Warming in the pipeline

The effect of reducing sulphur emissions without addressing greenhouse gases

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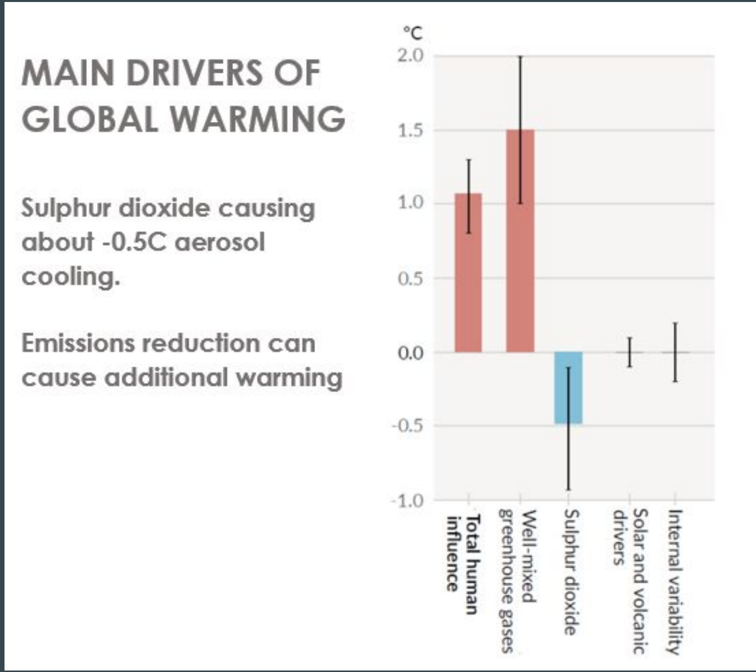
Global Temperature anomaly from 1850-1900 (C3S/ECMWF ERA 5)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Jan	0.5	0.3	0.1	0.6	0.2	0.3	0.2	0.4	0.4	0.5	0.7	0.8	0.4	0.8	0.6	0.5	0.5	0.6	0.8	0.4	0.7	0.8	0.7	0.6	0.6	0.8	0.6
Feb	0.5	0.1	0.0	0.6	0.0	0.3	0.1	0.4	0.4	0.3	0.7	0.7	0.5	0.8	0.4	0.3	0.6	0.7	0.6	0.6	0.7	0.8	0.7	0.7	0.3	1.0	0.7
Mar	0.4	0.1	0.2	0.5	0.2	0.3	-0.1	0.4	0.4	0.5	0.6	0.8	0.3	0.8	0.5	0.4	0.5	0.5	0.7	0.6	1.0	0.7	0.7	0.6	0.5	0.7	0.6
Apr	0.4	0.2	0.3	0.5	0.2	0.3	0.1	0.4	0.4	0.4	0.7	0.7	0.4	0.6	0.4	0.4	0.6	0.6	0.7	0.6	0.9	0.8	0.5	0.6	0.6	0.8	0.5
May	0.3	0.2	0.3	0.5	0.1	0.3	0.0	0.5	0.4	0.4	0.7	0.6	0.5	0.7	0.6	0.4	0.6	0.6	0.7	0.5	0.8	0.7	0.5	0.6	0.5	0.6	0.5
Jun	0.3	0.1	0.4	0.4	0.1	0.1	0.1	0.4	0.2	0.4	0.6	0.6	0.4	0.6	0.3	0.4	0.4	0.6	0.7	0.4	0.6	0.9	0.5	0.5	0.6	0.7	0.5
Jul	0.3	0.1	0.4	0.3	0.1	0.1	0.2	0.4	0.3	0.3	0.6	0.6	0.5	0.5	0.3	0.3	0.4	0.7	0.6	0.6	0.7	0.8	0.3	0.4	0.5	0.7	0.6
Aug	0.1	0.1	0.3	0.2	0.2	0.0	0.1	0.3	0.1	0.4	0.5	0.6	0.3	0.5	0.4	0.4	0.4	0.5	0.6	0.5	0.6	0.7	0.3	0.4	0.4	0.7	0.7
Sep	0.2	0.2	0.3	0.2	0.0	0.0	0.2	0.2	0.1	0.4	0.5	0.5	0.3	0.6	0.4	0.3	0.3	0.6	0.7	0.5	0.6	0.6	0.2	0.3	0.6	0.6	0.5
Oct	0.2	0.1	0.3	0.2	0.0	0.0	-0.1	0.2	0.2	0.5	0.4	0.4	0.3	0.4	0.4	0.2	0.3	0.5	0.5	0.5	0.7	0.5	0.3	0.4	0.6	0.7	0.4
Nov	0.2	0.1	0.3	0.3	0.1	0.1	0.1	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.3	0.3	0.4	0.5	0.4	0.4	0.8	0.5	0.3	0.4	0.6	0.7	0.7
Dec	0.2	0.2	0.5	0.3	0.2	0.1	0.3	0.4	0.4	0.8	0.5	0.7	0.7	0.5	0.4	0.4	0.5	0.8	0.6	0.7	0.8	0.6	0.5	0.6	0.7	0.6	0.7
	0.3	0.2	0.3	0.4	0.1	0.2	0.1	0.4	0.3	0.4	0.6	0.6	0.4	0.6	0.4	0.4	0.4	0.6	0.6	0.5	0.7	0.7	0.5	0.5	0.5	0.7	0.6

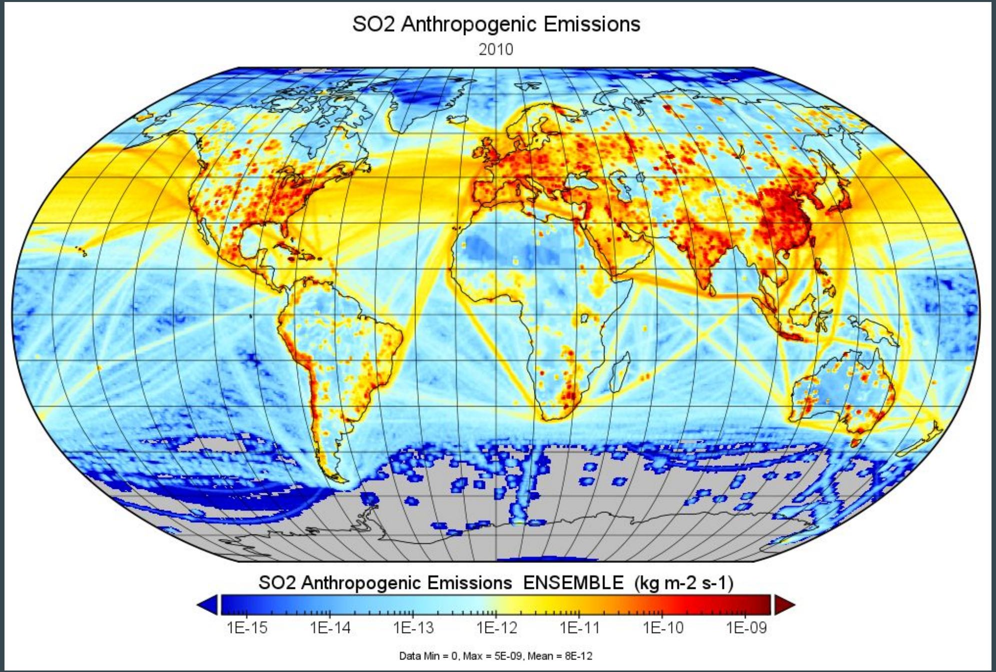
	1997	**1998**	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	**2015**	**2016**	2017	2018	2019	2020	2021	2022	**2023**
Jan	0.6	0.9	0.7	0.6	0.7	1.1	1.1	0.9	1.1	0.9	1.3	0.6	1.0	1.1	0.9	0.8	1.1	1.1	1.2	1.5	1.4	1.2	1.2	1.5	1.2	1.2	1.2
Feb	0.7	1.1	0.9	0.8	0.7	1.0	0.9	1.0	1.0	1.1	1.1	0.6	0.9	1.2	0.8	0.8	1.0	0.9	1.2	1.6	1.5	1.2	1.3	1.6	1.0	1.2	1.3
Mar	0.8	0.9	0.6	0.7	0.8	1.1	0.8	0.9	1.0	0.9	1.0	0.9	0.8	1.2	0.9	0.8	1.0	1.0	1.2	1.6	1.4	1.2	1.5	1.4	1.1	1.3	1.5
Apr	0.6	1.0	0.6	0.8	0.8	0.8	0.8	0.9	1.0	0.8	1.1	0.8	0.9	1.2	0.9	0.9	0.9	1.0	1.0	1.4	1.2	1.2	1.3	1.4	1.1	1.2	1.2
May	0.6	1.0	0.6	0.6	0.8	0.9	0.8	0.6	0.9	0.8	0.9	0.7	0.9	1.1	0.8	1.0	0.9	1.0	1.0	1.2	1.2	1.1	1.2	1.3	1.1	1.1	1.3
Jun	0.7	1.0	0.6	0.6	0.7	0.8	0.7	0.7	0.9	0.9	0.8	0.6	0.8	0.9	0.8	0.9	0.9	0.9	1.0	1.1	1.0	1.0	1.2	1.2	1.0	1.1	1.4
Jul	0.6	0.9	0.6	0.5	0.8	0.8	0.8	0.5	0.9	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.8	0.9	1.0	1.2	1.1	1.1	1.2	1.1	1.1	1.2	1.5
Aug	0.7	0.9	0.6	0.6	0.7	0.8	0.8	0.6	0.8	0.9	0.8	0.7	0.8	0.8	0.9	0.9	0.9	0.9	1.0	1.2	1.1	1.0	1.2	1.1	1.1	1.1	1.5
Sep	0.7	0.8	0.6	0.6	0.7	0.8	0.9	0.8	0.9	0.9	0.7	0.8	0.9	0.9	0.9	0.9	1.0	1.0	1.1	1.2	1.1	1.0	1.2	1.3	1.2	1.2	1.7
Oct	0.8	0.7	0.5	0.5	0.7	0.8	1.0	0.9	1.0	1.0	0.8	0.9	0.9	1.0	0.9	1.1	0.9	1.0	1.3	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.7
Nov	0.9	0.7	0.6	0.6	1.0	0.8	0.9	1.0	1.0	1.0	0.9	1.0	1.0	1.0	0.8	1.1	1.0	1.0	1.3	1.3	1.1	1.1	1.3	1.5	1.2	1.1	1.8
Dec	0.9	0.8	0.7	0.6	1.0	0.8	1.1	0.9	1.0	1.1	0.8	0.9	1.0	0.8	0.9	0.9	1.1	1.1	1.5	1.3	1.3	1.3	1.5	1.2	1.3	1.2	
	0.7	0.9	0.6	0.6	0.8	0.9	0.9	0.8	1.0	0.9	0.9	0.8	0.9	1.0	0.9	0.9	0.9	1.0	1.1	1.3	1.2	1.1	1.3	1.3	1.2	1.2	1.5

Global warming is mainly caused by greenhouse gases released from burning of fossil fuels.

Fossil fuel burning also releases sulphur, which reduces global warming by reflecting sunlight and by making clouds more reflective, larger and longer lasting.

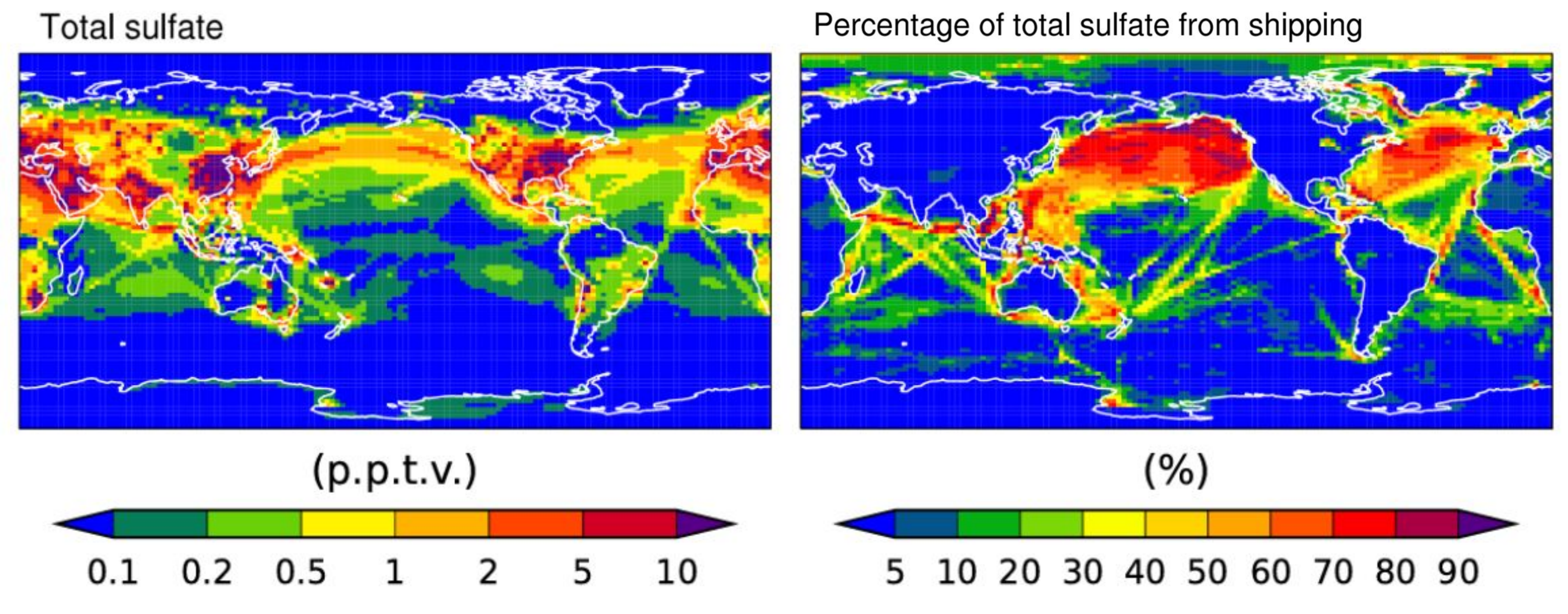


Adapted from IPCC AR6 WG1 Figure SPM.2



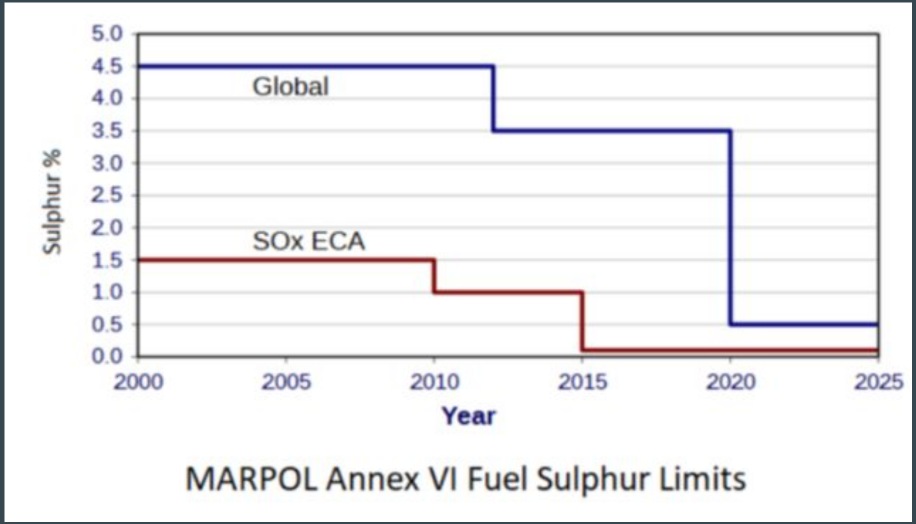
NASA, MERRA-2 Anthropogenic SO2

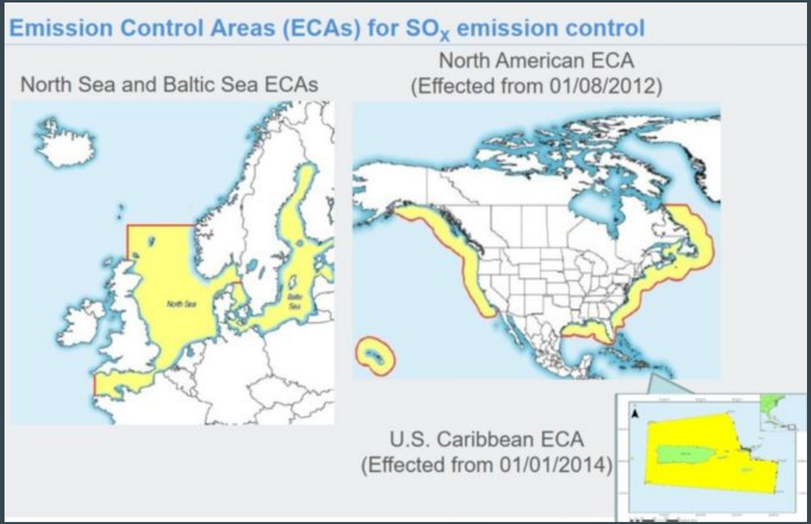
Total sulfate from all natural and human sources, and the percentage from global shipping



Warming in the pipeline, Figure 20. Total anthropogenic and natural; and shipping sulfate simulations from Jin et al.

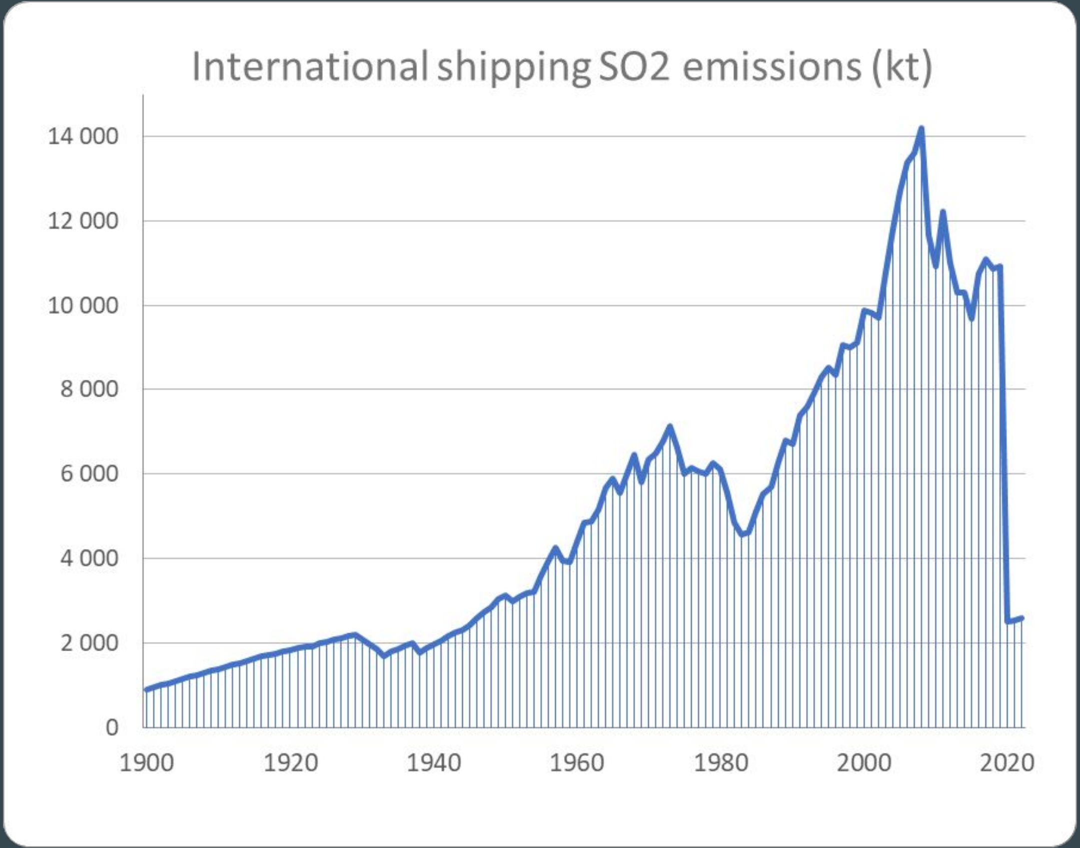
Regulation of the International Maritime Organization (IMO) significantly reduced sulphur emissions over seas and oceans, both over Emissions Control Areas and globally





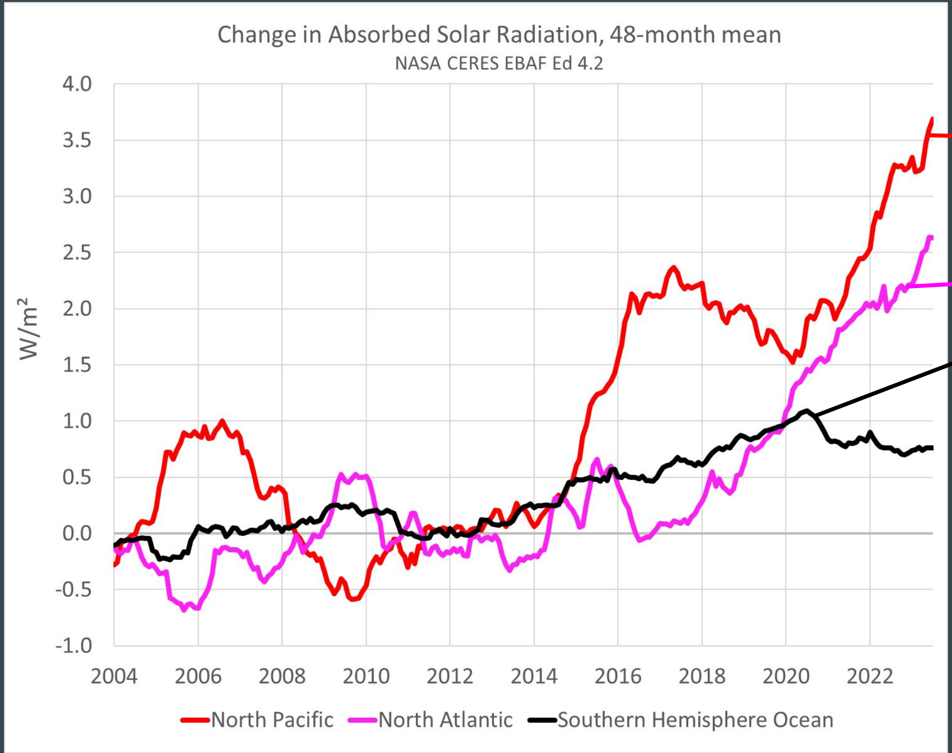
Global and regional shipping regulations from the International Maritime Organization (IMO)

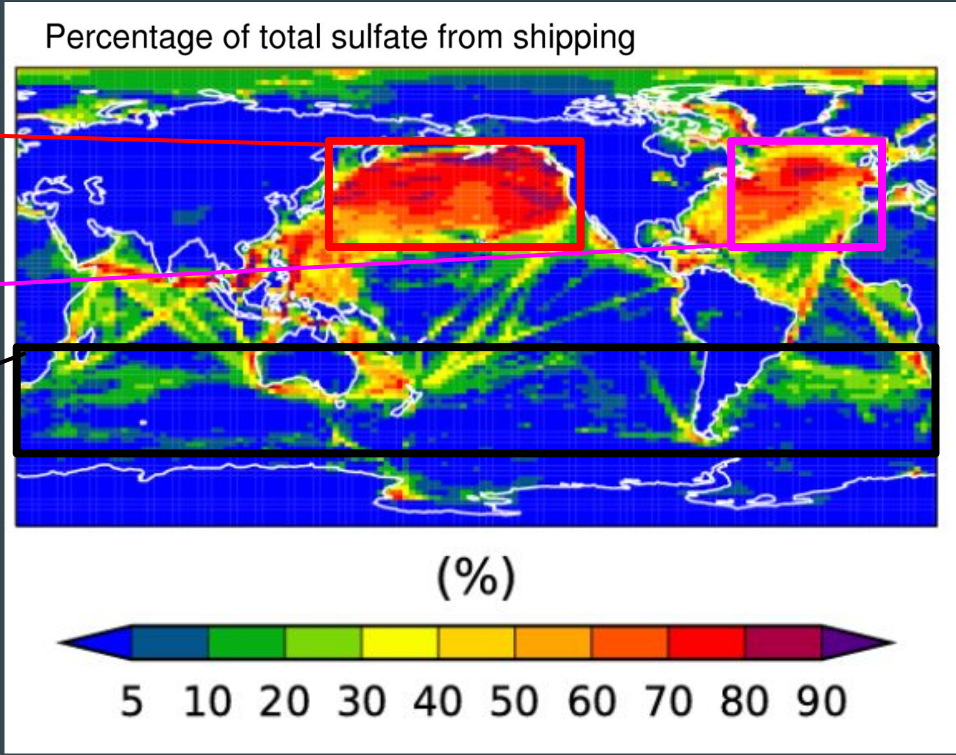
Changes in international sulfur dioxide emissions

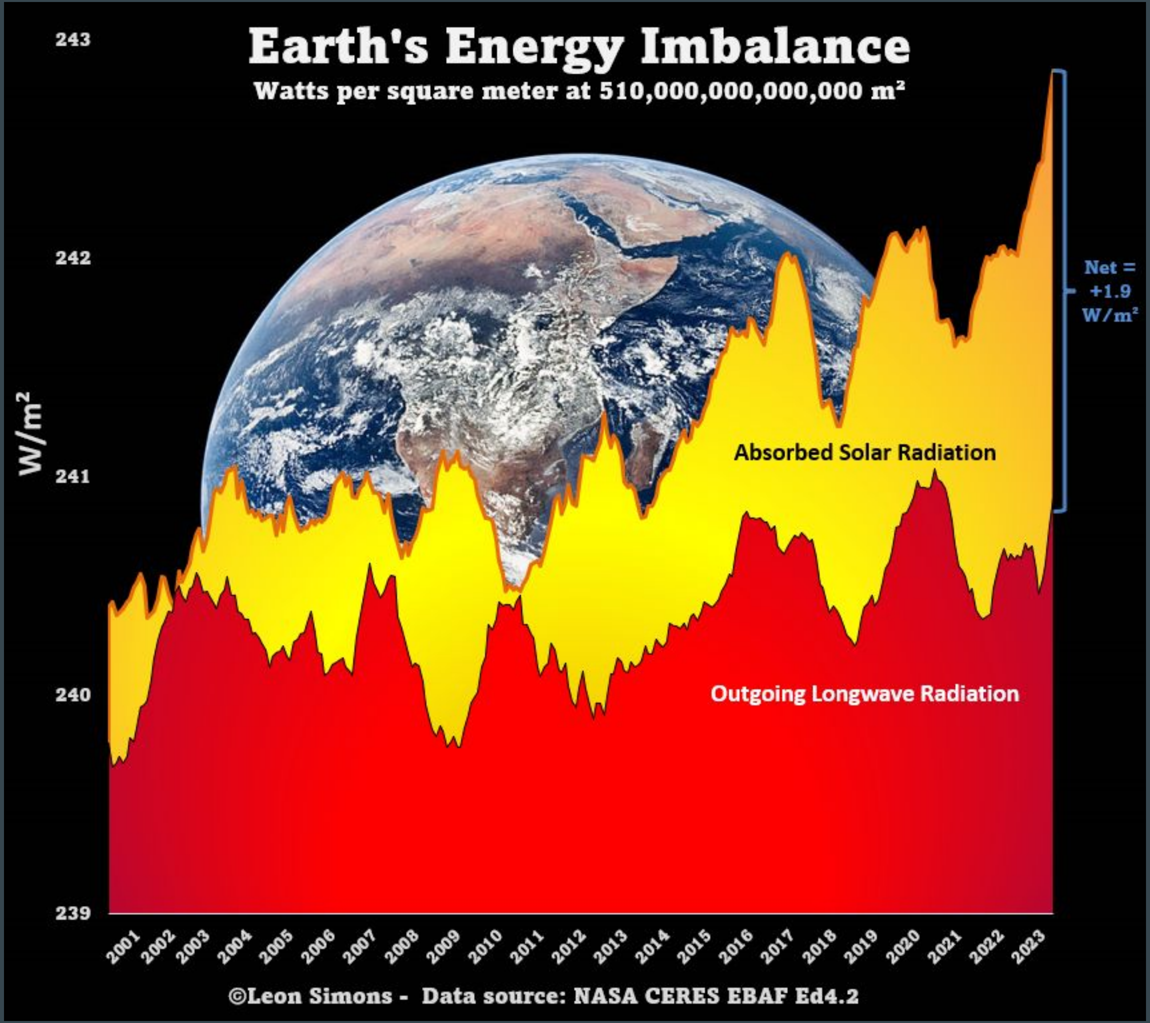


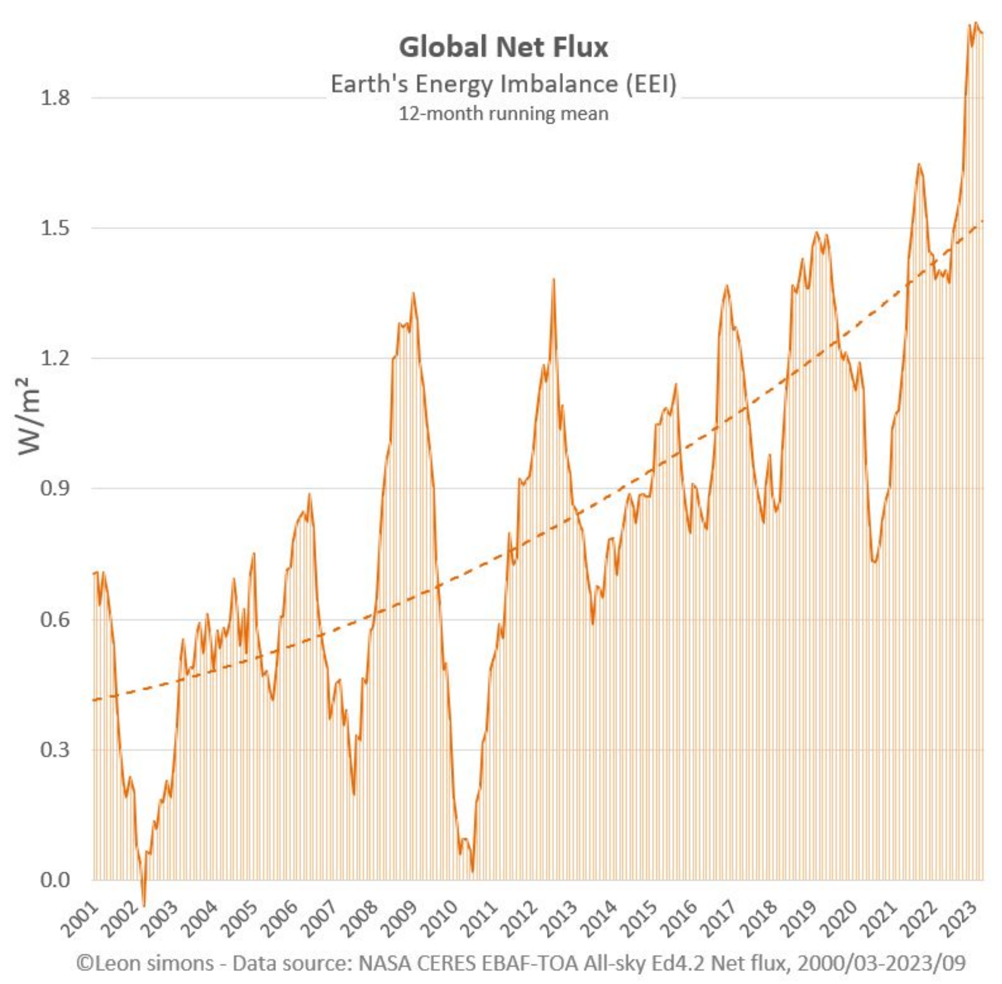
Global sulfur dioxide emissions from international shipping. Sources: CEDS and Corbett et al.

Change in Absorbed Sunlight in ocean regions with and without large shipping emissions changes

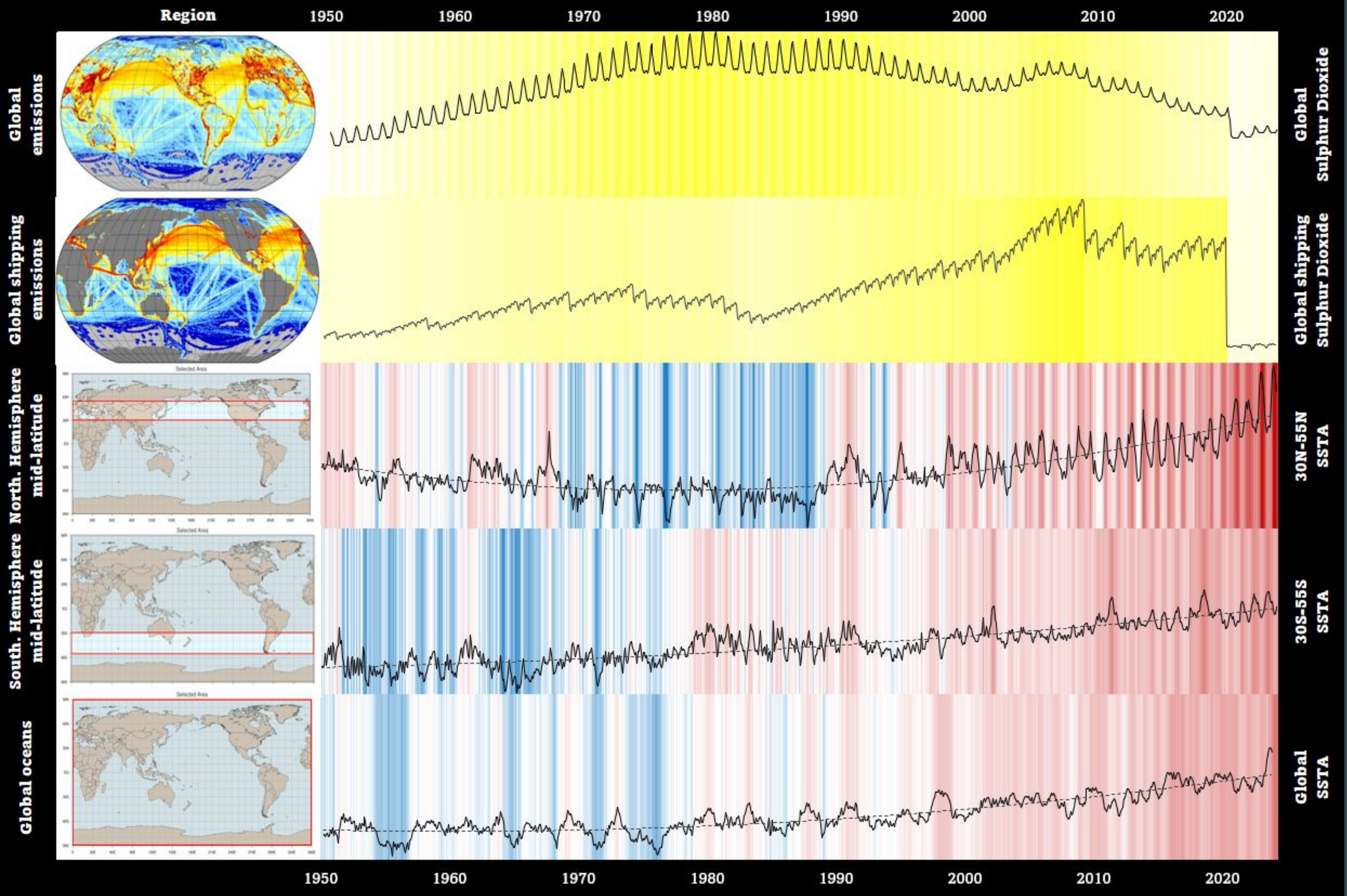





Earth's Energy Imbalance
Watts per square meter at 510,000,000,000,000 m²
W/m²
243
242
241
240
239
Net = +1.9 W/m²
Absorbed Solar Radiation
Outgoing Longwave Radiation
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
©Leon Simons - Data source: NASA CERES EBAF Ed4.2


Global Net Flux
Earth's Energy Imbalance (EEI)
12-month running mean
W/m²
1.8
1.5
1.2
0.9
0.6
0.3
0.0
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
©Leon simons - Data source: NASA CERES EBAF-TOA All-sky Ed4.2 Net flux, 2000/03-2023/09

Monthly Total Anthropogenic, and International-Shipping Sulphur Dioxide (SO2) Emissions
Regional and Global Sea Surface Temperature Anomalies (SSTAs)



Thank you

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Annexures

- IPCC Greenhouse gases and aerosols and preindustrial forcings
- Faustian bargain
- Regional effects of shipping emission changes
- Ocean area, heat uptake and desulphurisation
- Compliance to shipping emission control regulations
- Drivers of global warming
- Regional surface air temperature response IPCC AR6 WG1
- Drivers of the increase in Earth’s net heat uptake, Loeb et al. (2021)
- Aerosol termination shock

Increasing greenhouse gases warm the planet

Aerosols cause regional and global cooling (less warming)

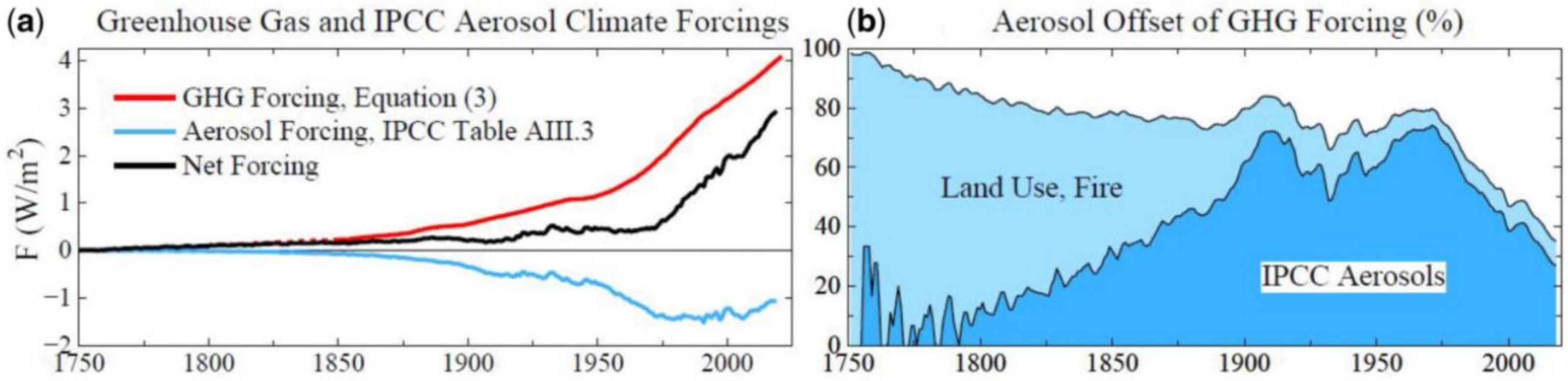


Figure 17. (**a**) Estimated greenhouse gas and aerosol forcings relative to 1750 values. (**b**) Aerosol forcing as percent of GHG forcing. Forcings for dark blue area are relative to 1750. Light blue area adds 0.5 W/m^2 forcing estimated for human-caused aerosols from fires, biofuels and land use.

Warming in the pipeline, Figure 17

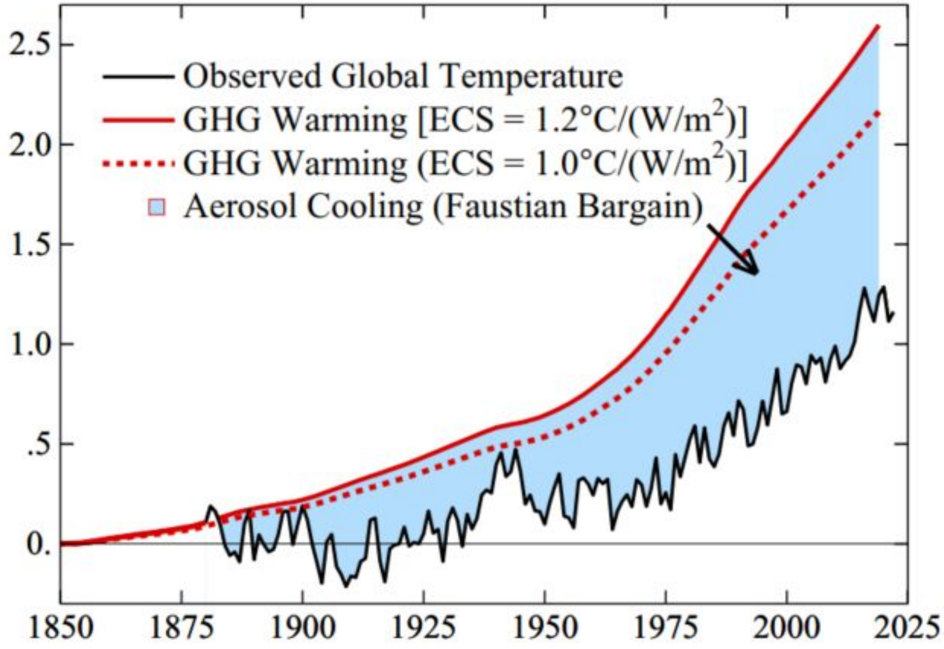


Figure 13. Observed global surface temperature (black line) and expected GHG warming with two choices for ECS. The blue area is the estimated aerosol cooling effect. The temperature peak in the World War II era is in part an artifact of inhomogeneous ocean data in that period [63].

Warming in the pipeline, Figure 13

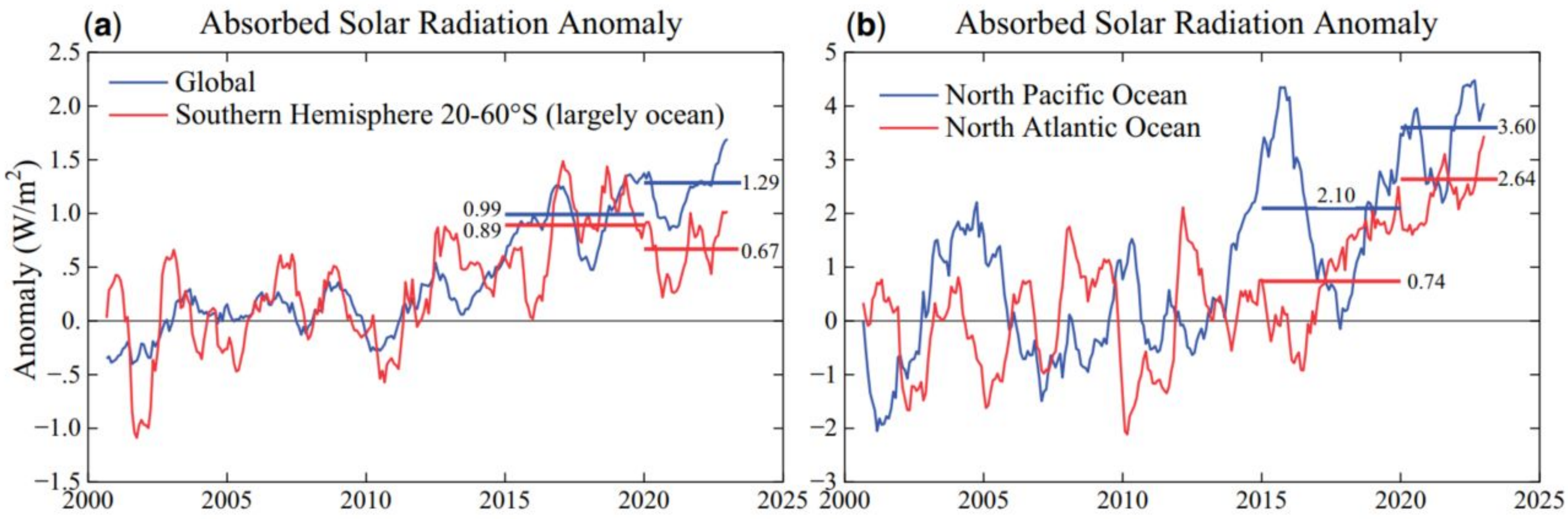
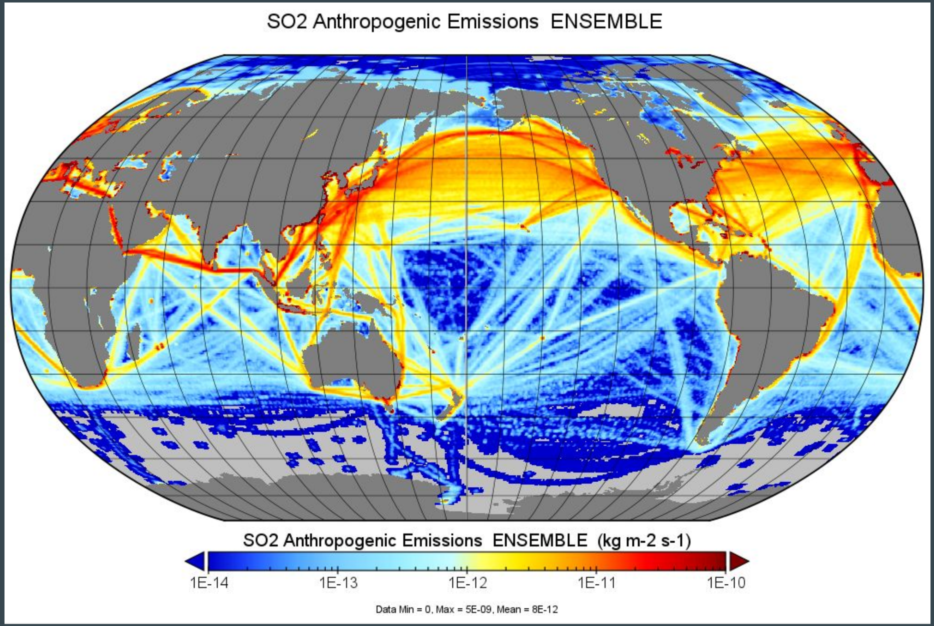
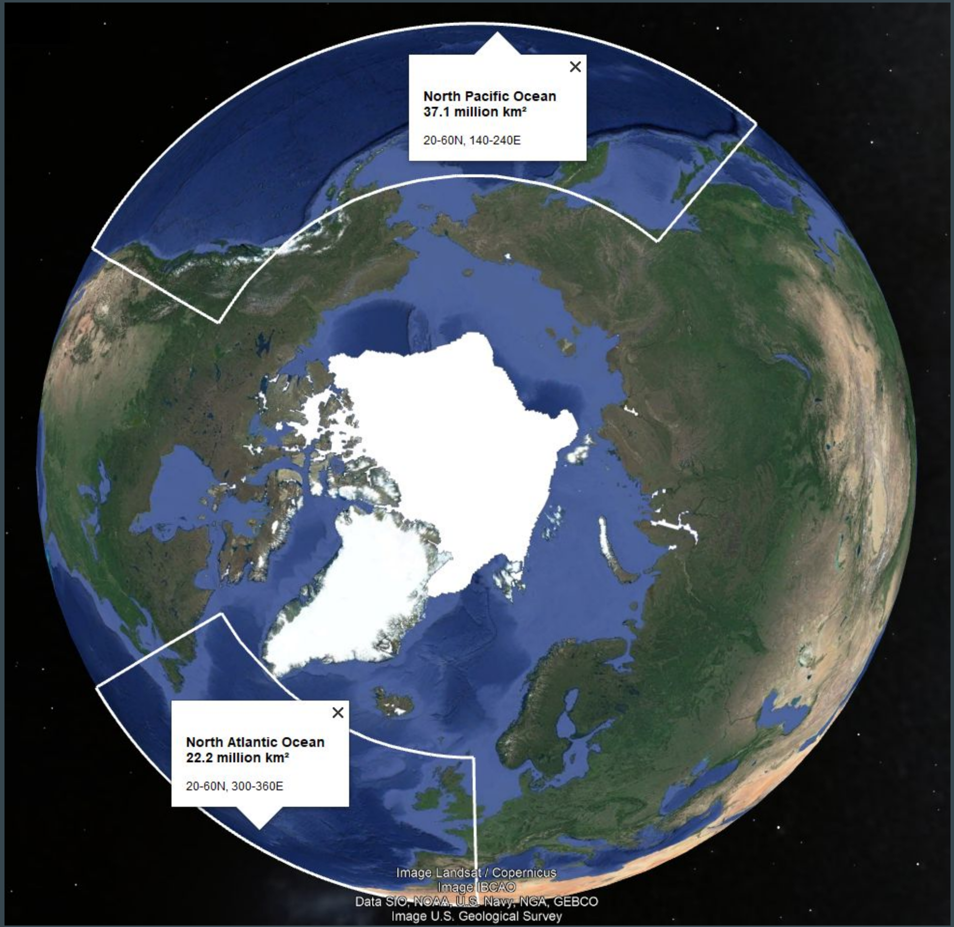


Figure 22. Absorbed solar radiation for indicated regions relative to first 120 months of CERES data. Southern Hemisphere 20–60°S is 89% ocean. North Atlantic is (20–60°N, 0–60°W) and North Pacific is (20–60°N, 120–220°W). Data source: http://ceres.larc.nasa.gov/order_data.php.

The North Pacific and Atlantic Oceans show dense shipping traffic and are expected to show effects of sulfur reductions.

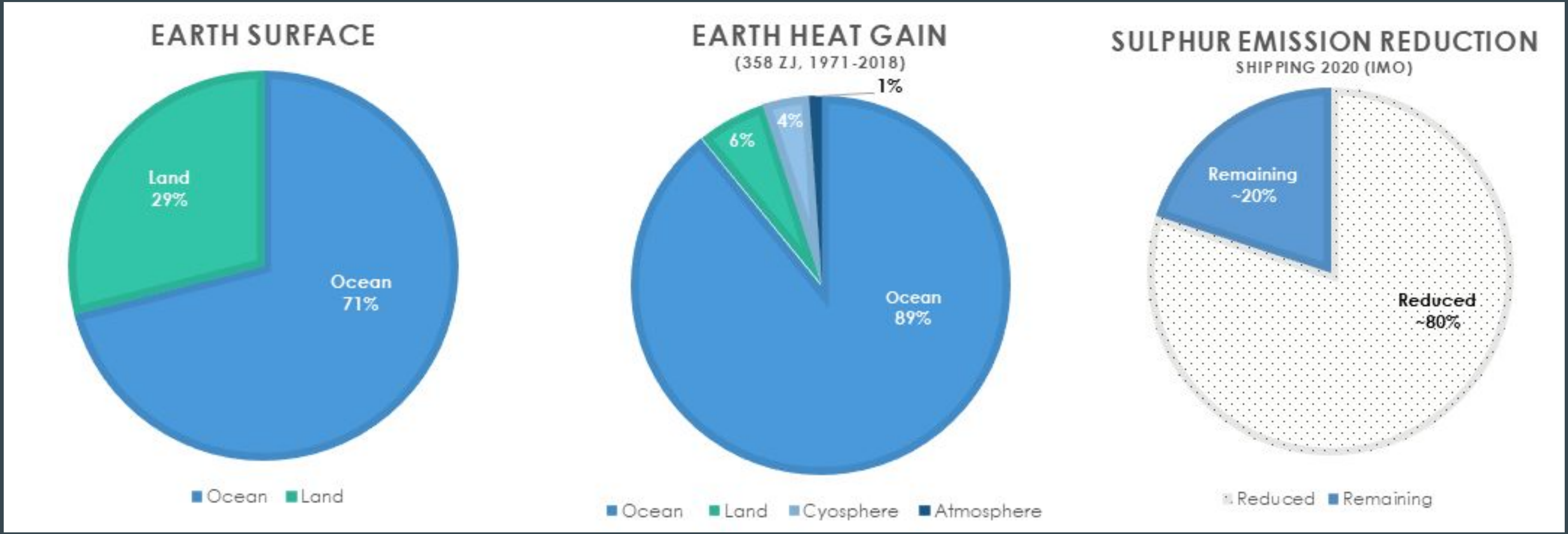




A large part of the planet is covered by oceans.

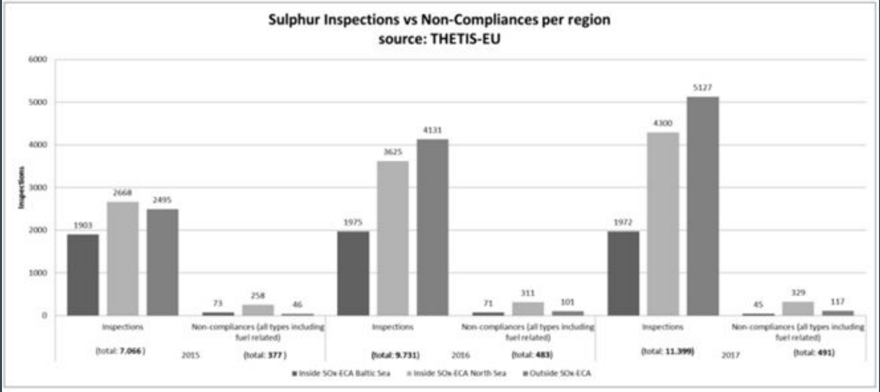
Most Earth Heat Gain warms oceans water

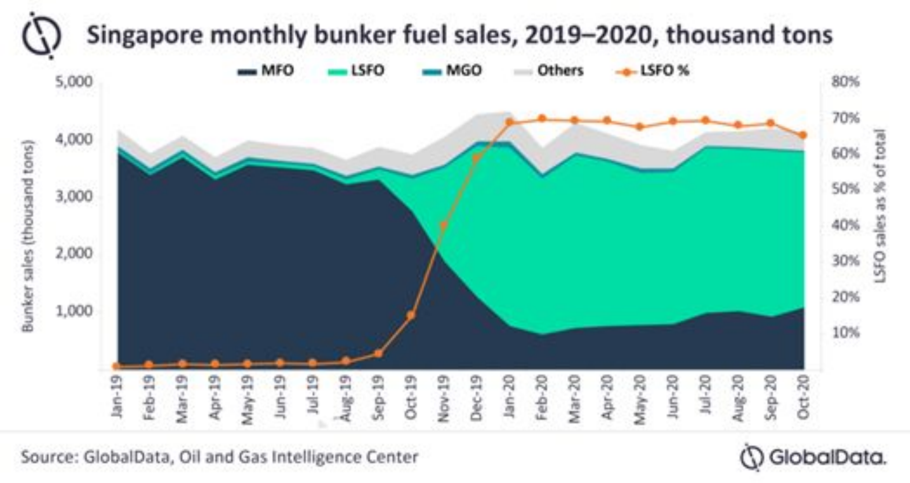
Sulphur emissions over oceans from shipping reduced with ~80% from 2020

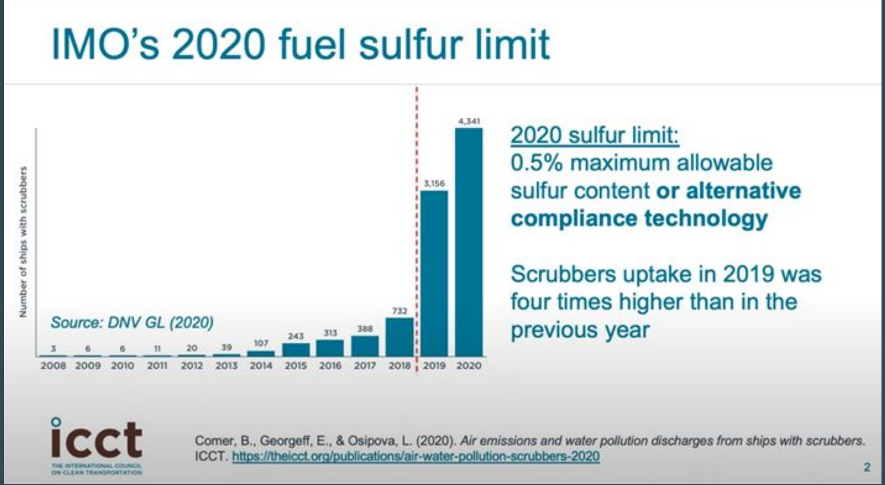


Compliance to shipping emission control regulations

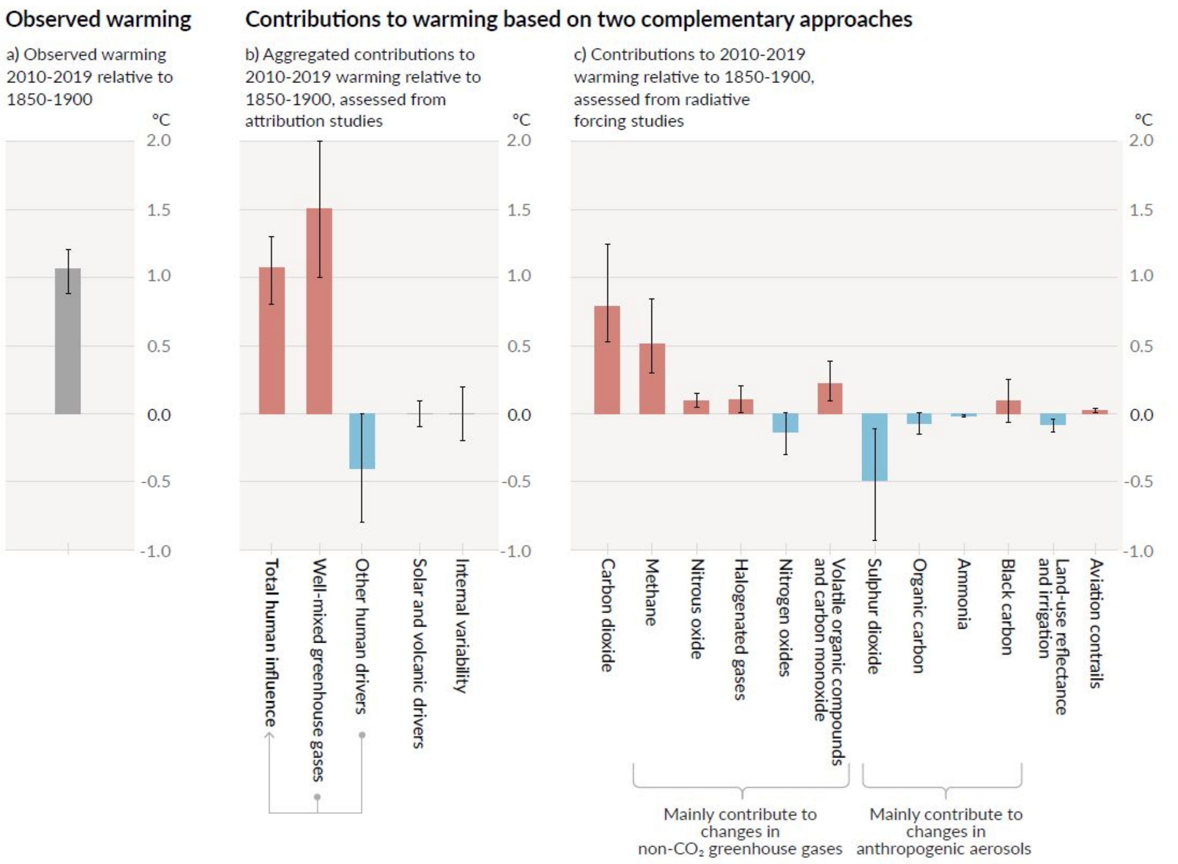
Inspections of compliance, low sulfur fuel sales and scrubber installations indicate strong compliance to sulphur fuel regulations.







Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling



IPCC AR6 WG1 SPM.2

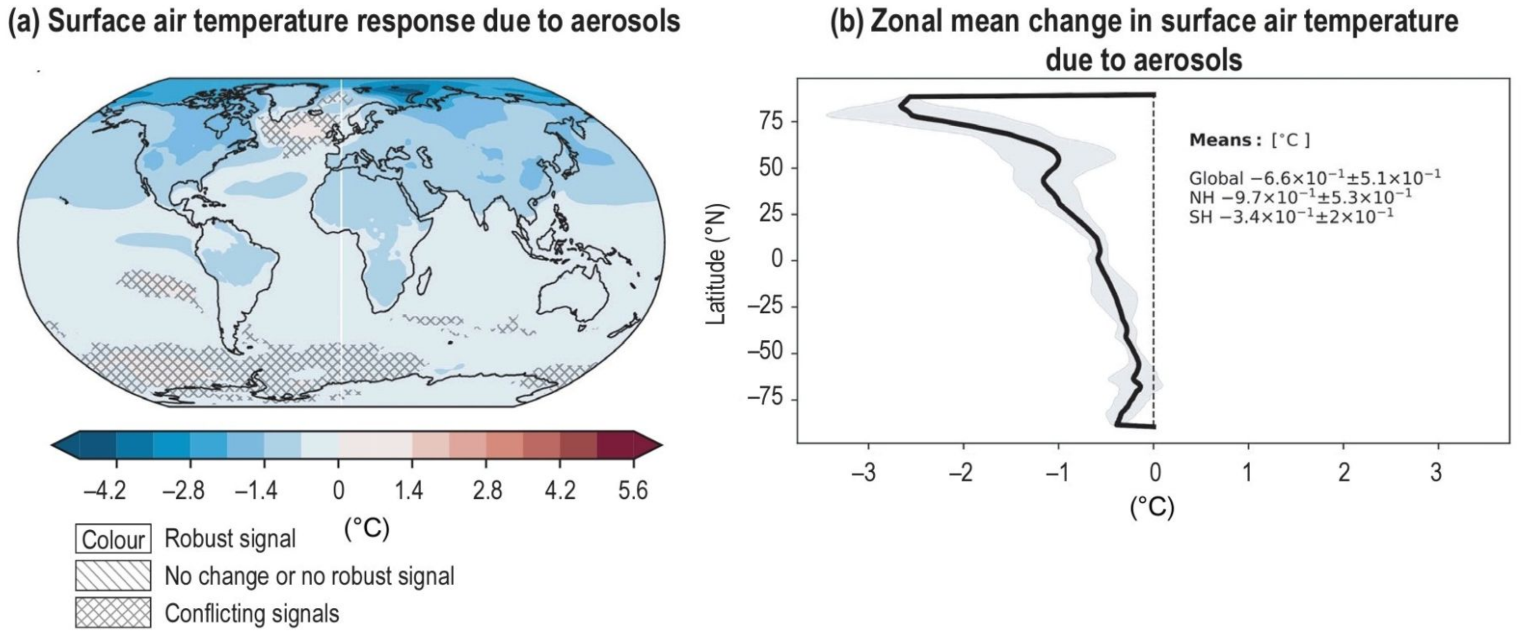
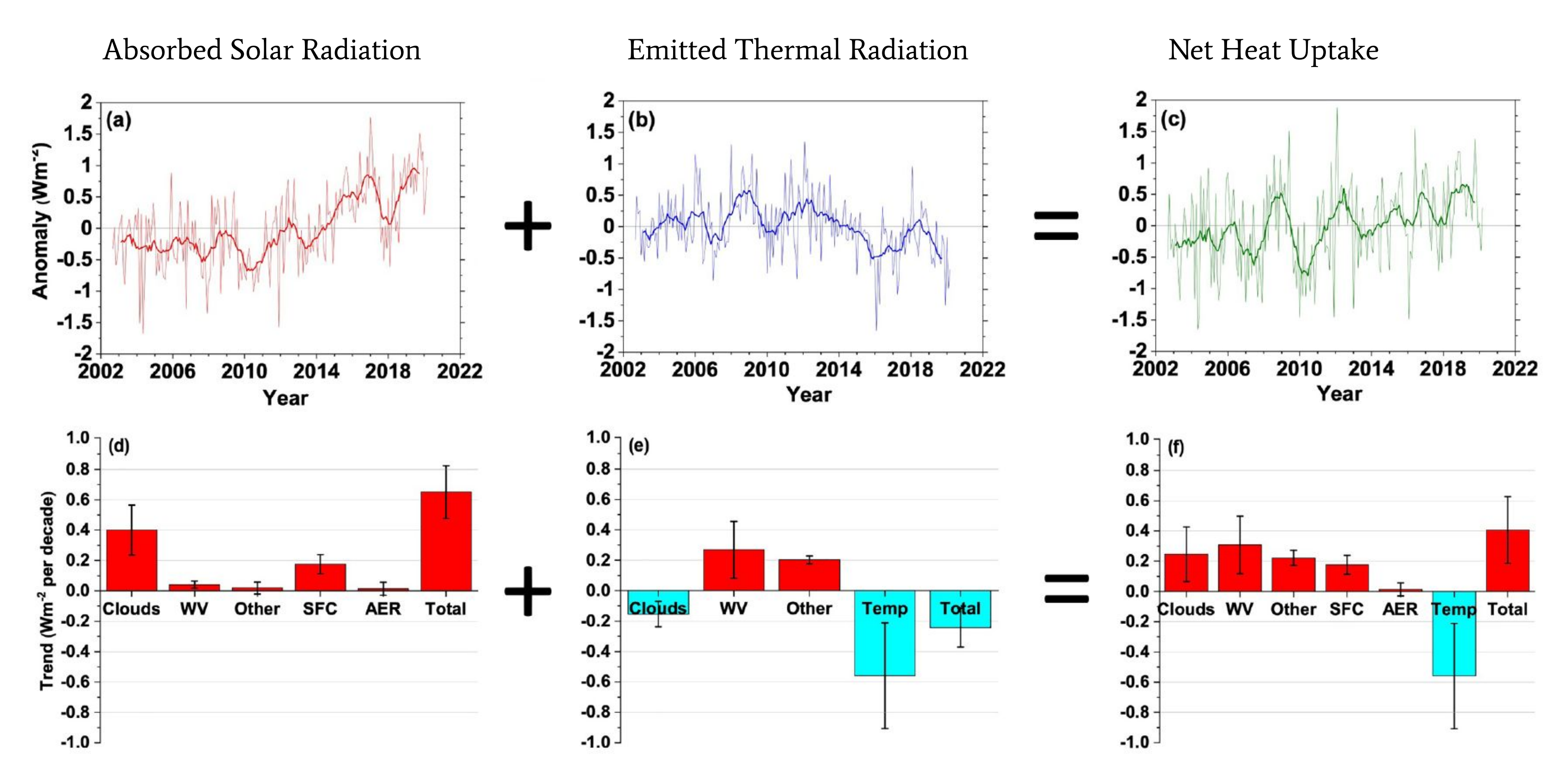


Figure 6.13 | Multi-model mean surface air temperature response over the recent past (1995–2014) induced by aerosol changes since 1850. Calculation is based on the difference between CMIP6 'historical' and AerChemMIP 'hist-piAer' experiments averaged over 1995–2014, where **(a)** is the spatial pattern of the annual mean surface air temperature response, and **(b)** is the mean zonally averaged response. Model means are derived from the years 1995–2014. Uncertainty is represented using the advanced approach: No overlay indicates regions with robust signal, where ≥66% of models show change greater than variability threshold and ≥80% of all models agree on sign of change; diagonal lines indicate regions with no change or no robust signal, where <66% of models show a change greater than the variability threshold; crossed lines indicate regions with conflicting signal, where ≥66% of models show change greater than variability threshold and <80% of all models agree on sign of change. For more

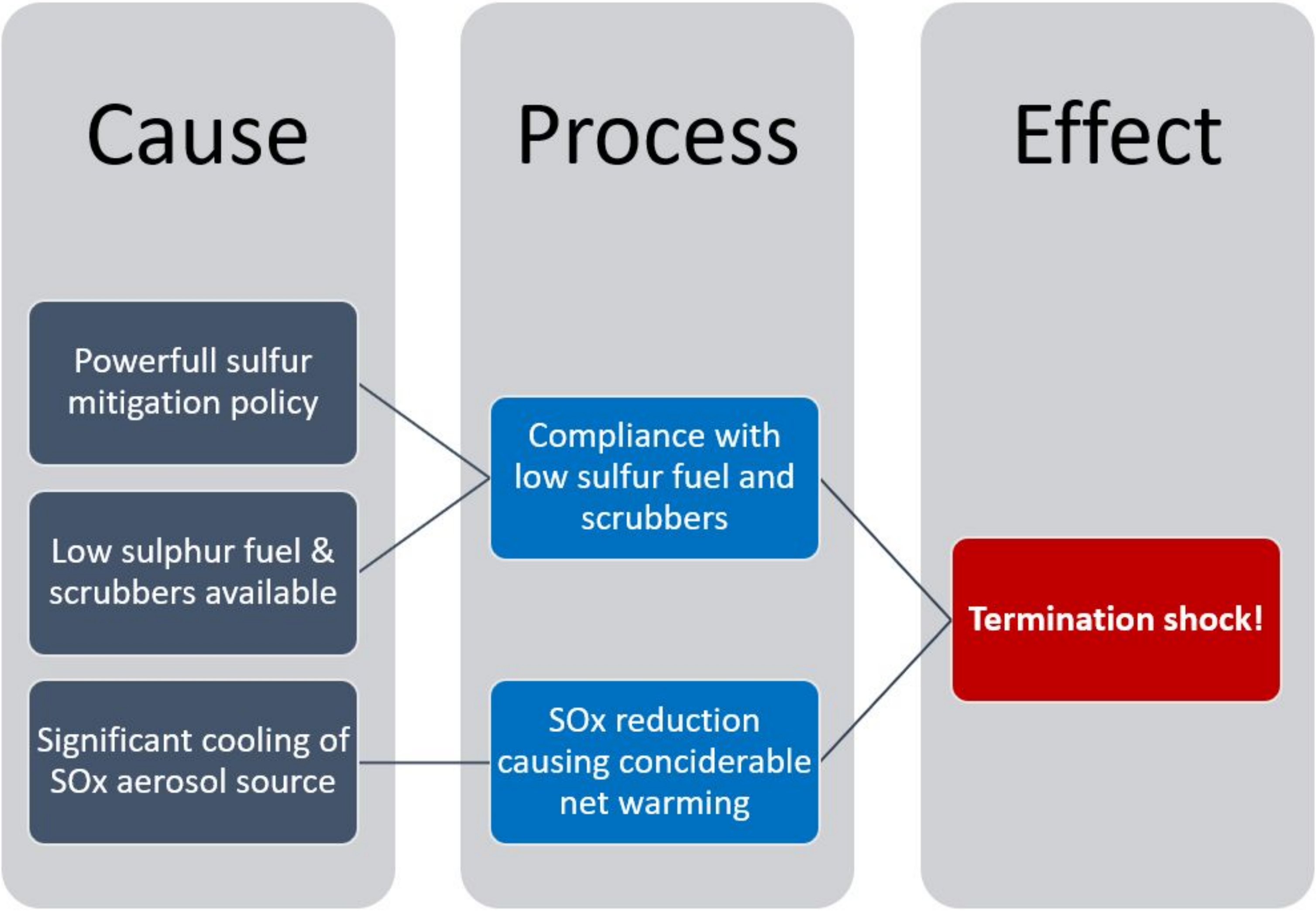
IPCC AR6 WG1 Chapter 6, Figure 6.13

Increase in Earth net heat uptake



(2002/09–2020/03)

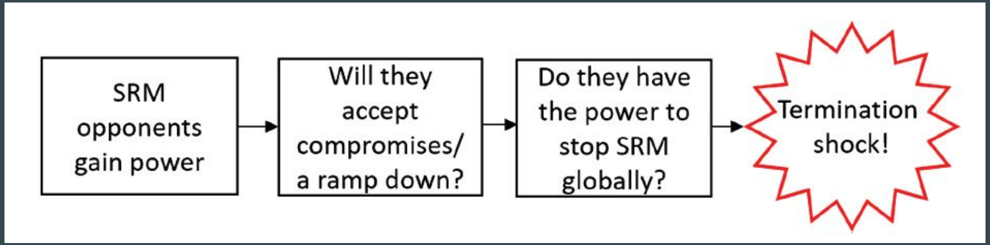
Loeb et al. 2021


Cause
Process
Effect
Powerfull sulfur mitigation policy
Low sulphur fuel & scrubbers available
Significant cooling of SOx aerosol source
Compliance with low sulfur fuel and scrubbers
SOx reduction causing conciderable net warming
Termination shock!

Aerosol termination shock

The term termination shock is generally used to describe effects from sudden abruption of intentional Solar Radiation Management (SRM) such as stratospheric aerosol injections. Past and current anthropogenic SOx emissions could be classified as unintentional SRM and rapid abruption could cause a similar thermal shock. Research suggests a threshold at 0.2°C of warming per decade.

Parker et al. (2018) showed that for a termination shock to occur, ramp down of emissions need to be sudden, which would require the will and power to stop SRM globally. The rapid reduction of SOx emissions from global shipping could prove unintentional abrupt cessation of SRM. If the higher range ERF effects of IMO 2020 are a reality, this could be quantified as a termination shock, even more so when combined with other SOx reduction effects.



Parker et al. (2018)