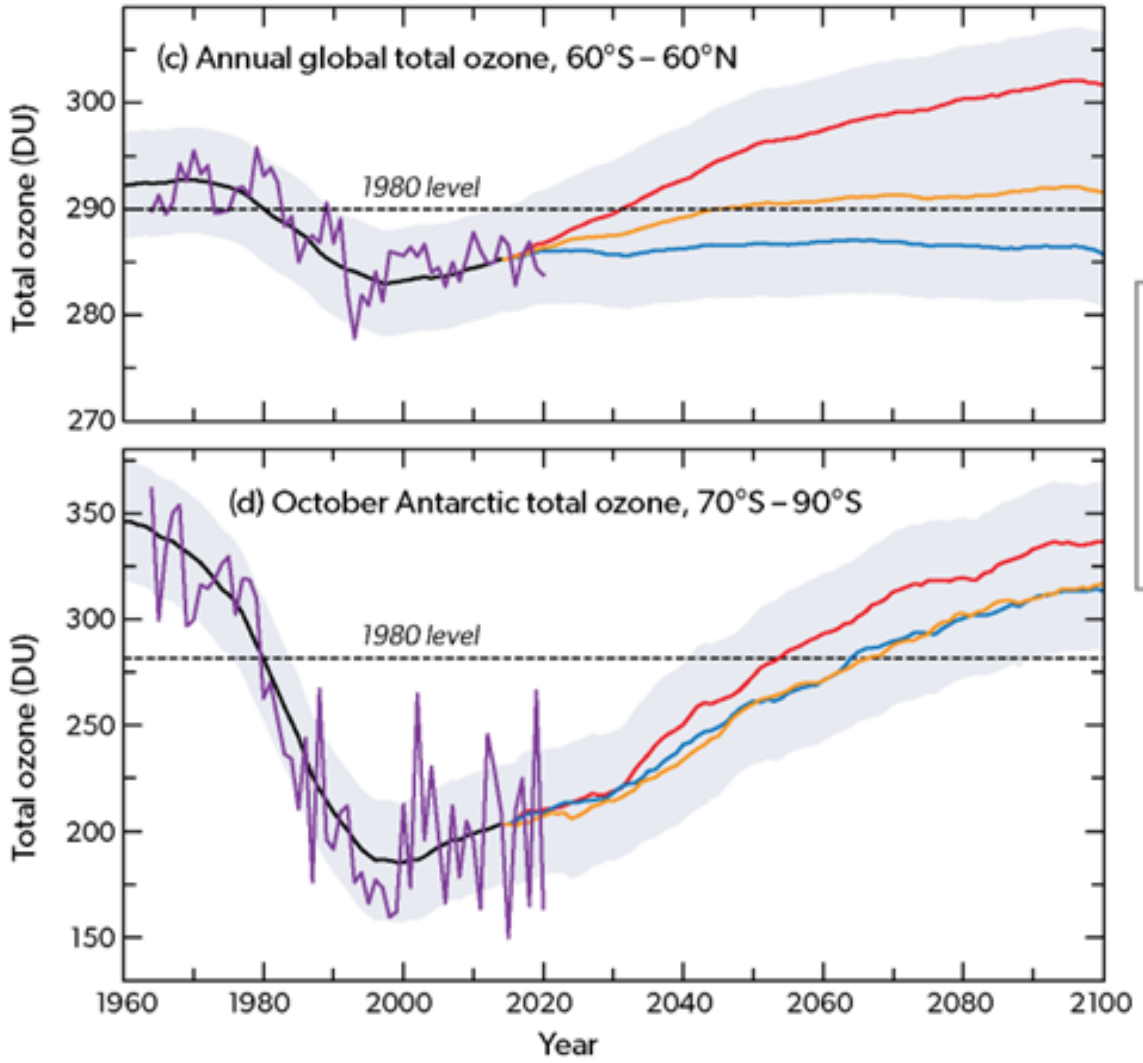
No new Assessed Science available for this talk. But the IPCC documents have an advantage over individual refereed papers in that assessments were created in a context of intense scrutiny of the entire refereed literature.

There is a lot of misinformation circulating under the guise of "Reports." Check their breadth and depth before accepting them as authoritative.

SOME STATS:
IPCC 6th WG1 Report: The Scientific Basis, 2021
2409 Pages
198 Coordinating Lead Authors and Lead Authors
36 Review Editors
615 Contributing Authors
78,007 Review Comments submitted by 1891 expert reviewers and 47 governments. Comments and responses are online
"For the first time in the IPCC, WGI recommended the implementation
of FAIR (findable, accessible, interoperable, reusable) data principles
in the assessment to document and curate the data assessed and included in report figures."

They review and assess the science. They do not do research as IPCC. All member states can nominate people for these roles.

Montreal Protocol Results
Policy driven by Assessed Science Worked for stratospheric ozone (killed by CFCs)



1% reduction in stratospheric ozone -> 2% increase in skin cancer (light skin). Ban on existing refrigerants made life more expensive in poor countries.

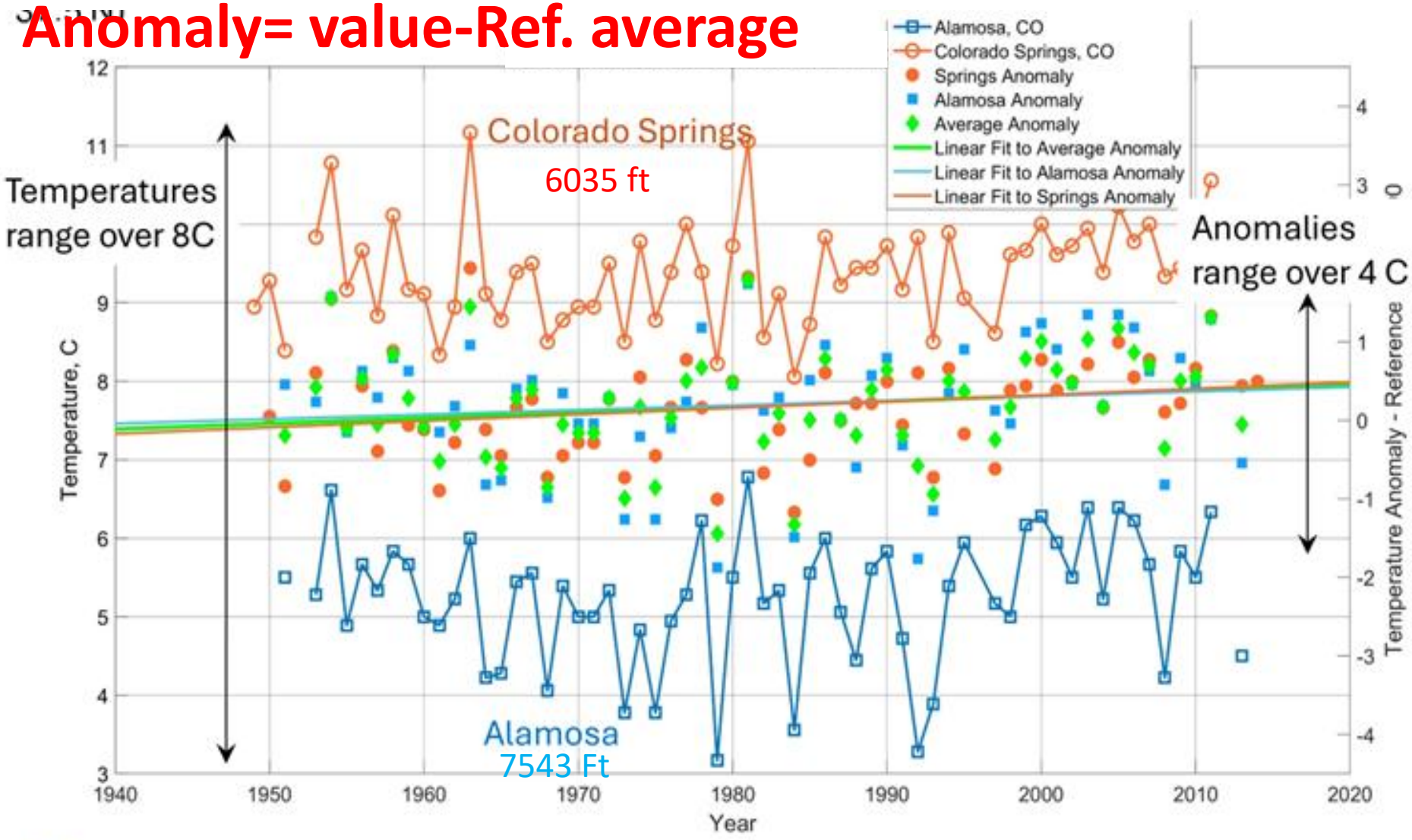
So the Protocol arranged for the Global North to help pay the Global South to buy the new expensive refrigerants. Chemical companies happy. Entire planet participated.

Fundamentals of Climate Science

- Definitions
- Measurements and Results
- Physical Principles and Explanations

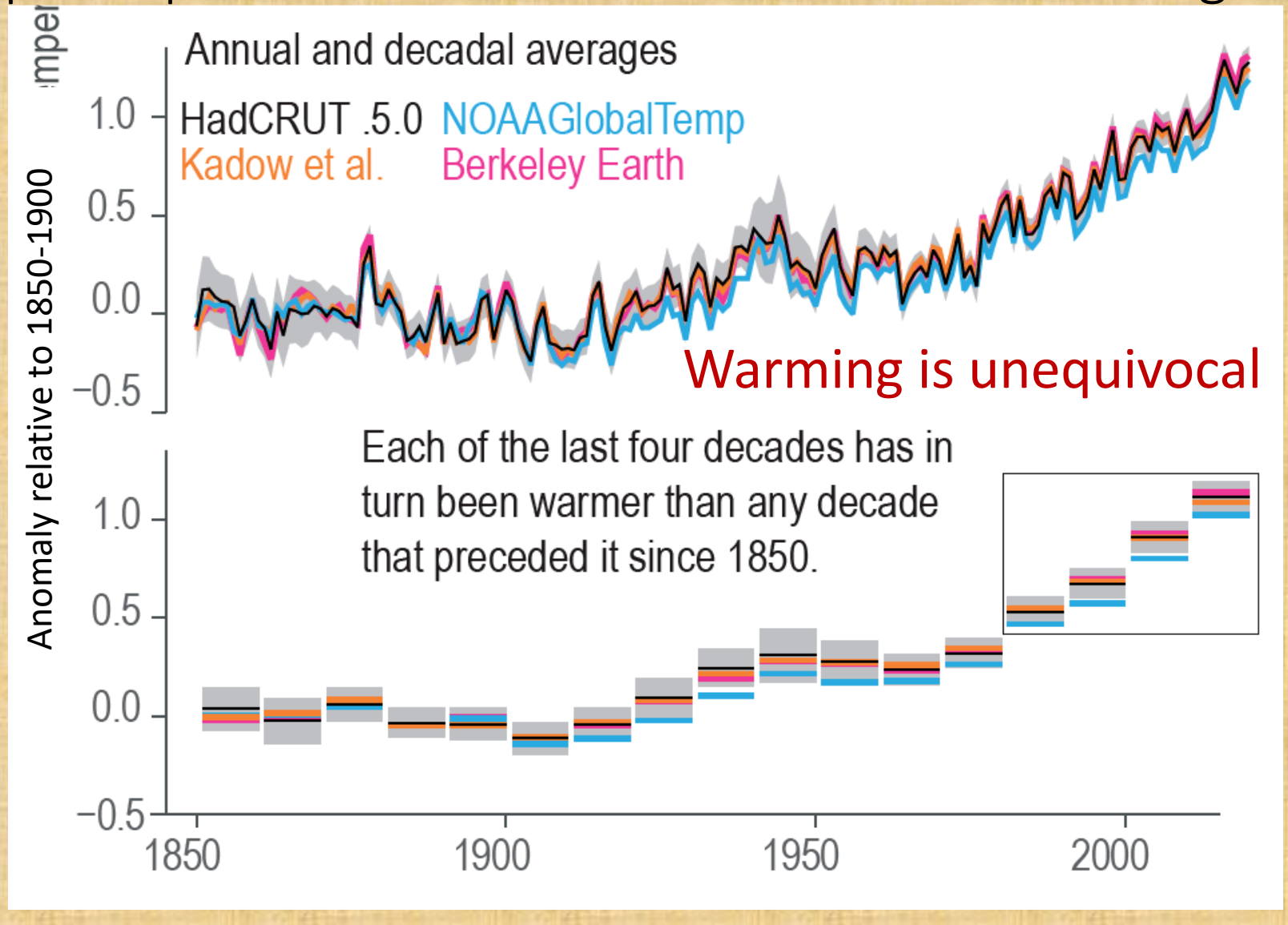
Example of Temperature Anomaly in Two CO towns. Different altitude. Similar Anomalies.

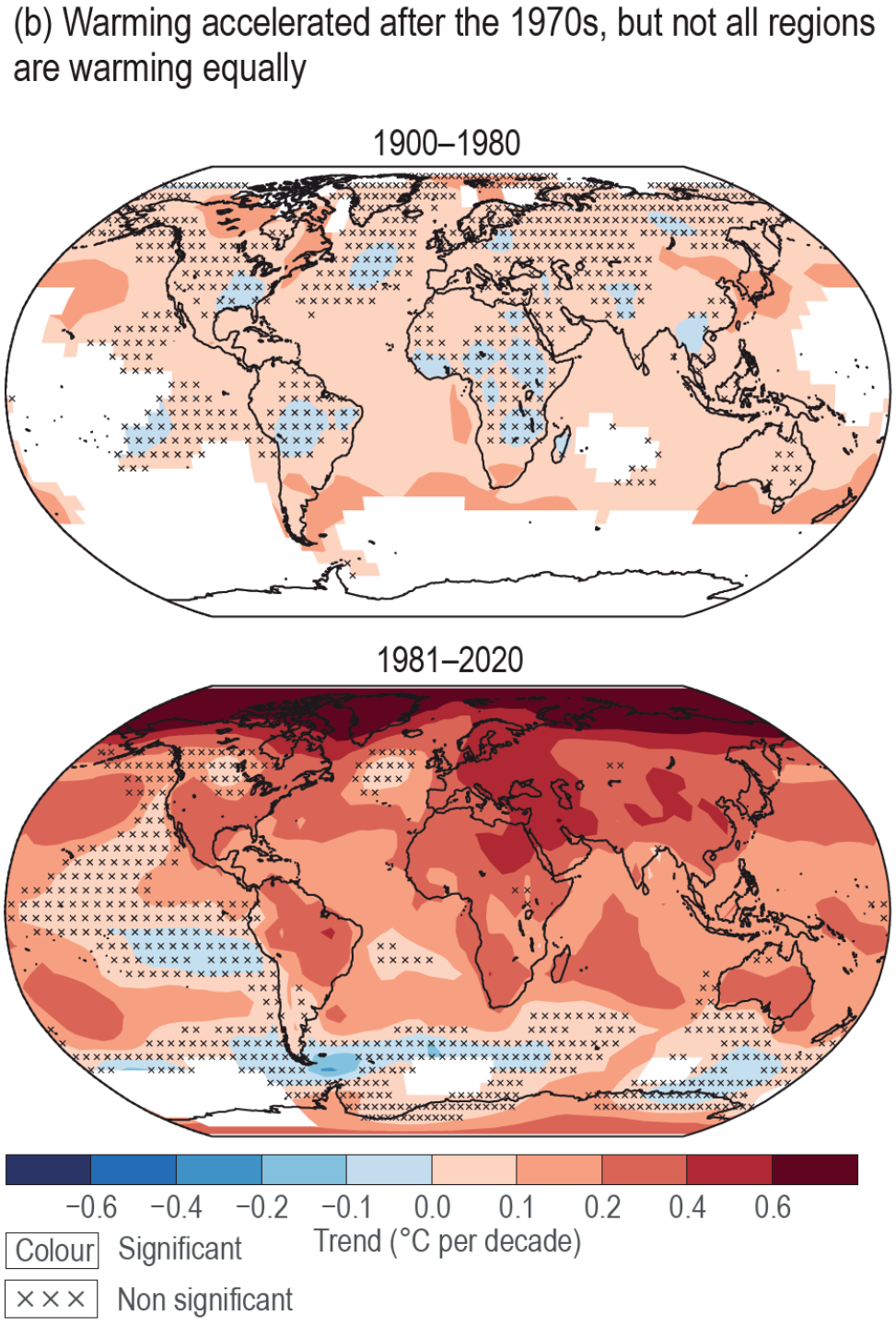
Anomaly= value-Ref. average



IPCC WG1 AR6 Fig 2.11

Intergovernmental Panel on Climate Change Working Group 1 Report of the 6th Assessment. Global Average





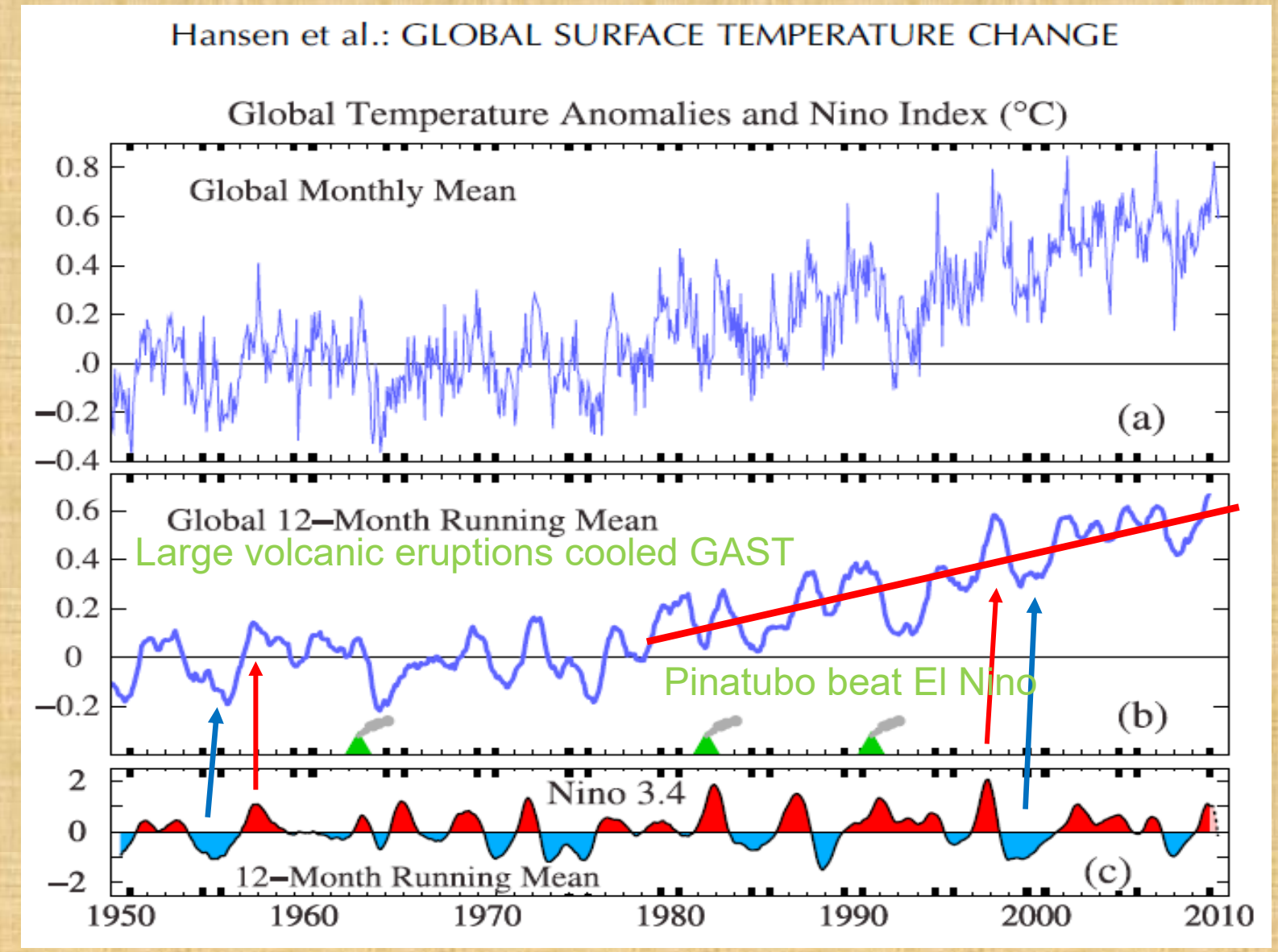
IPCC WG1 AR6 Fig 2.11

Trends more significant in later period.

Artic region is warming fastest. The loss of sea ice for much of the summer results in increased absorption of solar energy by the dark water which leads to more melting and more absoption. Water evaporates increasing the humidity and water vapor is an added GHG which adds warming. Words are easy to say but careful analysis suggests it is a little complicated.

FOX News Photo from Pearl Street in Boulder CO Looking toward Louisville and Superior Dec 30, 2021. Marshall Fire. 1000 homes burned in hours. 2 died. ~100 mph winds across Hwy 93. NWS reports that fires under those conditions are unfightable. 20 largest fires in Colorado history occurred after 2000. Anything changing?

Variability and Trend: ENSO Volcanoes and CO_2

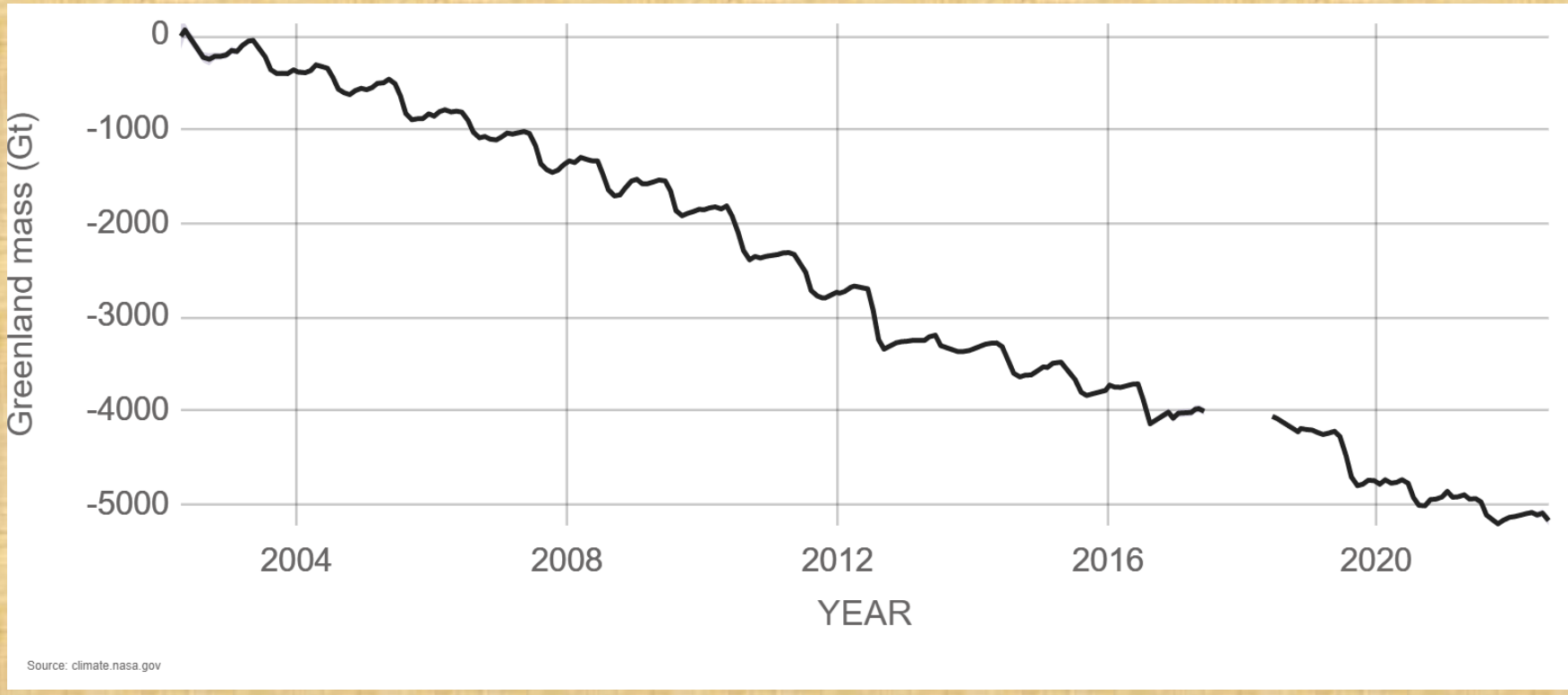


The Trend (red line) is due to CO2.

El Nino (Warms GAST)
La Nina (Cools GAST)
They tend to balance out.

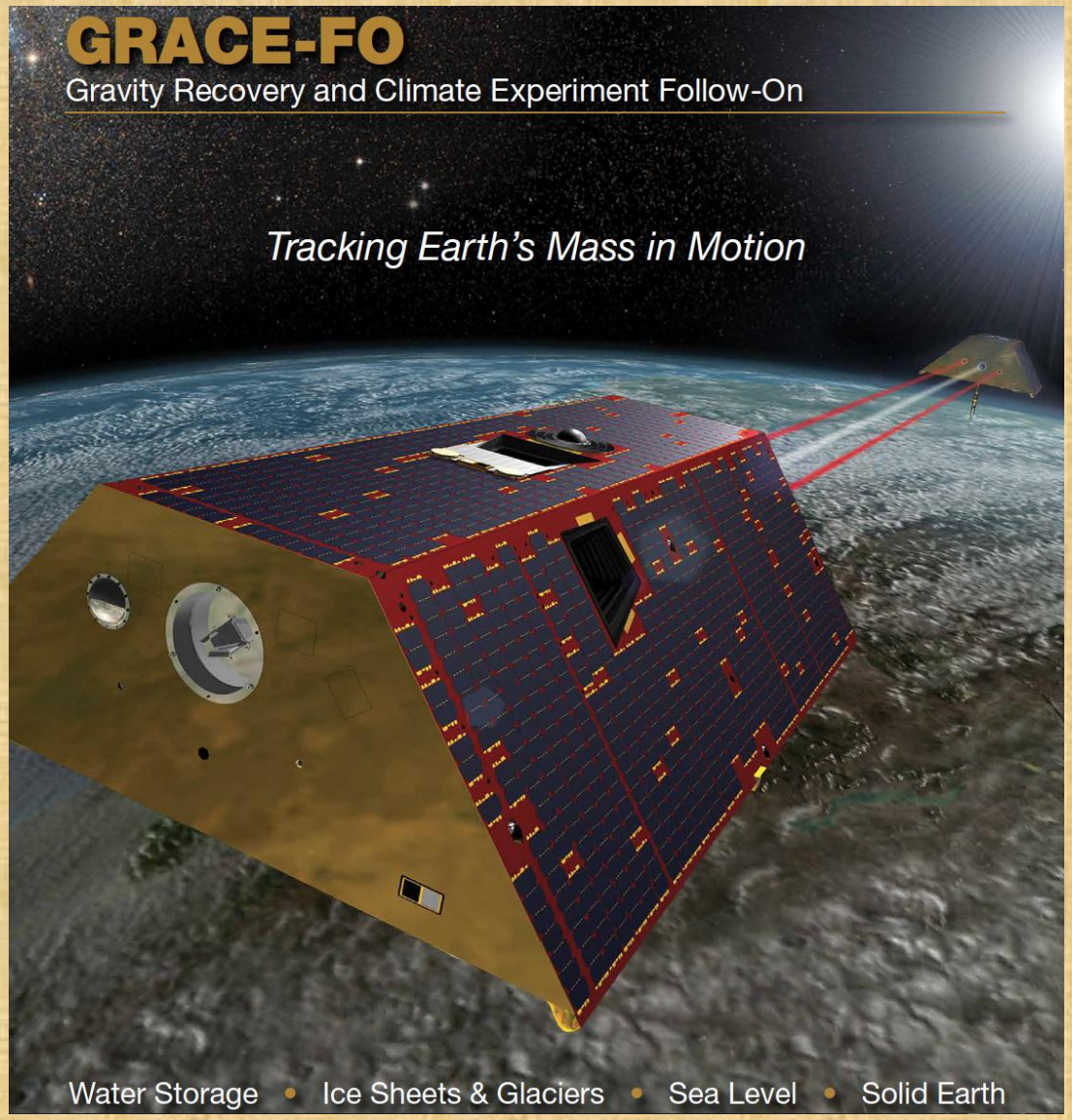
GRACE Greenland Ice Sheet Data

https://climate.nasa.gov/vital-signs/ice-sheets/



1 gigaton $=10^9$ metric tonnes $= 10^{12}$ kg

GRACE and GRACE-FO



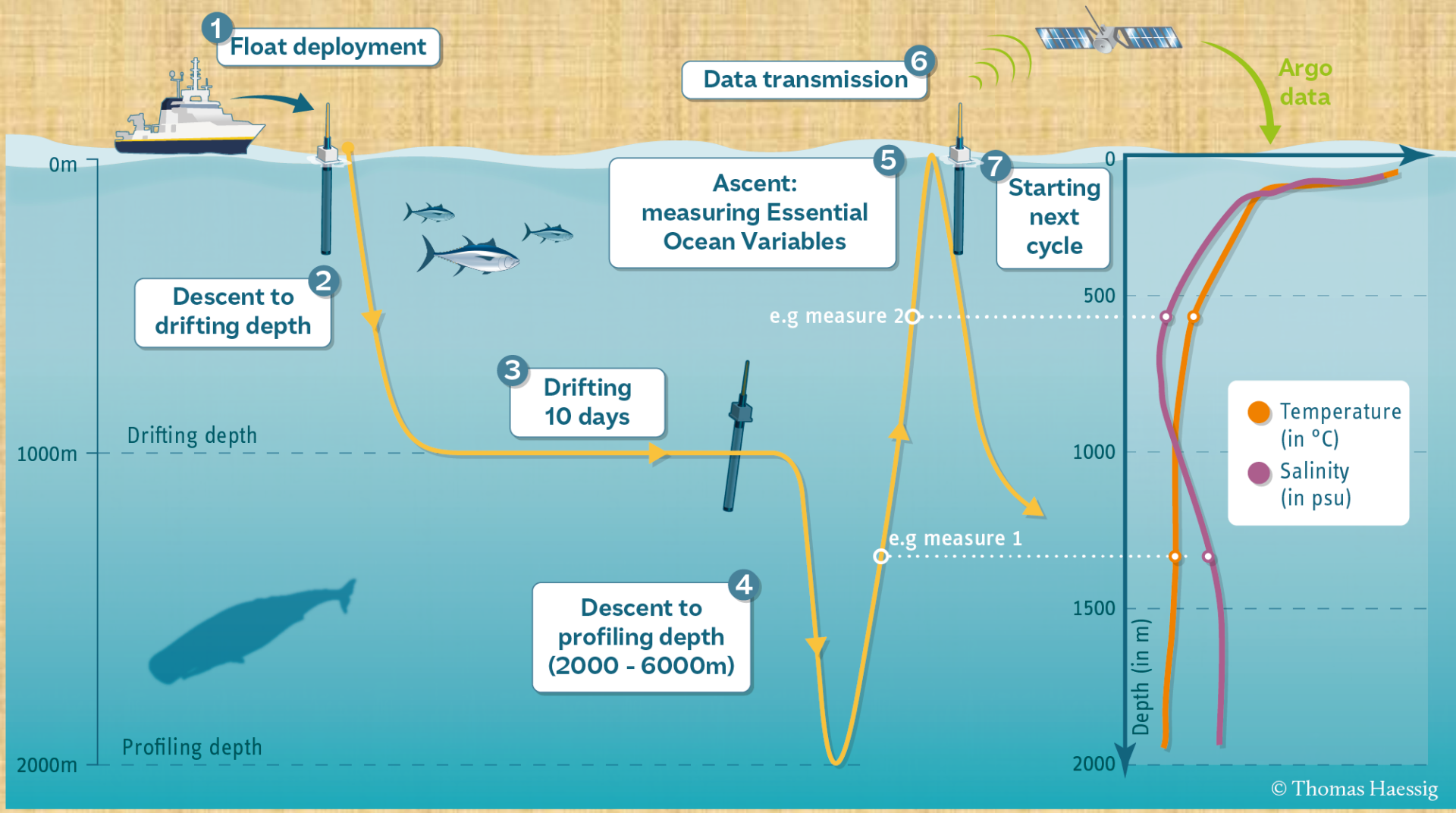
Grace and Grace-FO measure the distance between satelites very accurately. They use interferometry to monitor this distance continuously. When the lead satellite passes over accumulated mass it speeds up. The inter unit distance increases and is measured.

Example of Grace FO data use.

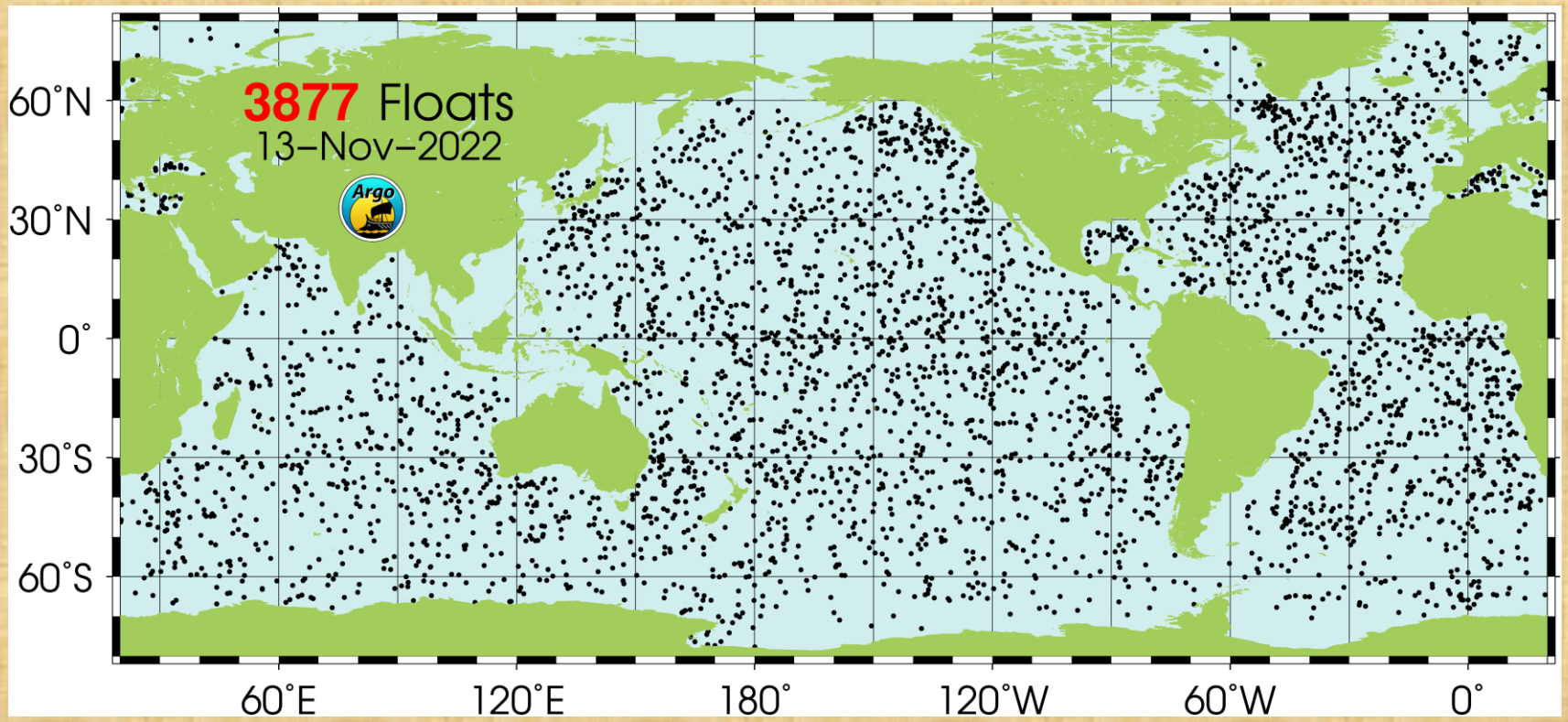
https://gracefo.jpl.nasa.gov/news/153/drought-in-the-northern-great-plains/

Deep Argo is going to 6,000 m
https://argo.ucsd.edu/about/mission/

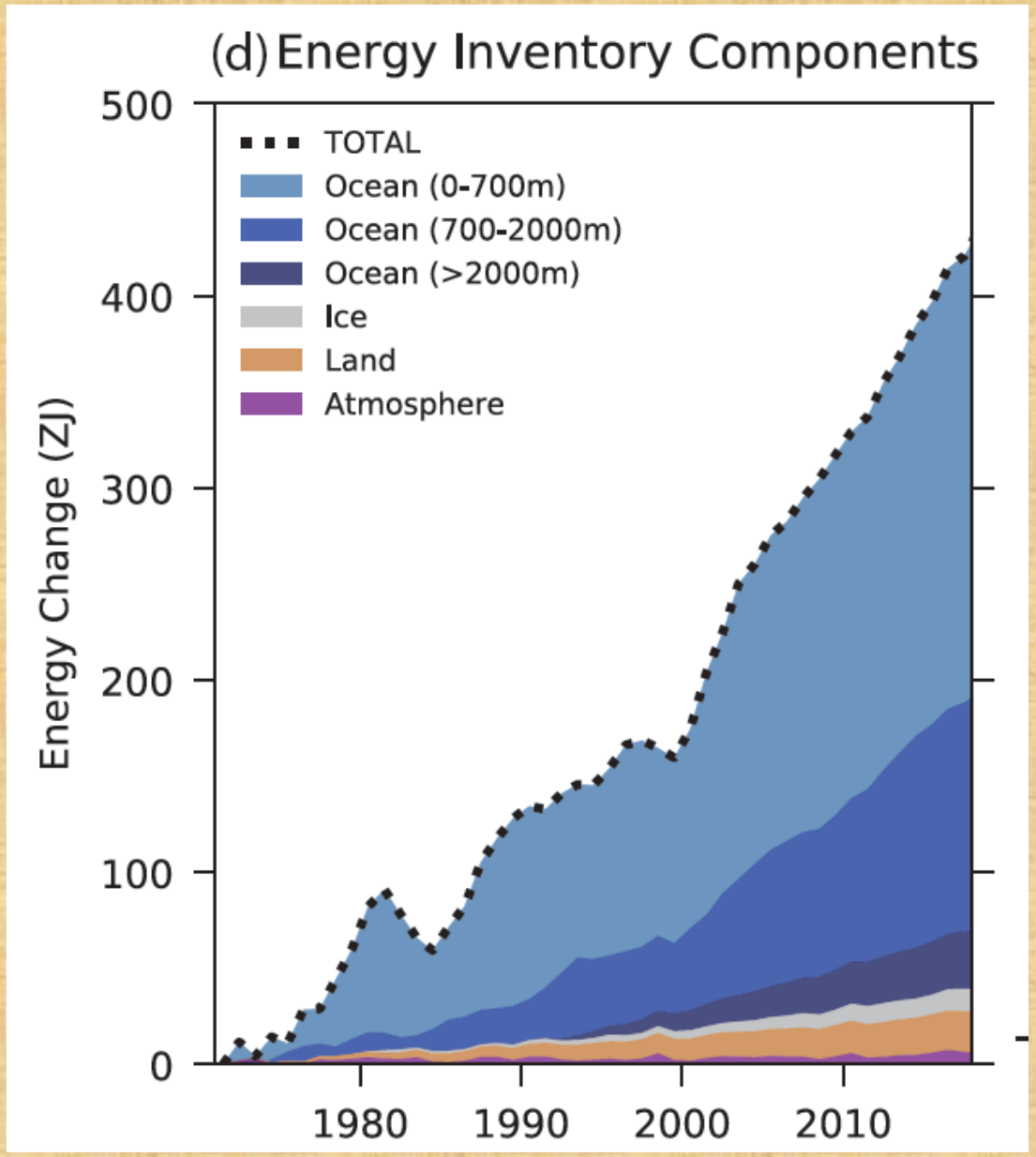
ARGO Floats



Coverage by ARGO Floats



Started in 2000, Over 2 million profiles by 2018.
Temperature accuracy to 0.002 C



Most of the added energy ends up in the ocean.

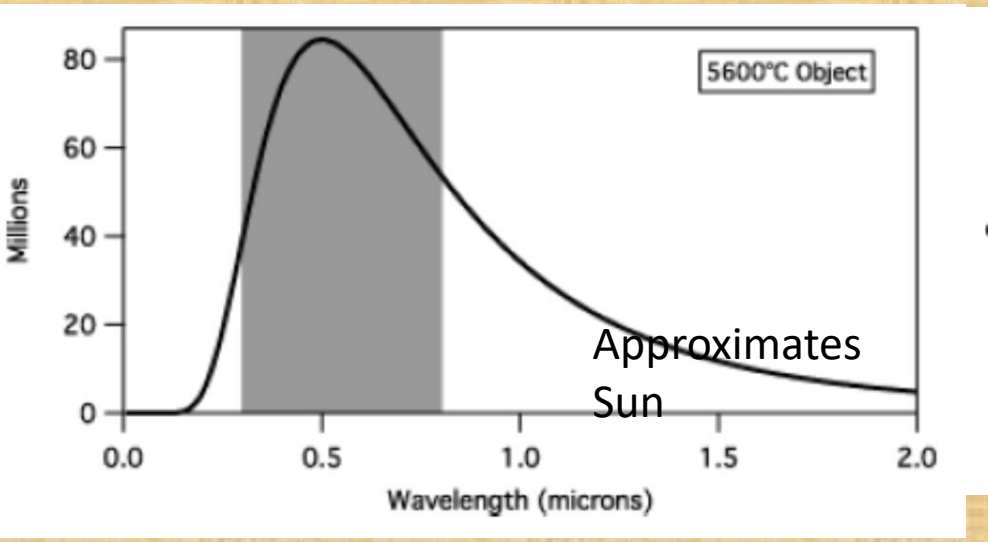
The Argo System monitored the ocean. Grace and Grace FO monitored the ice. The atmosphere was well monitored by the NOAA Advanced Microwave Sensing Units orbiting the earth. Boreholes were used to monitor the warming to the land.

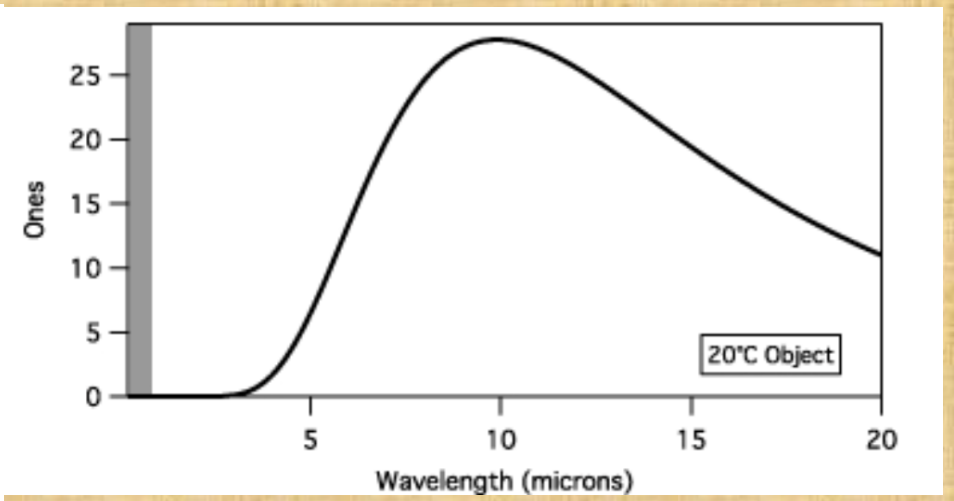
Prior to these technical advances, it was more challenging.

The energy of the absorbed photons was transferred to the land, water, ice and air. The result was warming, melting and evaporation governed by the First Law. Energy is conserved.

Essential Radiation Concepts

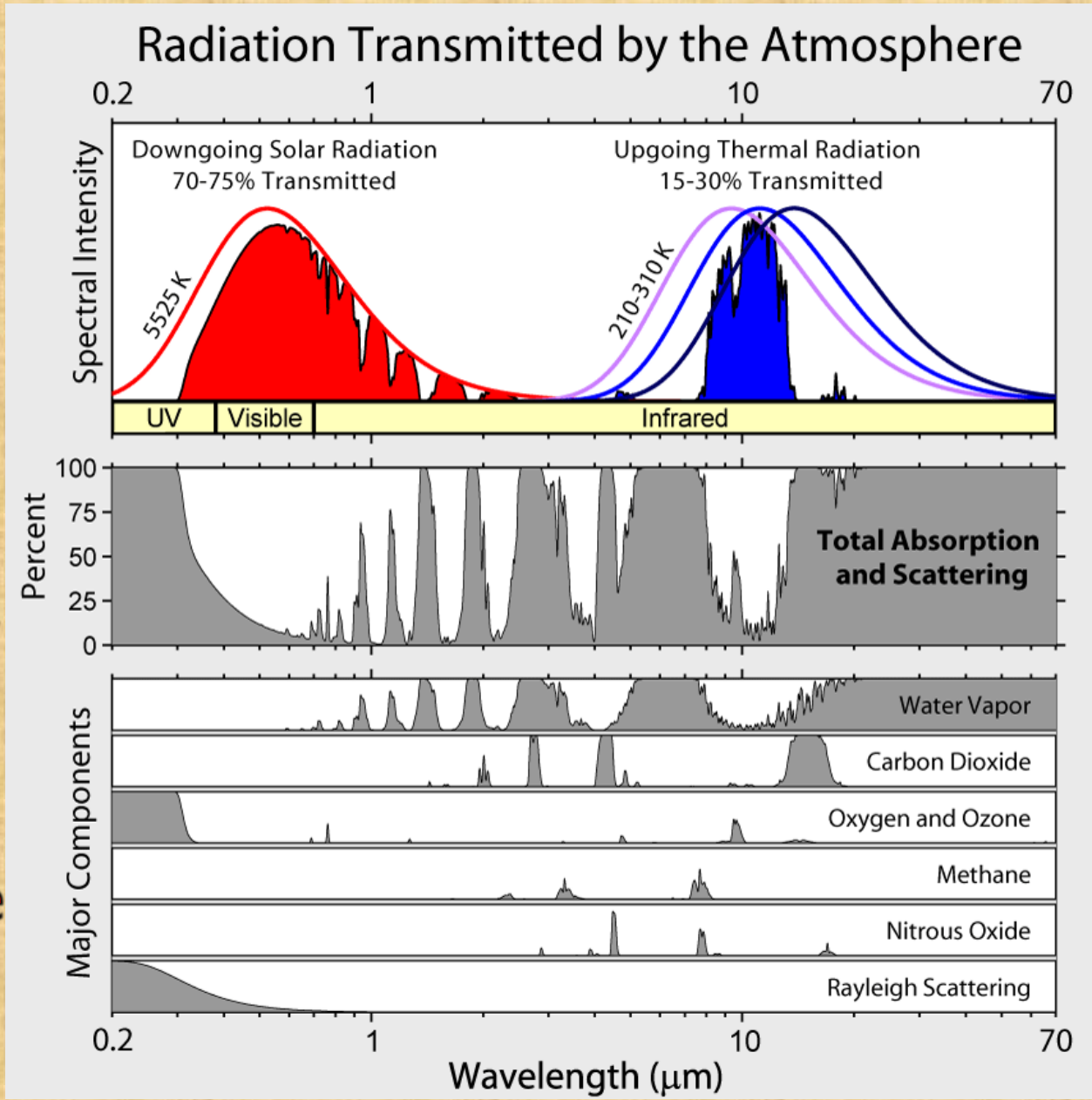
- Photons are discrete packets of electromagnetic energy
- Thermal radiation is emitted by all stuff warmer than absolute zero
  - P w/m^2 = σAT^4 T in Kelvin, A area m^2, σ = 5.67 x 10^{-8}





Vertical Axis: w/m^2/micron. Figure Andy Dessler. Solar radiation is short wavelength (shortwave)
Thermal radiation from Earth is long wavelength (longwave). Grey shows visible wavelengths.
Short wavelengths pass through GHGs. Some long wavelengths are absorbed.

Downward Solar Left (red) missing UV wavelengths due to absorption of UV by Stratospheric Ozone. Hence concern over depeletion.. Visible penetrates.
Upward Thermal Infrared absorbed by Greenhouse Gases in atmosphere. Absorption of long wave reduces escape of energy to space. Leads to imbalance and warming.



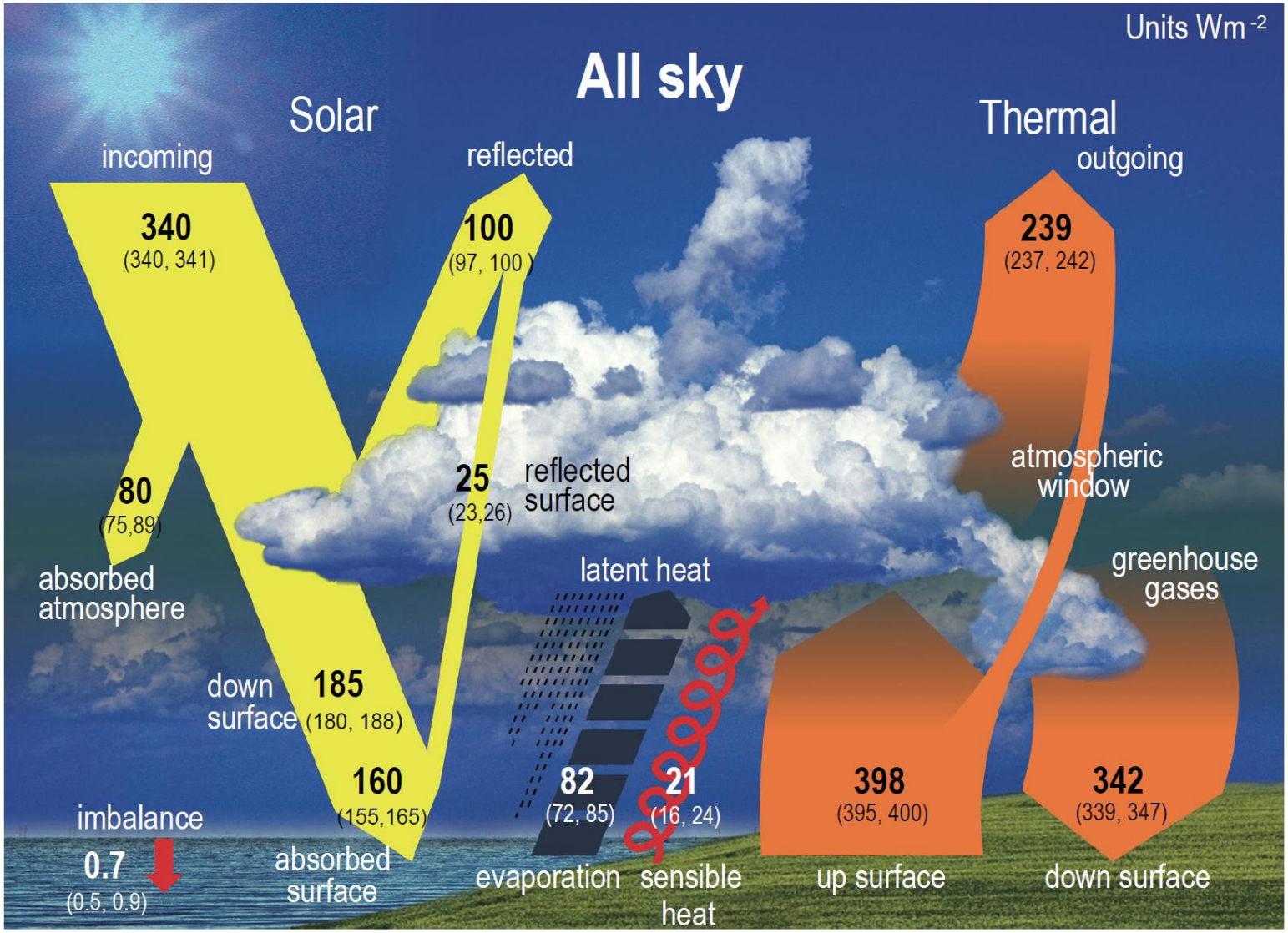
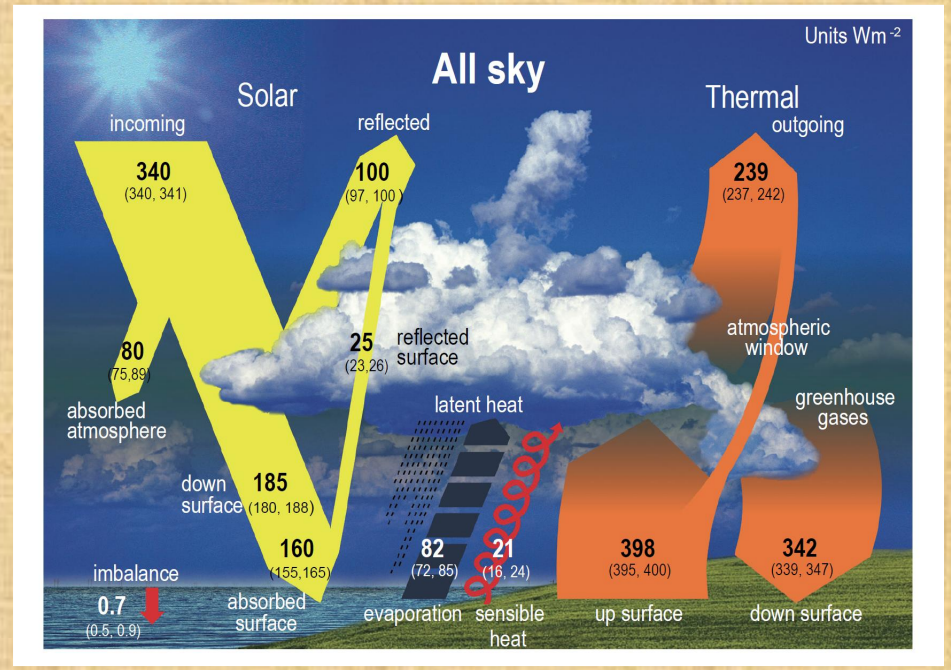


Figure 7.2 | Schematic representation of the global mean energy budget of the Earth. Beginning of 21st Century. IPCC WG1 AR6.

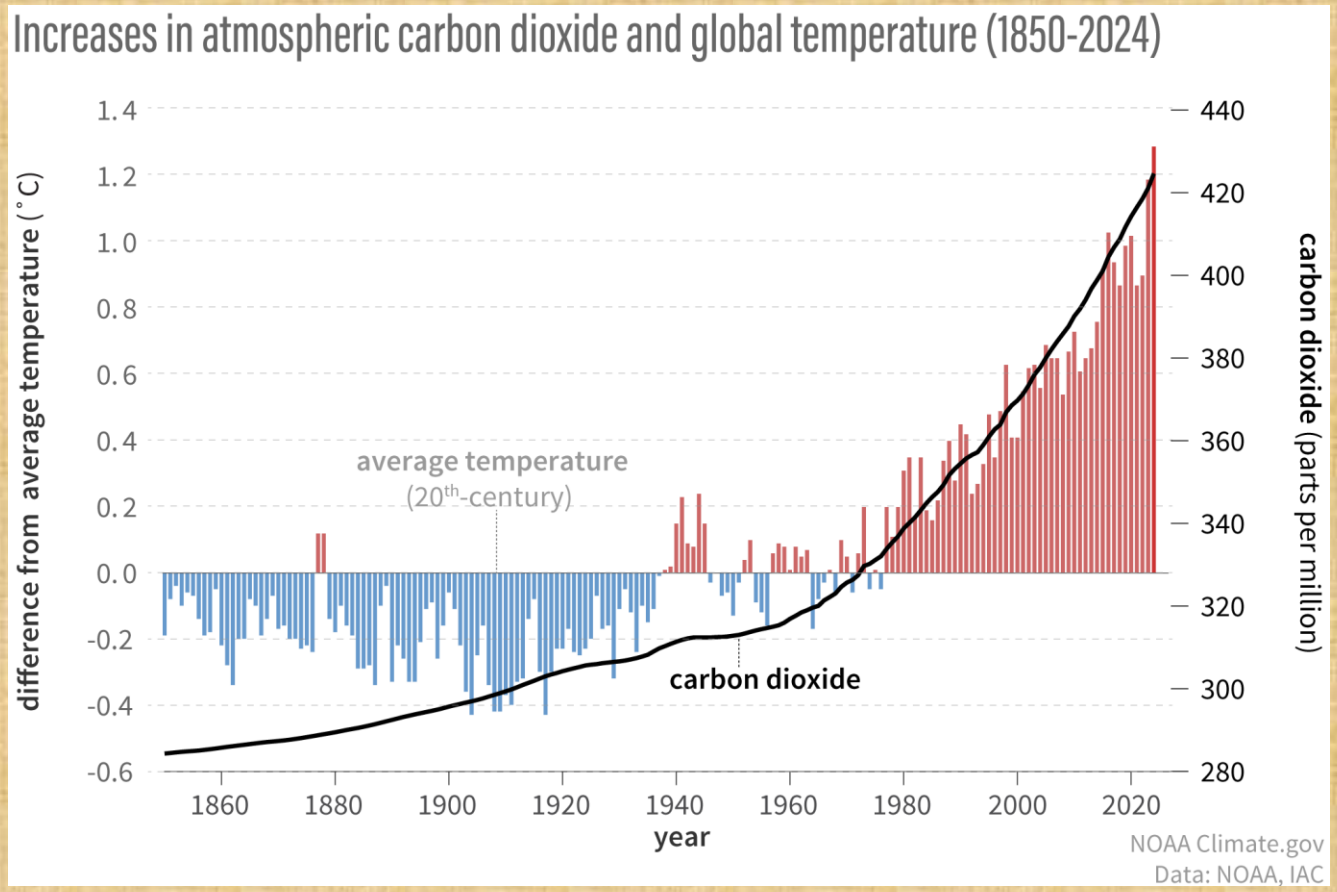
Incoming =340 W/m^2 , Outgoing = 239 thermal + 100 reflected = 339 W/m^2 , Imbalance =0.7 W/m^2

Water vapor is the most abundant greenhouse gas. Its abundance is controlled by atmospheric temperatures.
The long-lived greenhouse gases (CO2, CH4, N2O) are increasing the greenhouse effect as their abundances increase and are driving the increasing temperatures seen in the atmosphere.



Pictured radiation Imbalance contributes energy to the climate system. First law tells us that this energy will increase internal energy or do work. In climate this happens by warming, melting or evaporating. Work is done by climate as well in storms.
Warming the atmosphere or the surface works to restore balance because that increases the thermal radiation in the upward direction and that which escapes increases the outgoing radiation.
Warming may change cloud patterns which in turn may act to increase warming.

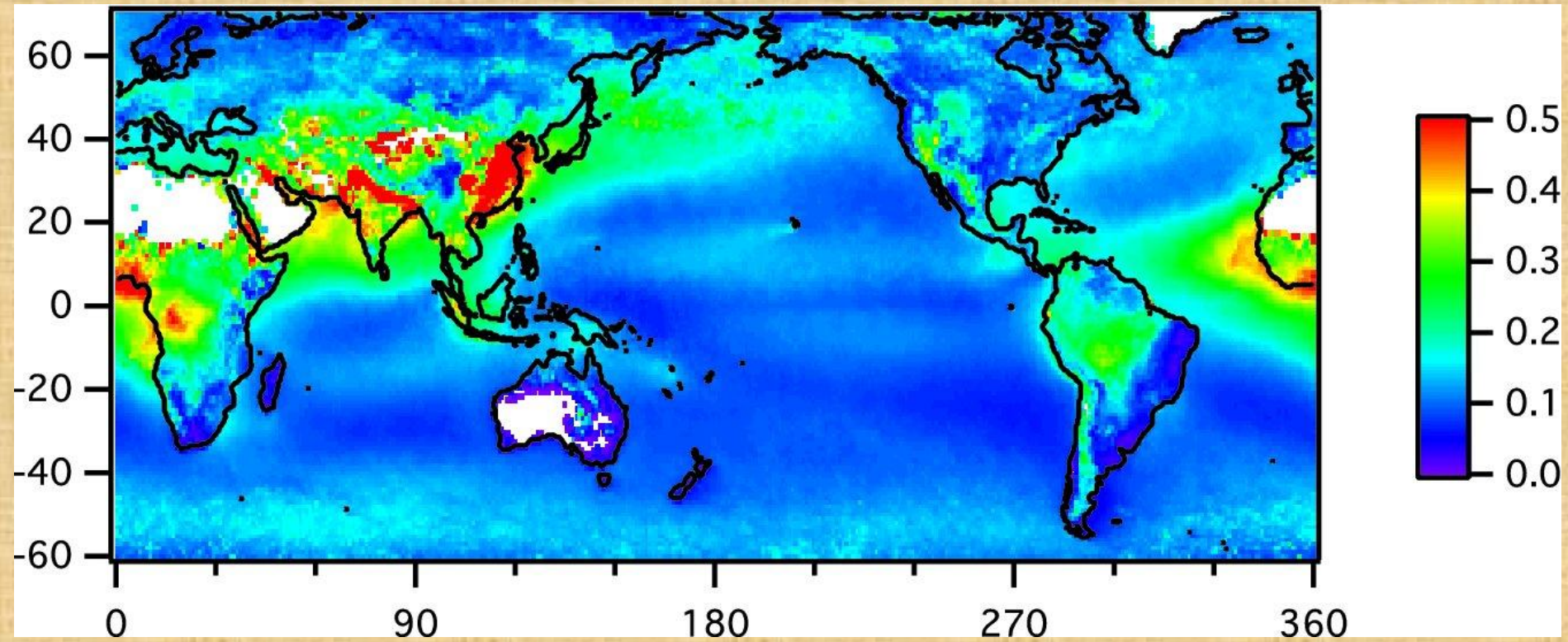
Increasing aerosol and cloud particles may increase reflected sunlight and therefore cool the climate.



Correlation between Global Average Surface Temperature anomaly and CO2 abundance makes a graphic statement abour what is driving warming.

Light Scattered from Aerosol and Cloud Particles Play an important Role in Energy Balance.

The rate of warming may be increasing as countries clean up the aerosol poltution that makes their citizens sick.



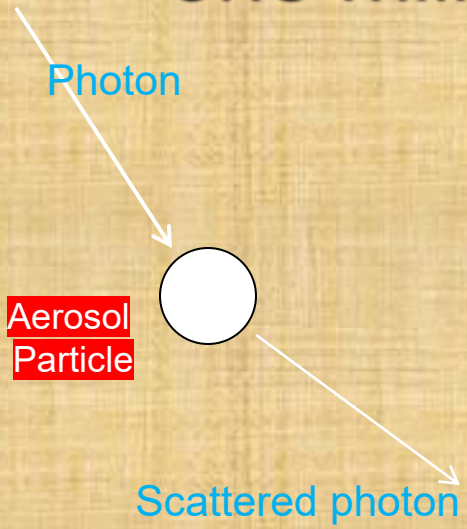
Annual Average Aerosol Optical Depth measured by MODIS (instrument on a satellite) from 2004 to 2008. (Optical Depth is a measure of how much scattering occurs. White areas have no data)

The US does not look like China looked when these data were acquired because of USEPA. We started to clean up in the 1970s. Now, many countries are doing this including China.

The result may be increasing the radiation imbalance by reducing the solar radiation reflected to space.

Denver seen from Golden on a clean day and a polluted day

Poor visibility results from light scattering by particles (usually smaller than 1 micron – one millionth of a meter)



- We tell the difference between two things because we can distinguish the photons that come from them.
- If the photons are mixed up by scattering, we can not distinguish the things.
- Contrast falls.

- If sunlight is scattered back to space, that energy is not absorbed by the climate system
- Pollution tends to cool.
- Cleaning the air tends to warm and may explain the increasing warming that some see now.

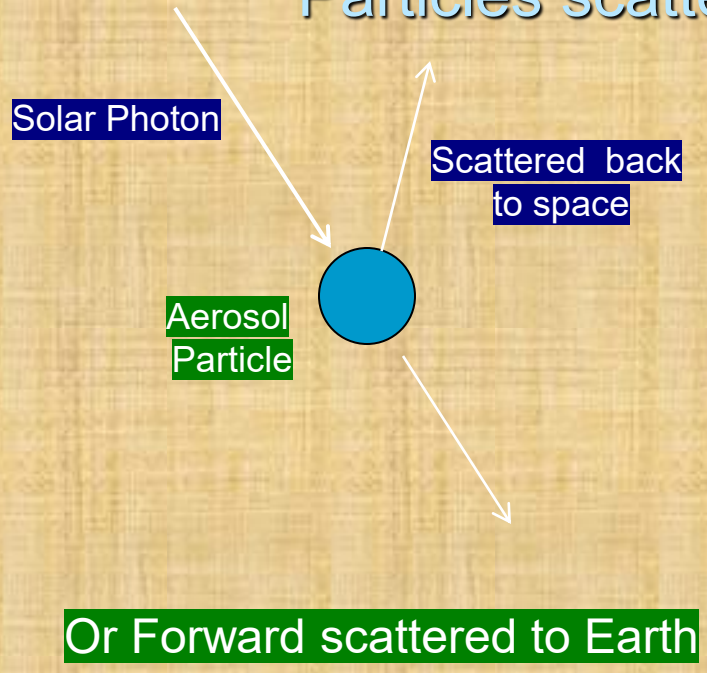
SomePollution Cools. So add Pollution to the stratosphere (like a volcano) to Cool Climate?

- Aerosol in the stratosphere has a longer lifetime than aerosol in the troposphere where it rains. Months to years versus days to weeks.
- The rocks in the volcanic injection fall out very rapidly. The SO2 gas is converted to H2SO4 liquid and forms droplets.
- The droplets reflect sunlight to space. Cool climate.
- Unintended consequences – modify precipitation ? Disturb the monsoon? Alter weather patterns at lower altitudes? Have frightened scientists away from this SRM (solar radiation management)
- Now interest is ramping up in Geoengineering or SRM.

What Next?

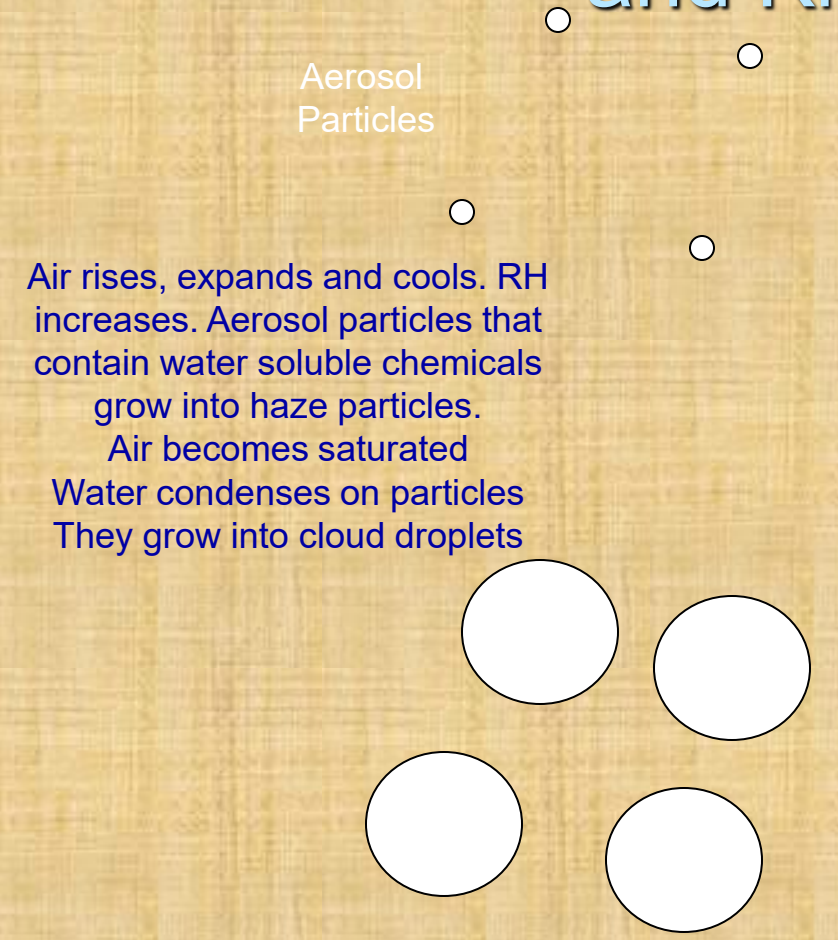
- "Sulfur emissions are declining sharply as countries started cleaning up air pollution. Global SO2 emissions today are 48% lower than they were in 1979 and 40% lower than in 2006 (China saw a massive 70% decline since 2008!). This is the primary contributor to the acceleration in global warming in recent years."
  - Air pollution kills and cools by about 0.5 C
  - Countries care about pollution.
- Climate Brink - Hausfather

Climate Aerosol-radiation Interaction: Particles scatter light back to space



- Probability of scattering (forward or back) depends on size and composition
- Many are sulfate particles (sulfuric acid, ammonium sulfate) or organics or nitrates that scatter
- Soot absorbs.

Climate Aerosol-Cloud Interaction (Talk to CSU: DeMott and Kreidenweis)

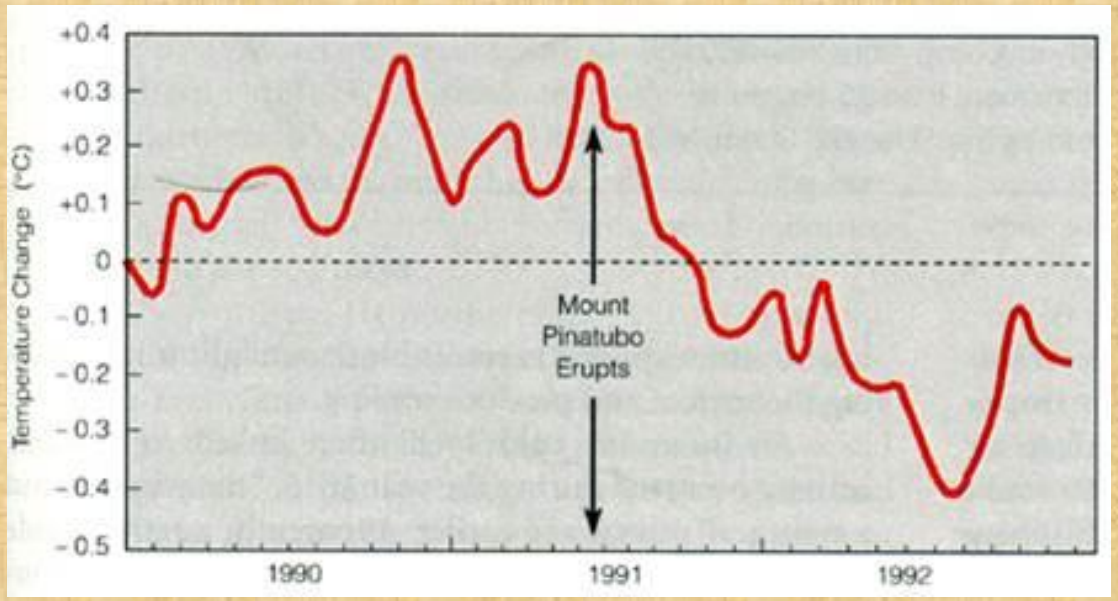


- Cloud properties changed due to increased aerosol (nuclei)
  - May scatter more light (more droplets)
  - May rain less (smaller droplets unable to fall)
  - May last longer and scatter more.

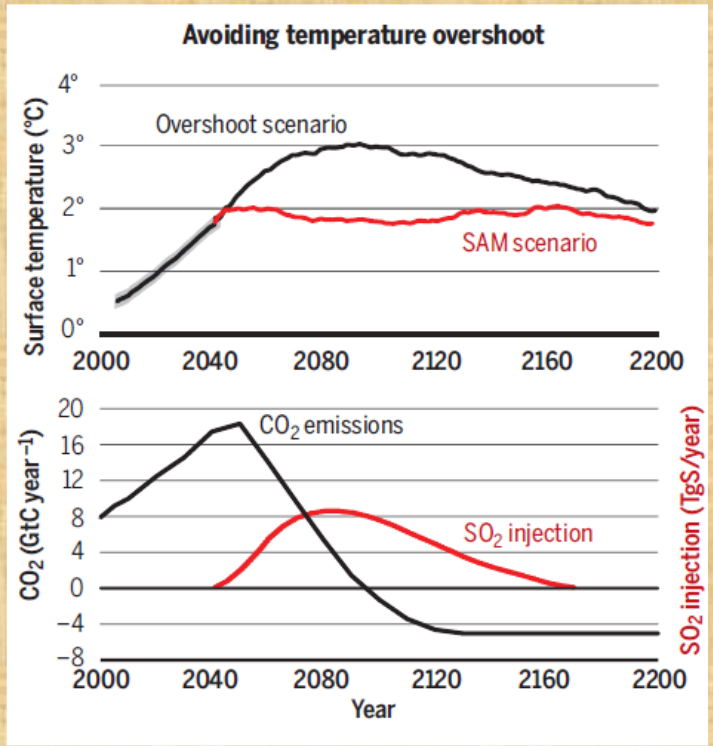
Why is it difficult to know how much aerosol impacts climate?

- You can't see ice nuclei from space.
- A small fraction of aerosol can serve as ice nuclei.
- Water cloud nuclei can arise from aerosol processes that start on the nanometer scale and can not be detected from space.
- In situ measurements are limited.

Injection of Aerosol into the Stratosphere to Cool Climate?



Some Encourage Study of Albedo Modification. Recent NY Times opinion piece suggests there may be growing support.
https://www.nytimes.com/2025/09/21/opinion/geoengineering-planet-cooling-sulfur.html

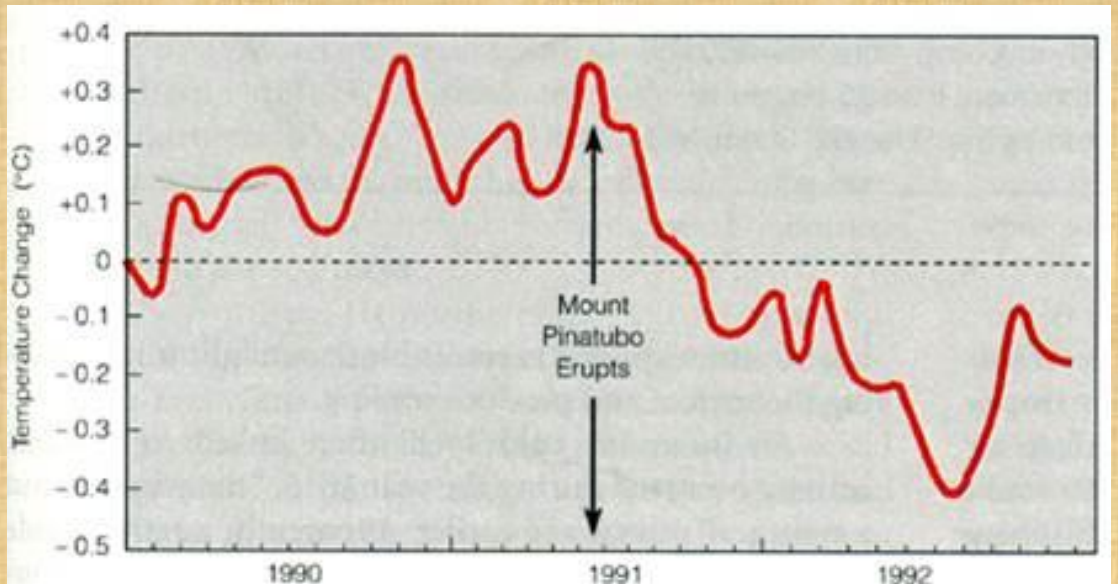


Albedo Enhancement Schemes

- Add particles to stratosphere to increase albedo
- Enhance low-level, marine clouds to increase albedo
- Put a 1000 km x 1000 km parasol in space to reduce sunlight. (We do not know how to do this today.)
- First two are cheap.

Volcanic Eruptions Resulted in Long-lived Particles in the Stratosphere

- Temperature decrease following Pinatubo injection was 0.3C for 3 years with 20 Mt SO_2.
- Robock and Liu [1994], models, and Trenberth and Dai [2007], observations following the 1991 Pinatubo eruption, found large reductions in the strength of the global hydrological cycle including in precipitation, soil moisture, and river flow.
- Possibly disrupts Asian Monsoon. (endangers food to billions)
- Volcanic eruptions have also been observed to produce large stratospheric ozone depletion following the 1982 El Chichon and 1991 Pinatubo eruptions [Solomon, 1999].



- Not very expensive to inject SO_2 gas. Atmospheric chemistry will make H_2SO_4 which makes particles. Same chemistry as acid rain.

- If they are the same size as volcanic particles (around 1 micron) they will cool and persist.

- We do not know for sure that this will occur as hoped. The imagined injections do not mimic volcanic ones in location and amount.

- From Robock et al., GRL, 2009 (canvas>files>readings)

Modeled Temperature Cools Quickly when Injections Start and Warms Quickly When They Stop (Robock et al., 2008). Models show decreased precipitation.

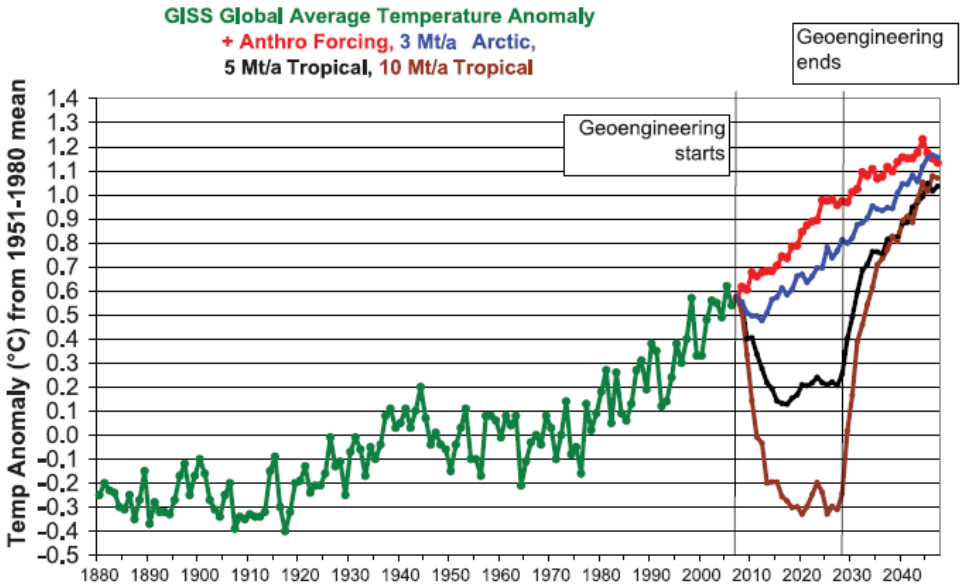


Figure 1. Global average surface air temperature change from the A1B anthropogenic forcing run (red), Arctic 3 Mt/a SO_2 (blue), tropical SO_2 5 Mt/a (black), and tropical 10 Mt/a SO_2 (brown) cases in the context of the climate change of the past 125 years. Observations (green) are from the National Aeronautics and Space Administration Goddard Institute for Space Studies analysis [*Hansen et al.*, 1996]

THE BENEFITS, RISKS, AND COSTS OF STRATOSPHERIC GEOENGINEERING

A. Robock, A. Marquardt, B. Kravitz, and G. Stenchikov :GRL, 2009

Benefits	Risks
1. Cool planet	1. Drought in Africa and Asia
2. Reduce or reverse sea ice melting	2. Continued ocean acidification from CO2
3. Reduce or reverse land ice sheet melting	3. Ozone depletion
(Keith et al., 2016 think it can be done without this.)	
4. Reduce or reverse sea level rise	4. No more blue skies
5. Increase plant productivity	5. Less solar power
6. Increase terrestrial CO_2 sink	6. Environmental impact of implementation
	7. Rapid warming when stopped

THE BENEFITS, RISKS, AND COSTS OF STRATOSPHERIC GEOENGINEERING

A. Robock, A. Marquardt, B. Kravitz, and G. Stenchikov :GRL

Risks, continued

8. Cannot stop effects quickly
9. Human error
10. Unexpected consequences
11. Commercial control
12. Military use of technology
13. Conflicts with current treaties
14. Whose hand on the thermostat
15. Ruin terrestrial optical astronomy
16. Moral hazard – the prospect of it working would reduce drive for mitigation
17. Moral authority – do we have the right to do this?

Governance Questions

- Who gets to choose to do it?
- Who gets to choose how much to do?
- Who decides when to stop?
- What kind of global agreements are necessary?
- What if a company or country set up to try to do this?