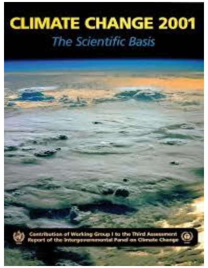
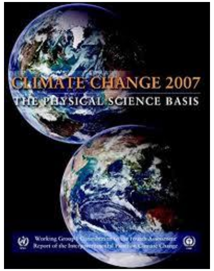
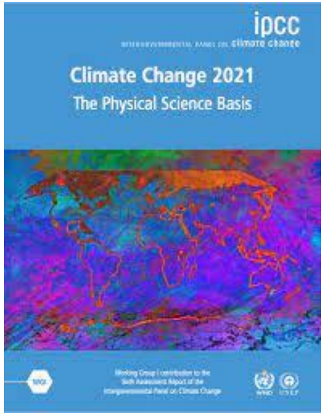
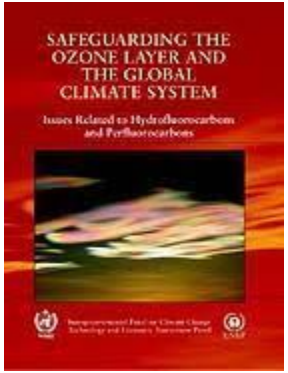
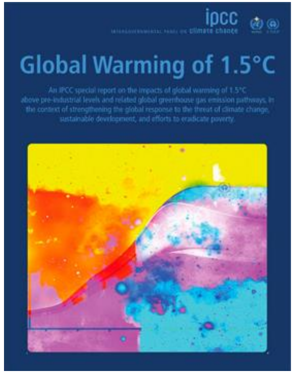
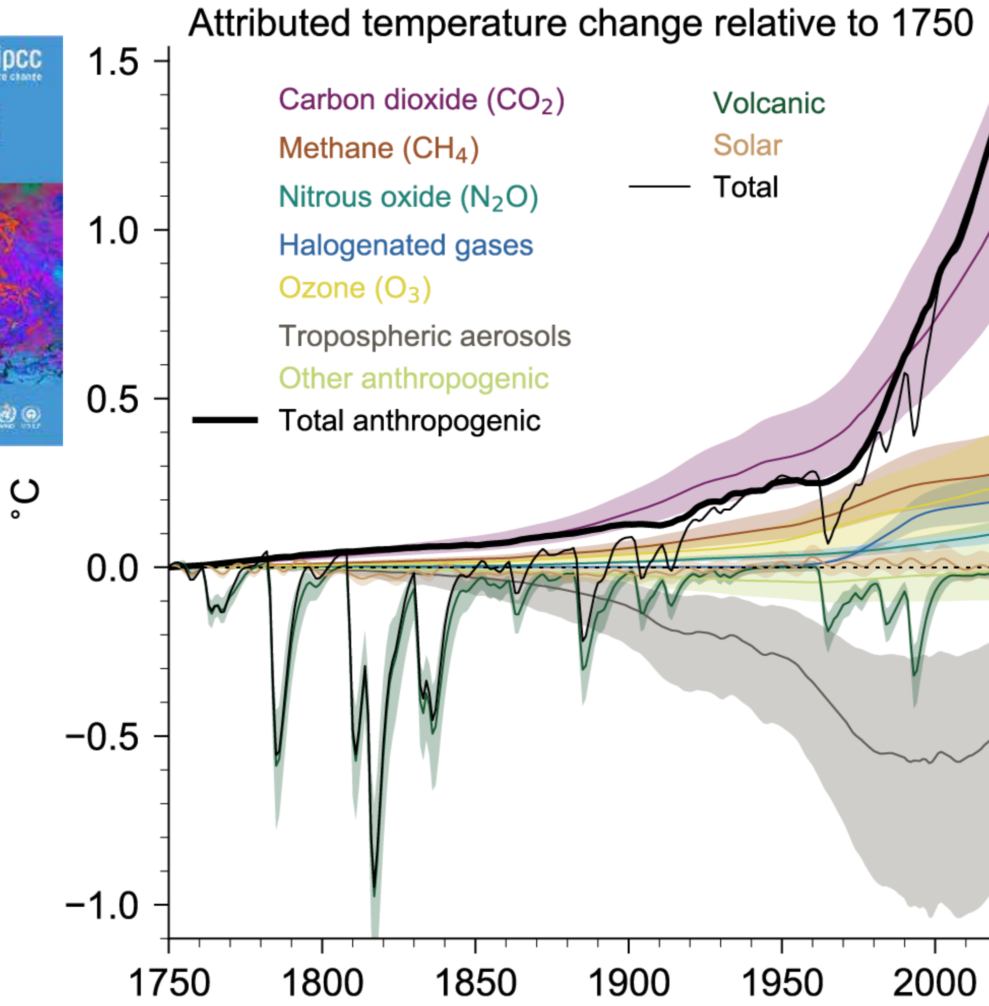
Priestley Centre for Climate Futures
Collaborating for a better future

UNIVERSITY OF LEEDS

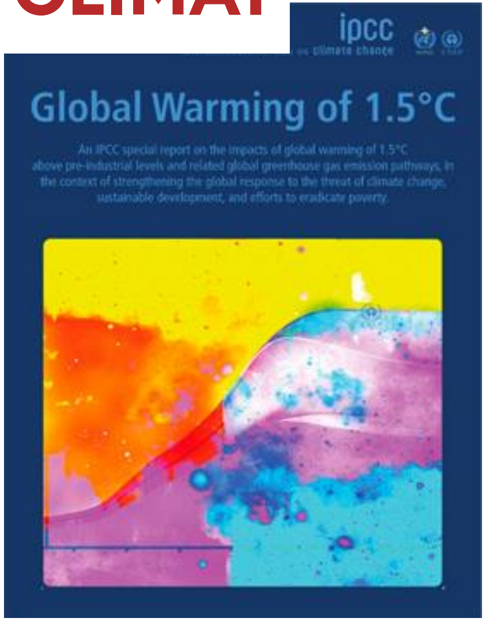
Piers Forster
@piersforster

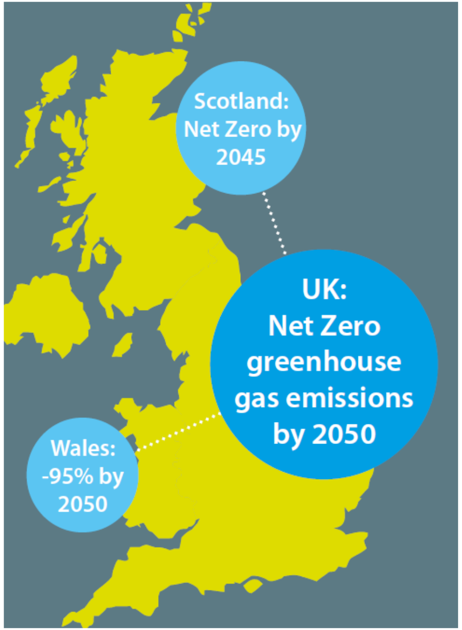
Navigating New Horizons: Low-Carbon Fuels in Aviation and Shipping


CLIMATE CHANGE 2001
The Scientific Basis

CLIMATE CHANGE 2007
THE PHYSICAL SCIENCE BASIS

ipcc
CLIMATE CHANGE 2013
The Physical Science Basis

ipcc
Climate Change 2021
The Physical Science Basis

SAFEGUARDING THE
OZONE LAYER AND
THE GLOBAL
CLIMATE SYSTEM
Issues Related to Hydrofluorocarbons
and Perfluorocarbons

ipcc
Global Warming of 1.5°C

Attributed temperature change relative to 1750
°C
1.5
1.0
0.5
0.0
−0.5
−1.0
1750
1800
1850
1900
1950
2000
Carbon dioxide (CO_2)
Methane (CH_4)
Nitrous oxide (N_2O)
Halogenated gases
Ozone (O_3)
Tropospheric aerosols
Other anthropogenic
Total anthropogenic
Volcanic
Solar
Total

UK and France Net Zero 2050. International leadership:
All greenhouse gases; targets includes aviation and shipping

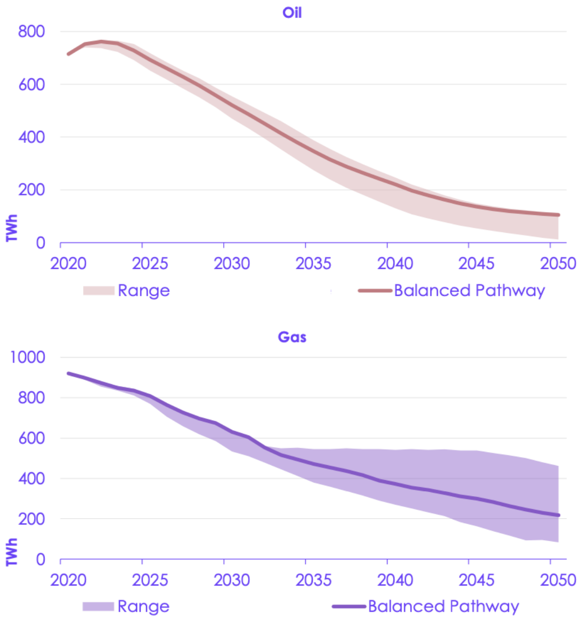




27 June 2019: Climate change act amended and Net zero emissions of greenhouse gases in 2050 becomes law in the UK

(d) Transitioning away from fossil fuels in energy systems, in a just, orderly and equitable manner, accelerating action in this critical decade, so as to achieve net zero by 2050 in keeping with the science;

Figure 2 Consumption of oil and gas in the CCC's Sixth Carbon Budget analysis



Source: CCC analysis.

Shipping

Present:

99% oil based fuels, very small amount of biofuel

2020 Global sulphur < 0.5%

Short term:

Methanol (needs source of carbon, e.g. biogenic waste, methane from manure or carbon capture)

Hybrid systems

Longer term:

Ammonia (regulation and safeguards to use, hydrogen or electrolysis)

Hydrogen?

Aviation

Present:

Jet-A1 fuel, 1-2 biofuel flights

NOx regulated emissions

Short term:

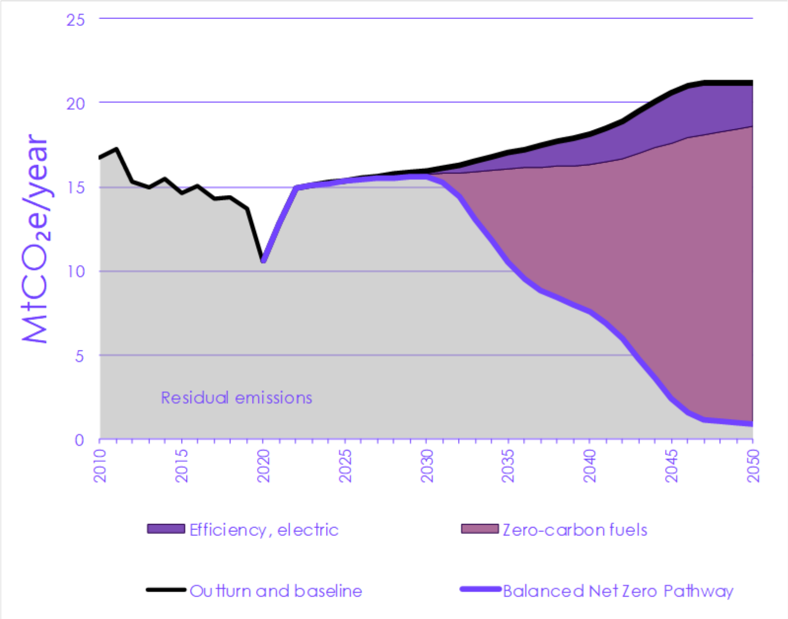
Sustainable aviation fuels (biofuels to efuels) ; e-fuels need carbon capture and green energy

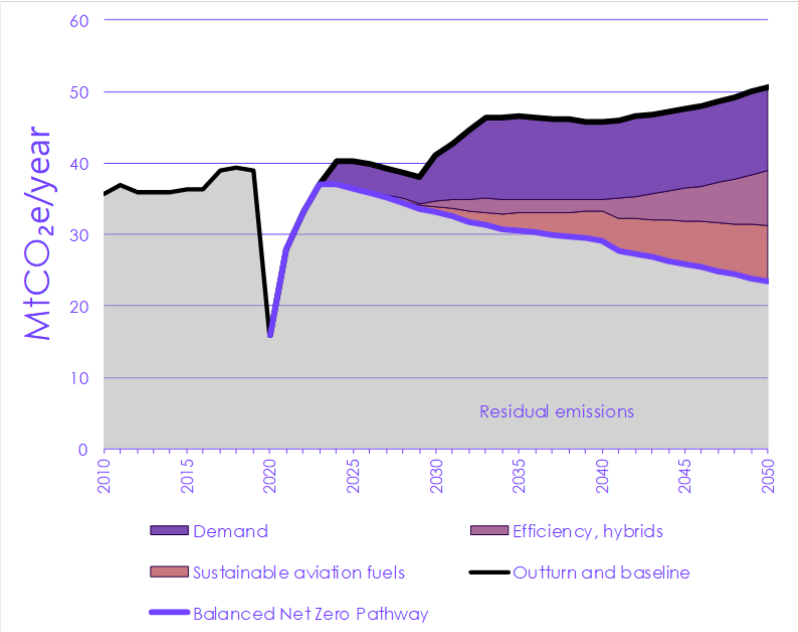
Hybrid systems

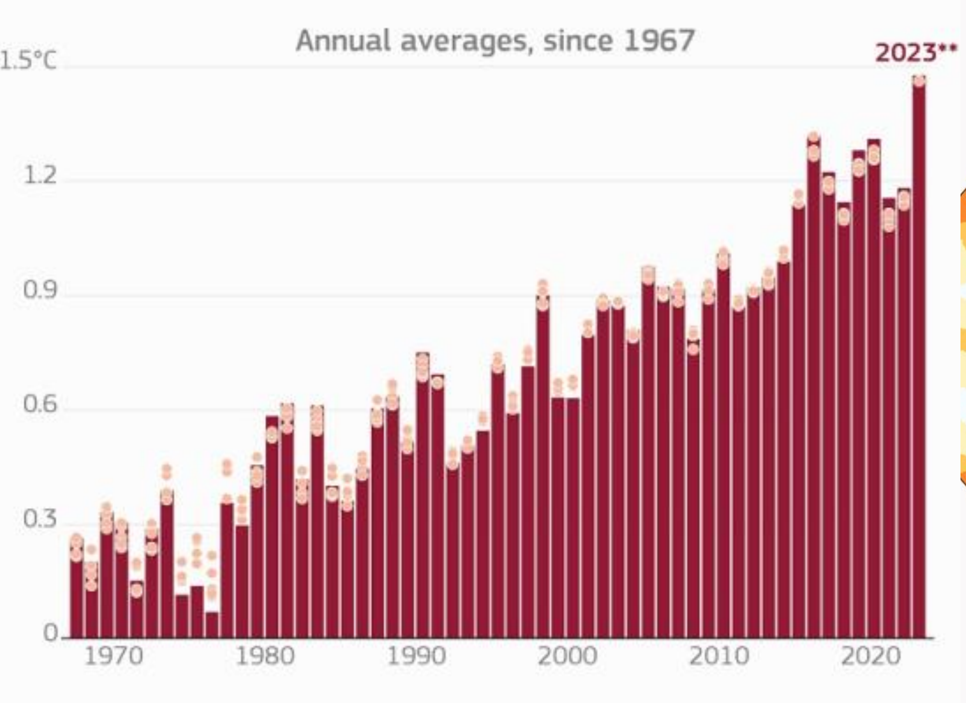
Longer term:

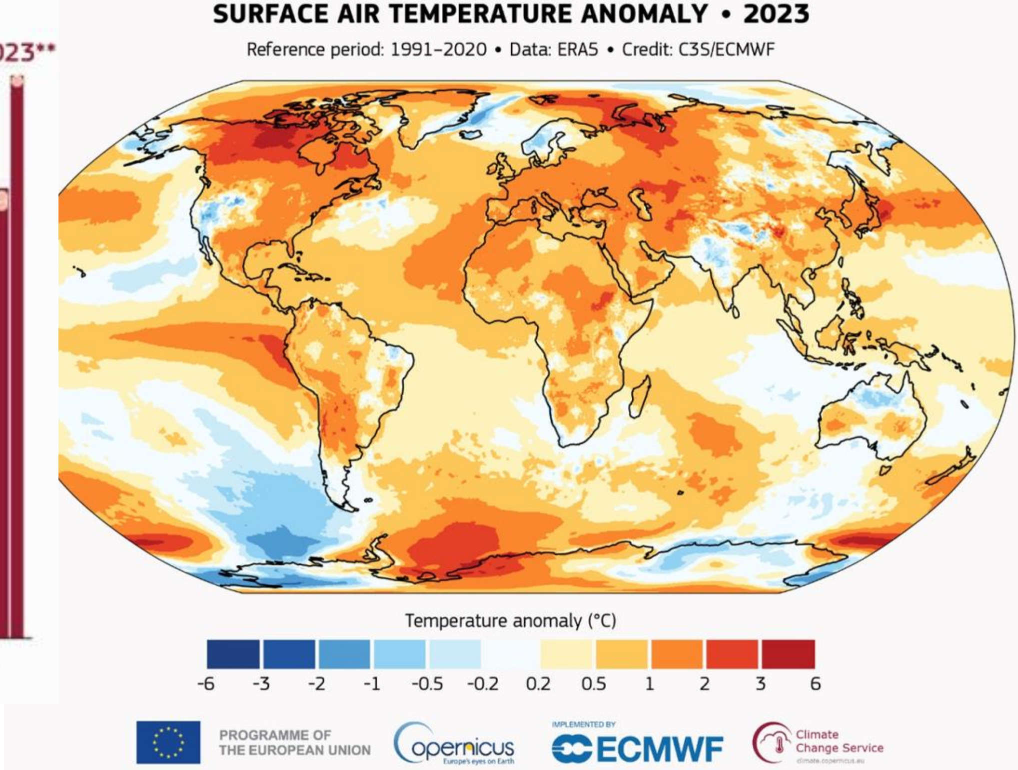
Hydrogen – needs airframe changes and cryogenic storage

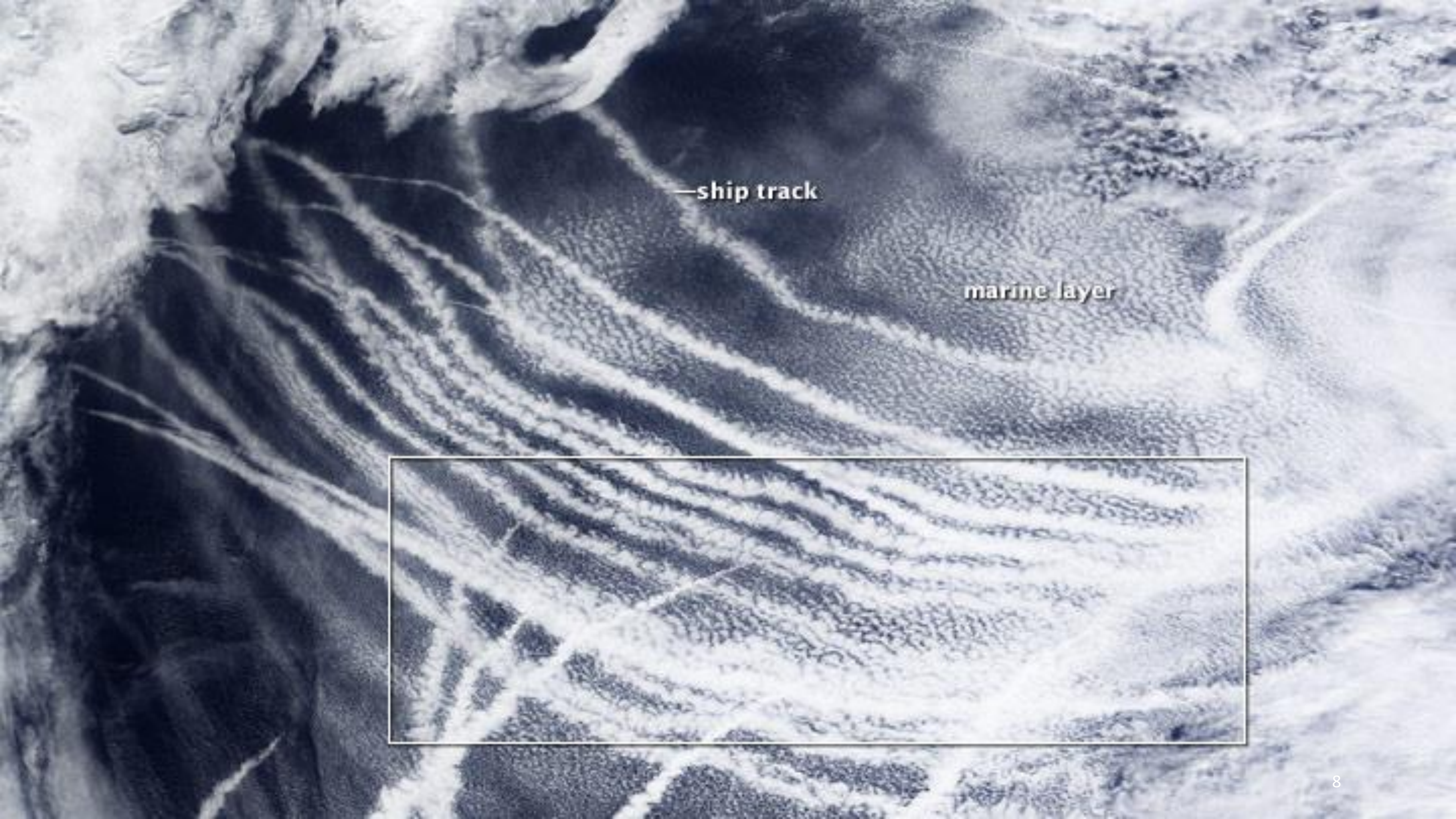
Fuel cells?

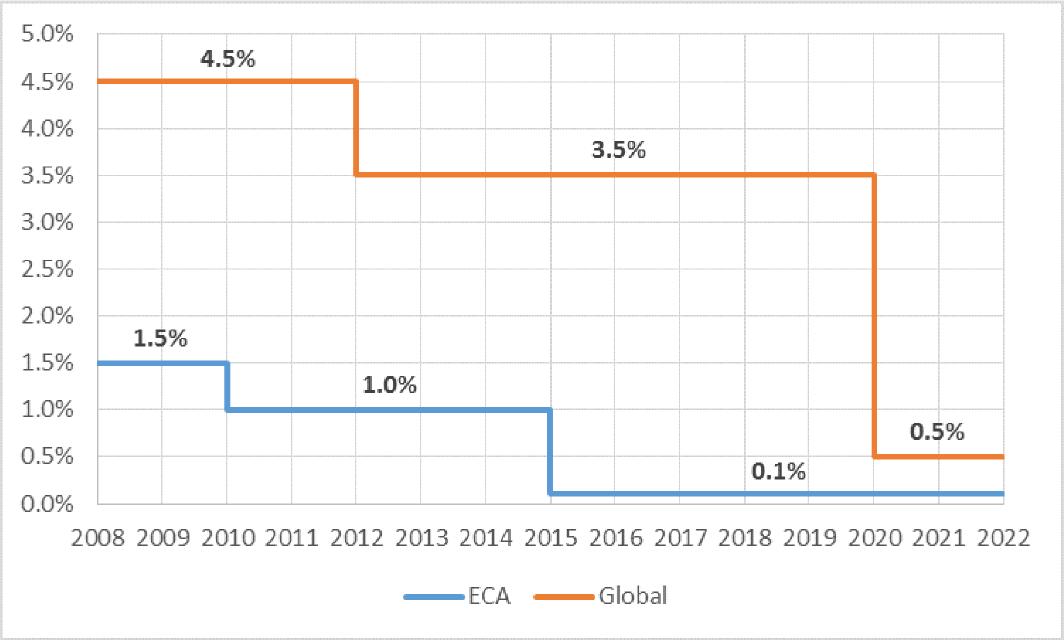

MtCO2e/year
25
20
15
10
5
0
Residual emissions
2010
2015
2020
2025
2030
2035
2040
2045
2050
Efficiency, electric
Zero-carbon fuels
Outturn and baseline
Balanced Net Zero Pathway


MtCO2e/year
60
50
40
30
20
10
0
Residual emissions
2010
2015
2020
2025
2030
2035
2040
2045
2050
Demand
Efficiency, hybrids
Sustainable aviation fuels
Outturn and baseline
Balanced Net Zero Pathway

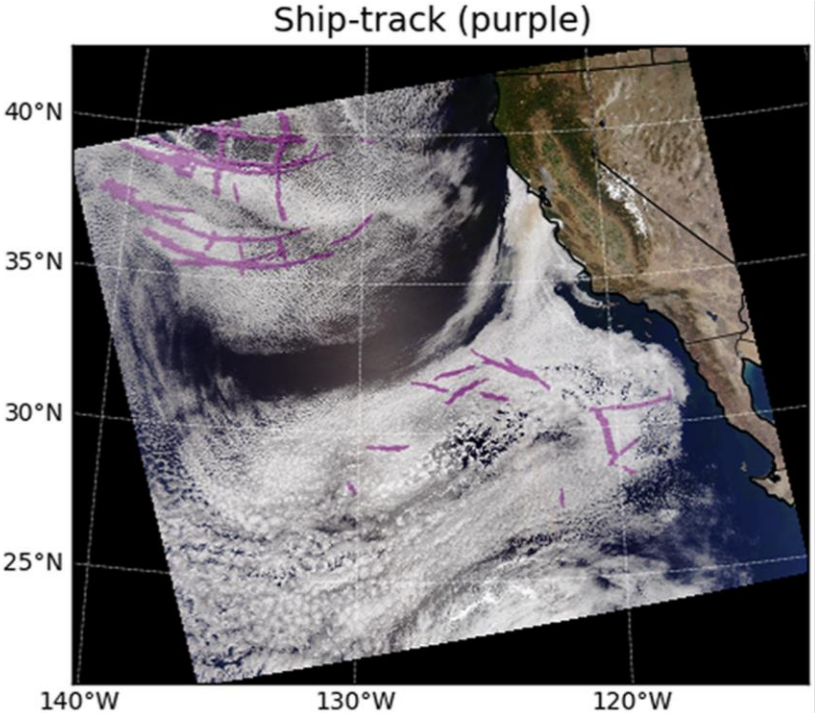

Annual averages, since 1967
2023**
1.5°C
1.2
0.9
0.6
0.3
0
1970
1980
1990
2000
2010
2020


SURFACE AIR TEMPERATURE ANOMALY • 2023
Reference period: 1991–2020 • Data: ERA5 • Credit: C3S/ECMWF
Temperature anomaly (°C)
-6 -3 -2 -1 -0.5 -0.2 0.2 0.5 1 2 3 6
PROGRAMME OF THE EUROPEAN UNION
opernicus
IMPLEMENTED BY
ECMWF
Climate Change Service


ship track
marine layer

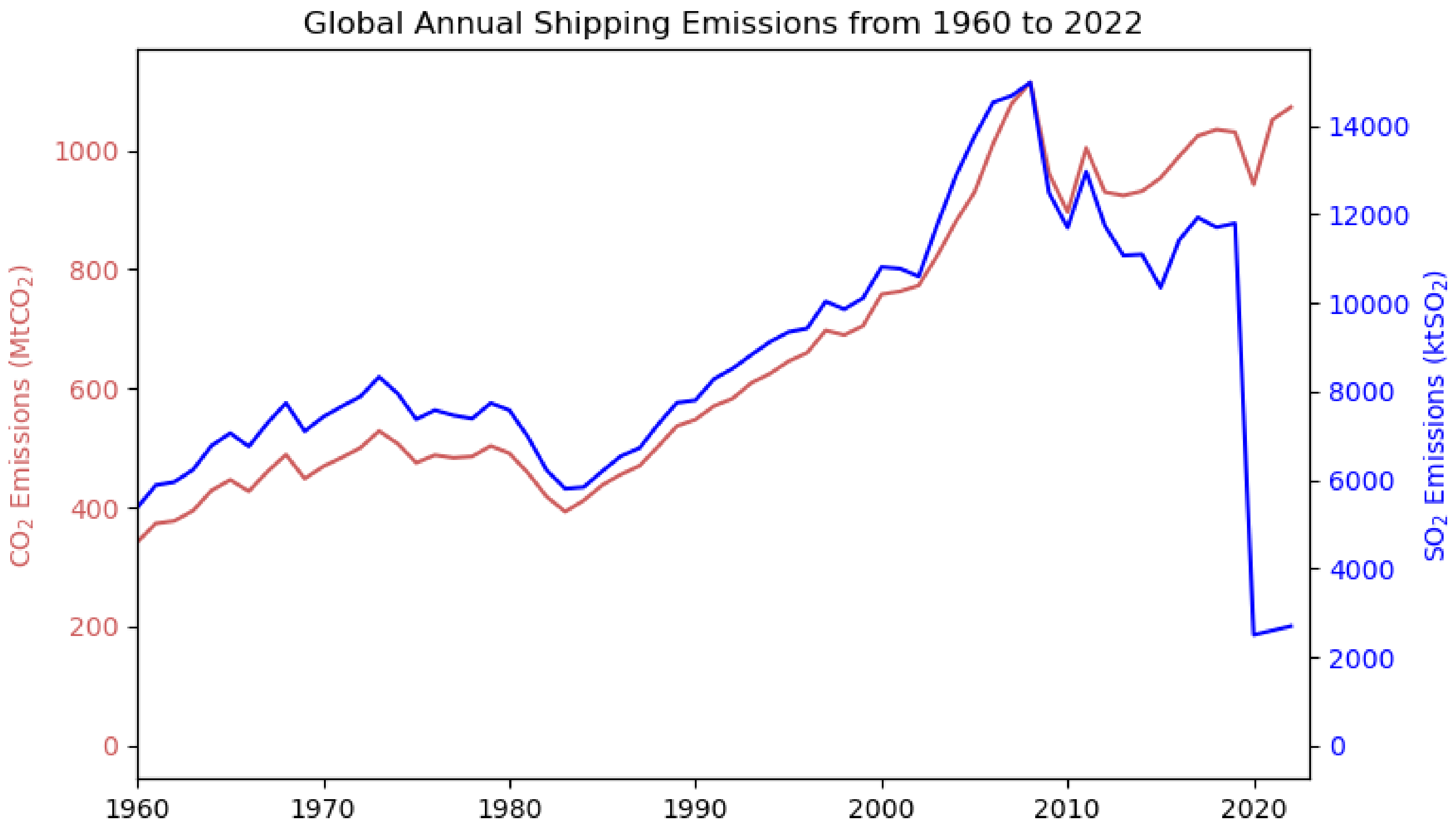


Clear Seas, 2022



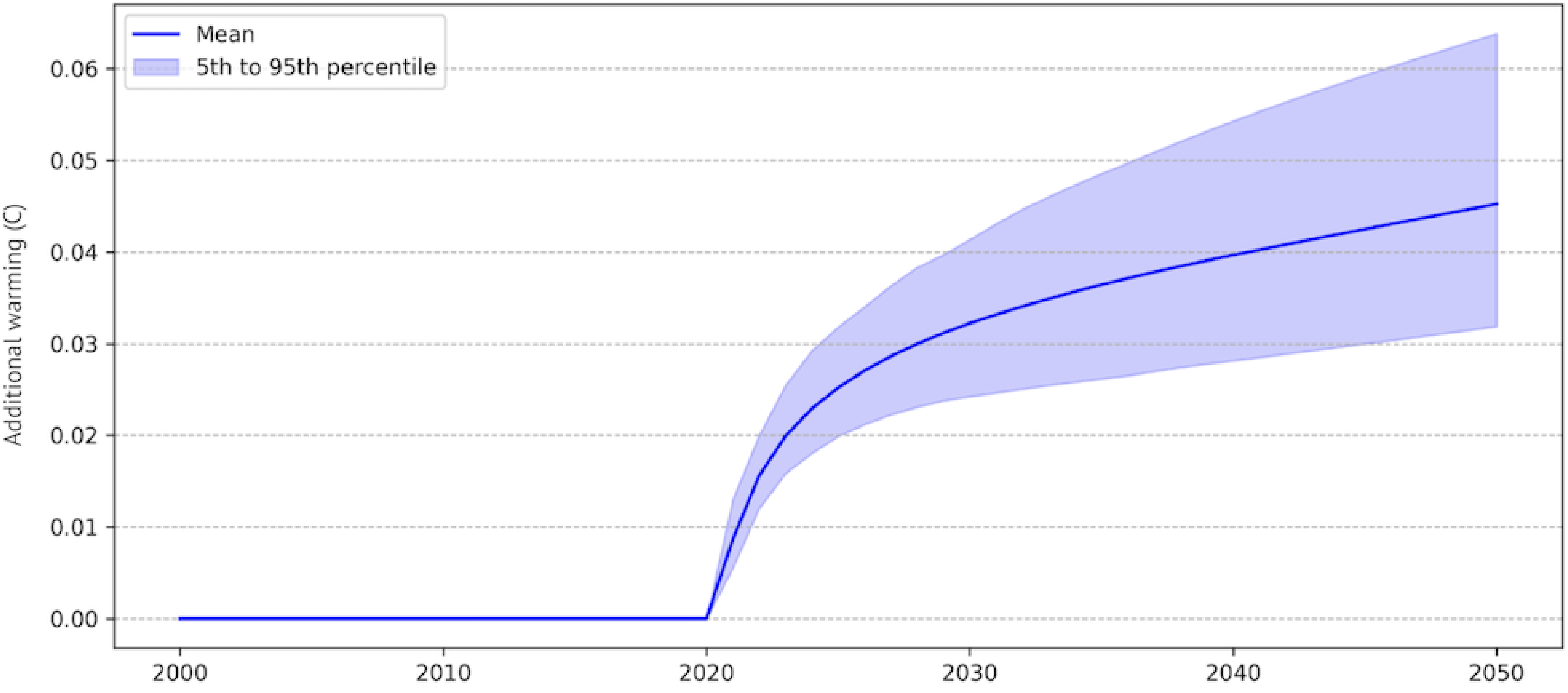
Yuan et al. 2022 Science Advances

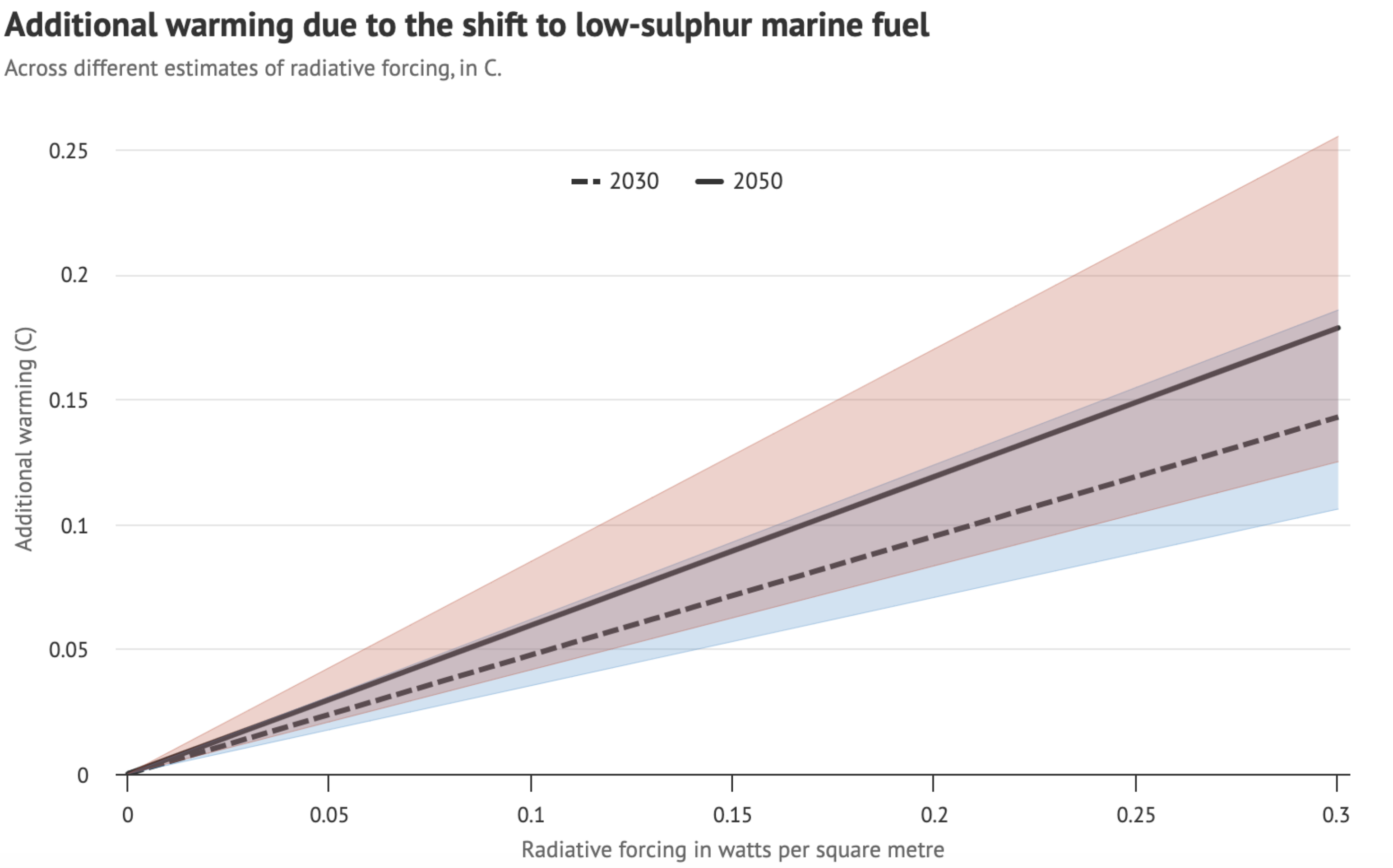
0.02 to 0.27 Wm-2 Radiative Forcing



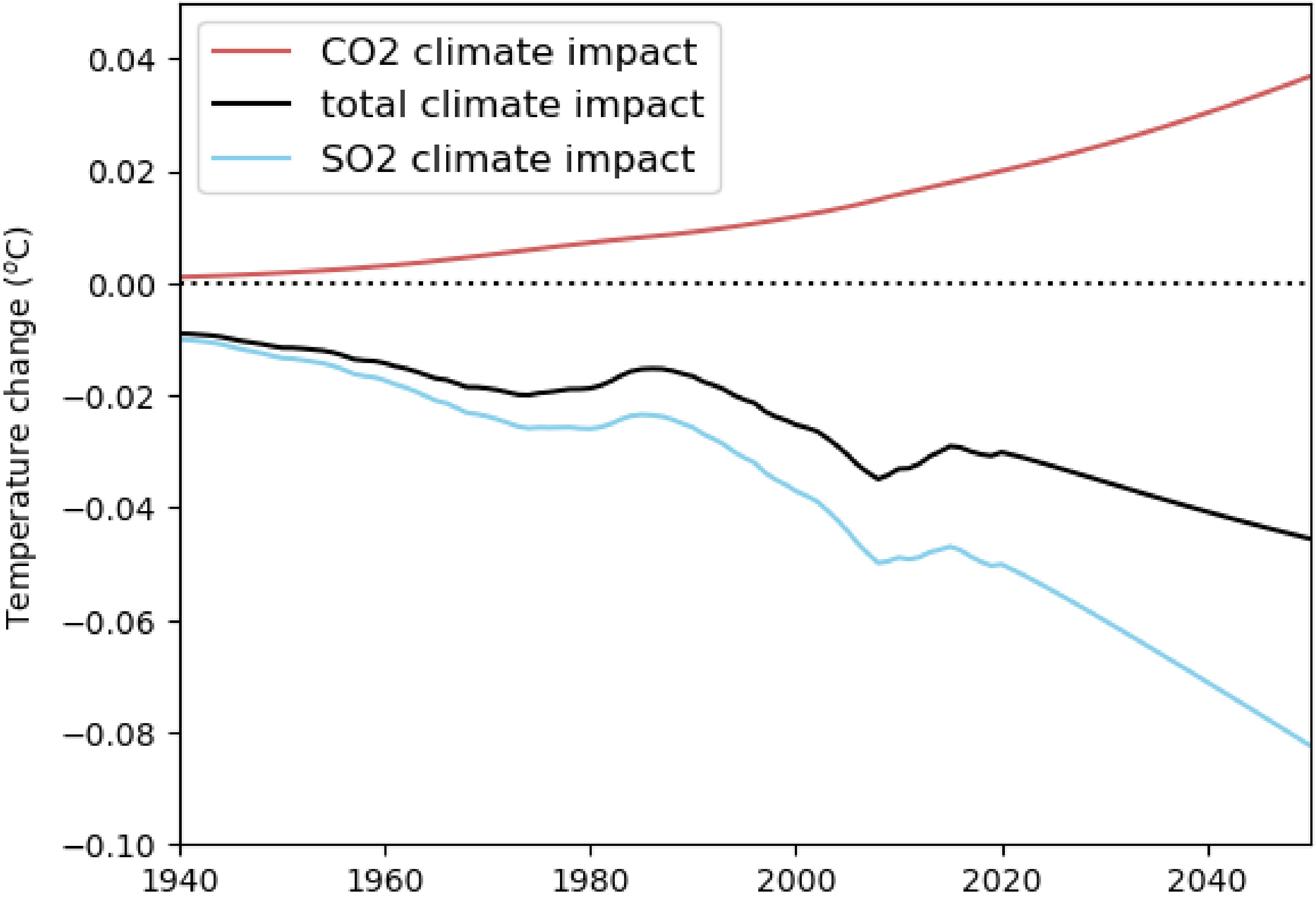
Data from Forster et al. ESSD 2022

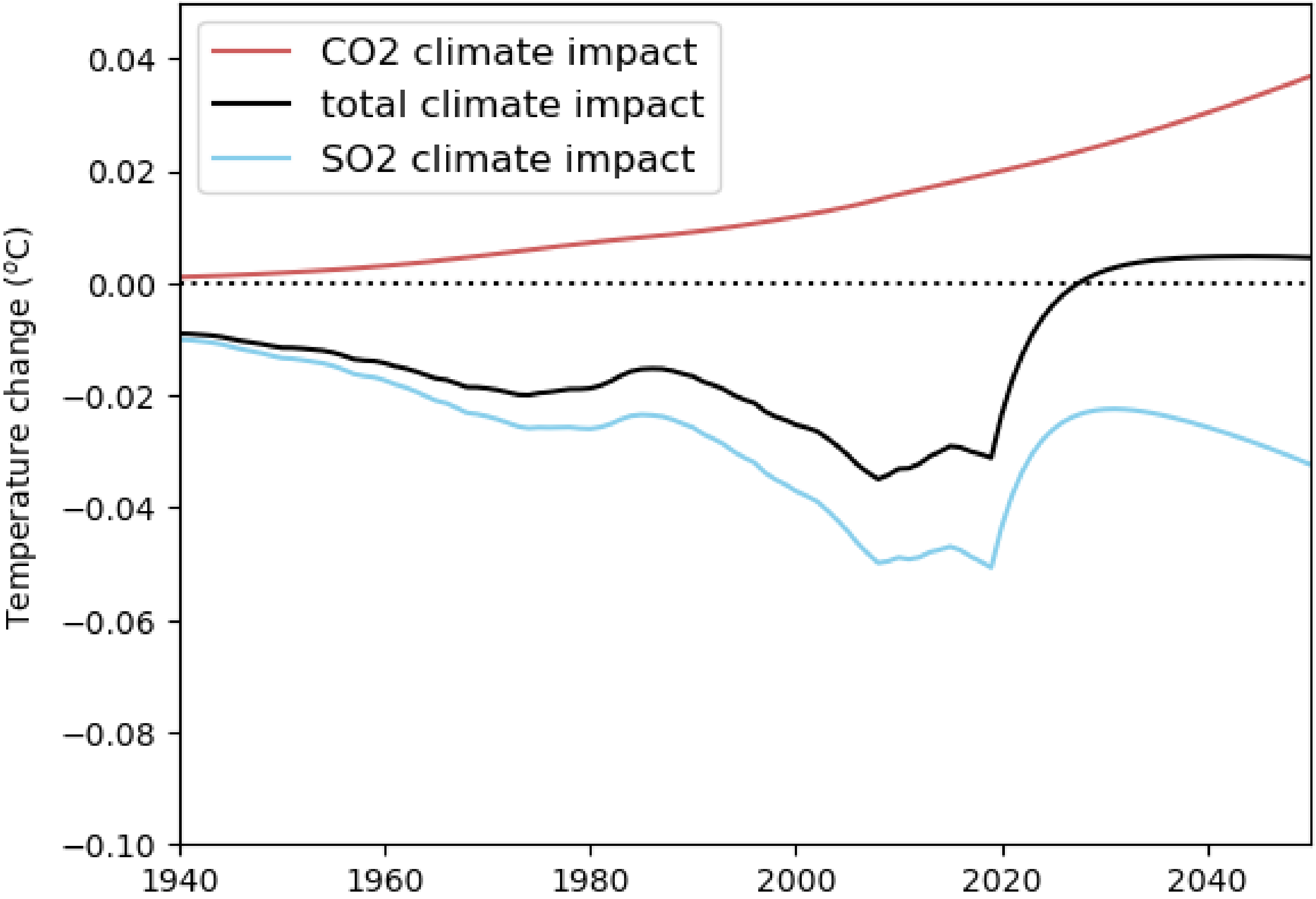
Additional warming due to low-sulphur marine fuels (C)

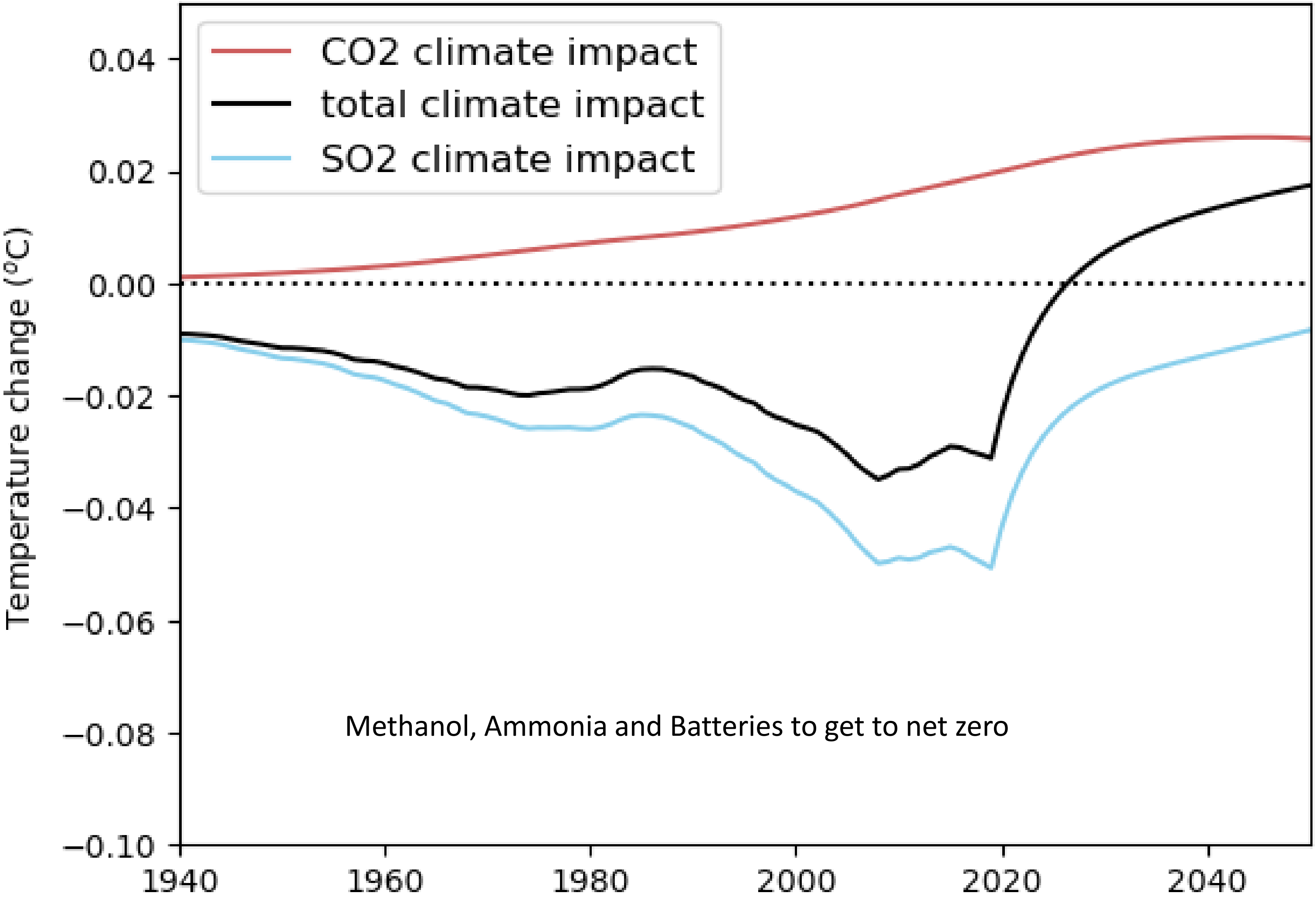


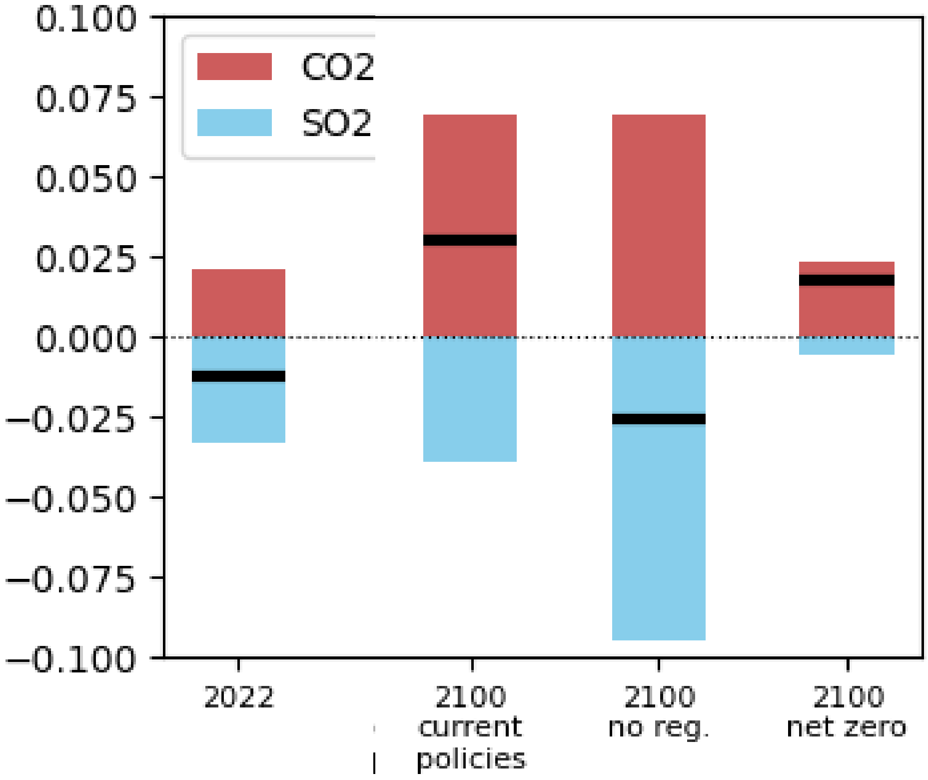


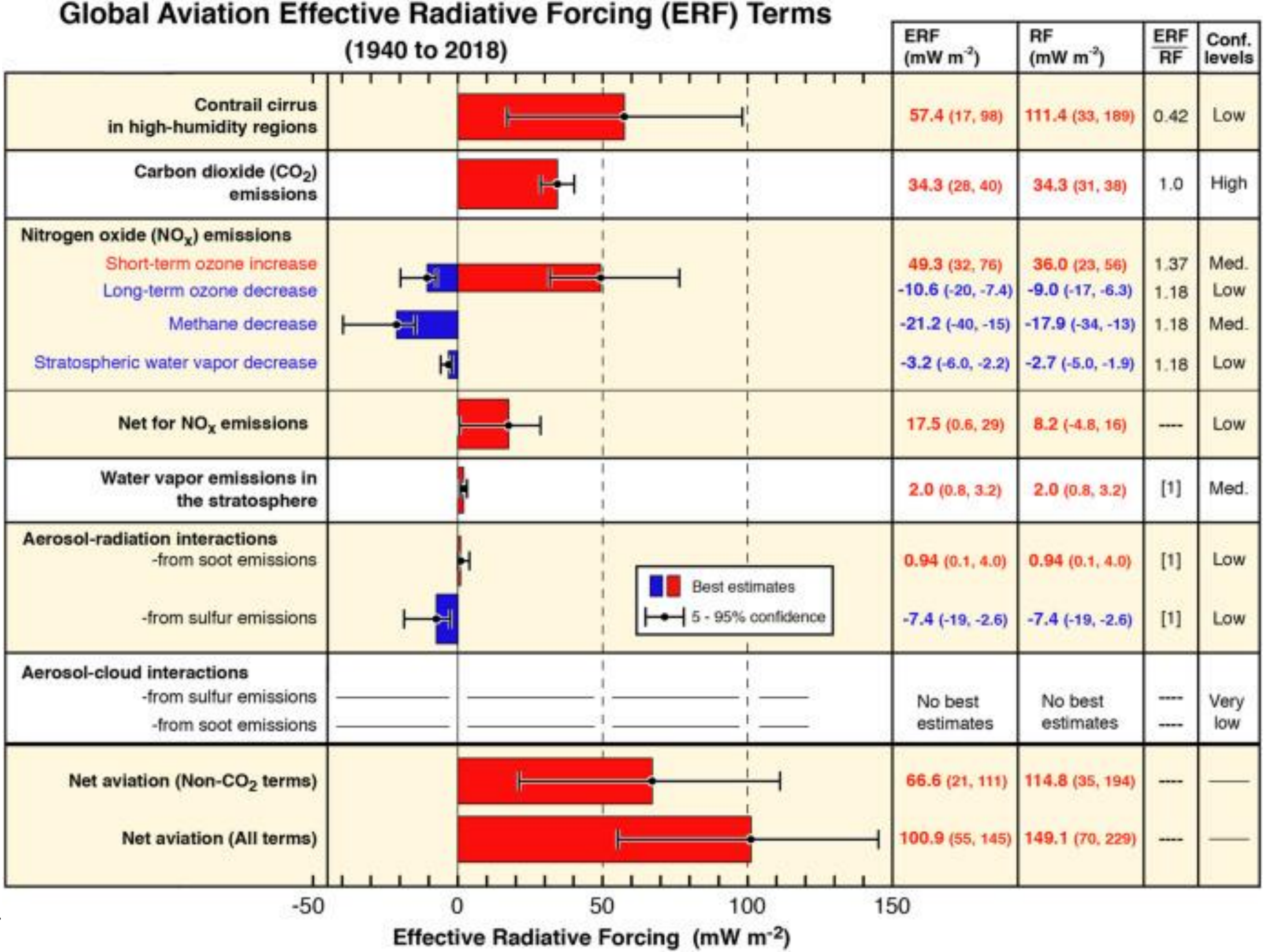
Hausthfather and Forster, CarbonBrief 2022


CO2 climate impact
total climate impact
SO2 climate impact
Temperature change (°C)
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
1940
1960
1980
2000
2020
2040

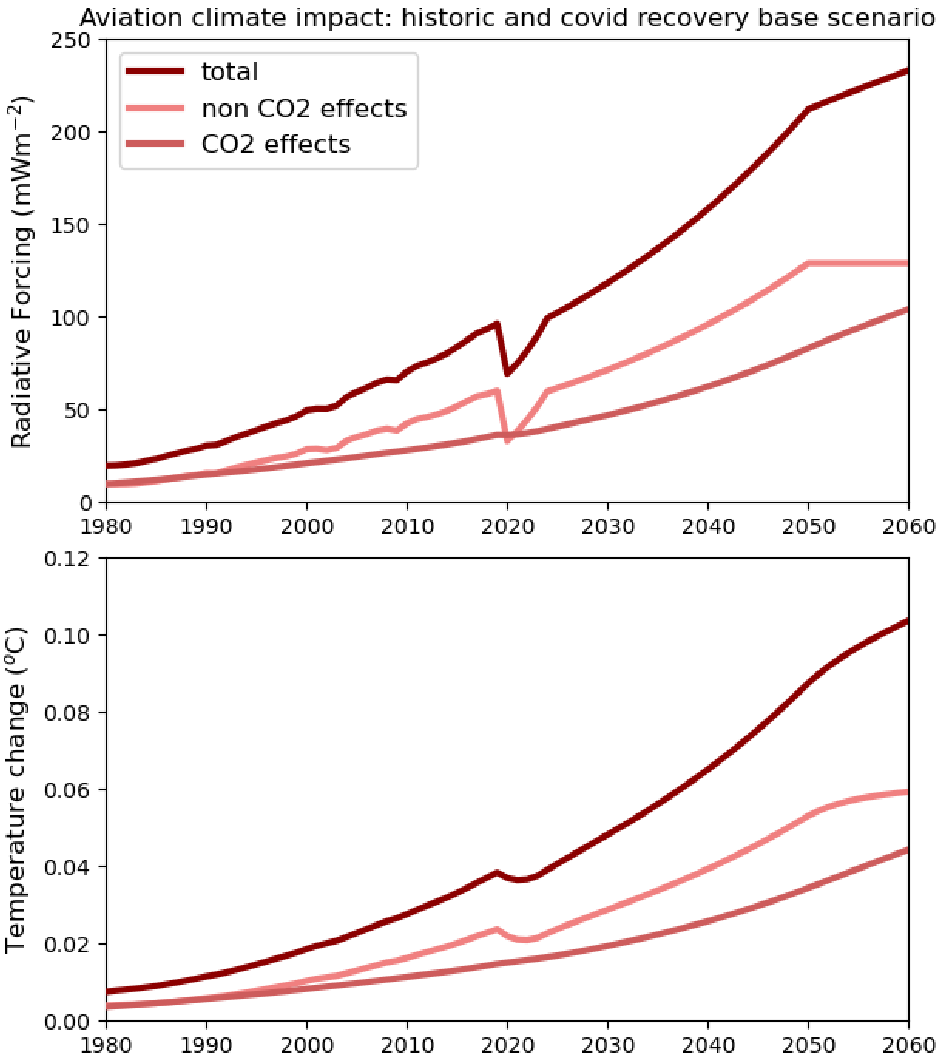

CO2 climate impact
total climate impact
SO2 climate impact
Temperature change (°C)
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
1940
1960
1980
2000
2020
2040

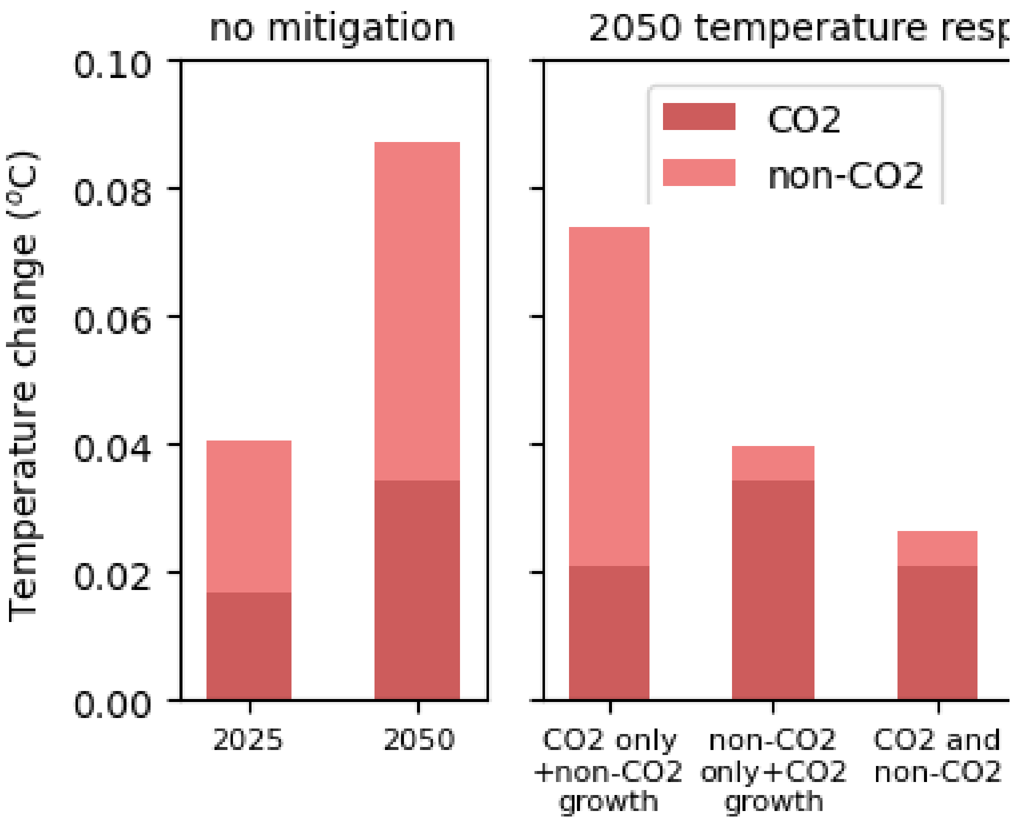

CO2 climate impact
total climate impact
SO2 climate impact
Temperature change (°C)
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
1940
1960
1980
2000
2020
2040
Methanol, Ammonia and Batteries to get to net zero


CO2
SO2
0.100
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
−0.100
2022
2100
current
policies
2100
no reg.
2100
net zero

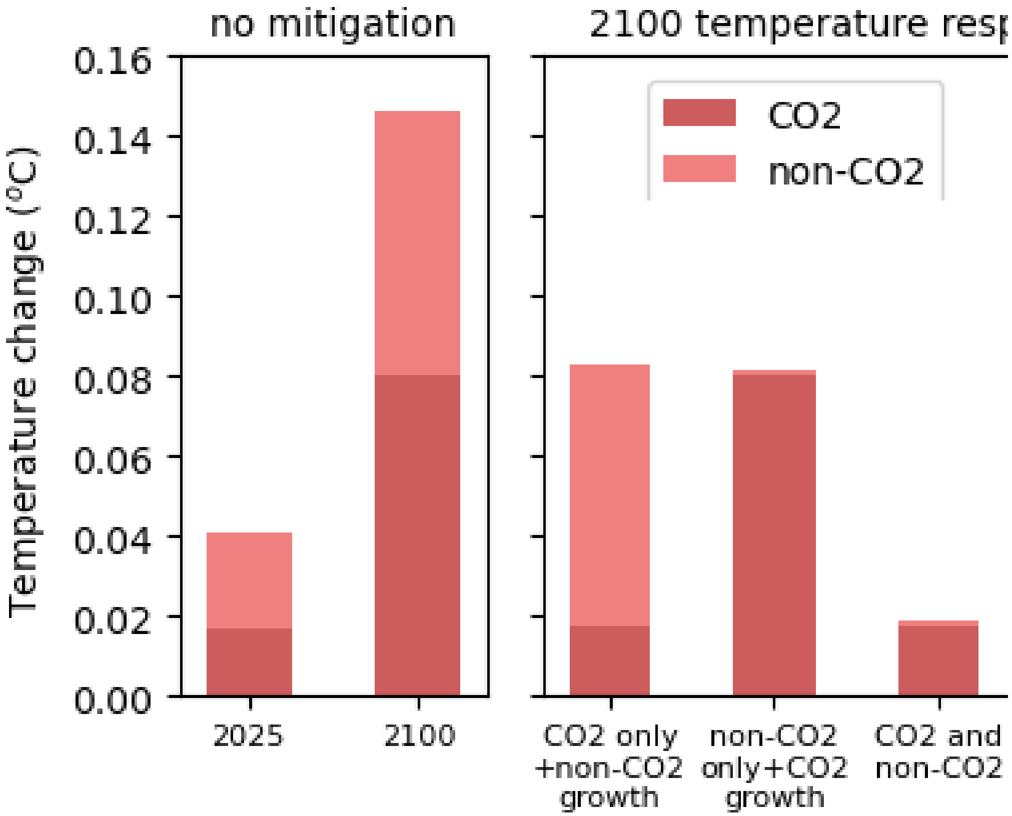


Lee et al. 2021


Aviation climate impact: historic and covid recovery base scenario
total
non CO2 effects
CO2 effects
Radiative Forcing (mWm^{-2})
250
200
150
100
50
0
1980
1990
2000
2010
2020
2030
2040
2050
2060
Temperature change (^{o}C)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1980
1990
2000
2010
2020
2030
2040
2050
2060



Google and American Airlines


no mitigation
2100 temperature resp
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Temperature change (°C)
CO2
non-CO2
2025
2100
CO2 only +non-CO2 growth
non-CO2 only+CO2 growth
CO2 and non-CO2


RESOURCES
CLIMATE IMPACT
Fuel & technology
Range in 2035
One-off infrastructure
Operations on ground
In-flight
Total GHGs
Total climate impact
Fossil Jet Fuel - Base Case
All Ranges
Virgin Oil HEFA
All Ranges
Waste Oil HEFA
All Ranges
1st Gen Alcohol-to-Jet
All Ranges
Power-to-Liquid
All Ranges
Green Hydrogen Fuel Cell
<4000 km
Blue Hydrogen Combustion (Advanced Engine)
All Ranges
Green Hydrogen Combustion (Advanced Engine)
All Ranges

Figure A3.8.c Breakdown of shipping sector for additional investment

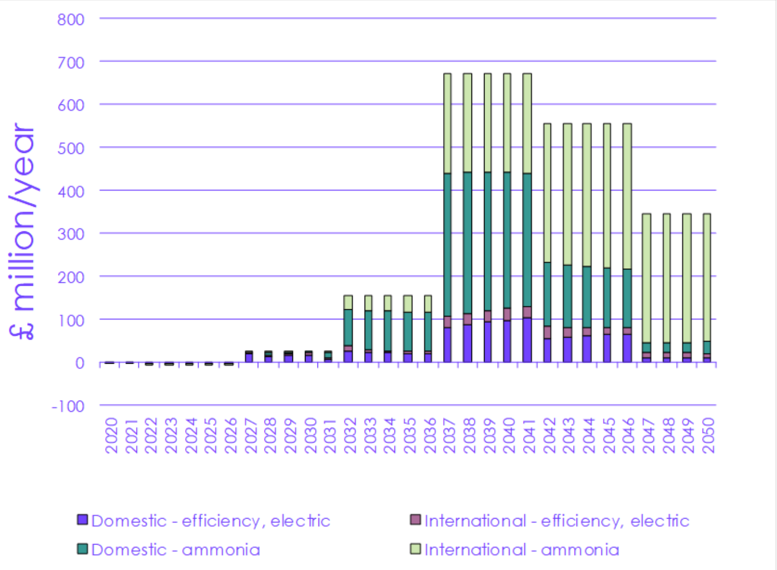
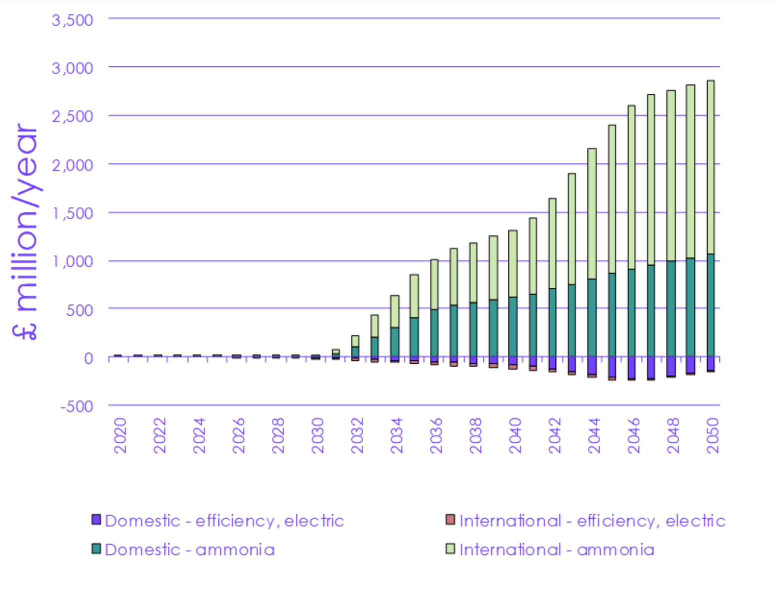


Figure A3.8.d Breakdown of shipping sector additional operating costs



Conclusions

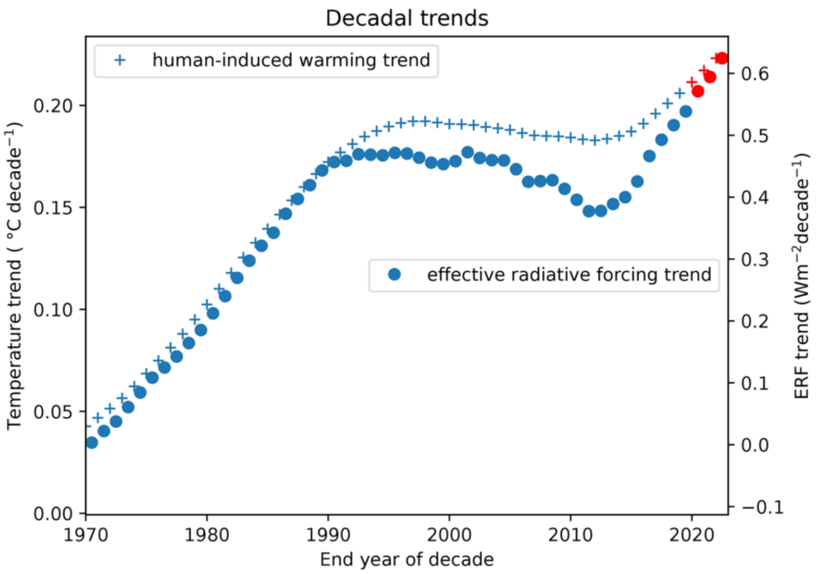
- Net zero for shipping better for climate and air pollution than not going net zero, provided NOx from ammonia controlled. Non-CO2 effects expected to reduce.
- → Solutions add cost but look doable, not a lot of efficiency gains

- Net Zero CO2 2050 aviation will likely need both demand growth controls, efficiency improvements, alternative fuels and offsets/removals. Non-CO2 impact will be significant
    - Alternative fuels may help with reducing contrail impacts
    - Contrail avoidance by flight routing changes or demand reduction can be used to reduce non-CO2 impact.

➢ Question on timeline of alternative fuels at scale and duel infrastructures

➢ Air quality climate tradeoffs for NOx but will persist for both aviation and shipping

Current warming trends, non-CO2 forcing, and the question of 1.5°C

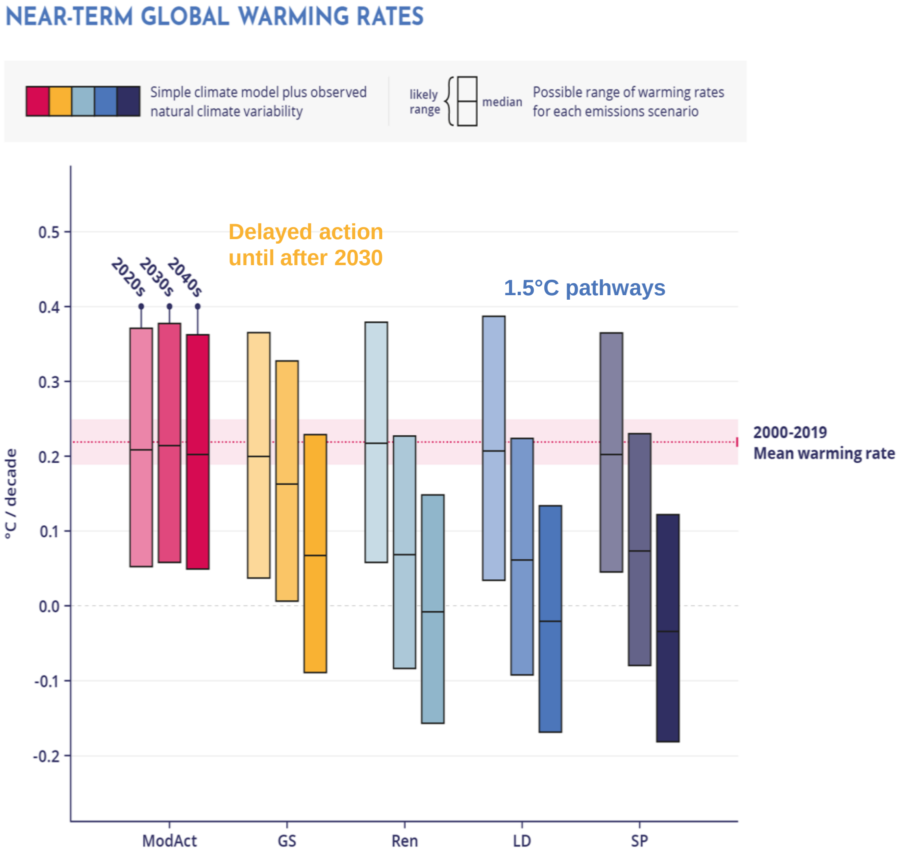


Left axis: decadal trends in human-induced warming

Right axis: effective radiative forcing (ERF) (Forster et al., 2023)

Current warming trends

- Current warming rates are around **0.2°C per decade**
- Halving emissions by 2030 would **halve warming rates** in the 2030s and halt warming in the 2040s
- Only **stringent near-term action** can substantially affect the global warming trajectory up to 2050



Research & innovation gaps

- Understanding near-term warming trajectories, emergence of mitigation benefits, and contribution **of different climate forcers**

Supplementary/alternative/slides to have in back pocket below

CONSTRAIN
DECADAL CLIMATE PROJECTIONS

Climate Change Tracker ☰ Share link

Version 0.9.8, last update November 1, 2023

Indicators of Global Climate Change for Policy Makers

IPCC AR6 consistent, updated indicators of human-induced global warming, greenhouse gas emissions, and the remaining global carbon budget. In partnership with IGCC

Recent Human-Induced Warming

More

in °C
Decade average 2013-2022
1.14
0.9 ~ 1.4
Annual average 2022
1.26
1 ~ 1.6

Current trajectory

More

+0.23
°C per decade

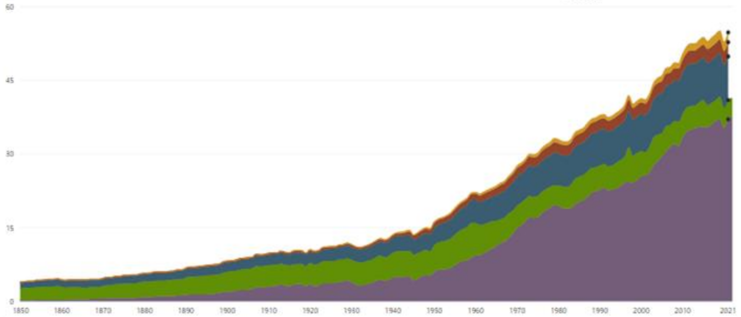
2034
approx. year 1.5 °C reached

Yearly Human-Induced Greenhouse Gas Emissions in CO_2 Equivalent

More

2021
in Gigatonnes CO_2e

37.1	3.9	8.9	2.9	2	54.8
CO_2 Fossil Fuels and Industry	CO_2 Land-use, Land-use change, Forestry	CH_4	N_2O	F Gasses	Total

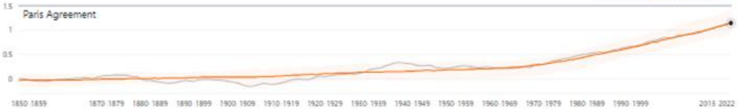


Human-Induced and Observed Global Warming

Decadal More

2013-2022
in °C

1.15	0.92 ~ 1.4 1.14
Observed	Human-induced



Current Remaining Carbon Budget and Trajectory

More

Remaining Carbon Budget in 2023
250
Gigatonnes of CO_2

Exhaustion rate in Gigatonnes of CO_2 per Year
-41
exhausted in
2029

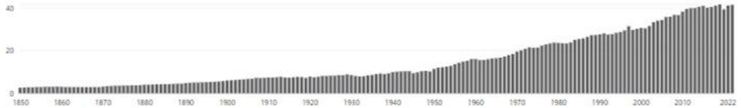
Likelihood to stay under 1.5 °C (2.7 °F)

17% 33% 50% 67% 83%

Yearly Total Human-Induced Net CO_2 Emissions

More

2022
in Gigatonnes
41.4



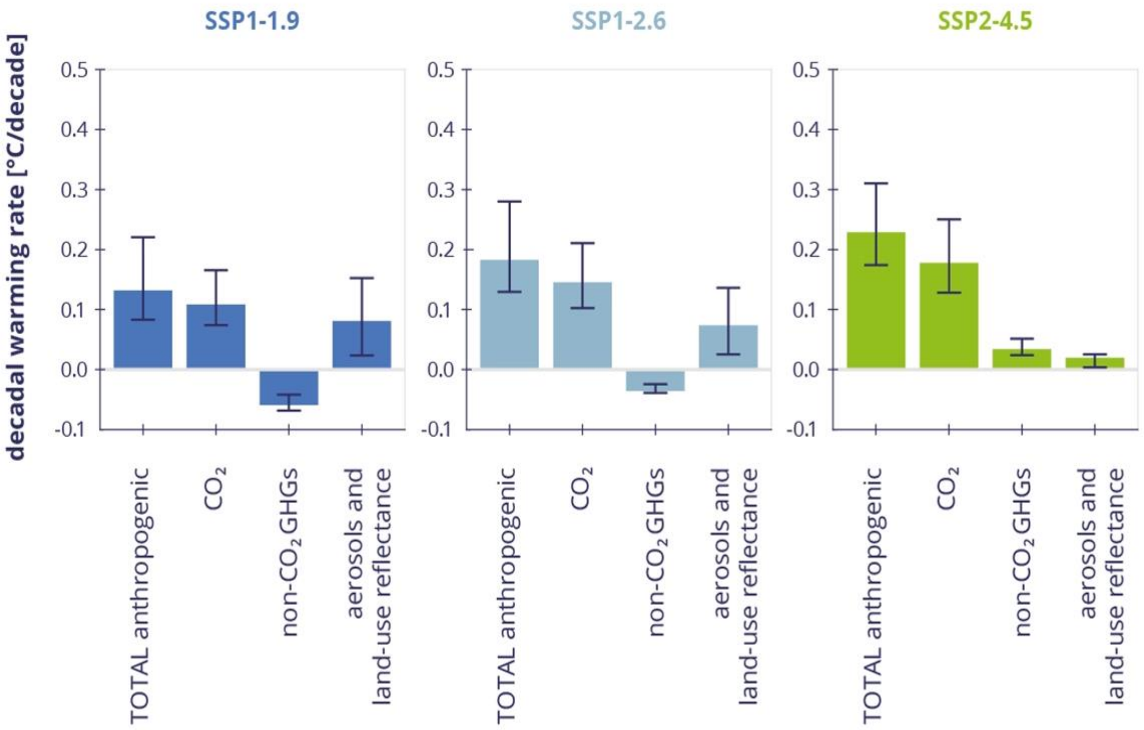
Most recent data from IGCC Collaboration, Global Carbon Project, PRIMAP-hist

Home Indicators for Policy Makers Global Warming CO_2 Carbon Dioxide CH_4 Methane N_2O Nitrous Oxide Charts and Articles Embedding About us Privacy & Terms

What is the role of non-CO2 emissions?

CONSTRAIN
CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

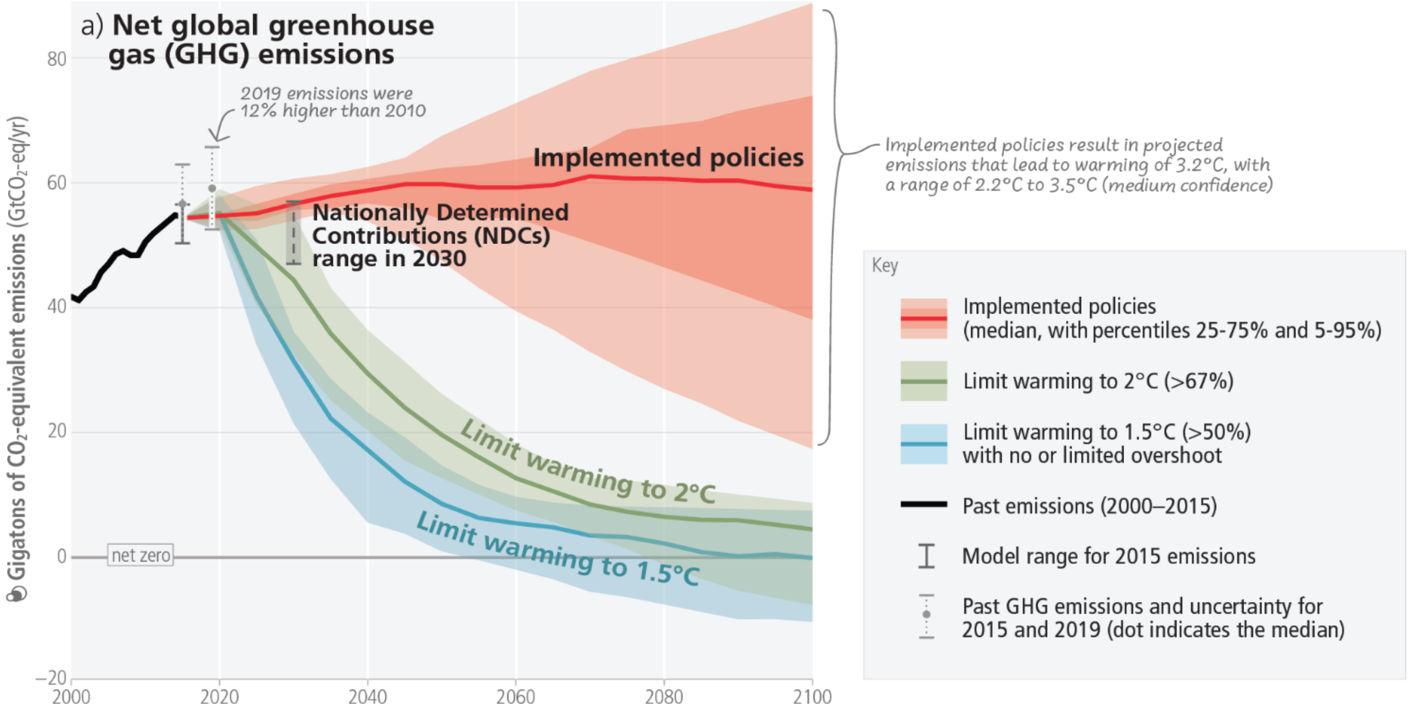
Average decadal warming over the next 20 years (2021-2040)



- The **interplay between aerosols and non-CO2 GHGs** (predominantly CH4) strongly affects the near-term response
- Improved understanding of **non-CO2 forcing contributions** is critical to understanding near-term warming

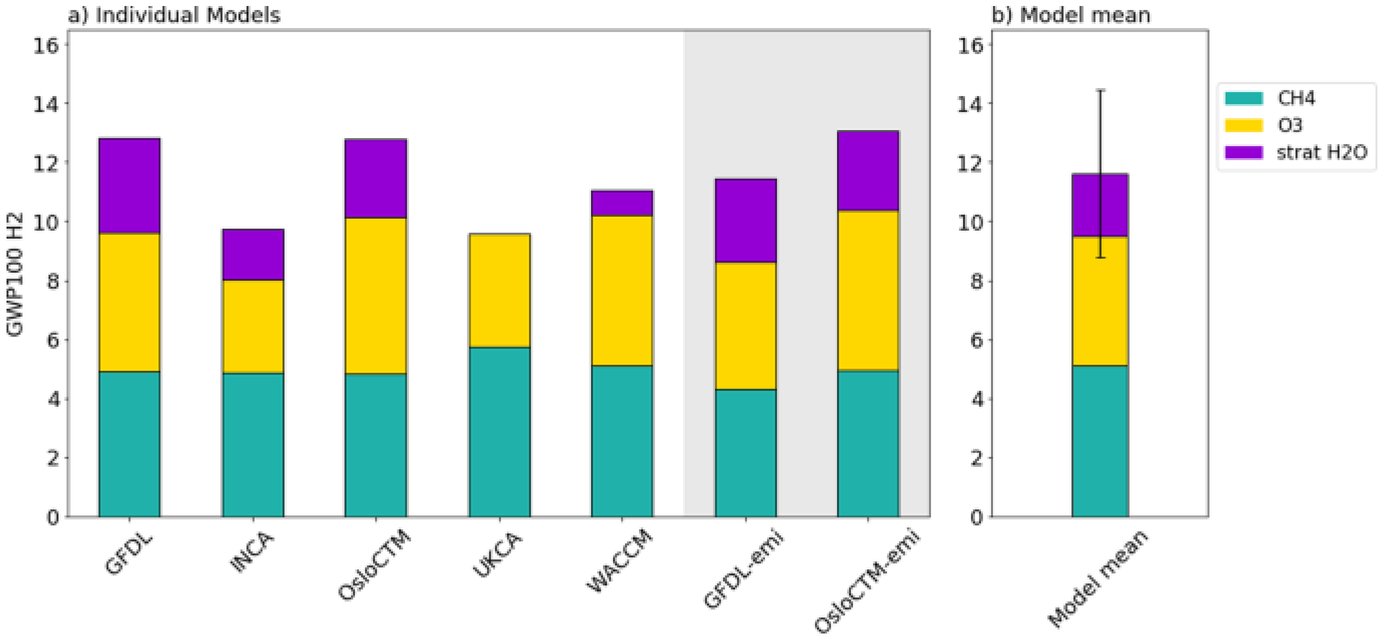
Limiting warming to 1.5°C and 2°C involves rapid, deep and in most cases immediate greenhouse gas emission reductions

Net zero CO_2 and net zero GHG emissions can be achieved through strong reductions across all sectors

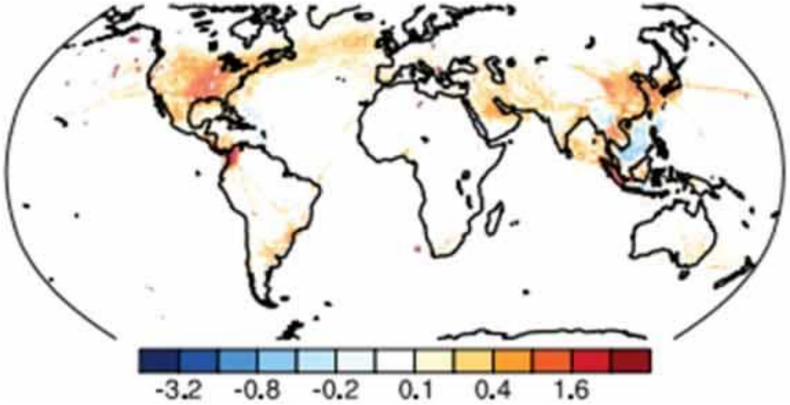


IPCC AR6 SYR Fig SPM5

Hydrogen GWP

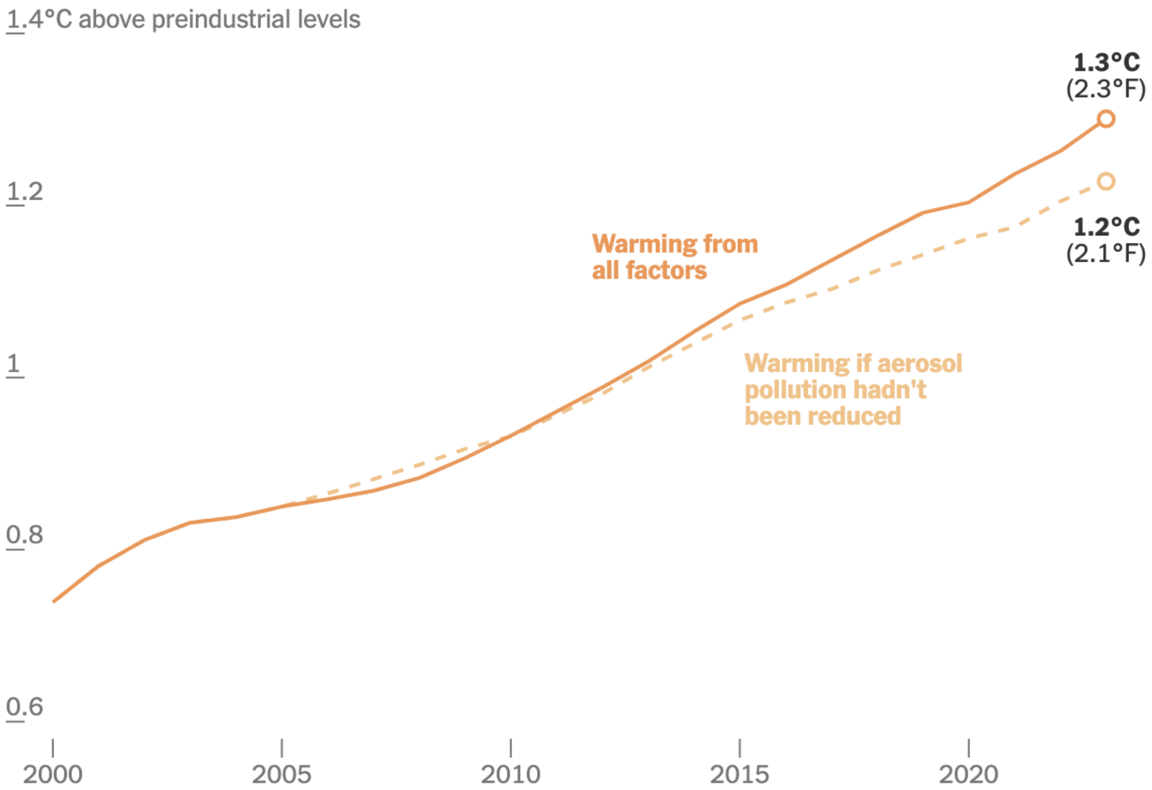


Sand et al. (2023) Comm Earth and Environment



Quaas et al. (2021)

Google Research (2023)



Hausfather and Smith (New York Times)

What is the role of non-CO2 emissions?

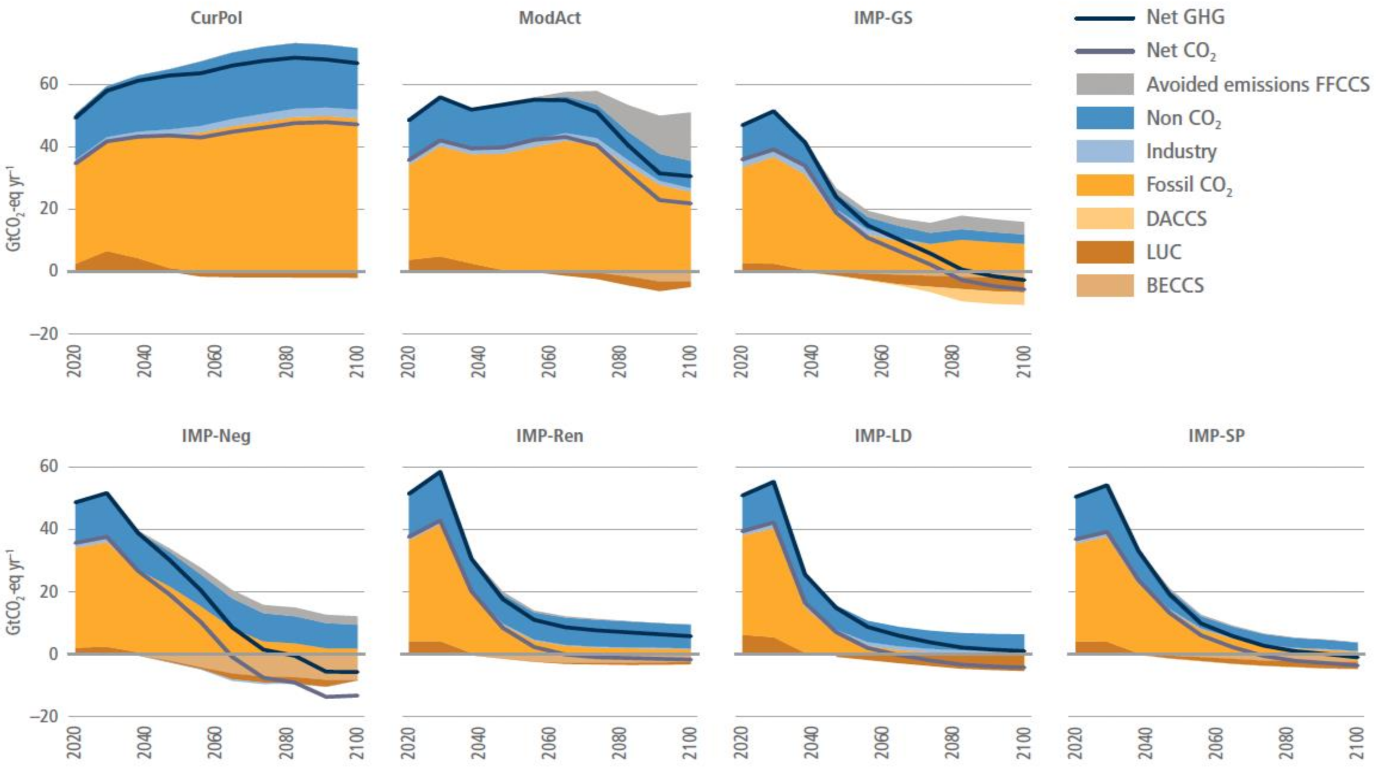


Figure 3.7 | The residual fossil fuel and industry emissions, carbon dioxide removal (CDR) {LUC, DACCS, BECCS}, and non-CO_2 emissions (using AR6 GWP-100) for each of the seven illustrative pathways (IPs). Fossil CCS is also shown, though this does not lead to emissions to the atmosphere (Section 3.2.5).