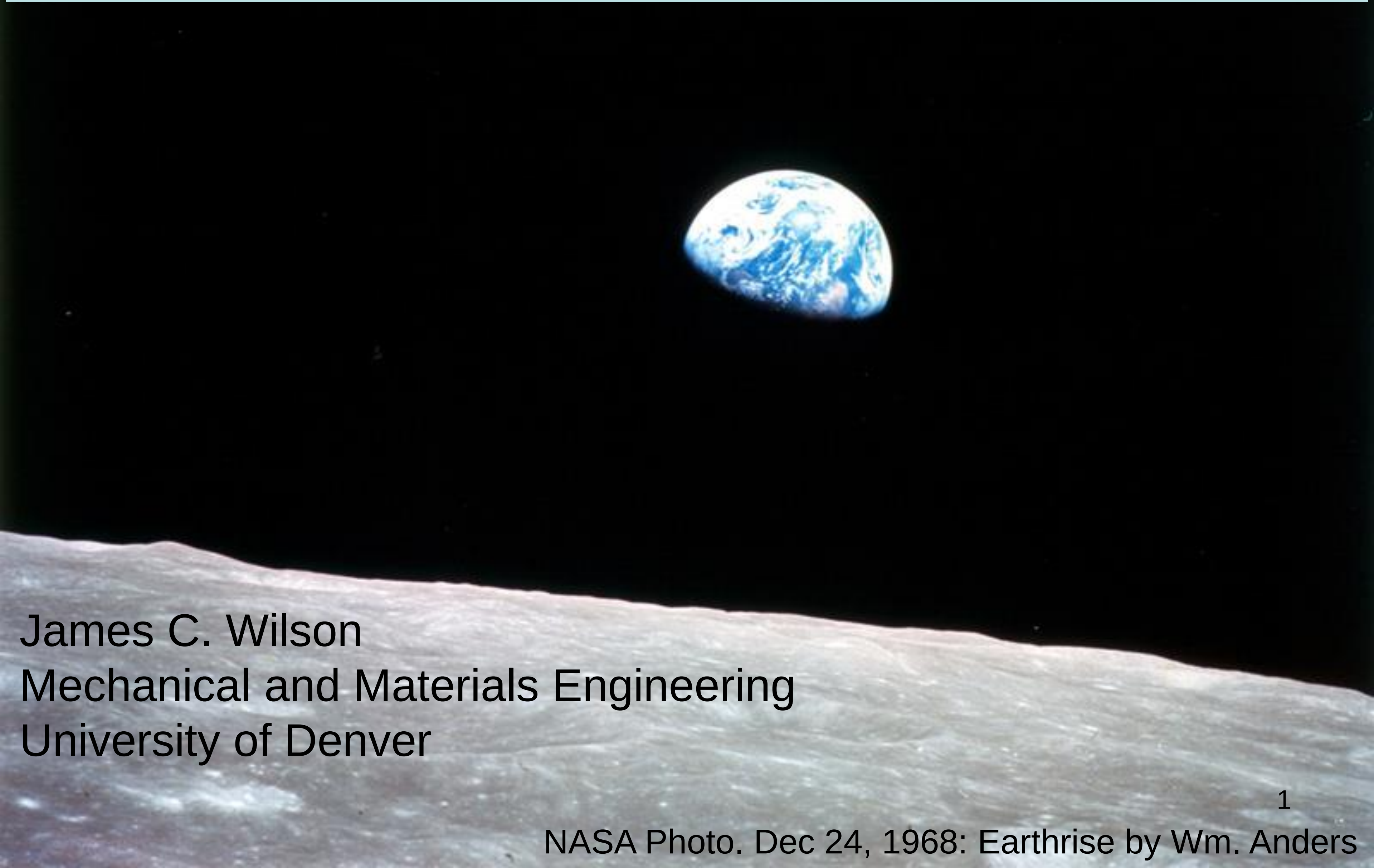
Energy Balance of the Climate System: Contribution of Clouds and Aerosol to Uncertain Futures



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NASA Photo. Dec 24, 1968: Earthrise by Wm. Anders

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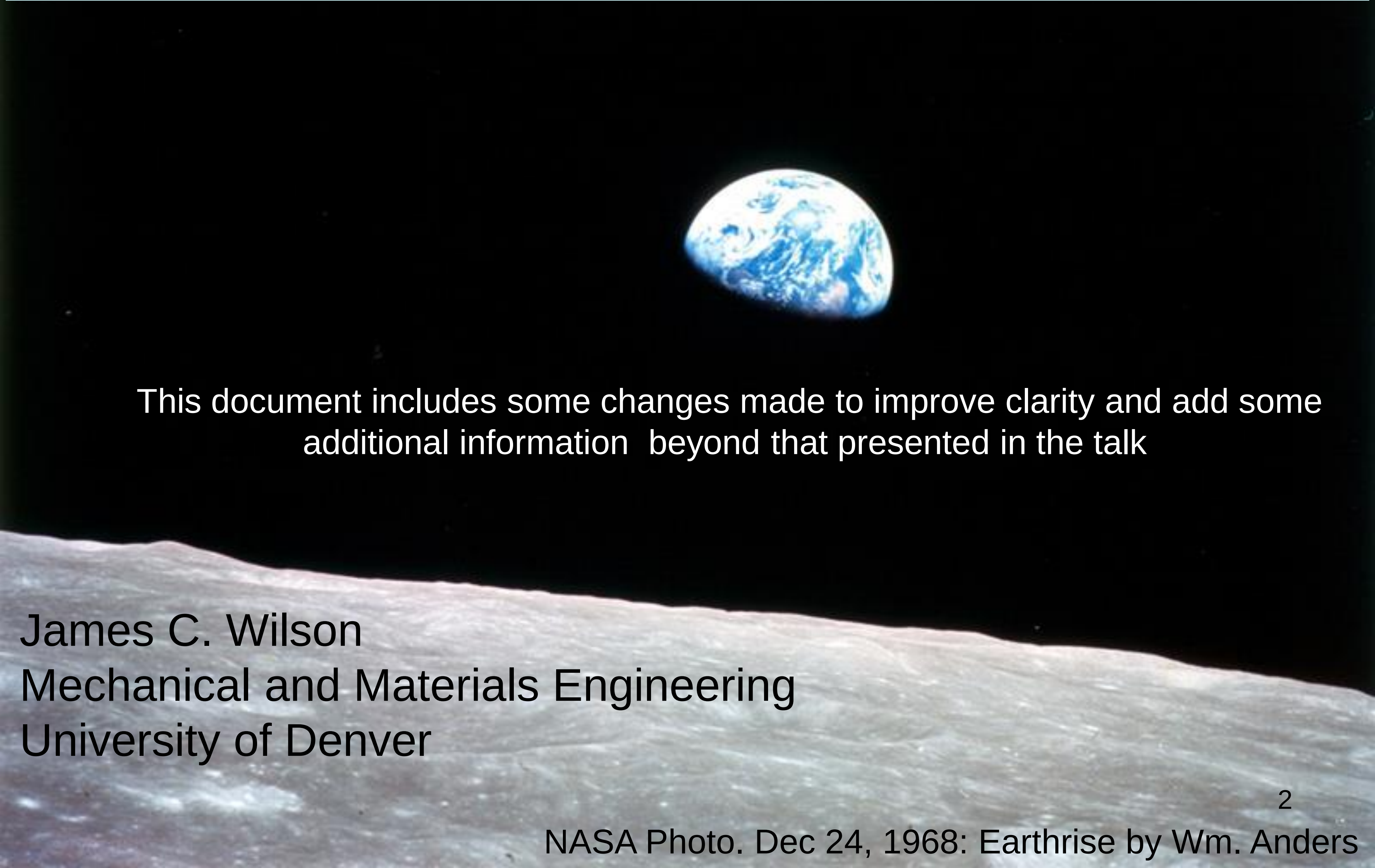

This document includes some changes made to improve clarity and add some additional information beyond that presented in the talk

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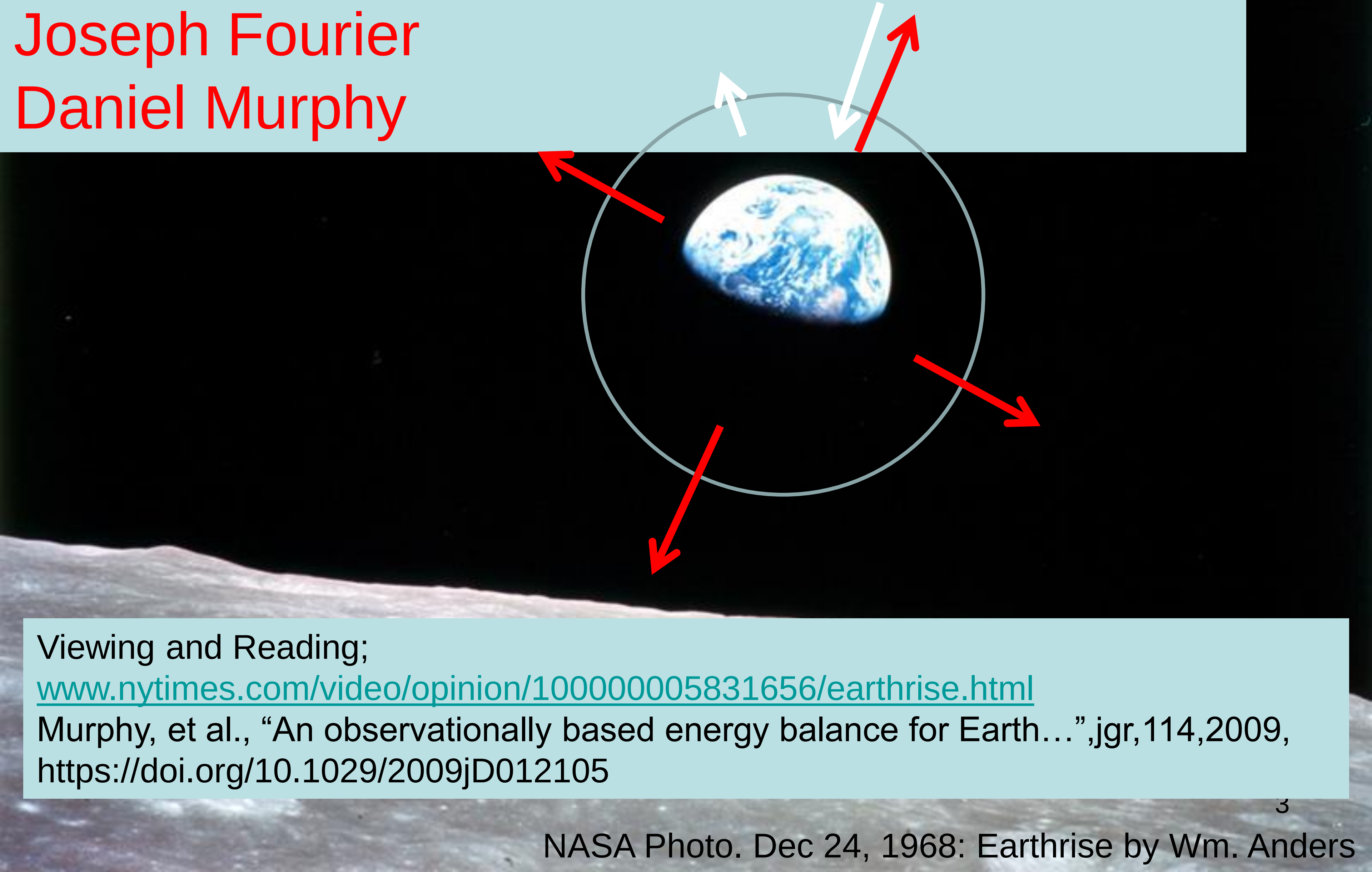
Acknowledgments:
William Anders, Jim Lovell, Frank Borman
Joseph Fourier
Daniel Murphy



Viewing and Reading;
www.nytimes.com/video/opinion/100000005831656/earthrise.html
Murphy, et al., “An observationally based energy balance for Earth…”,jgr,114,2009, https://doi.org/10.1029/2009jD012105

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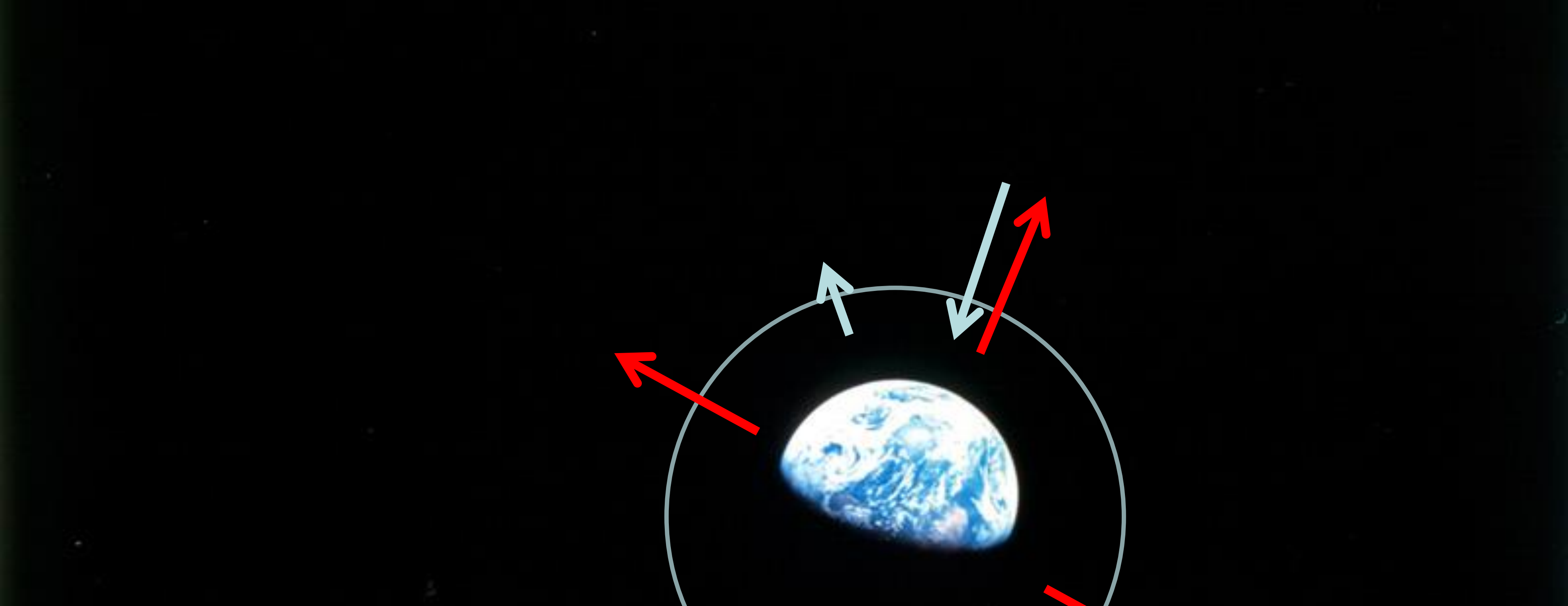
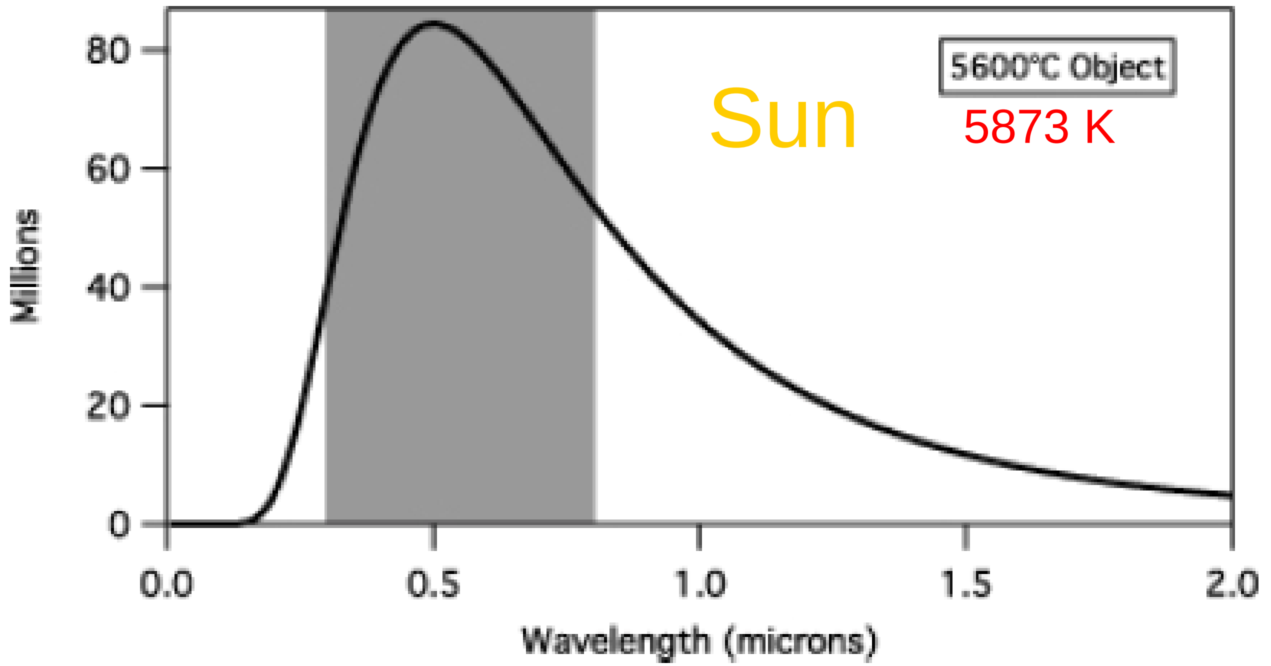
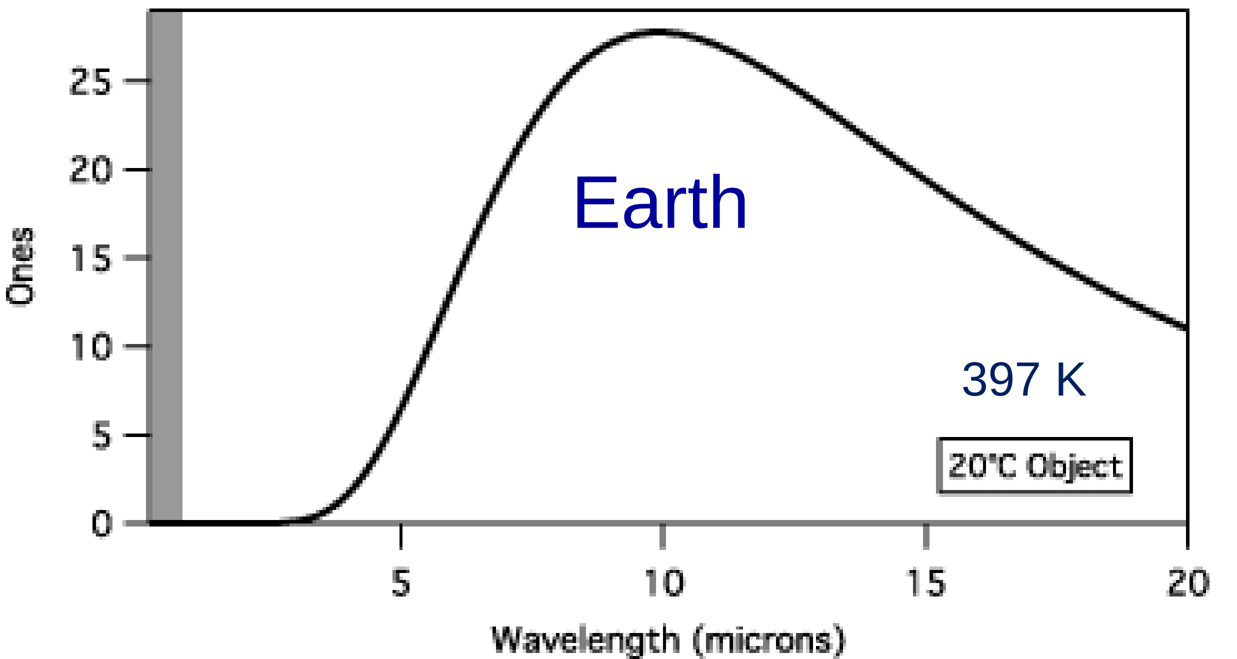


1. Climate system gets its energy from the sun
2. Climate system gets rid of energy by radiating infrared (IR) to space. Fourier called it dark energy after Hershel’s 1800 experiment.
3. Absorbed solar > escaping IR -> Warming
4. Escaping IR > Absorbed solar-> Cooling

NASA Photo. Dec 24, 1968: Earthrise by Wm. Anders





Vertical Axis: Watts/m^2 – µm

The climate radiates in the infrared because of its temperature.

Wavelength differences result in different interactions and fates in the atmosphere.

Fig: Andy Dessler

imBalance: Trenberth, Fasullo and Kiehl, BAMS, 2009

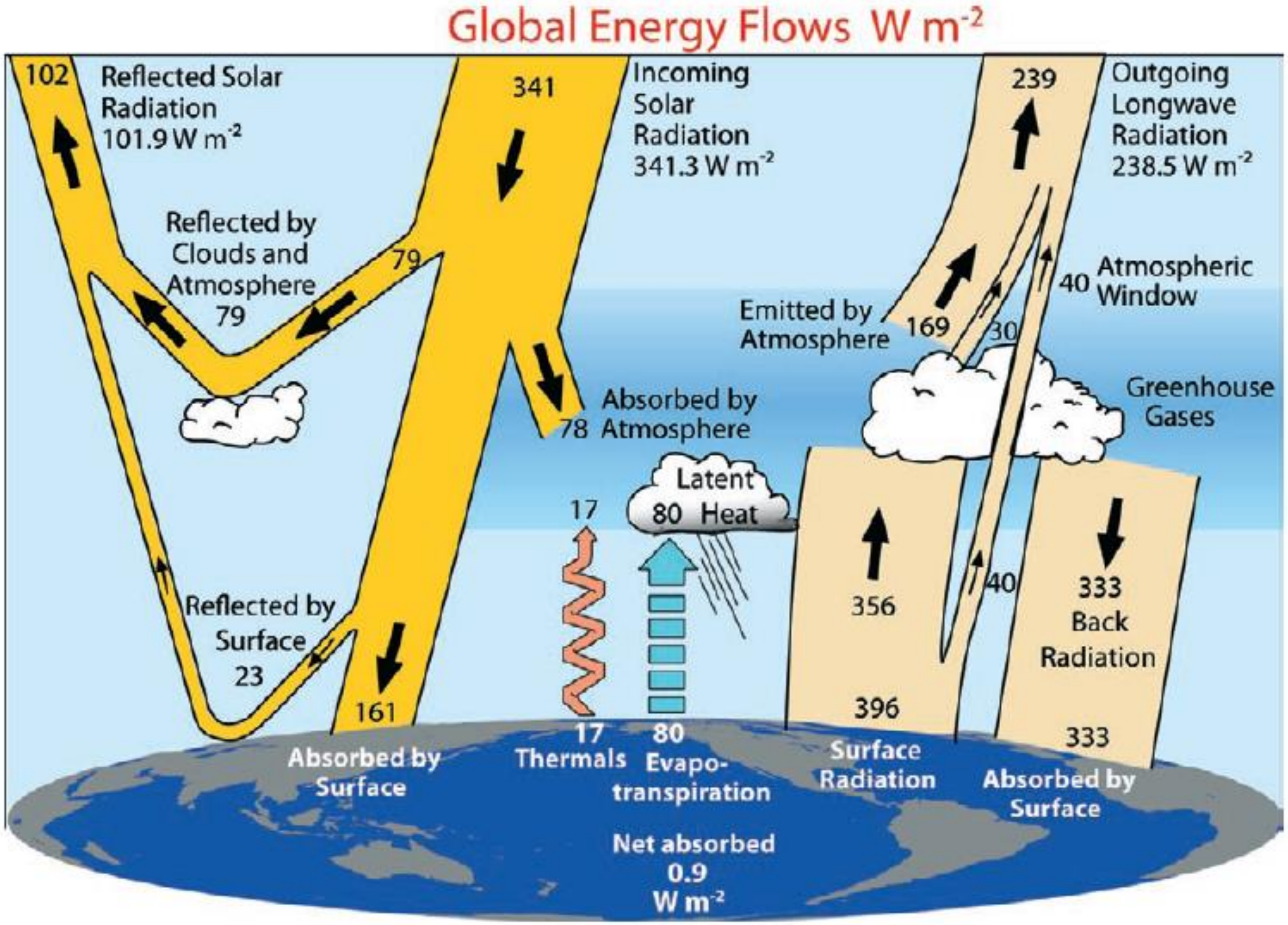
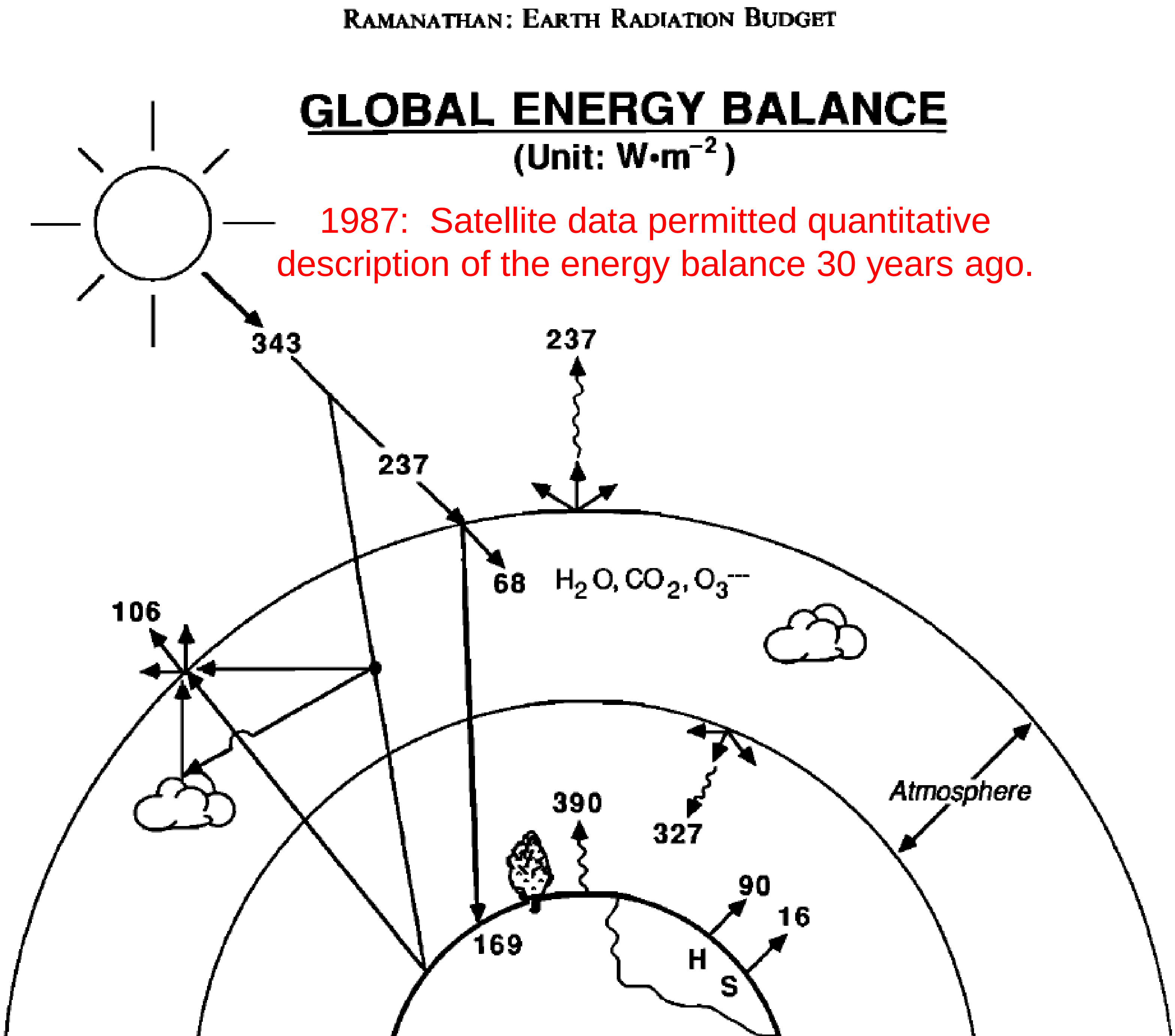


Fig. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Imballance is 0.9 Watts/m^2 and is small compared to incoming and outgoing. It is inferred from ocean from warming.

GHGs impede the escape of upwelling IR and add to downwelling energy, Water vapor is a potent GHG controlled by temperature and increased by warming driven by increases in CO_2, etc ,



1987: Satellite data permitted quantitative description of the energy balance 30 years ago.

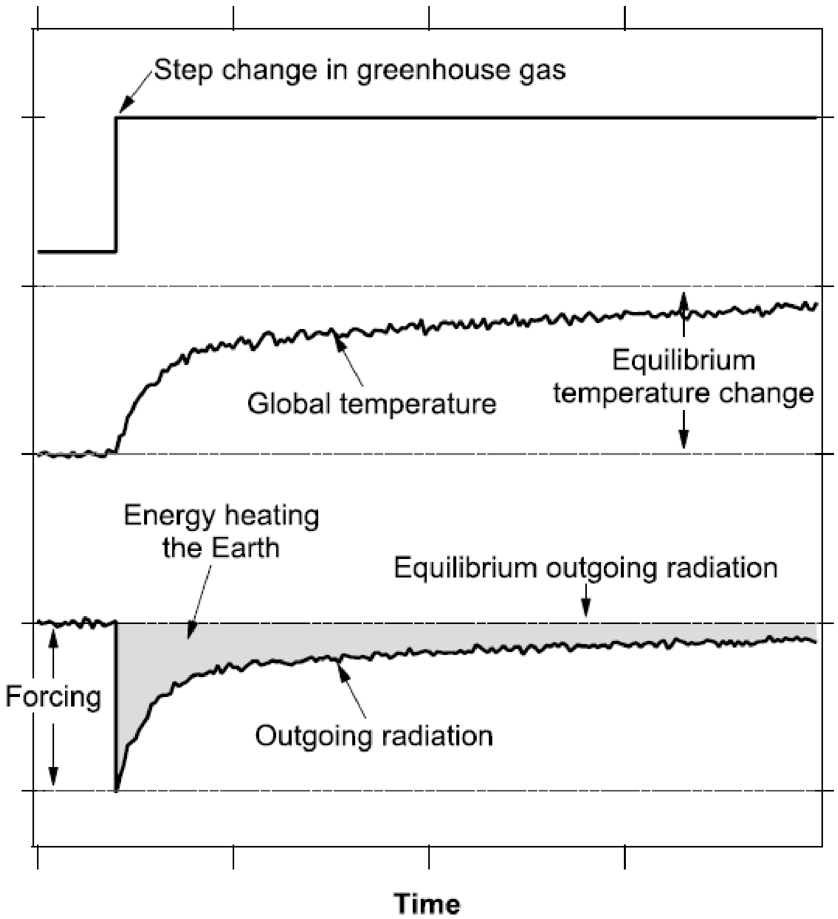
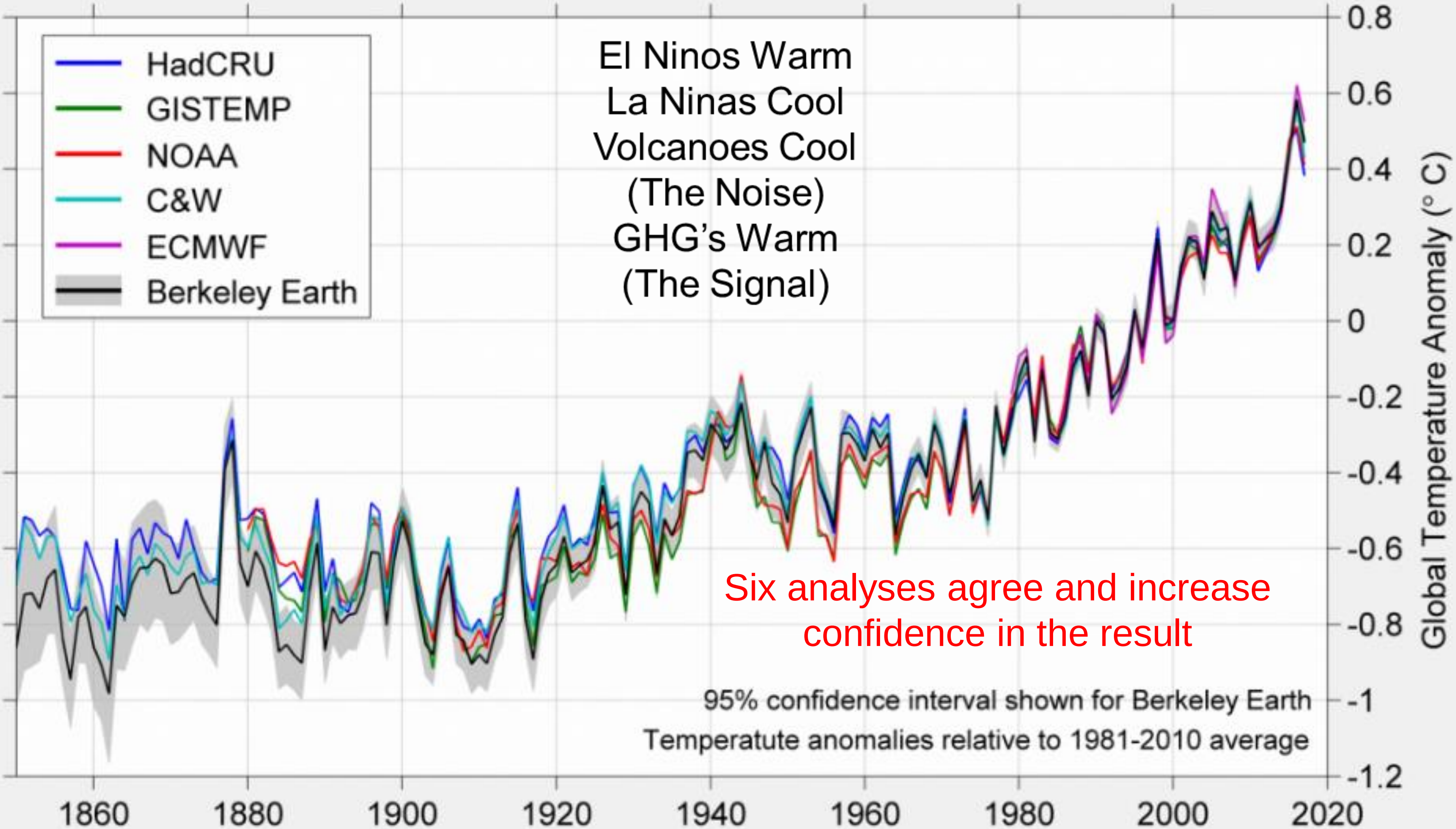


Figure 1. Illustrative sketch of the response of the Earth energy budget to an idealized step function change in a greenhouse gas. Outgoing radiation from the Earth at first decreases then returns toward an equilibrium value as the Earth warms. An initial rapid temperature response, as plotted here, reduces the amount of energy available to heat the Earth and slows the eventual approach to equilibrium.

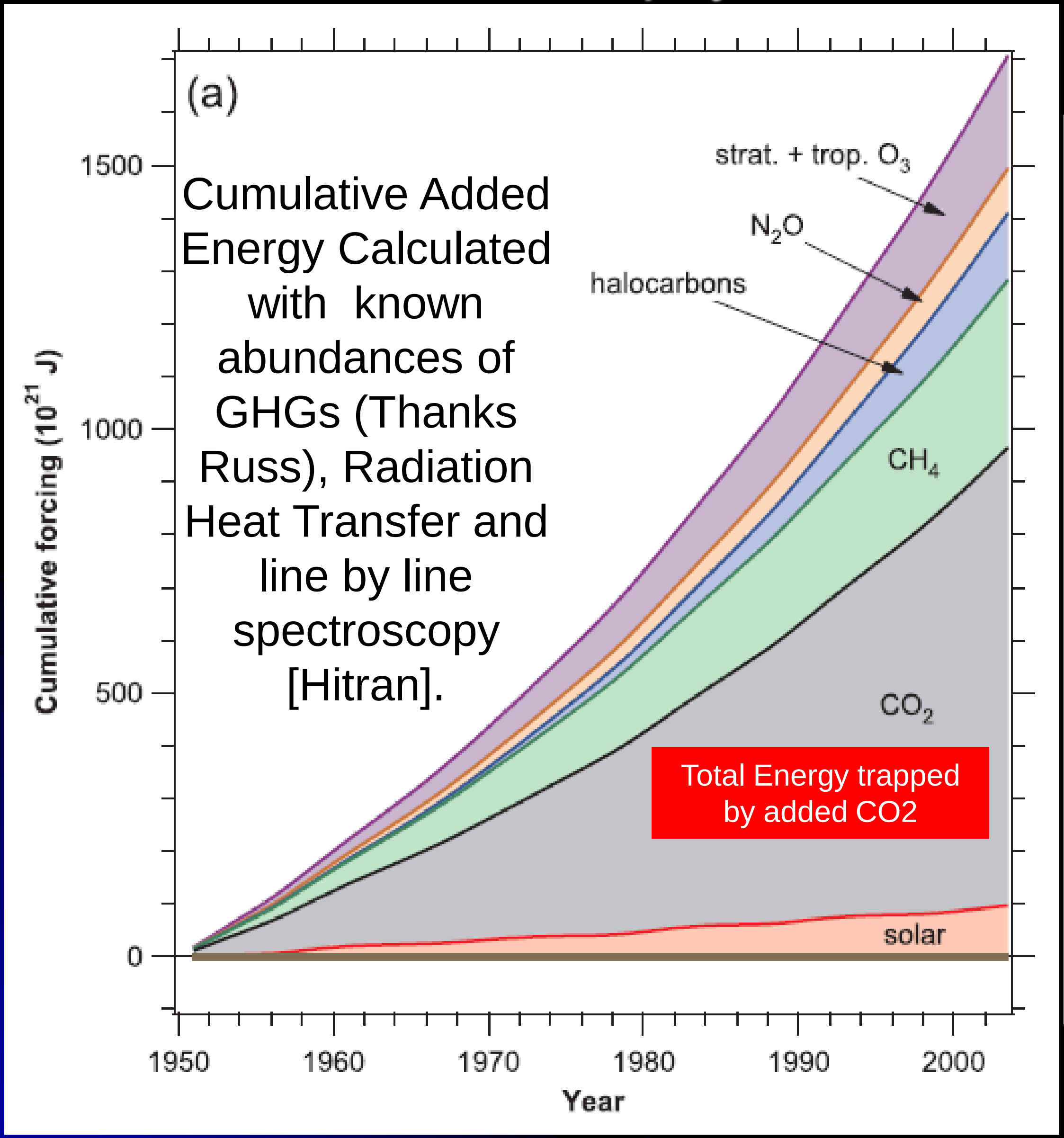
Murphy et al, 2009

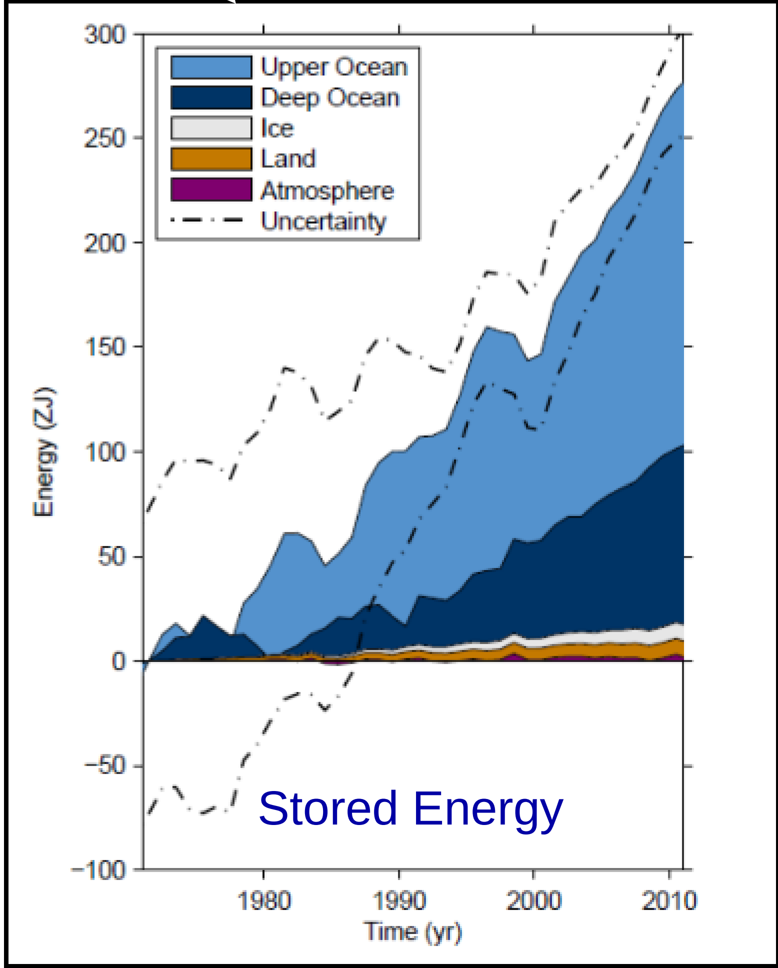
1. Start in balance
2. Add GHG - Escaping Infrared is reduced
3. Planet warms & escaping IR increases (σT^4)
5. Balance restored at warmer temperature.

GAST is going up. But it is not associated with a defined mass. So we can't apply First Law to it.



Added GHG's Impede Escape of IR and add Energy to the climate system.
Murphy et al, 2009. IPCC





The Change in Outgoing IR…

- Has be validated some time ago with spectrometers on satellites
  - The amounts of energy and the spectral details.
  - https://www.nature.com/articles/35066553

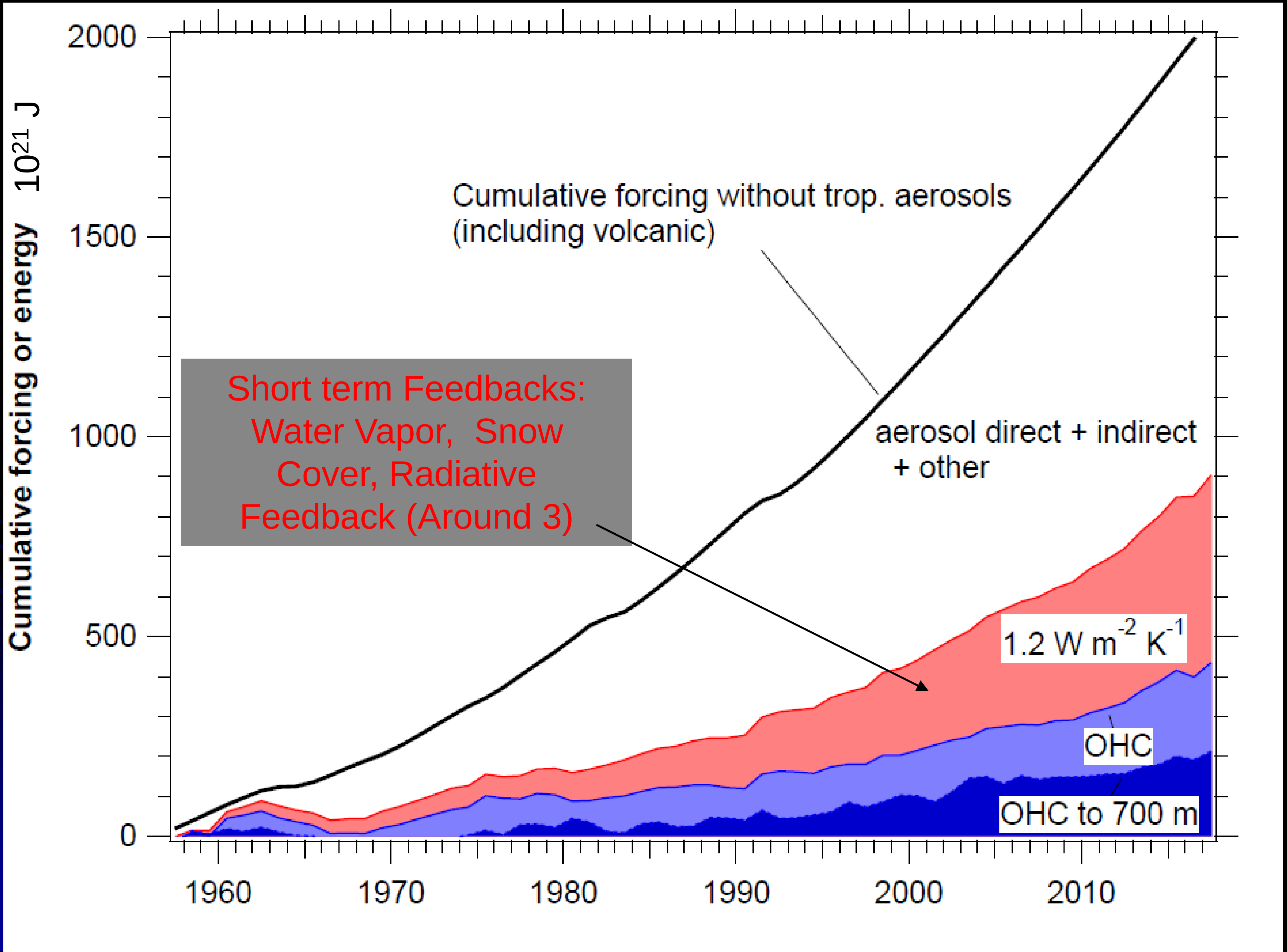
To Summarize

- Oceans get almost all of added energy.
- Added GHGs have reduced outgoing radiation by ~1700 ZJ (over plotted time period)
- 275 ZJ have showed up in climate
- Warming is the effect. Added GHGs are a cause.
- We have about 5x the cause that we need to explain the effect.
- If another cause is to be proposed, the entire 1700 ZJ from GHGs must be disposed of without warming climate and 275 ZJ must be found elsewhere. Also observed changes in outgoing IR intensity and wavelength need another explanation.

To Summarize

- So why haven't we warmed more?
- The answer is in changes in clouds and aerosols.
- The amounts are shown as a difference in the next slide.
- The increases in outgoing radiation minus the impact of the water vapor feedback are shown in the pink band. They reduce the amount of cooling required of aerosols and clouds.

Daniel Murphy: NOAA. Updated.



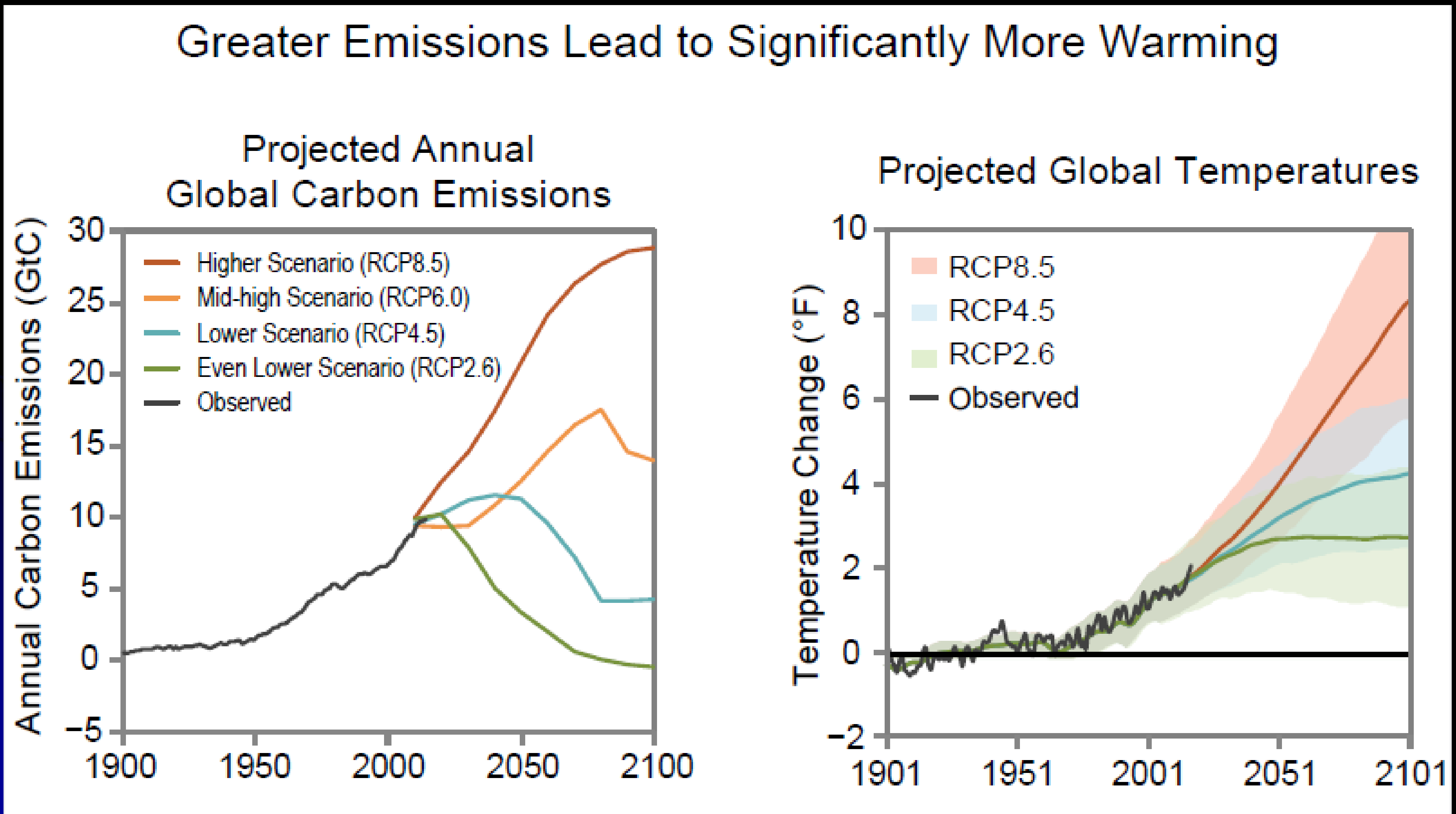
Aerosol Effects have been growing. So have:

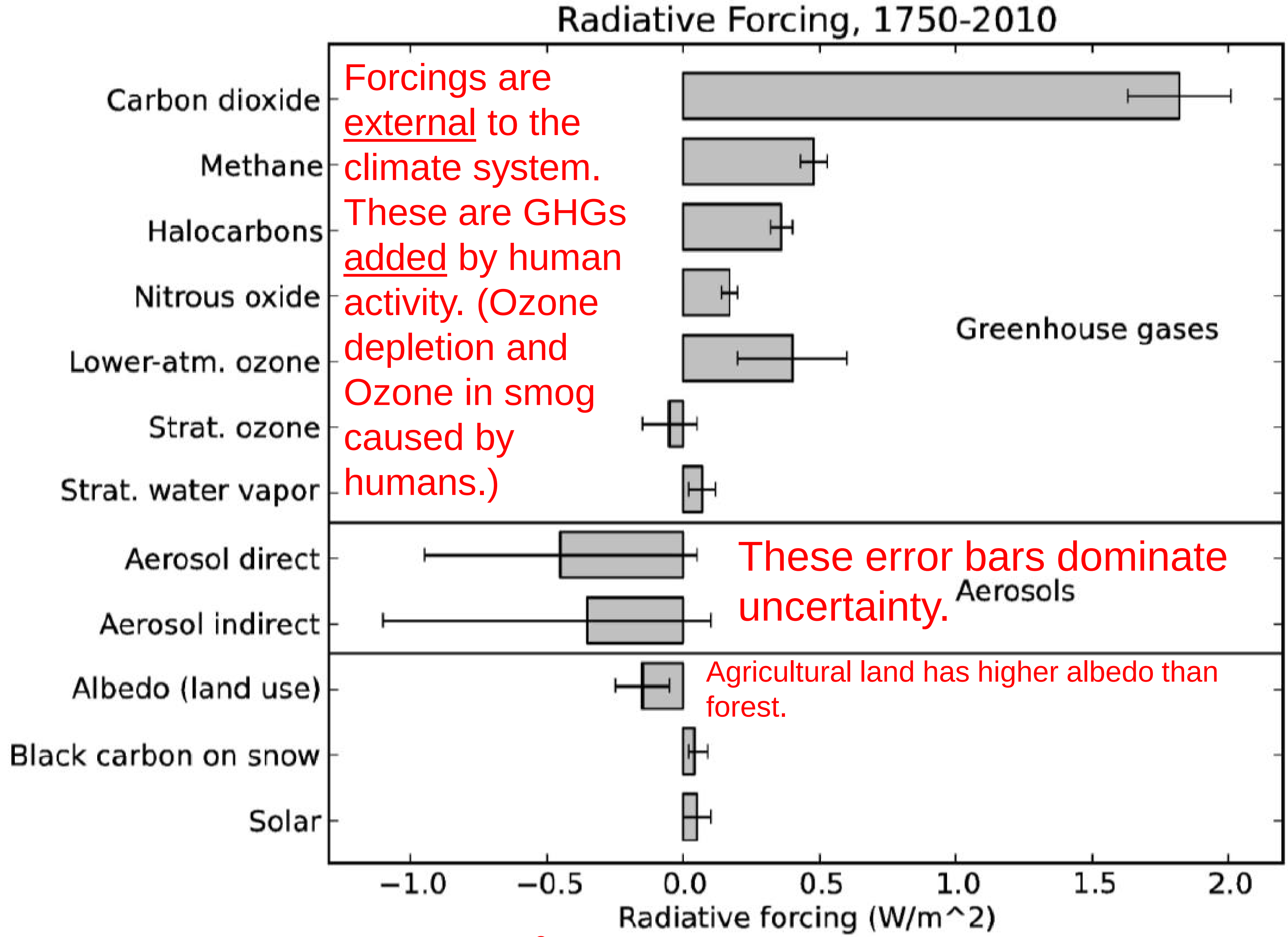
- Sulfur Emissions (Direct Effect)

  SO_2 -> H_2SO_4 -> Particles -> light reflected to space

- Cloud Modification (Indirect Effect)
  - Clouds form on small particles
  - Small particles have increased in number
  - More cloud droplets reflect more light to space
  - Other effects as well.

Model Projections of Future Temperatures: Range of projected temperatures shown by the width of the colored for each scenario.





Total net Forcing = + 2.3 w/m^2 (From 1.1 to 3.3 considering error bars)

Fig. 6.3 Radiative forcing caused by changes in the climate between 1750 and 2005. The error bars indicate the uncertainty of the estimate (based on values from Ciais et al., 2013).

The Problem: AR5WG1_CH. 9

- Cloud feedbacks represent the main cause for the range in modelled climate sensitivity (2.1C-4.7C).
  - the primary cloud-related factor contributing to the spread in equilibrium climate sensitivity is the low-level shortwave cloud feedback
  - Changes in the high-altitude clouds also induce climate feedbacks... the parameterisation of ice fall speed also emerges as one of the most important determinants of climate sensitivity

Cloud Parameterizations

- Cloud processes occur in micron sized spaces. Cloud droplets are millimeters in diameter. (Hair is about 100 microns in diameter)
- The climate model box size is currently ~100 km on a side.
- You can not describe the physics occurring on micron sized objects if your smallest box is ~100 km on a side.
- Therefore, you do not build your model cloud droplet by droplet from the fundamental physics. You use parameterizations which can differ from model to model.

Most Scenarios that Avoid the Most Dangerous Expected Effects of Climate Change Feature Overshoot in CO_2 and Later Drawdown.

- How to reduce climate impacts during this overshoot period?
- Some say Albedo Modification (see NAS Report)

Paul J. Crutzen: What to do?

- Artificially enhancing earth’s albedo.
- Cool climate by adding sunlight reflecting aerosol in the stratosphere (Budyko, 1977; NAS, 1992) might again be explored…

Paul J. Crutzen

How to do it?

- Put SO_2 in the tropics at high altitude – It gets carried into stratosphere
- In the stratosphere, chemical and micro-physical processes convert SO_2 into sub-micrometer sulfate particles.
- This has been observed in volcanic eruptions e.g., Mount Pinatubo in June, 1991, which injected some 10 Tg S, initially as SO2, into the tropical stratosphere (Wilson et al., 1993; Bluth et al., 1992).

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 compared to reducing emissions.

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.
- Volcanic eruptions have also been observed to produce large stratospheric ozone depletion following the 1982 El Chichon and 1991 Pinatubo eruptions [Solomon, 1999].

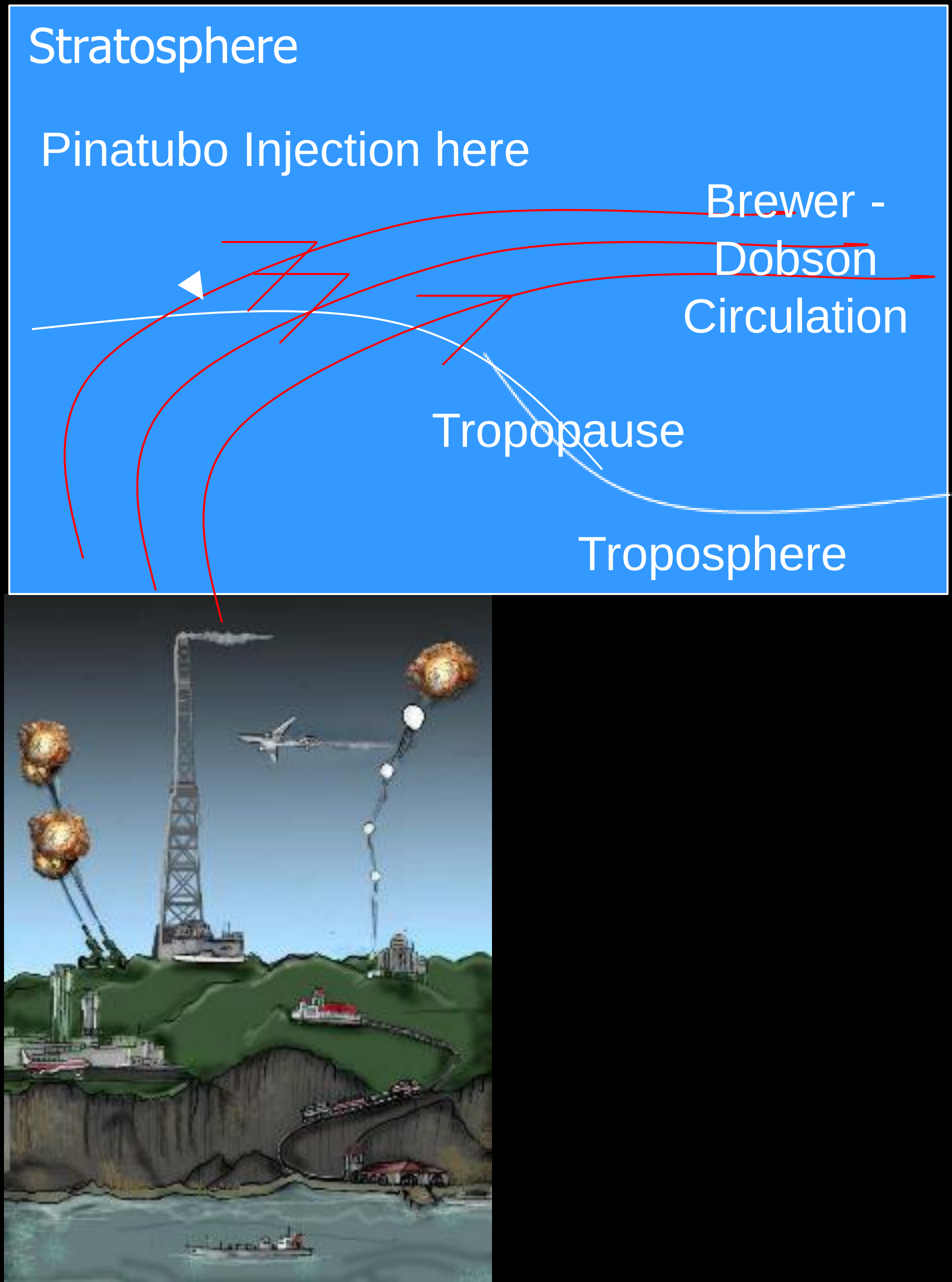
•Not very expensive to inject SO_2 gas. Atmospheric chemistry will make H_2SO_4 which makes particles. Same chemistry as acid rain.

•If they are the same size as volcanic particles (around 1 micron) and reach the stratosphere, 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.

•The injections imagined by the albedo enhancement schemes are occurring at 15-18 km altitude. The Pinatubo injection went in well above 20 km. The Albedo Enhancement Schemes assume that those different injection locations will result in the same particles in the end.

•I am skeptical. You note that we have measured volcanic, aircraft, natural particles at these altitudes and latitudes. My reasons for skepticism have to do with details of aerosol dynamics that are beyond the scope of this talk.



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

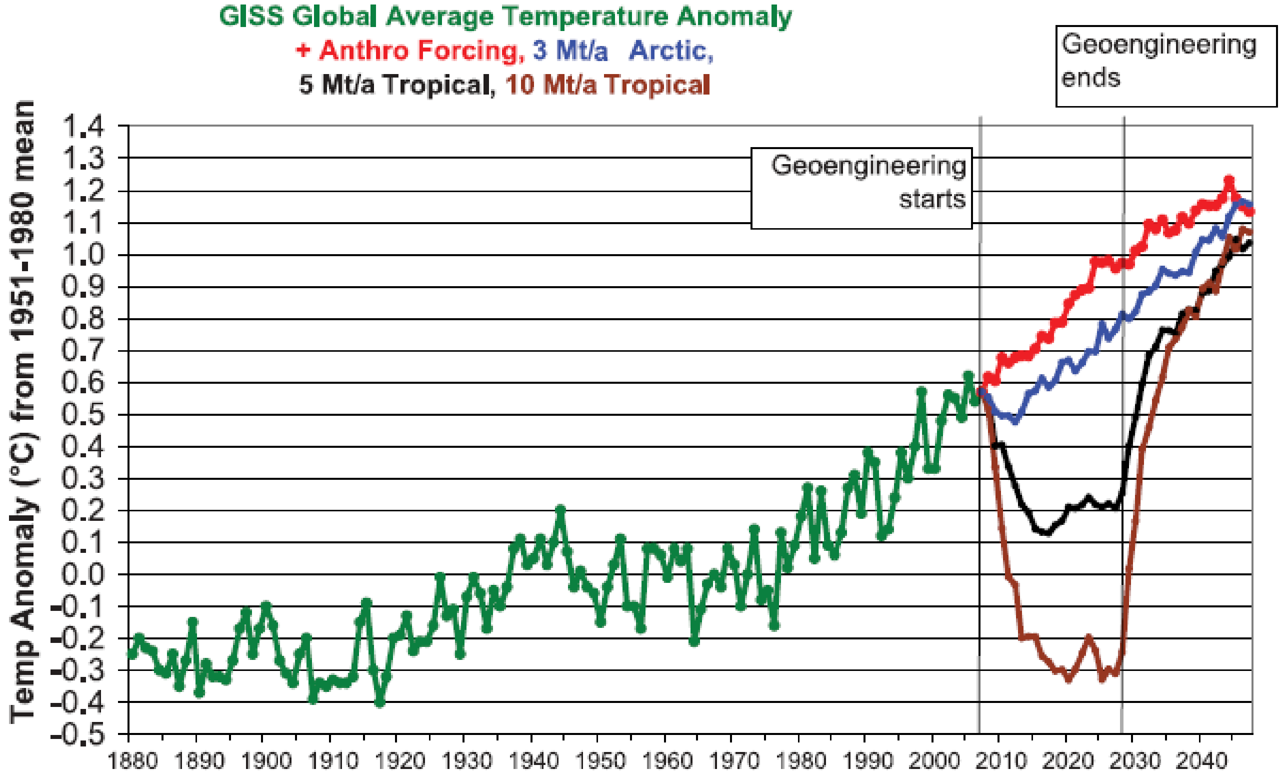


Figure 1. Global average surface air temperature change from the A1B anthropogenic forcing run (red), Arctic 3 Mt/a SO_2 (blue), tropical SO_2 5 Mt/a (black), and tropical 10 Mt/a SO_2 (brown) cases in the context of the climate change of the past 125 years. Observations (green) are from the National 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

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
4. Reduce or reverse sea level rise	4. No more blue skies
5. Increase plant productivity	5. Less solar power
6. Increase terrestrial CO2 sink	6. Environmental impact of implementation
	7. Rapid warming if 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?

Albedo enhancement of low-level maritime clouds (added)

- Put more droplets into marine stratus clouds by adding nuclei
  - More nuclei, smaller droplets, longer cloud persistence, whiter clouds and increased albedo
  - Some argue that we should be able to engineer the clouds and balance a doubling of CO_2.

Difficult to model these clouds and to predict outcomes. There are large uncertainties about impact. If brightening succeeds:

- Global changes in the distributions and magnitudes of ocean currents, temperature, rainfall and wind could result.
- alter the land–ocean temperature contrast, since the radiative forcing produced would be only over the oceans.

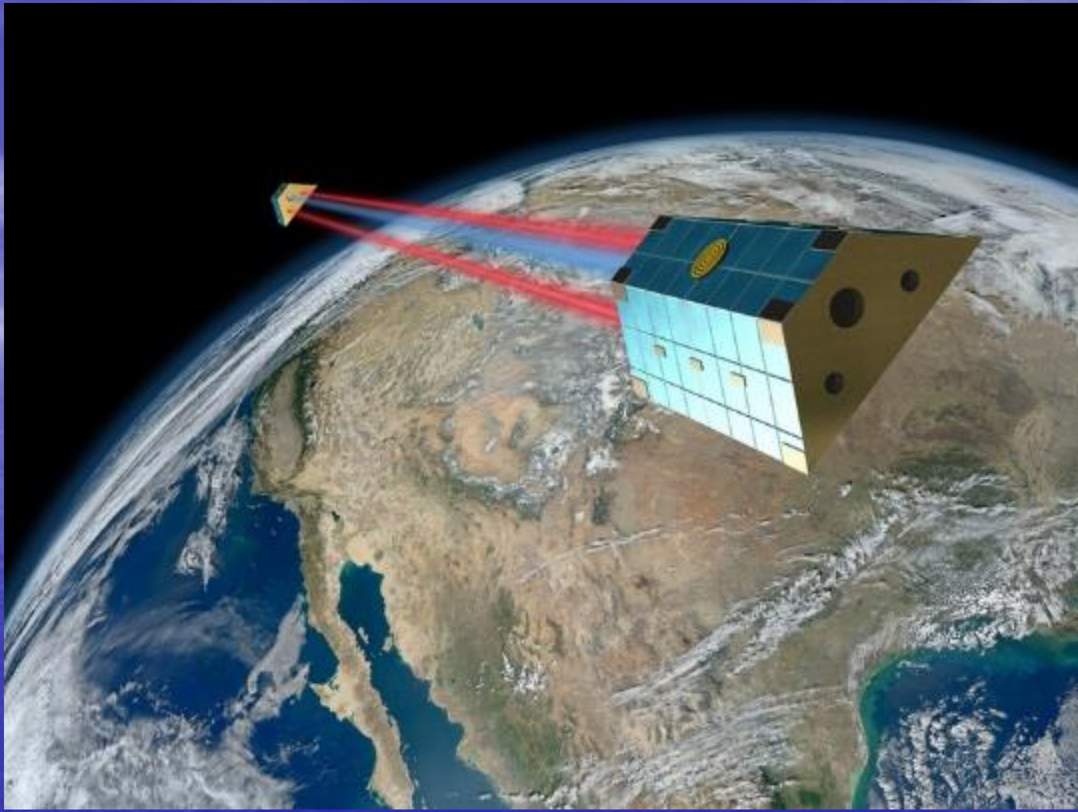
Data Used to Apply 1st Law

- Satellite atmospheric temperatures (NOAA MSUs and NOAA AMSU- UAH and RSS analysis)
- Ice sheet mass. GRACE
- Ocean heat content: ARGO
- Land mass temperatures: Bore Holes

Analysis

- First law of thermodynamics: Calculate changes in internal energy of each of these elements.
- Masses, specific heats and heat of fusion are known.
- Use measured changes in temperature and measured loss of land ice mass.

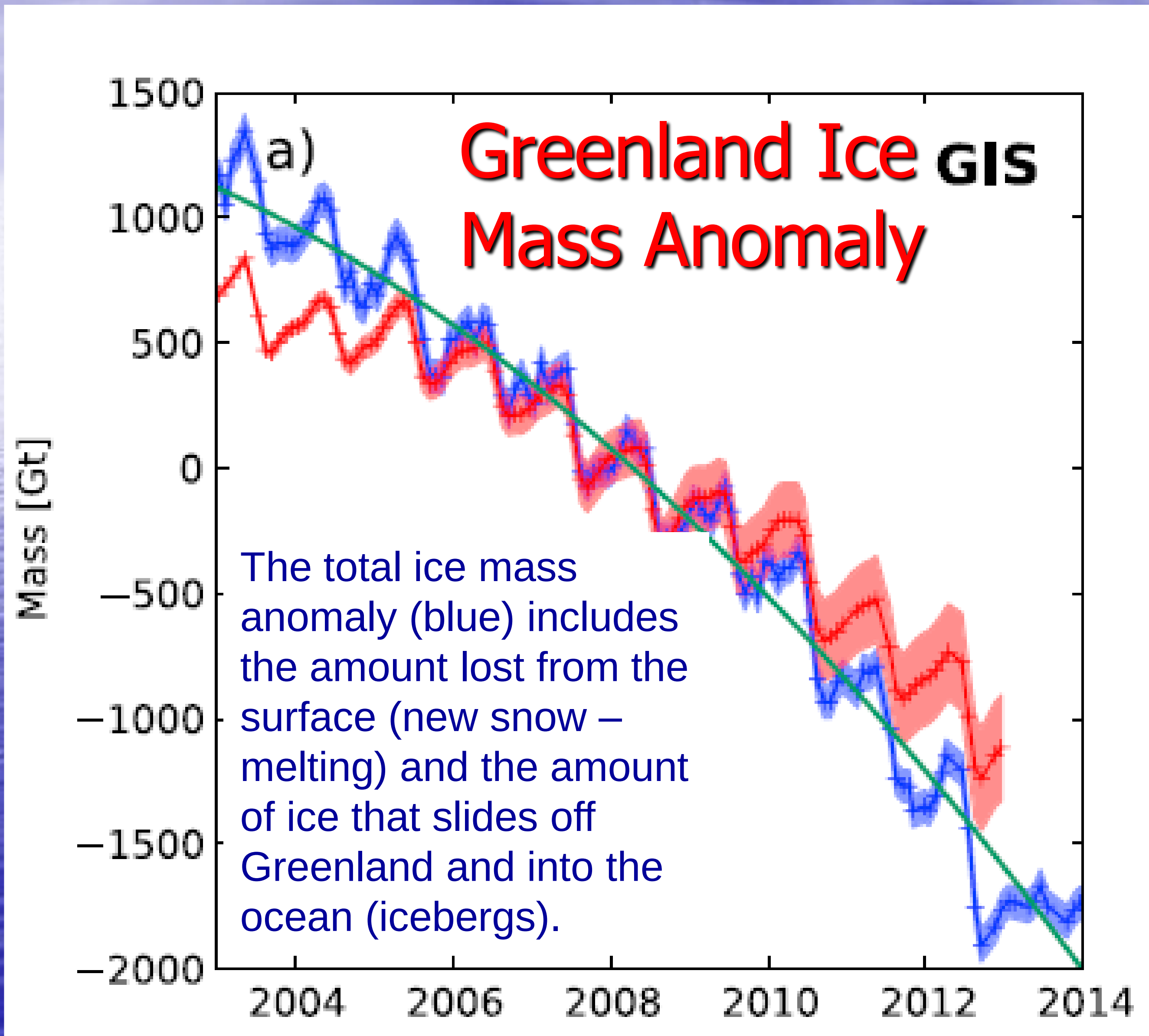
GRACE: Gravity Recovery and Climate Experiment



1. If mass in a location changes (ice melts and water goes elsewhere) the gravity over that location will change.
2. GRACE detects those changes in gravity and can therefore detect changes in mass distribution below.
3. GRACE is beautiful. GRACE is physics.

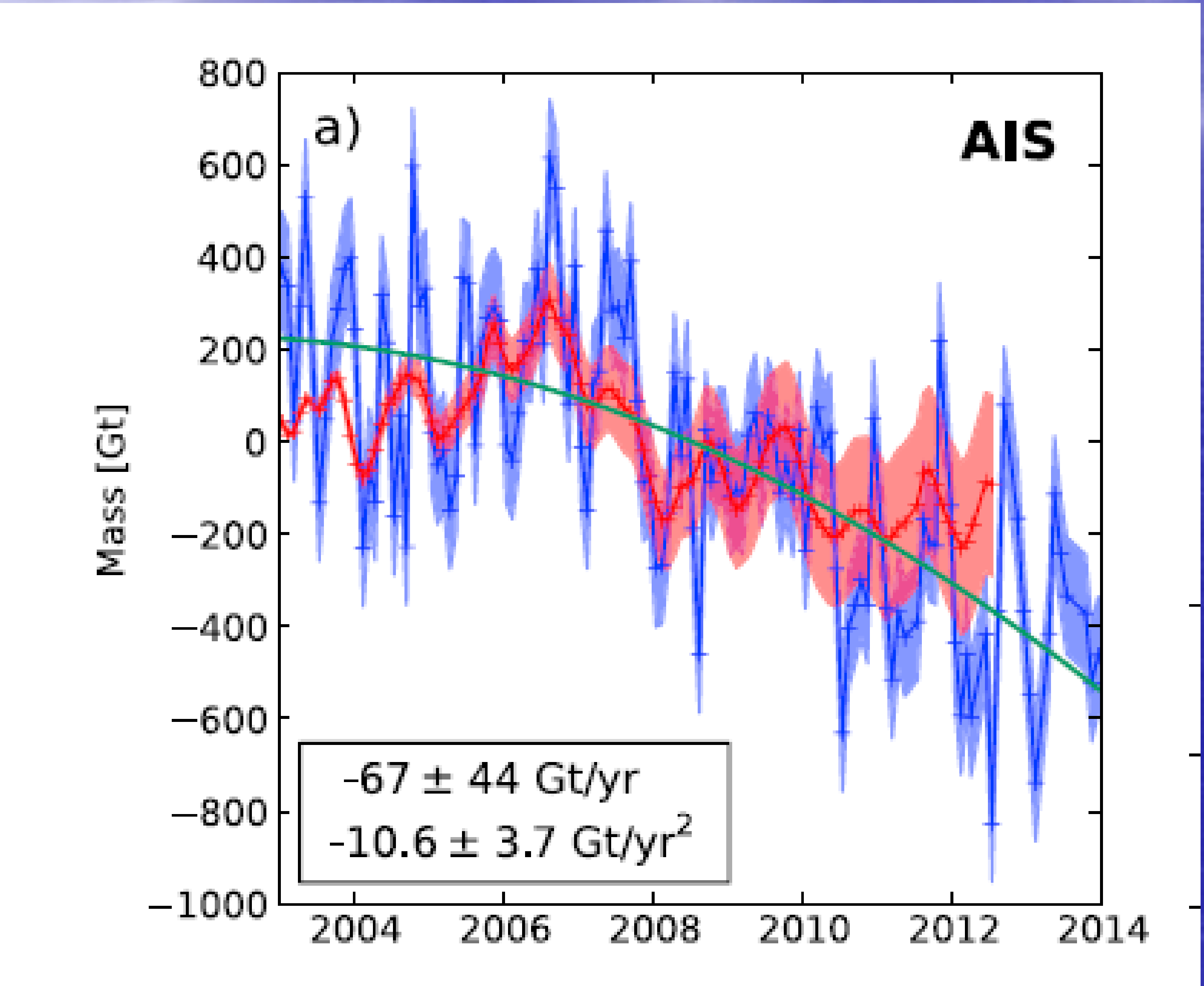
5. GRACE has been flying since March 2002 and has been used to study changes in ice, ground water and soil moisture
6. GRACE is done. Follow-on GRACE is planned.

Velicogna, I., T. C. Sutterley, and M. R. van den Broeke (2014), Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, J. Geophys. Res. Space Physics, 41, 8130–8137, doi:10.1002/2014GL061052.



Time series of ice mass, M(t), in Gt (Gigatonne) for (a) the entire Greenland ice sheet (GIS), Blue: GRACE Total Mass Anomaly Red: Cumulative Surface Mass Balance (New snow -surface melting)

Antarctic Ice Sheet – Mass Anomaly vs Time from GRACE



Time series of ice mass, M(t), in Gt (Gigatonne) for (a) the entire Antarctic ice sheet (AIS), Blue: GRACE Mass Anomaly Red: Cumlative Surface Mass Balance (New snow -surface melting)

ARGO Float

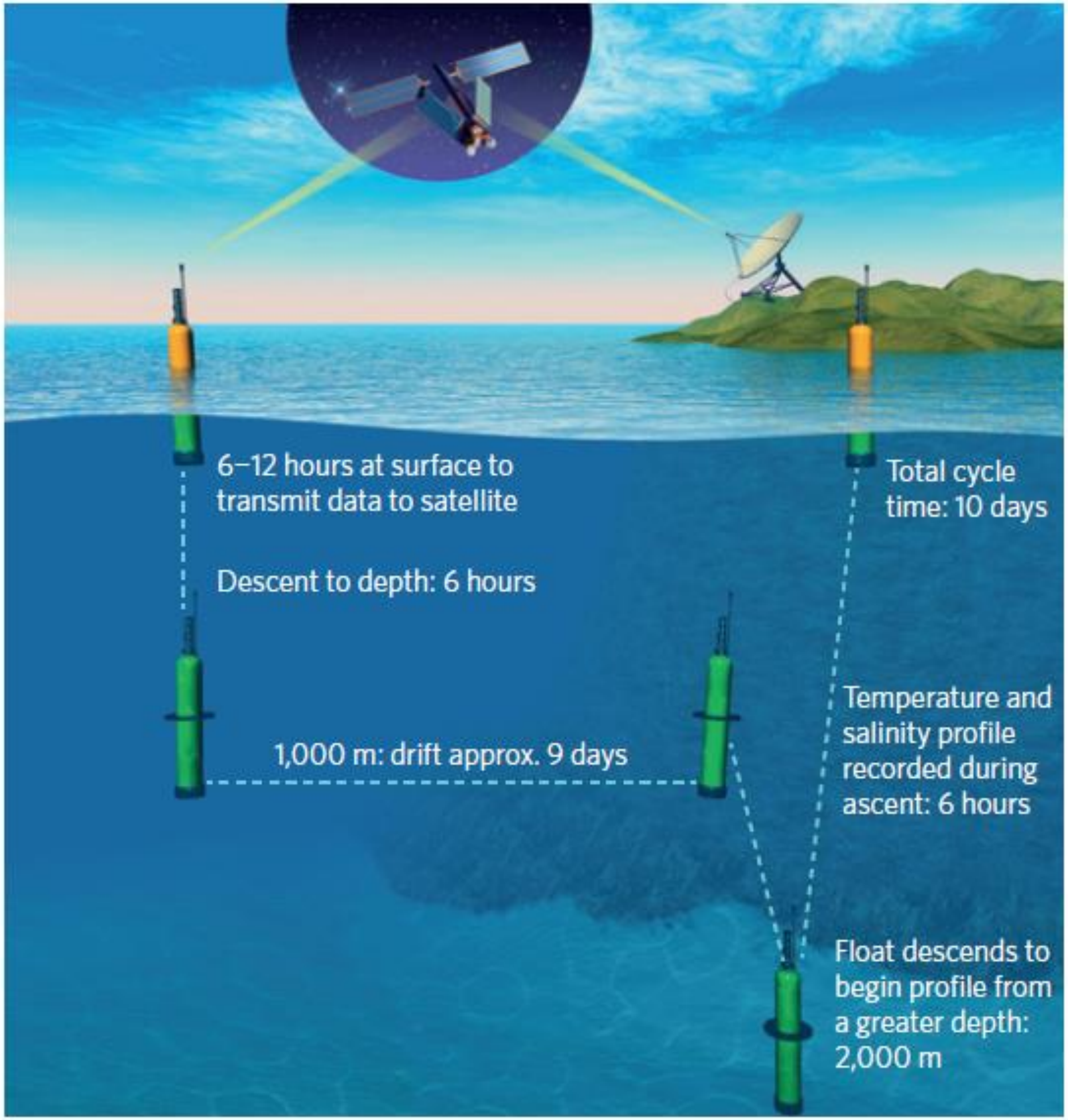
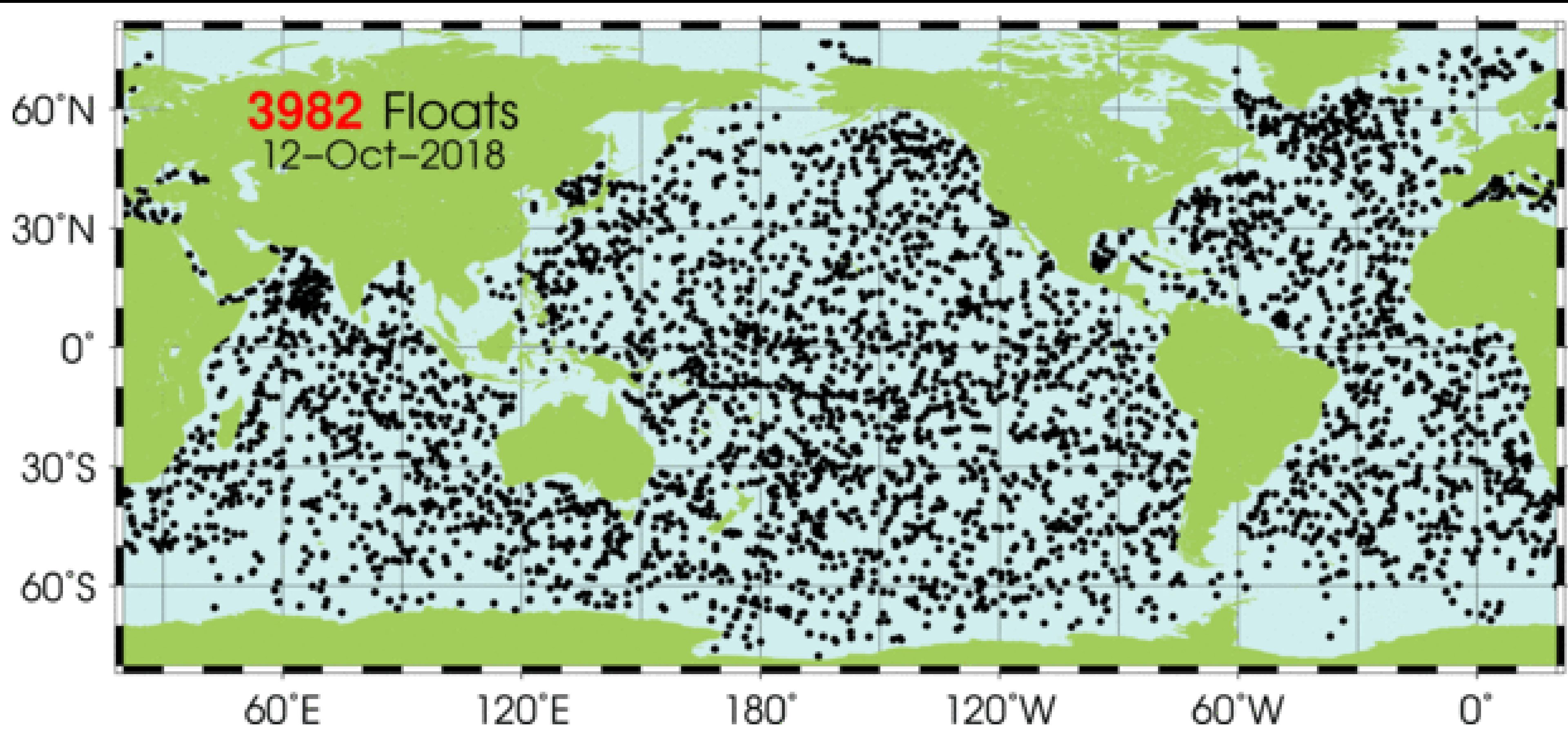


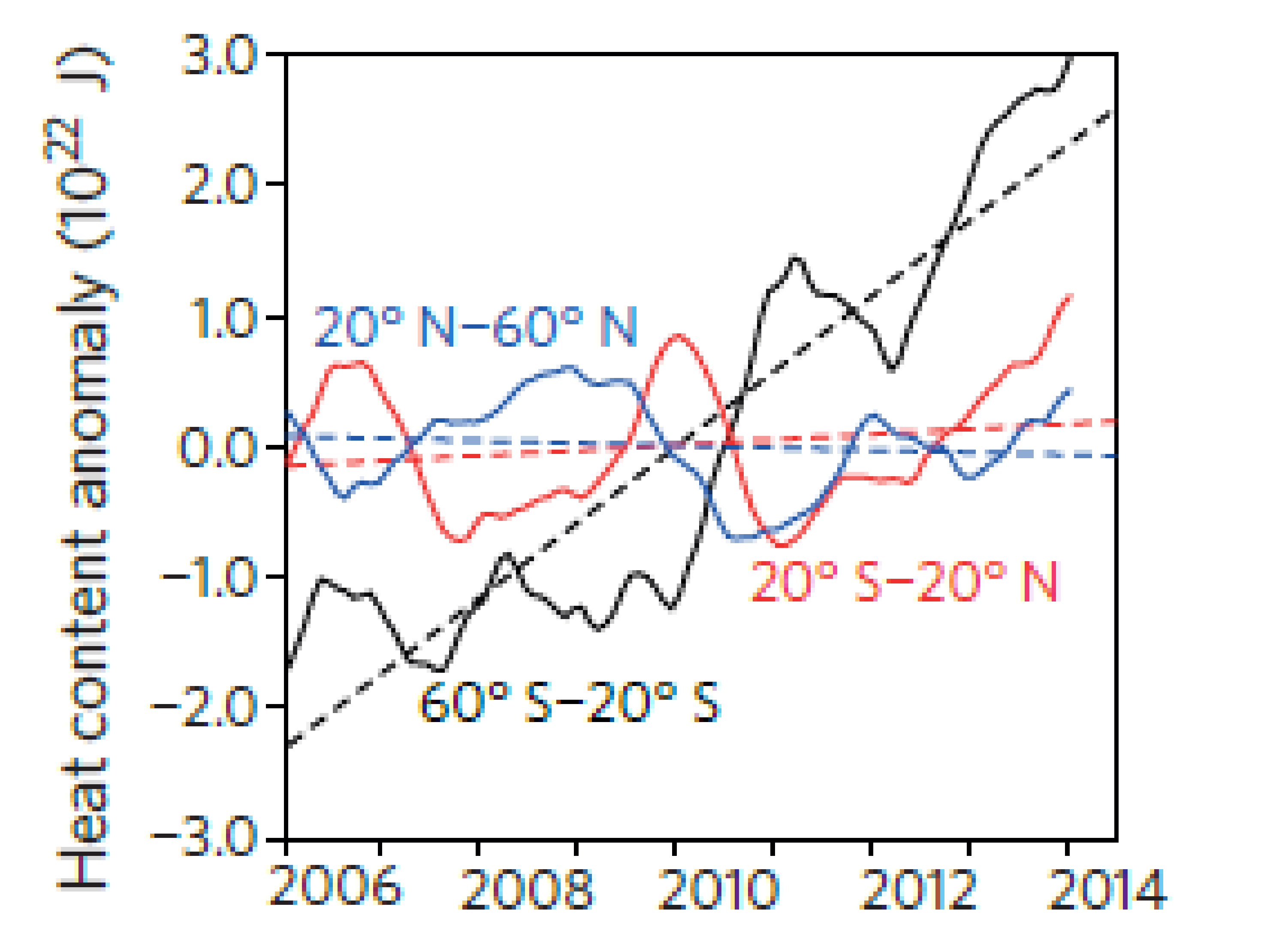
Figure 1 | The typical cycle of an Argo float. The float starts at the surface and dives to a depth of 1,000 m (the parking depth) where it rests for 9 to 10 days. After 9 days at rest it dives to a depth of 2,000 m, turns on

ARGO Floats



3982 Floats
12-Oct-2018
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°

ARGO Data Alone



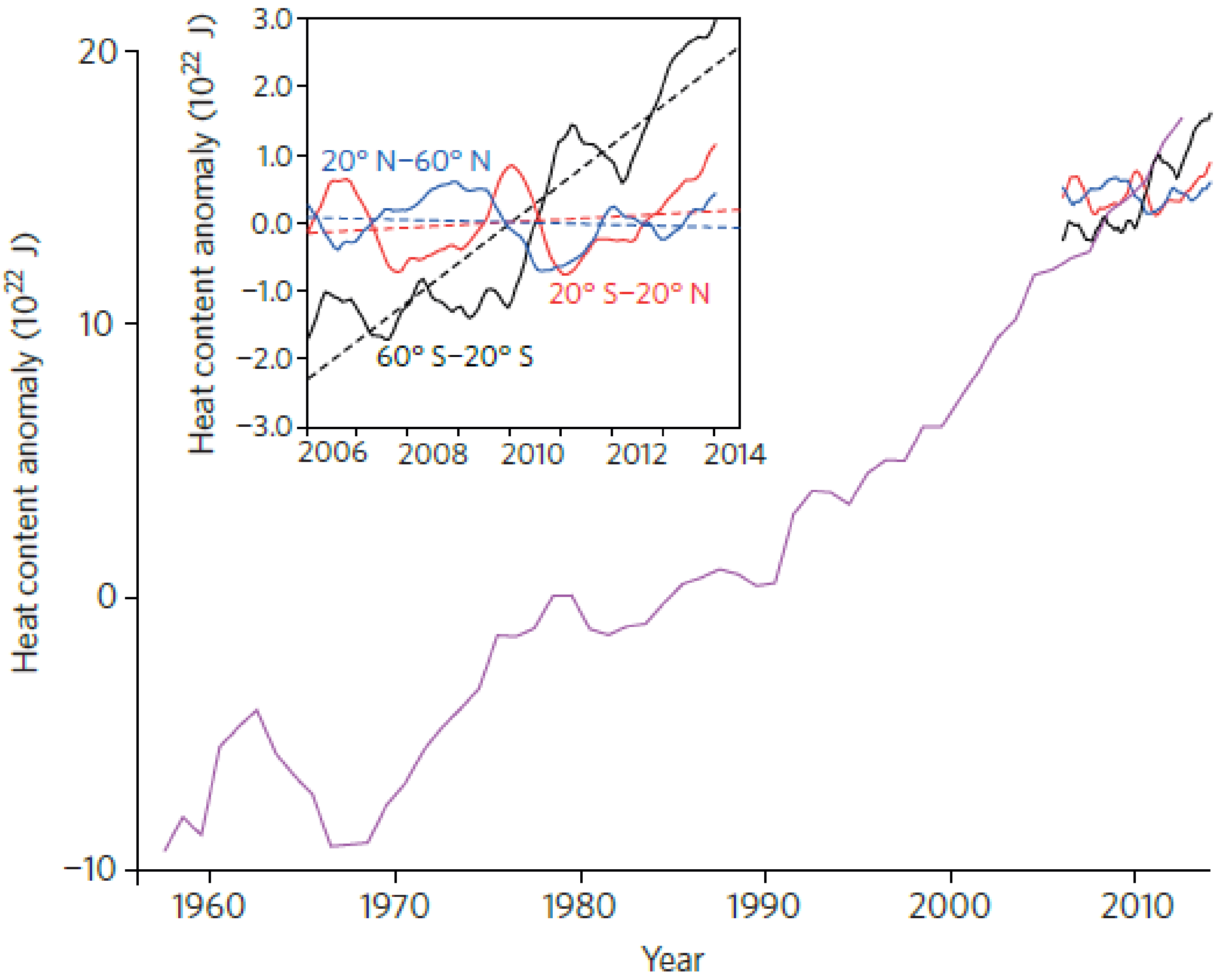
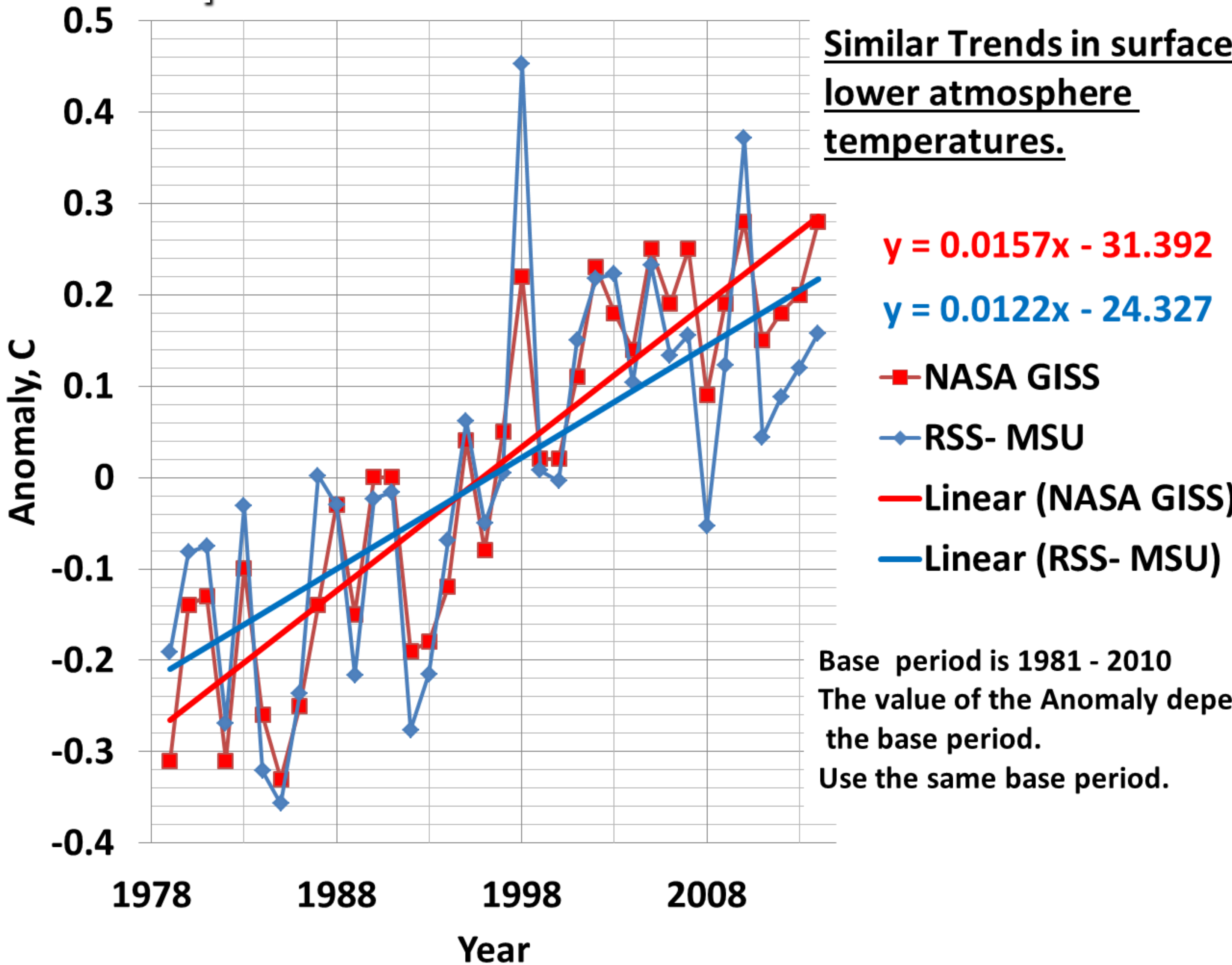


Figure 5 | Argo estimates of global heat content. Estimates of the heat content anomaly[27] for 60° S–20° S (black), 20° S–20° N (red) and 20° N–60° N (blue), and a global estimate (purple)[42]. Regression lines (dashed) are shown in the inset; adapted from ref. 27, Nature Publishing Group.

Ocean heat Content From Argo and Earlier Systems

Compare GAST and MSU Results



<u>Similar Trends in surface and lower atmosphere temperatures.</u>

Base period is 1981 - 2010

The value of the Anomaly depends upon the base period.

Use the same base period.

DU Aerosol Group Develops Instruments, Makes In situ Aerosol Measurements and Does Analysis

NASA Global Hawk
Altitude Cruising Range: 45,000 – 65,000 ft
Duration: 33 hrs
DU Aerosol Payload
First Science Mission: Winter 2010

NASA WB-57F
Altitude Cruising Range: 45,000 – 65,000 ft
Duration: 6 hrs
DU Aerosol Payload in nose

NASA Photos

DU Aerosol Group: Instruments & Inlets, Missions & Science

NASA ER-2, DC-8, WB-57F
NCAR C-130, HIAPER,Electra, UK FAAM, DLR Falcon
Russian Geophysica, NPGS Twin Otter…