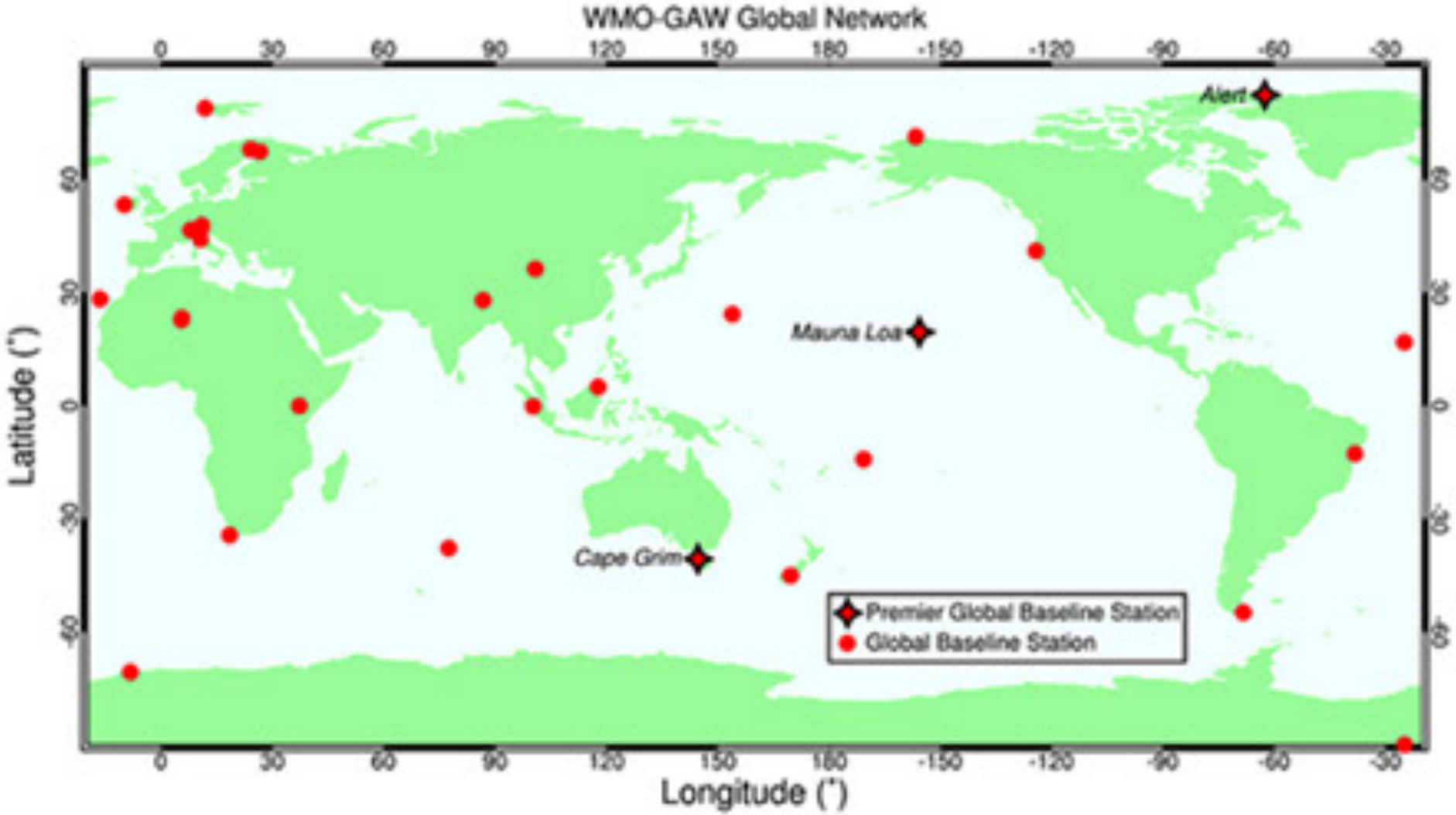
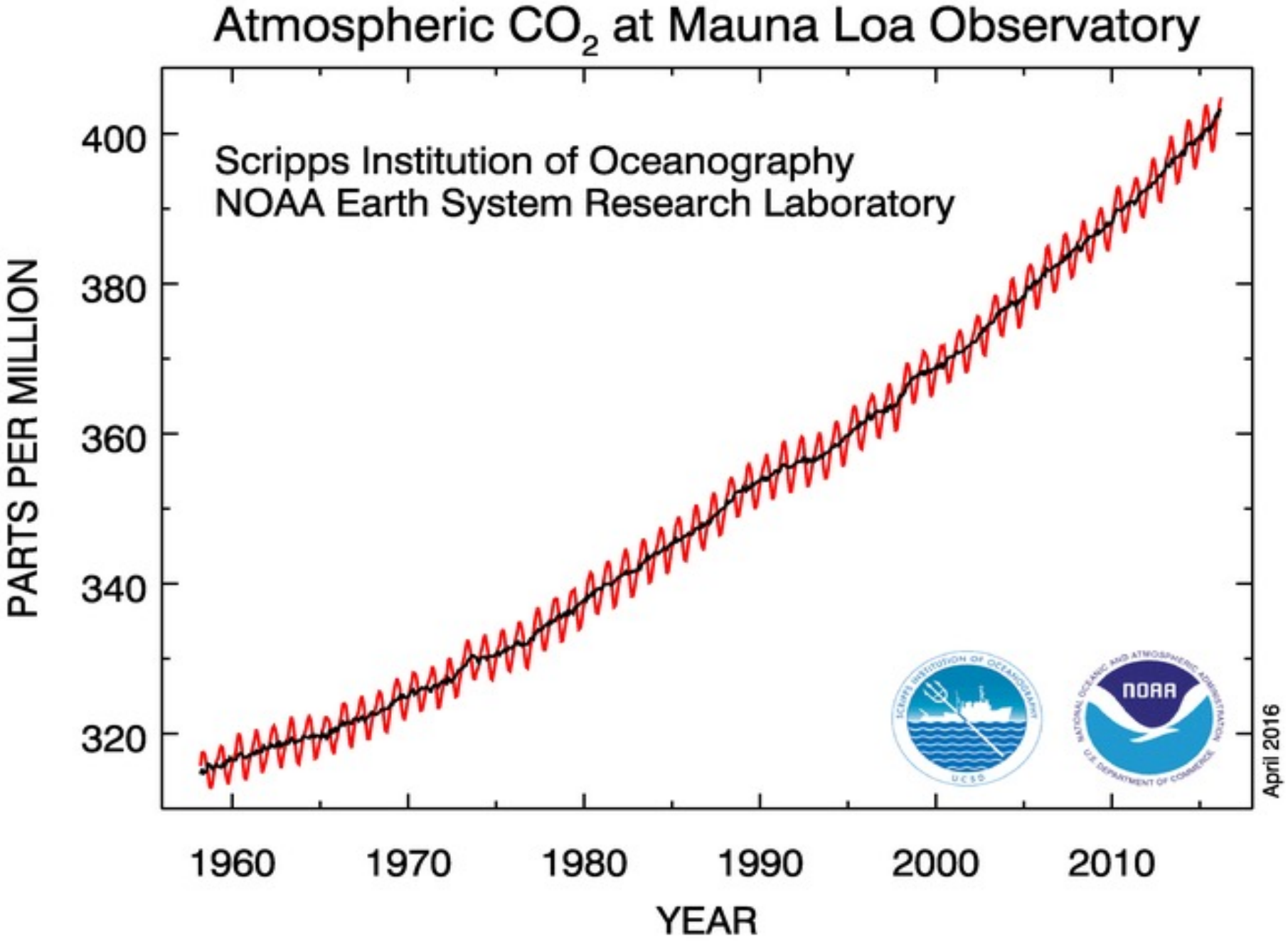
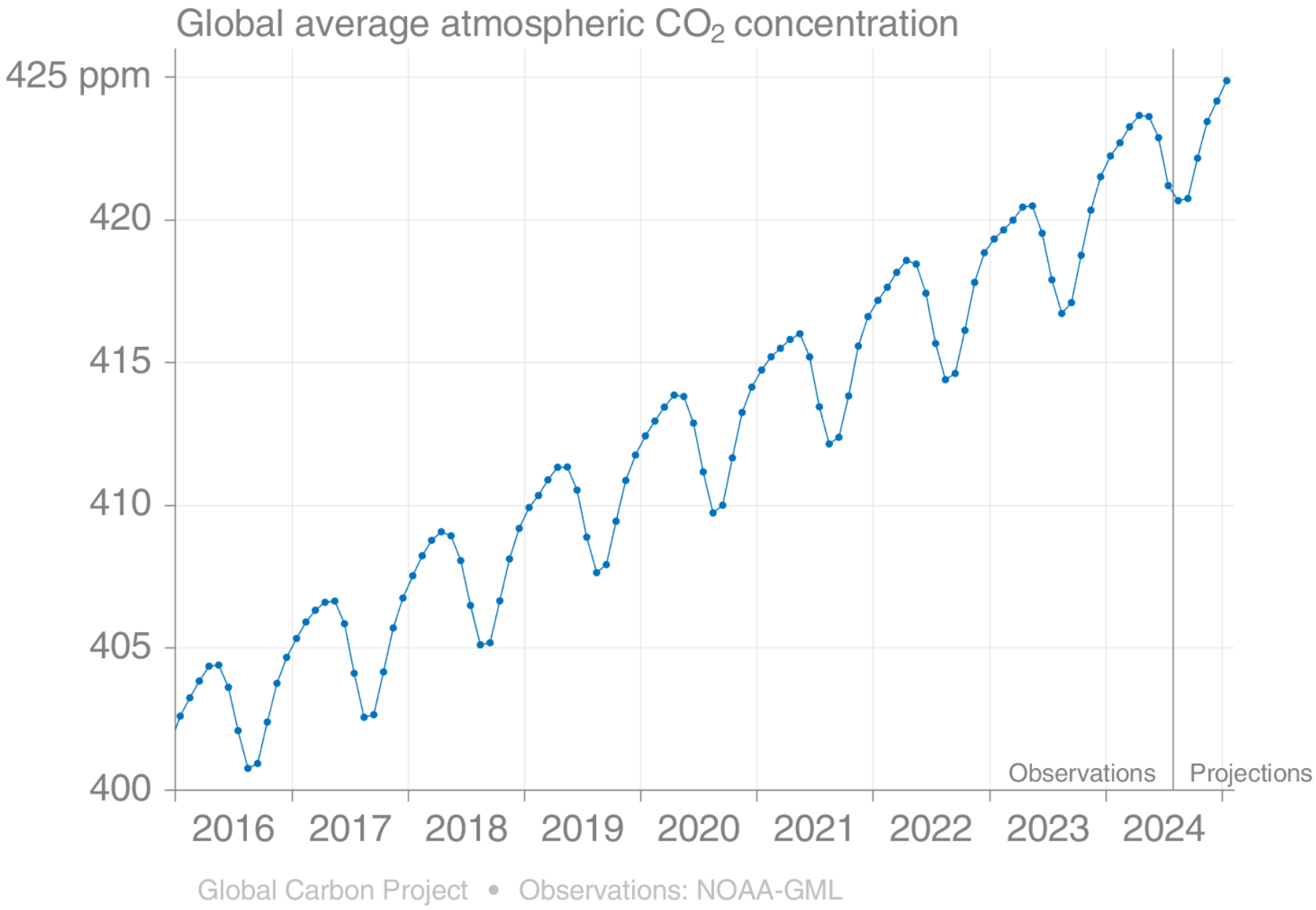
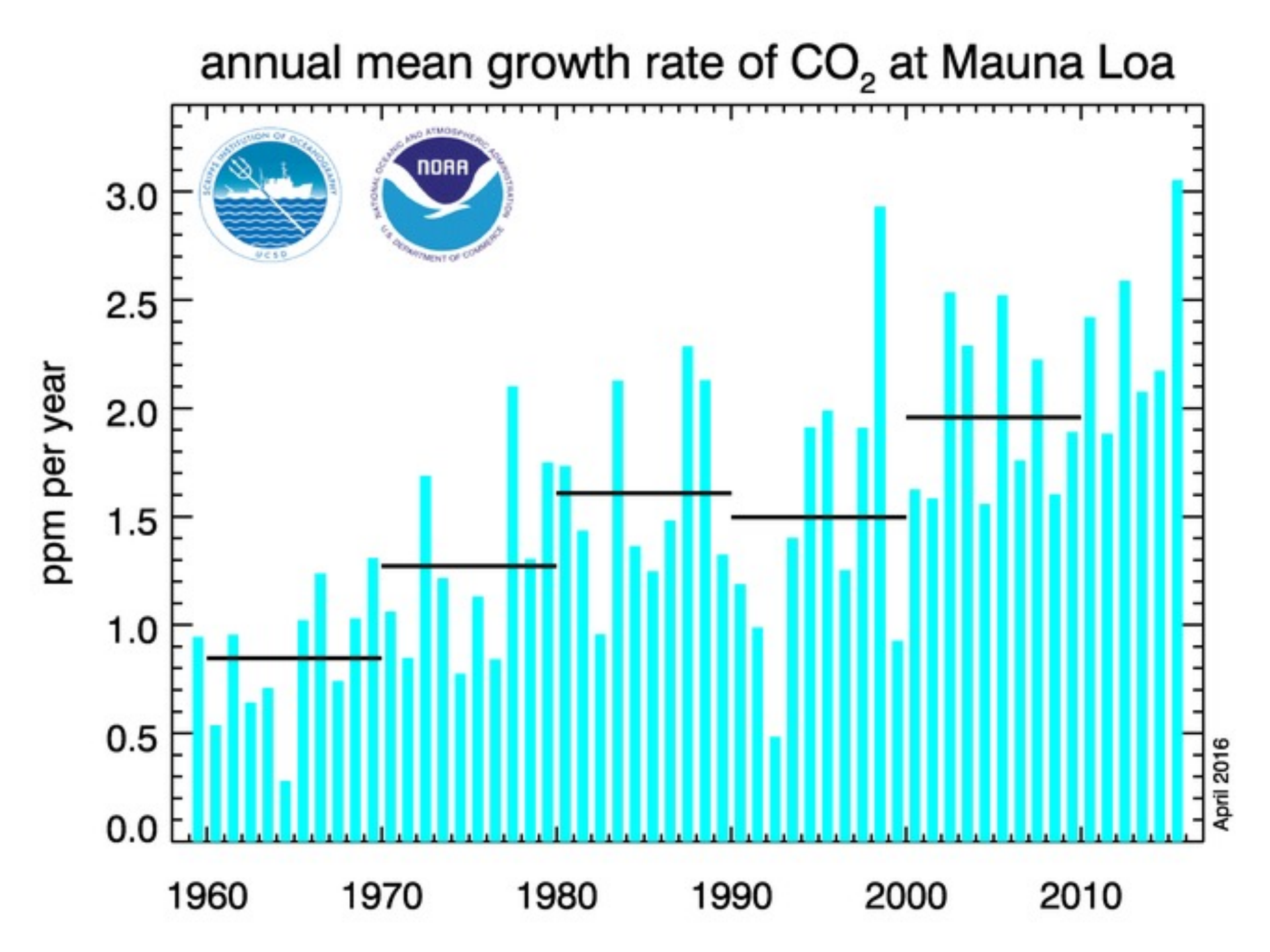
The Global Carbon Cycle

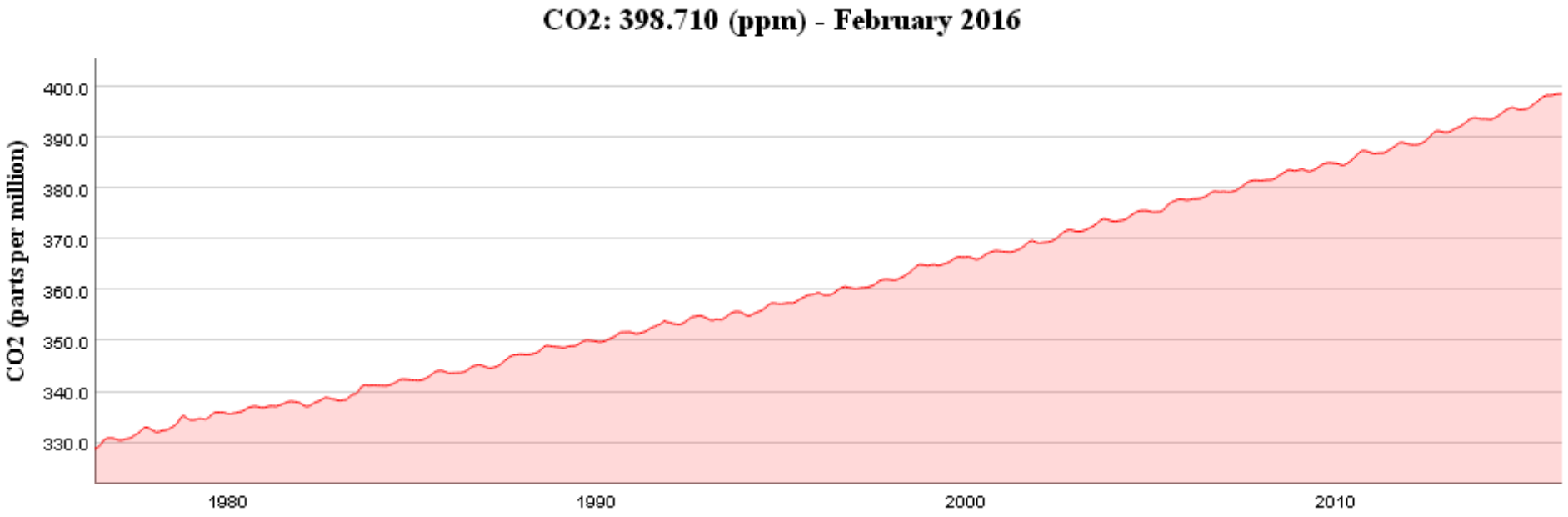

WMO-GAW Global Network
0
30
60
90
120
150
180
-150
-120
-90
-60
-30
60
30
0
-30
-60
Latitude (°)
Longitude (°)
Alert
Mauna Loa
Cape Grim
Premier Global Baseline Station
Global Baseline Station


Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
NOAA
April 2016

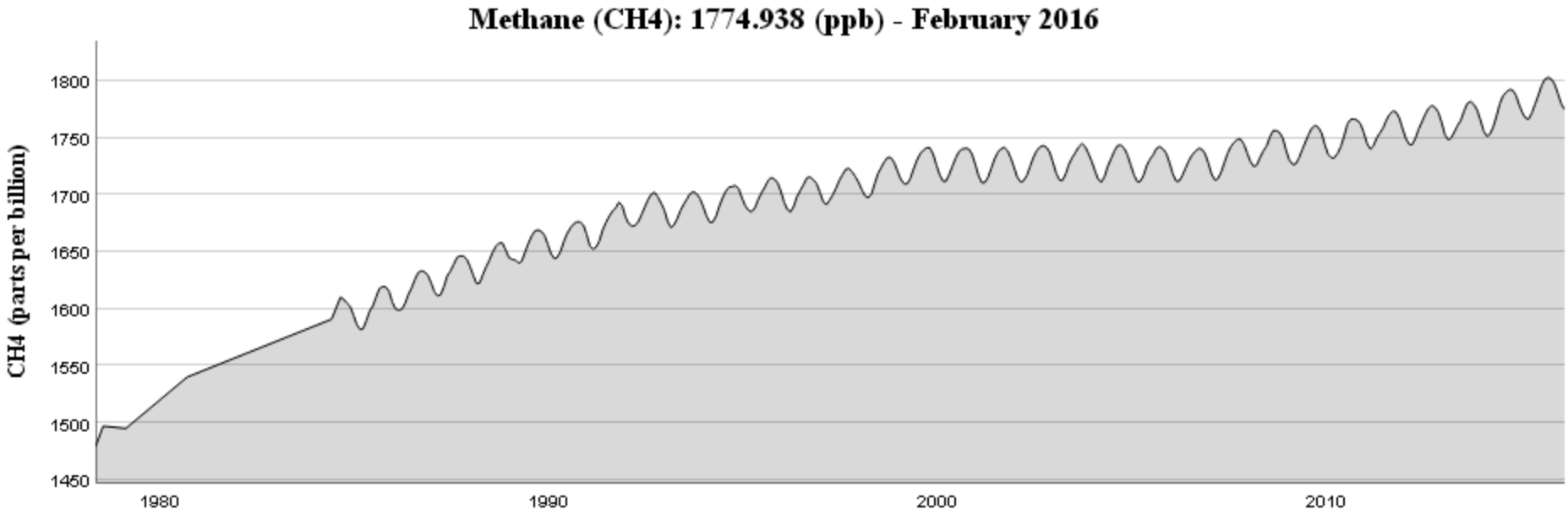

Global average atmospheric CO_2 concentration
425 ppm
420
415
410
405
400
2016
2017
2018
2019
2020
2021
2022
2023
2024
Observations
Projections
Global Carbon Project • Observations: NOAA-GML


annual mean growth rate of CO_2 at Mauna Loa
ppm per year
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1960
1970
1980
1990
2000
2010
April 2016

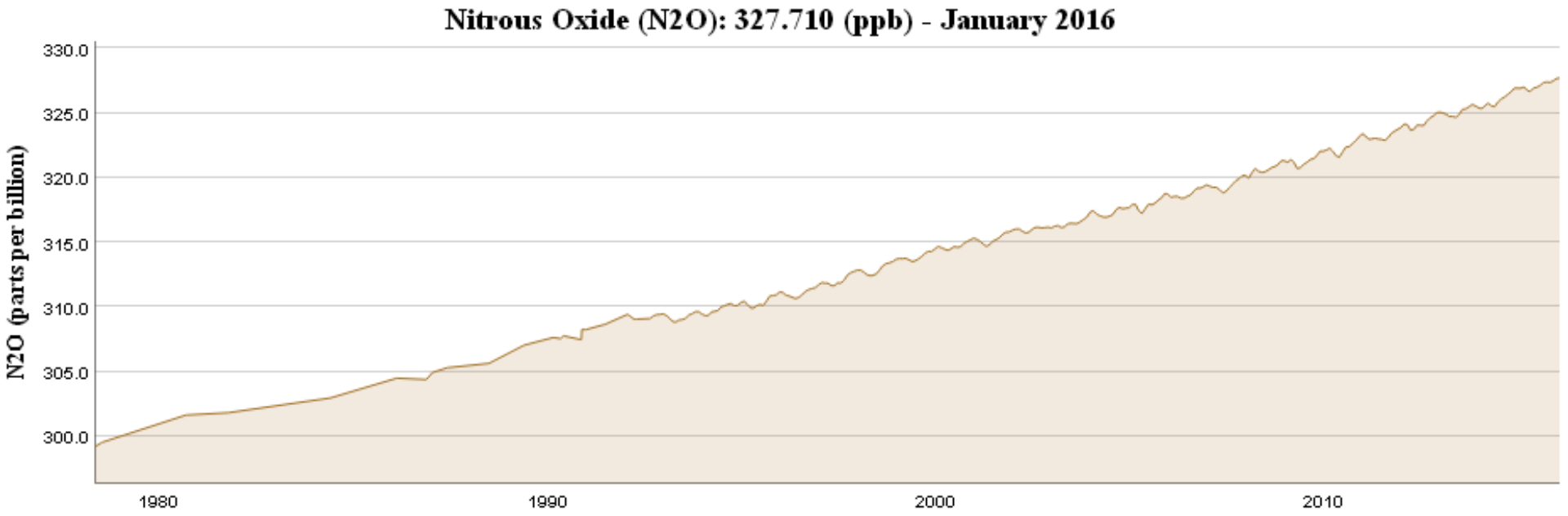
Cape Grim Tasmania CO_2

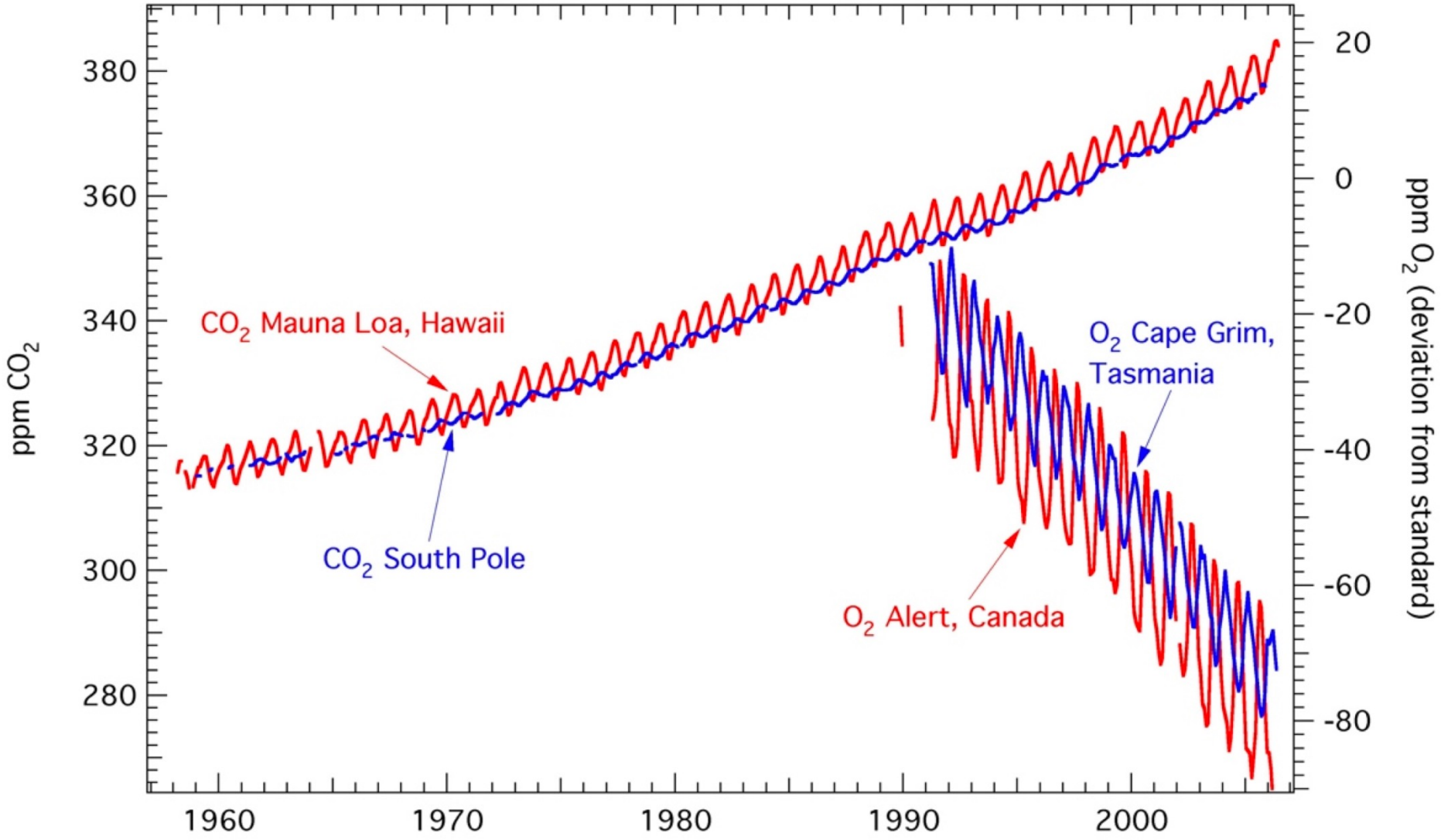


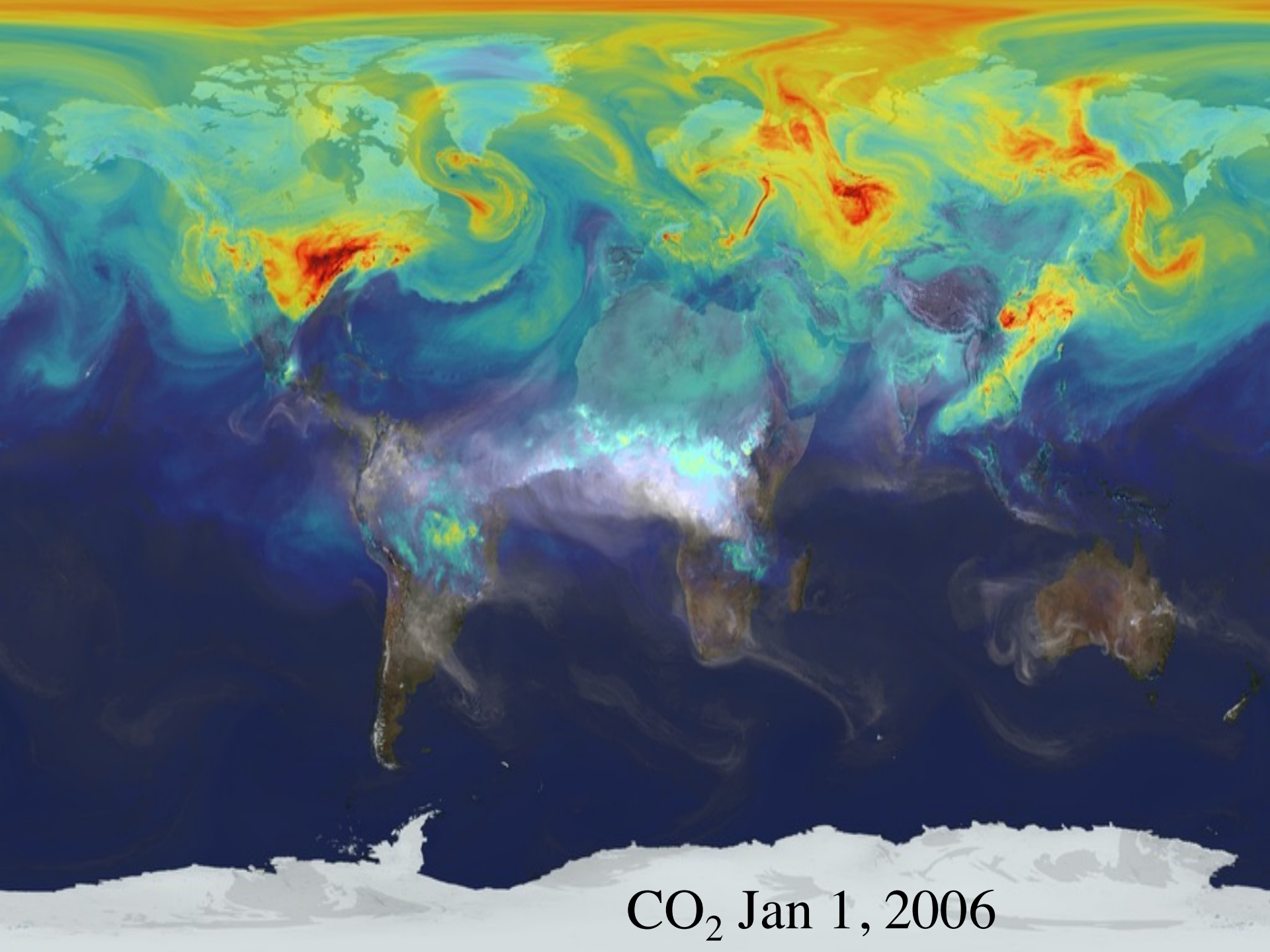
Cape Grim Tasmania CH_4



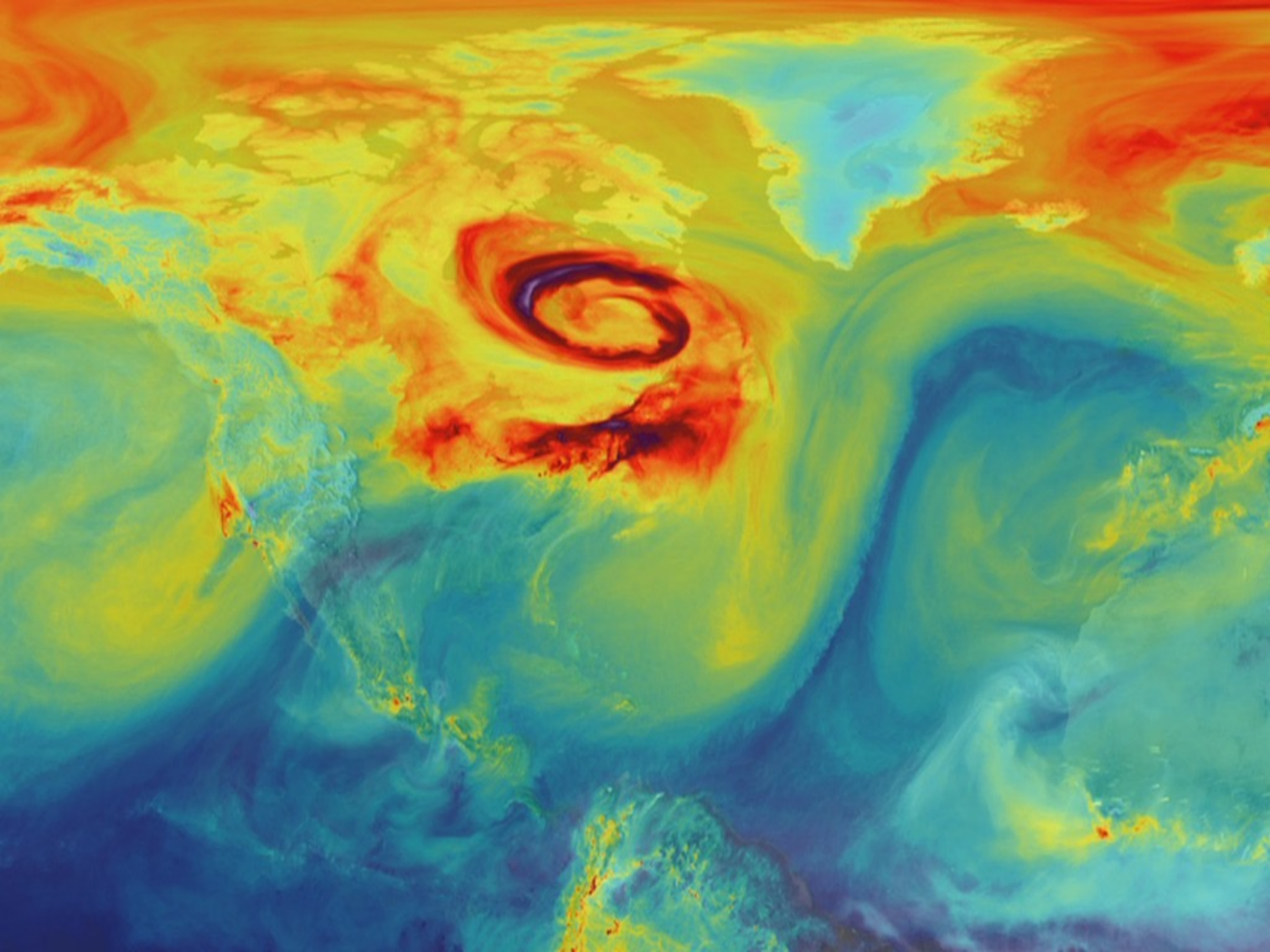
Cape Grim Tasmania N_2O




ppm CO2
380
360
340
320
300
280
20
0
-20
-40
-60
-80
ppm O2 (deviation from standard)
1960
1970
1980
1990
2000
CO2 Mauna Loa, Hawaii
CO2 South Pole
O2 Cape Grim, Tasmania
O2 Alert, Canada



CO_2 Jan 1, 2006

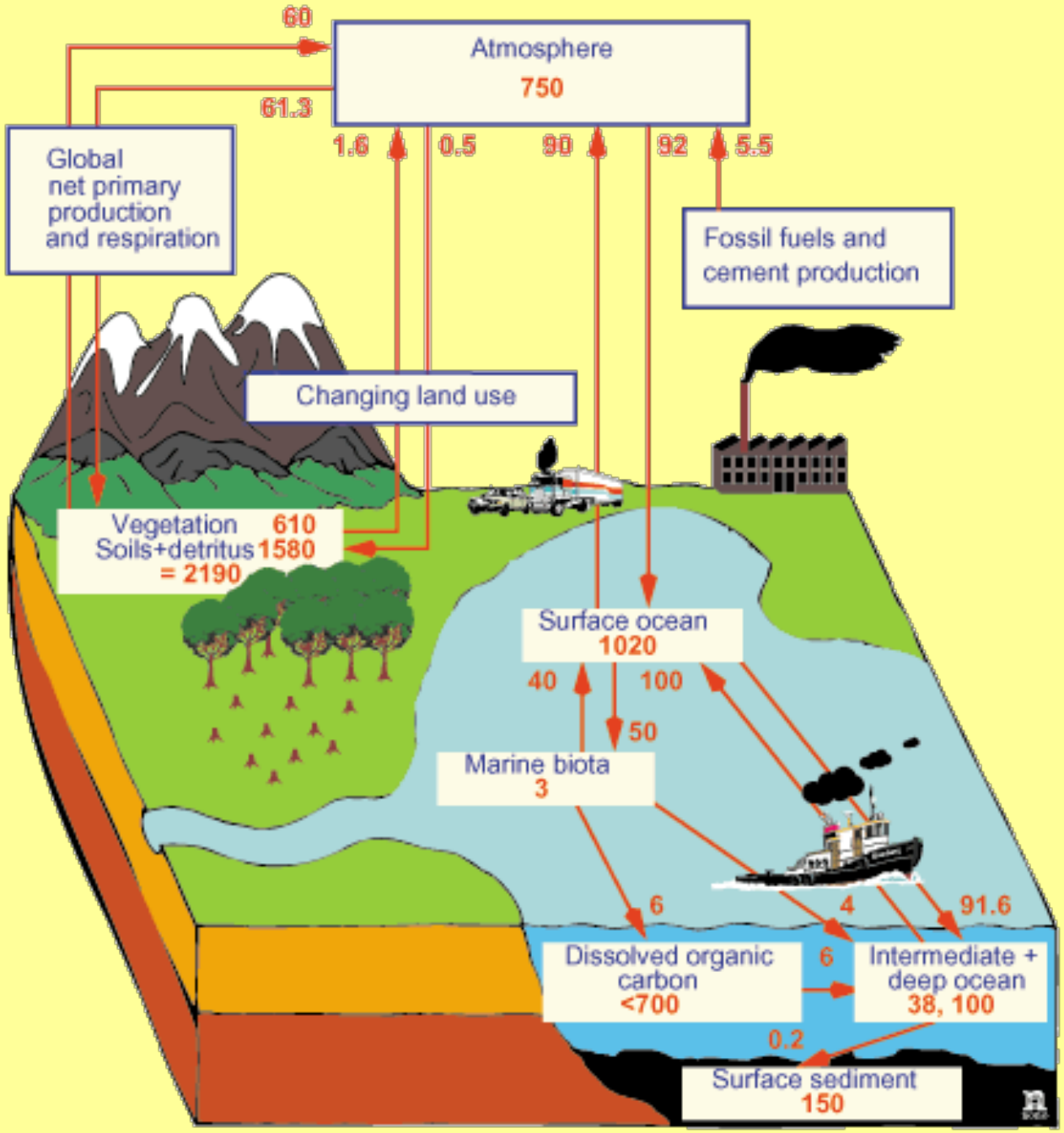


1 Pg = 1 Petagram = 1×10^{15}g = 1 x 10^{12} kg

=1 x 10^{9} metric tonnes = 1 gigatonne = 1 Gt

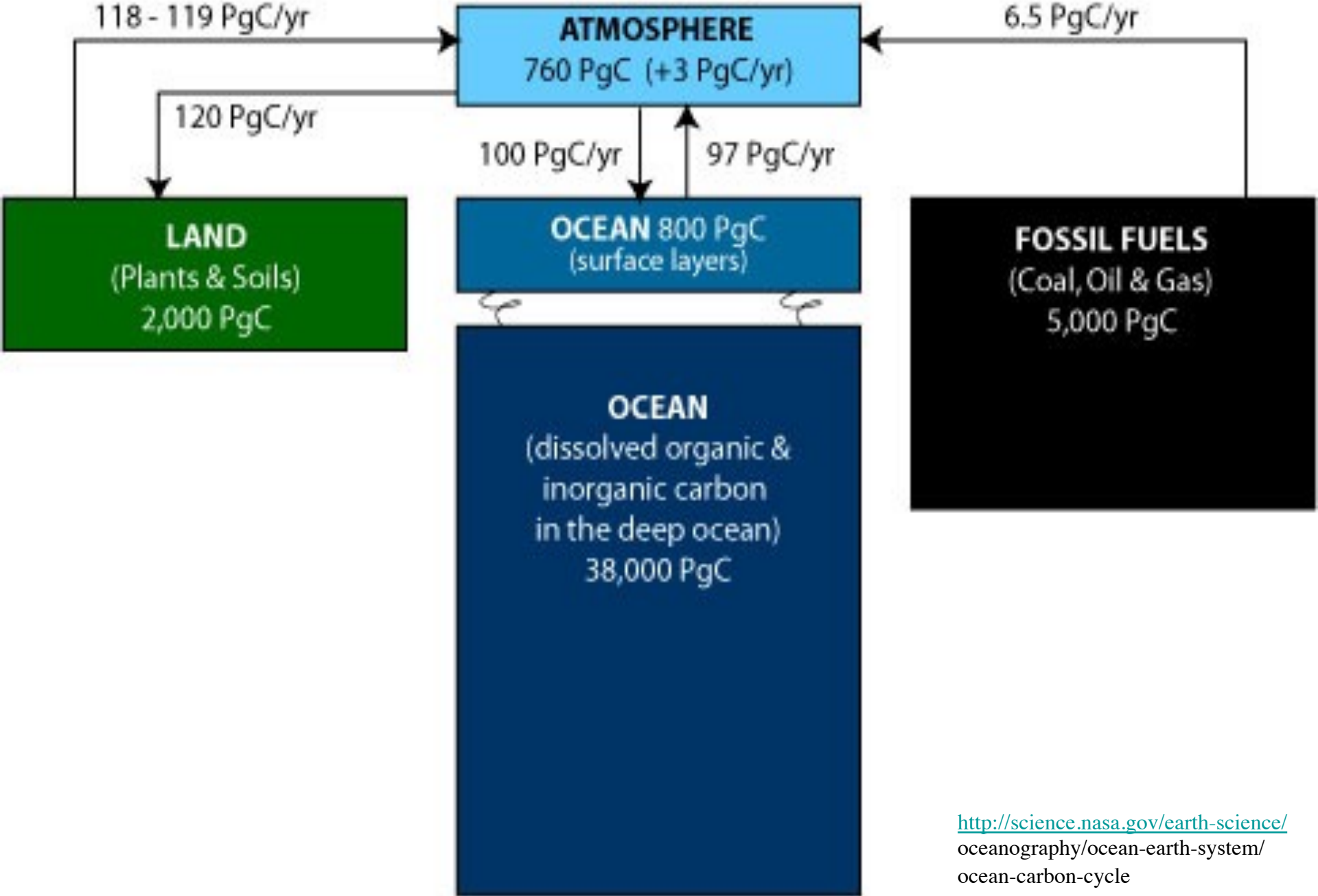
1 kg carbon (C) = 3.67 kg carbon dioxide (CO_2)

1 Pg C = 3.67 Gt CO_2

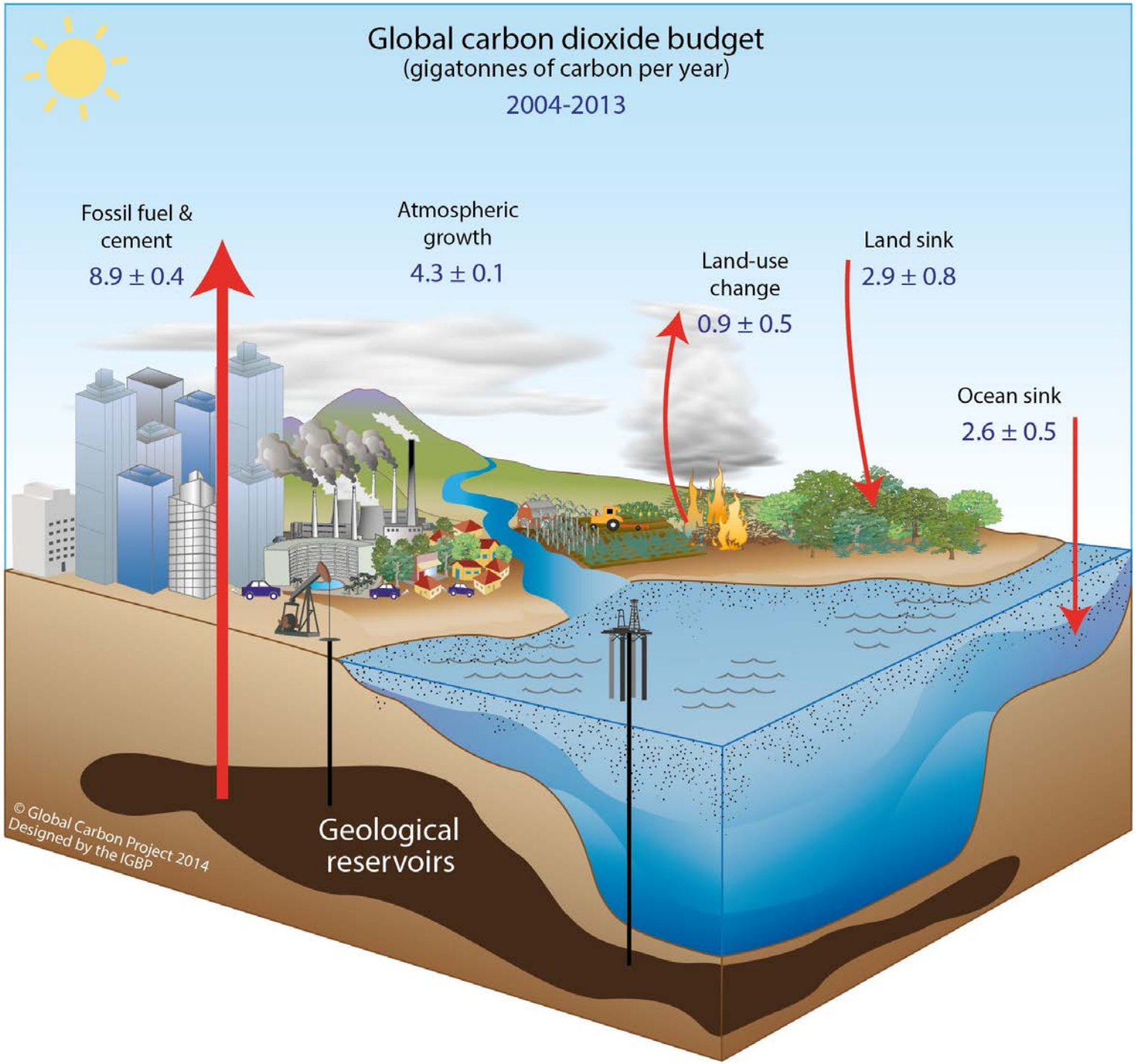


The numbers in boxes indicate the size in GtC of each reservoir.
On each arrow is indicated the magnitude of the flux in GtC/yr.

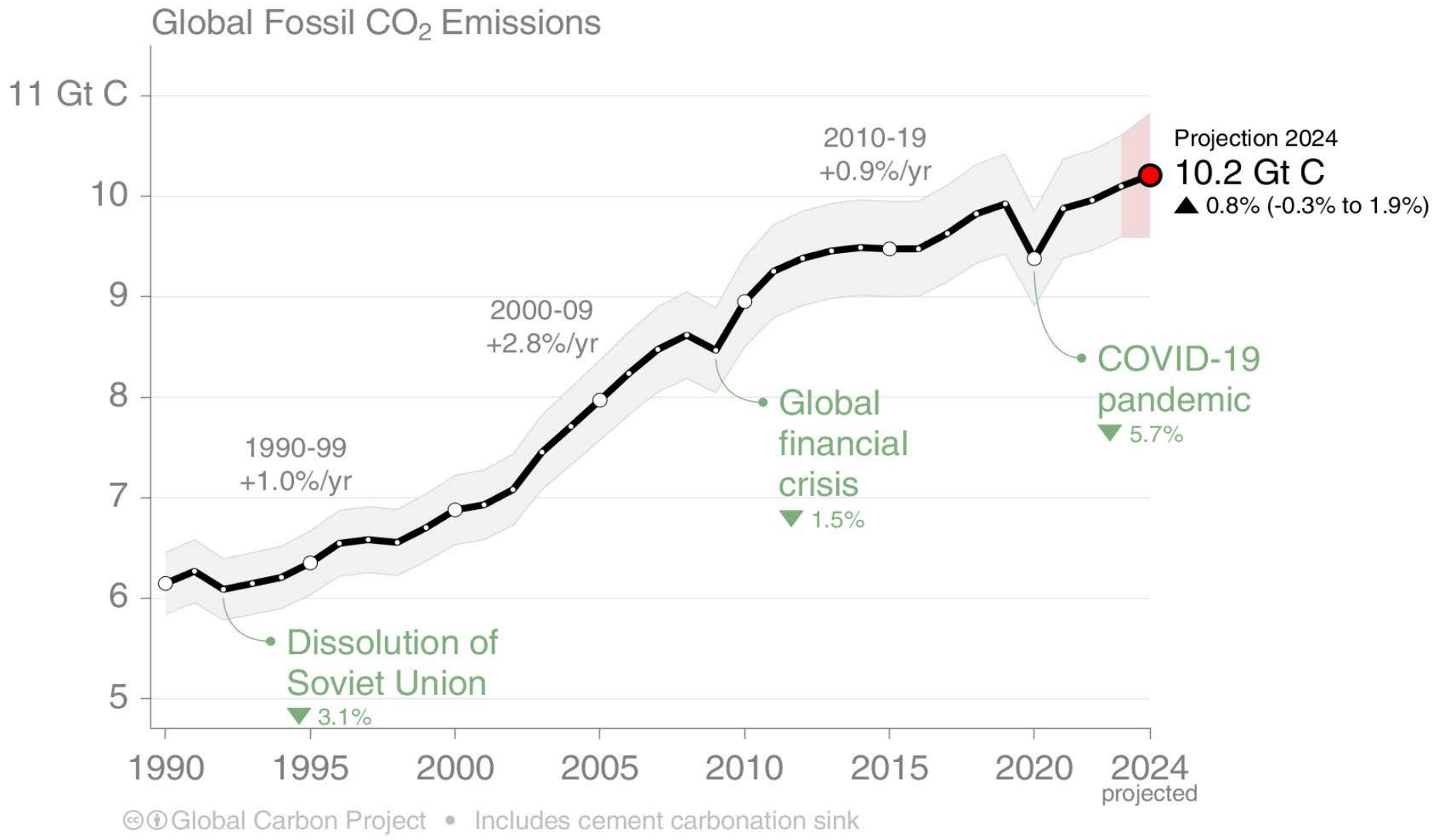
Global Flows of Carbon

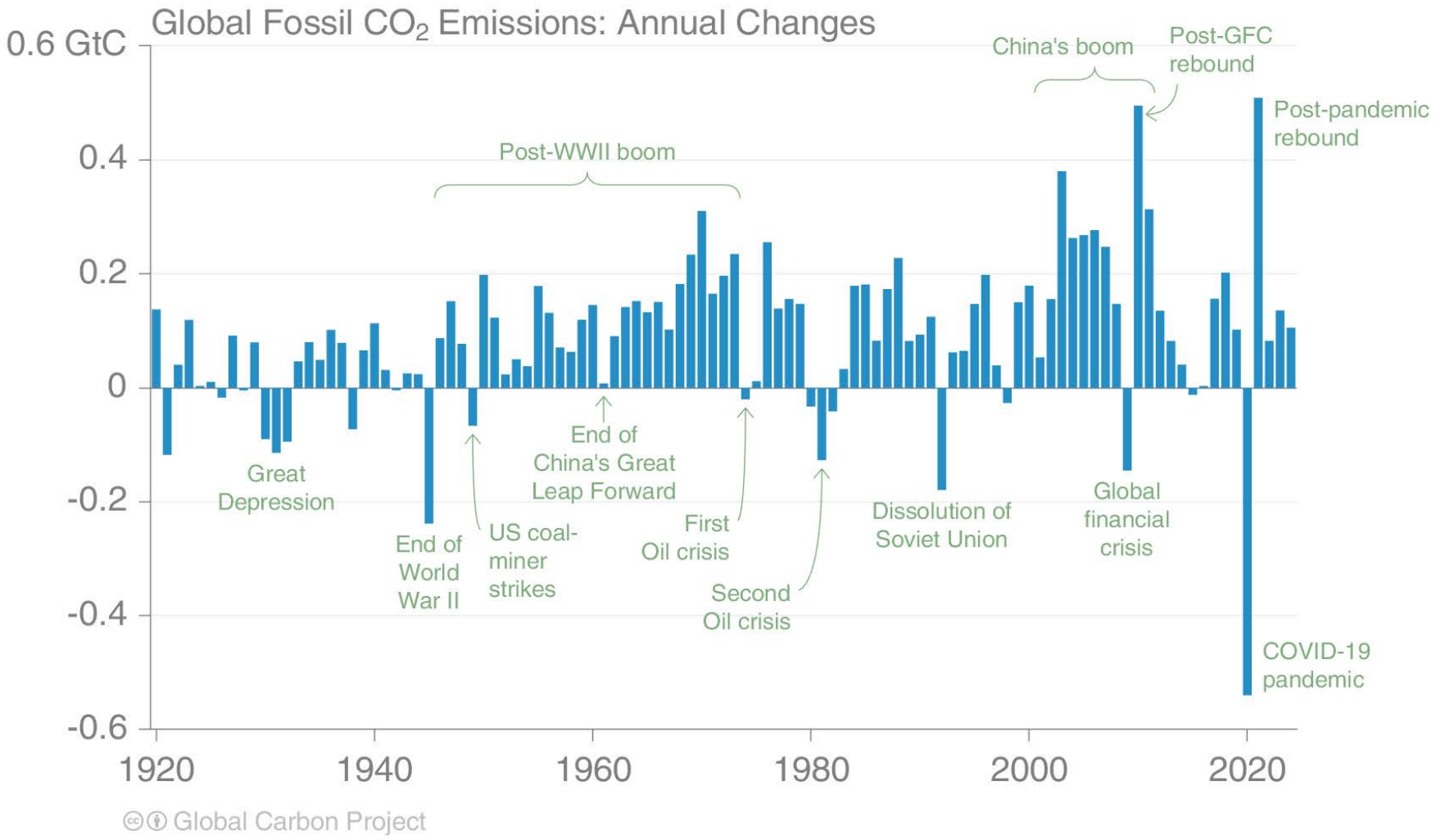


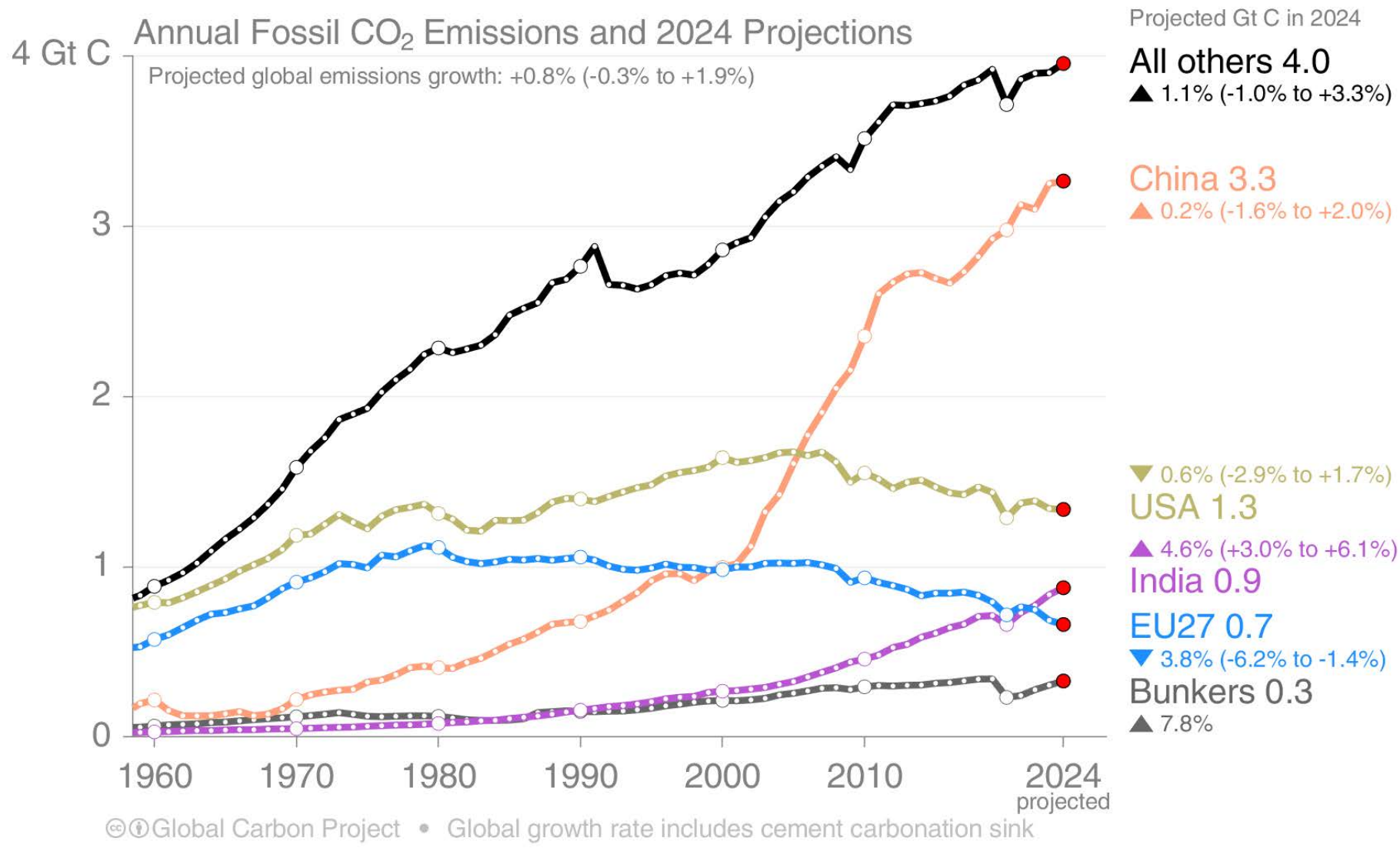
http://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-carbon-cycle

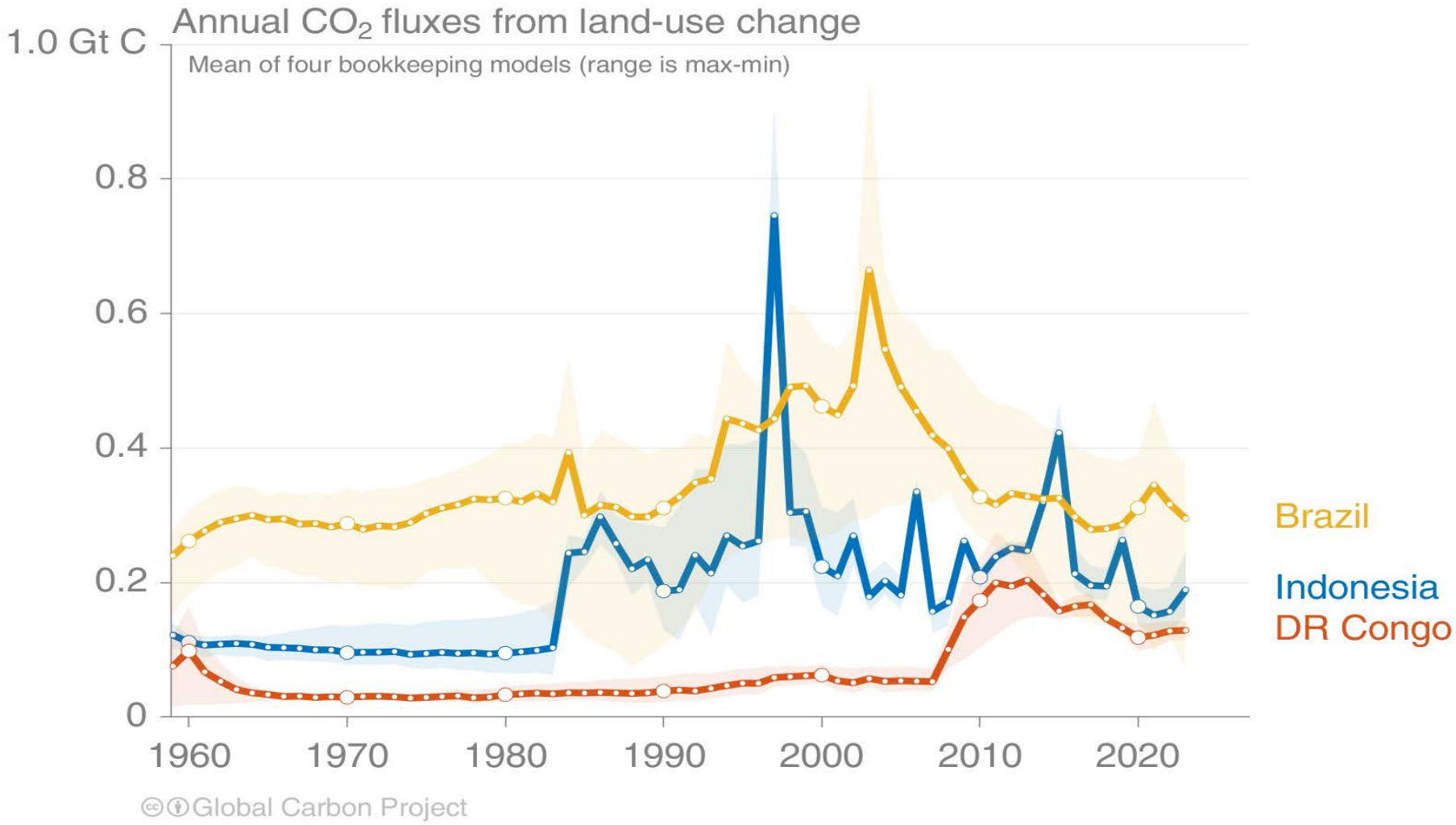

Global carbon dioxide budget
(gigatonnes of carbon per year)
2004-2013
Fossil fuel & cement
8.9 ± 0.4
Atmospheric growth
4.3 ± 0.1
Land-use change
0.9 ± 0.5
Land sink
2.9 ± 0.8
Ocean sink
2.6 ± 0.5
Geological reservoirs
© Global Carbon Project 2014
Designed by the IGBP

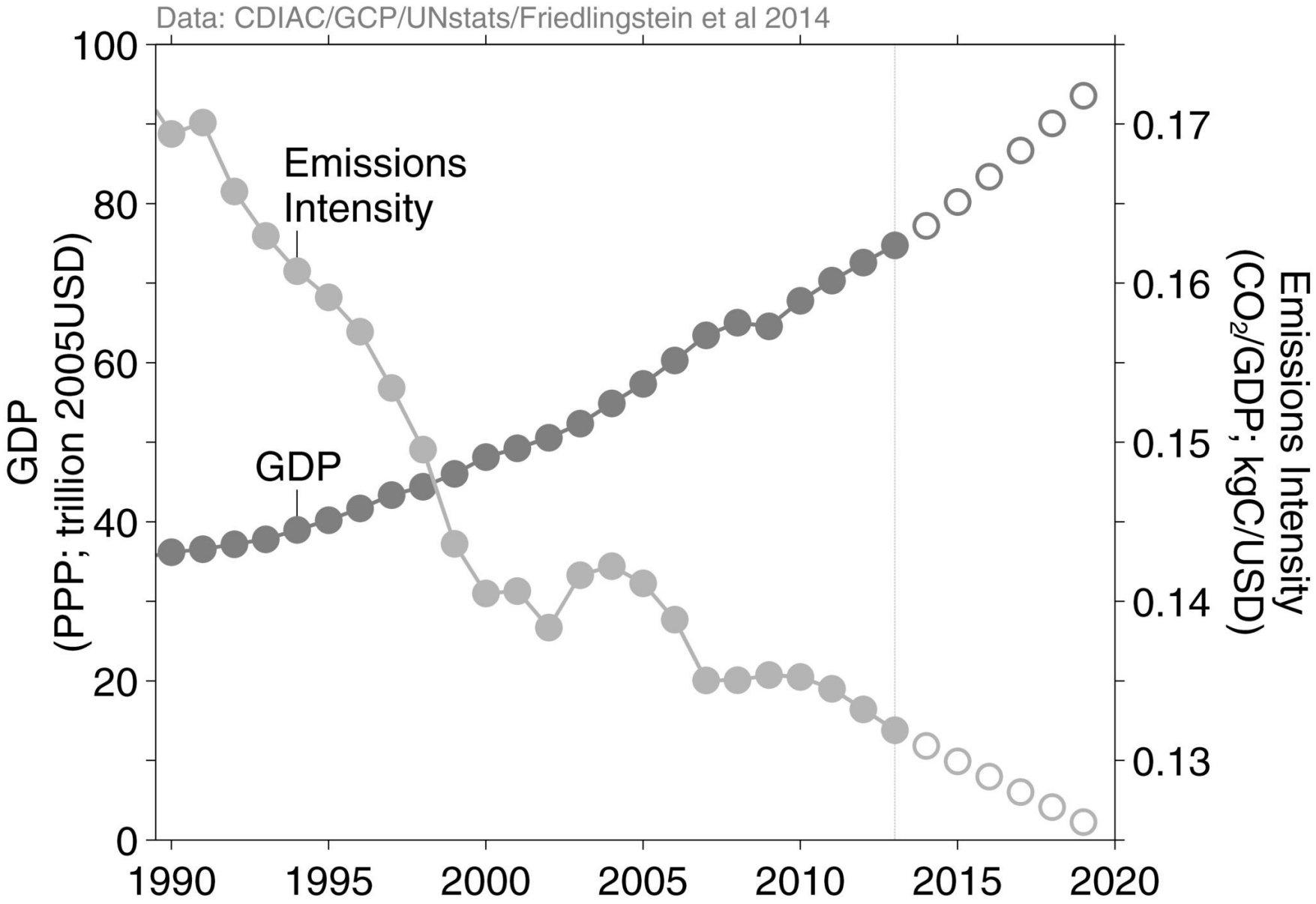
Observed Emissions


Global Fossil CO_2 Emissions
11 Gt C
10
9
8
7
6
5
1990-99
+1.0%/yr
2000-09
+2.8%/yr
2010-19
+0.9%/yr
Dissolution of Soviet Union
▼ 3.1%
Global financial crisis
▼ 1.5%
COVID-19 pandemic
▼ 5.7%
Projection 2024
10.2 Gt C
▲ 0.8% (-0.3% to 1.9%)
1990
1995
2000
2005
2010
2015
2020
2024
projected
Global Carbon Project • Includes cement carbonation sink

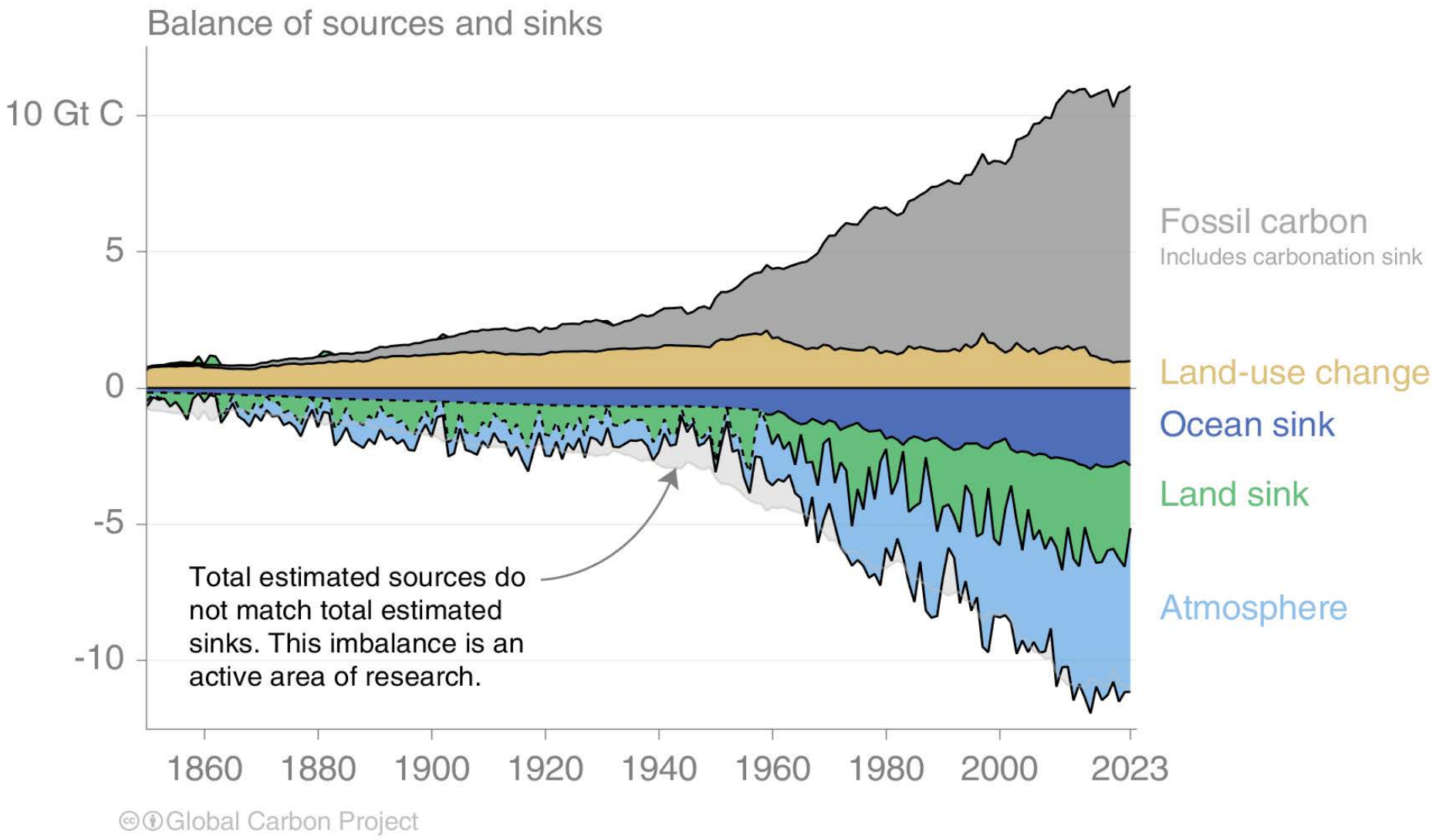

Global Fossil CO_2 Emissions: Annual Changes
0.6 GtC
0.4
0.2
0
-0.2
-0.4
-0.6
1920
1940
1960
1980
2000
2020
Post-WWII boom
China's boom
Post-GFC rebound
Post-pandemic rebound
Great Depression
End of World War II
US coal-miner strikes
End of China's Great Leap Forward
First Oil crisis
Second Oil crisis
Dissolution of Soviet Union
Global financial crisis
COVID-19 pandemic
Global Carbon Project


Annual Fossil CO_2 Emissions and 2024 Projections
Projected global emissions growth: +0.8% (-0.3% to +1.9%)
4 Gt C
3
2
1
0
1960
1970
1980
1990
2000
2010
2024
projected
Global Carbon Project • Global growth rate includes cement carbonation sink
Projected Gt C in 2024
All others 4.0
▲ 1.1% (-1.0% to +3.3%)
China 3.3
▲ 0.2% (-1.6% to +2.0%)
▼ 0.6% (-2.9% to +1.7%)
USA 1.3
▲ 4.6% (+3.0% to +6.1%)
India 0.9
EU27 0.7
▼ 3.8% (-6.2% to -1.4%)
Bunkers 0.3
▲ 7.8%


Annual CO_2 fluxes from land-use change
Mean of four bookkeeping models (range is max-min)
1.0 Gt C
0.8
0.6
0.4
0.2
0
1960
1970
1980
1990
2000
2010
2020
Brazil
Indonesia
DR Congo
Global Carbon Project


Data: CDIAC/GCP/UNstats/Friedlingstein et al 2014
Emissions
Intensity
GDP
GDP
(PPP; trillion 2005USD)
Emissions Intensity
(CO2/GDP; kgC/USD)
0
20
40
60
80
100
0.13
0.14
0.15
0.16
0.17
1990
1995
2000
2005
2010
2015
2020

Closing the Global Carbon Budget


Balance of sources and sinks
10 Gt C
5
0
-5
-10
1860
1880
1900
1920
1940
1960
1980
2000
2023
Fossil carbon
Includes carbonation sink
Land-use change
Ocean sink
Land sink
Atmosphere
Total estimated sources do not match total estimated sinks. This imbalance is an active area of research.
Global Carbon Project

Fate of Anthropogenic CO_2 Emissions (2002-2011 average)

8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

4.3±0.1 PgC/yr
46%

2.6±0.8 PgC/yr
28%

Calculated as the residual of all other flux components

26%
2.5±0.5 PgC/yr

Source: Le Quéré et al. 2012; Global Carbon Project 2012

GLOBAL CARBON project

Fate of anthropogenic CO_2 emissions (2014–2023)

Sources = Sinks

9.7 GtC/yr

90%

10%

1.1 GtC/yr

5.2 GtC/yr

48%

29%

3.2 GtC/yr

26%

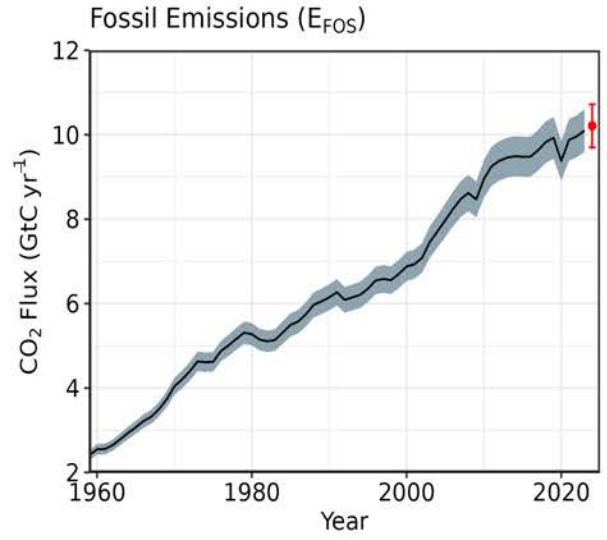
2.9 GtC/yr

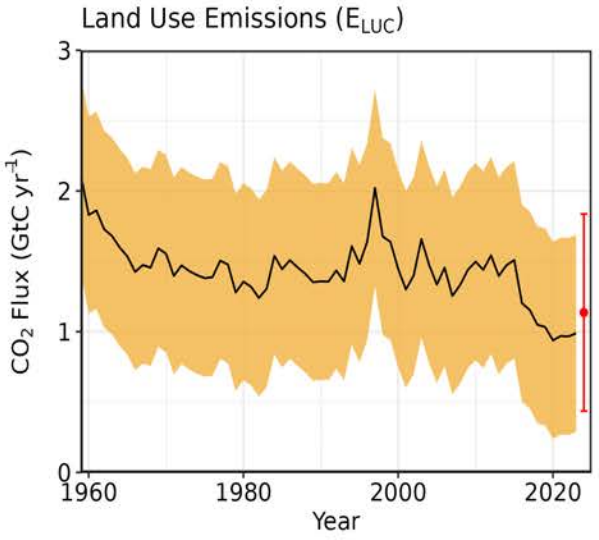
Budget Imbalance:
(the difference between estimated sources & sinks)

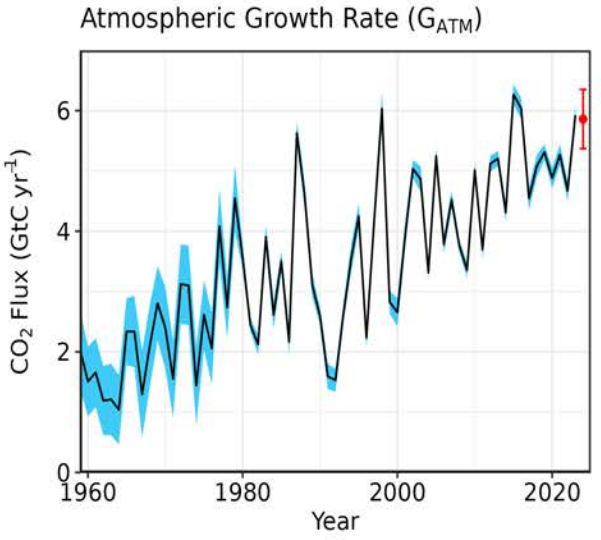
4%

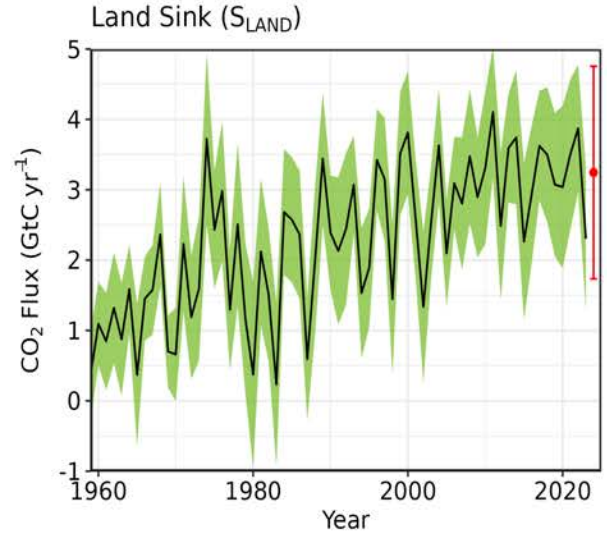
-0.4 GtC/yr

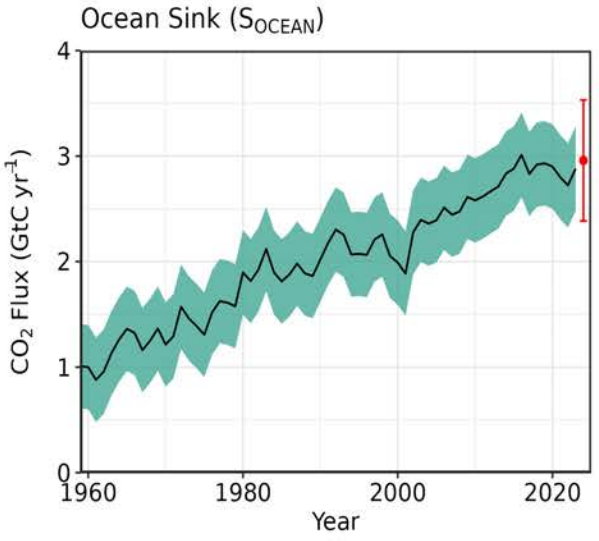
Source: Friedlingstein et al 2024; Global Carbon Project 2024

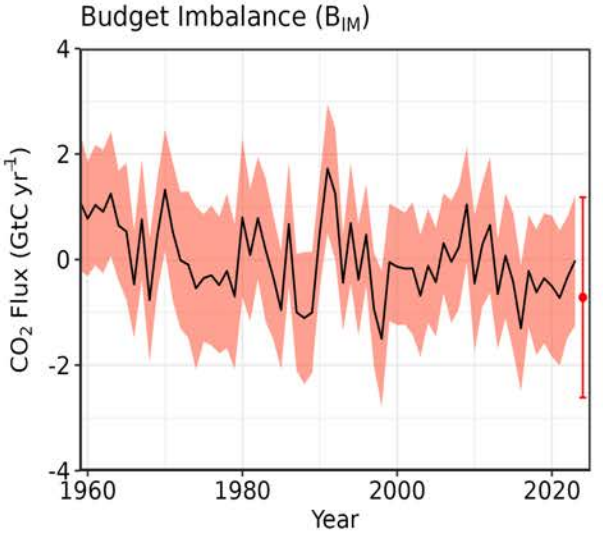

Fossil Emissions (E_{FOS})
CO_2 Flux (GtC yr^{-1})
Year

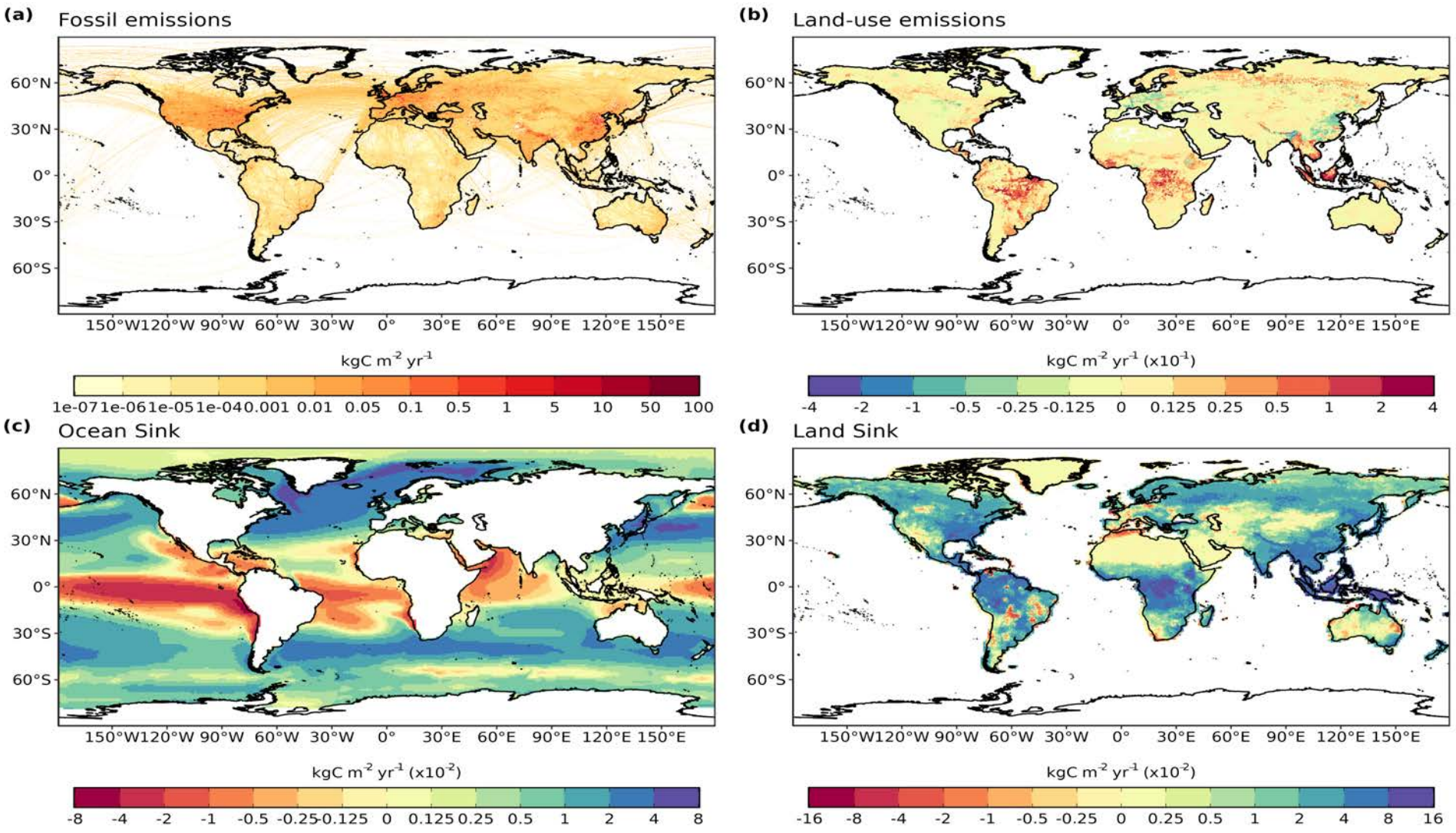

Land Use Emissions (E_{LUC})
CO_2 Flux (GtC yr^{-1})
Year

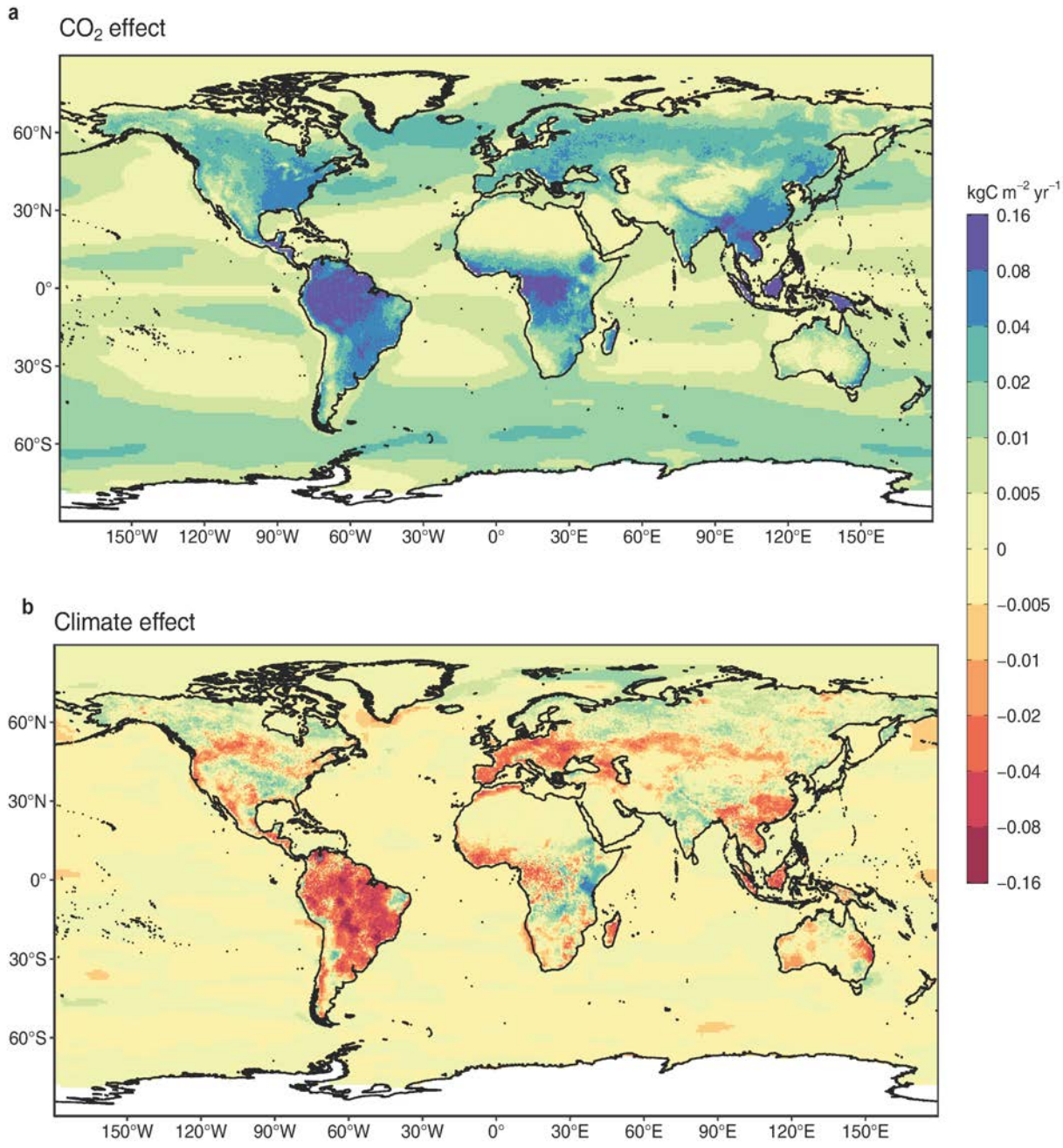

Atmospheric Growth Rate (G_{ATM})
CO_2 Flux (GtC yr^{-1})
Year


Land Sink (S_{LAND})
CO_2 Flux (GtC yr^{-1})
Year


Ocean Sink (S_{OCEAN})
CO_2 Flux (GtC yr^{-1})
Year

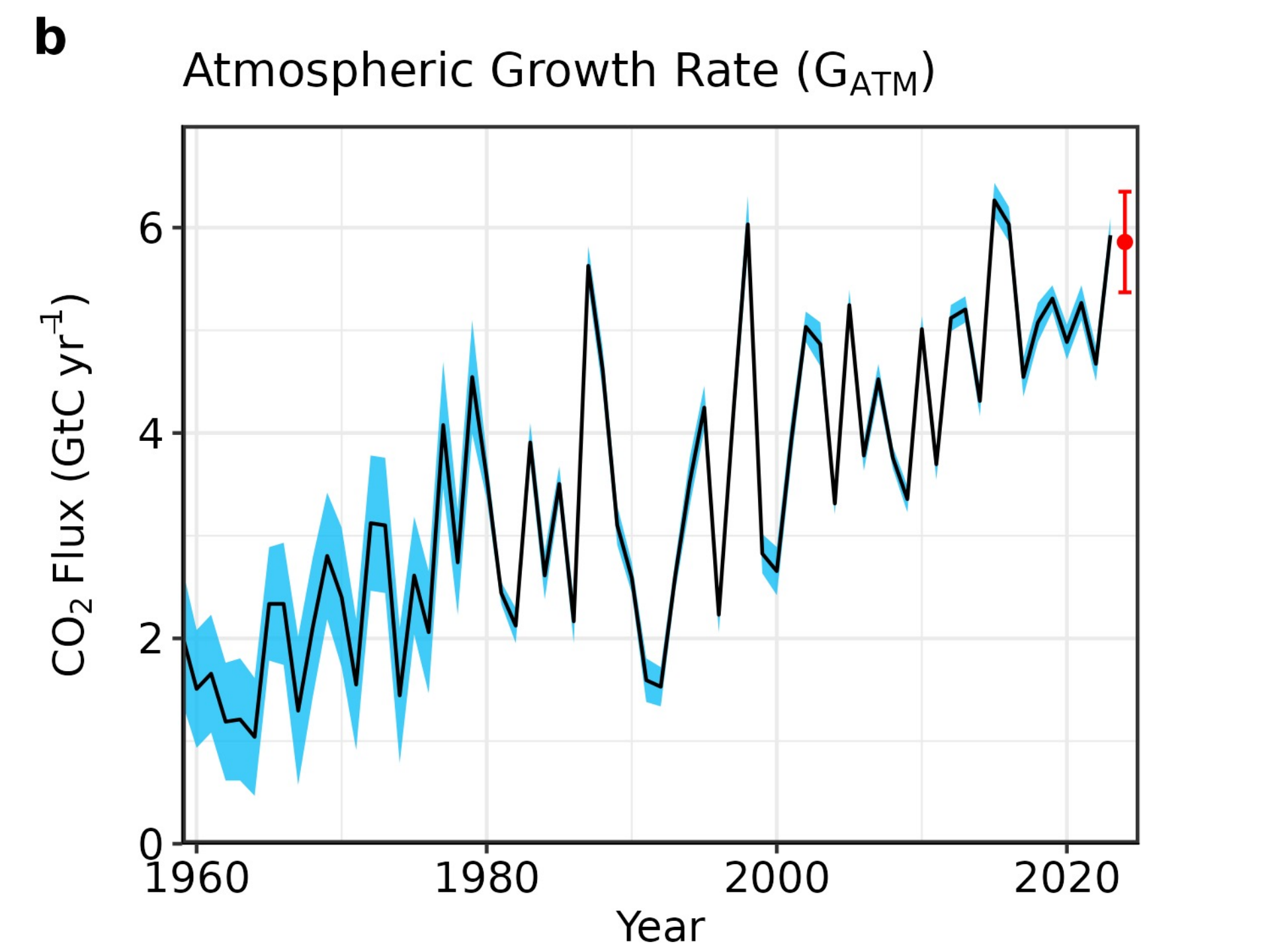

Budget Imbalance (B_{IM})
CO_2 Flux (GtC yr^{-1})
Year

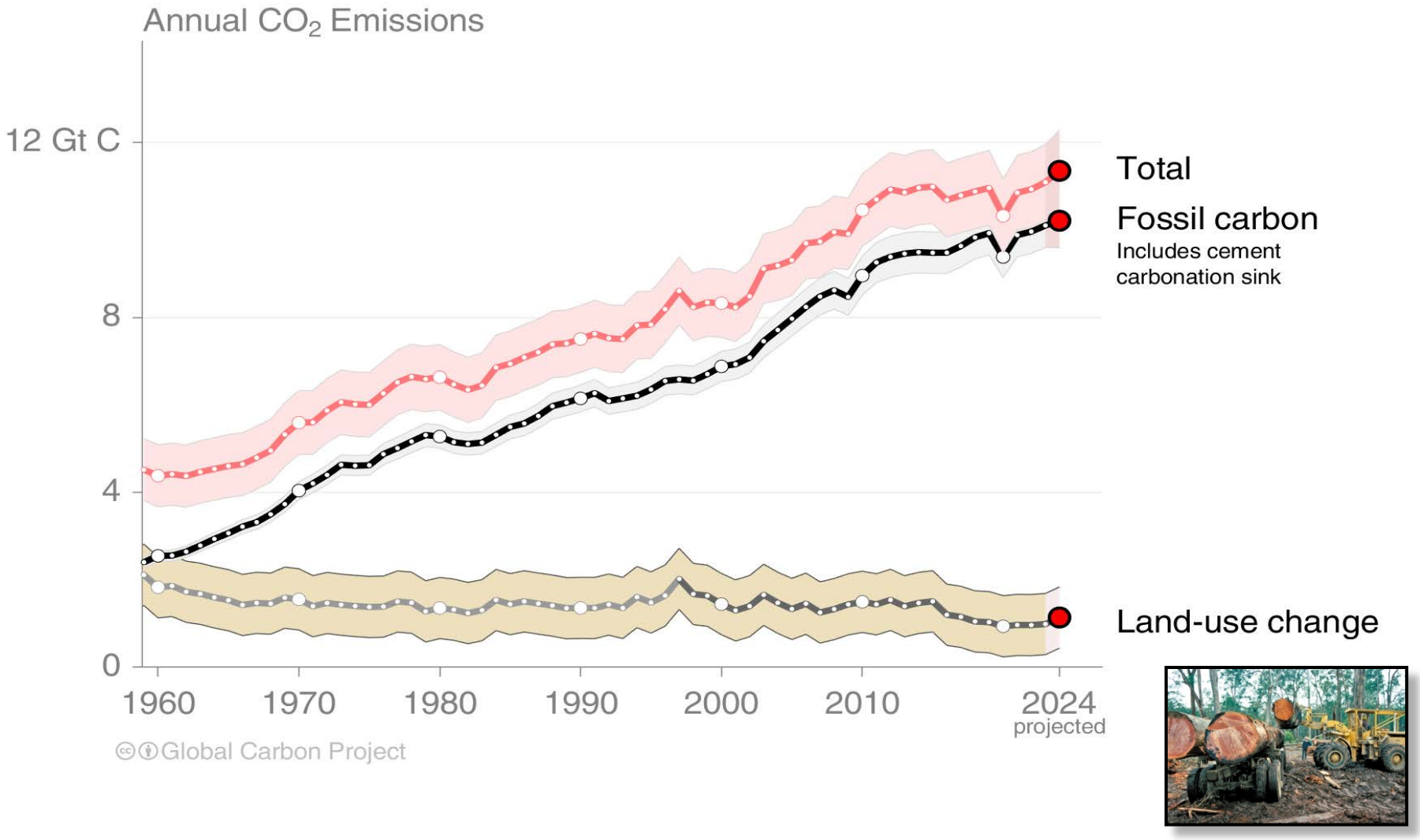

(a)
Fossil emissions
60°N
30°N
0°
30°S
60°S
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
kgC m-2 yr-1
1e-07 1e-06 1e-05 1e-04 0.001 0.01 0.05 0.1 0.5 1 5 10 50 100
(b)
Land-use emissions
60°N
30°N
0°
30°S
60°S
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
kgC m-2 yr-1 (x10-1)
-4 -2 -1 -0.5 -0.25 -0.125 0 0.125 0.25 0.5 1 2 4
(c)
Ocean Sink
60°N
30°N
0°
30°S
60°S
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
kgC m-2 yr-1 (x10-2)
-8 -4 -2 -1 -0.5 -0.25 -0.125 0 0.125 0.25 0.5 1 2 4 8
(d)
Land Sink
60°N
30°N
0°
30°S
60°S
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
kgC m-2 yr-1 (x10-2)
-16 -8 -4 -2 -1 -0.5 -0.25 0 0.25 0.5 1 2 4 8 16

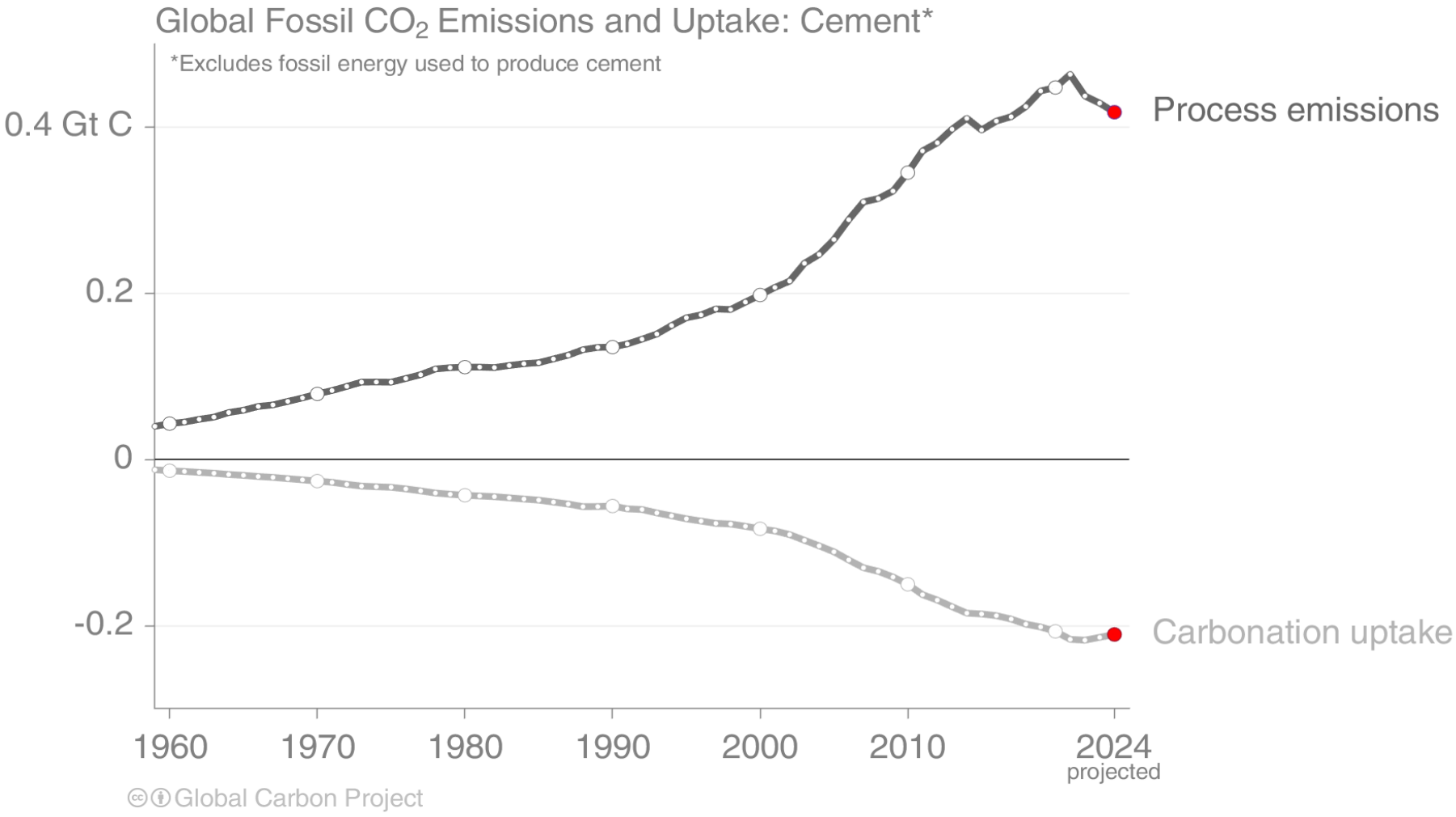


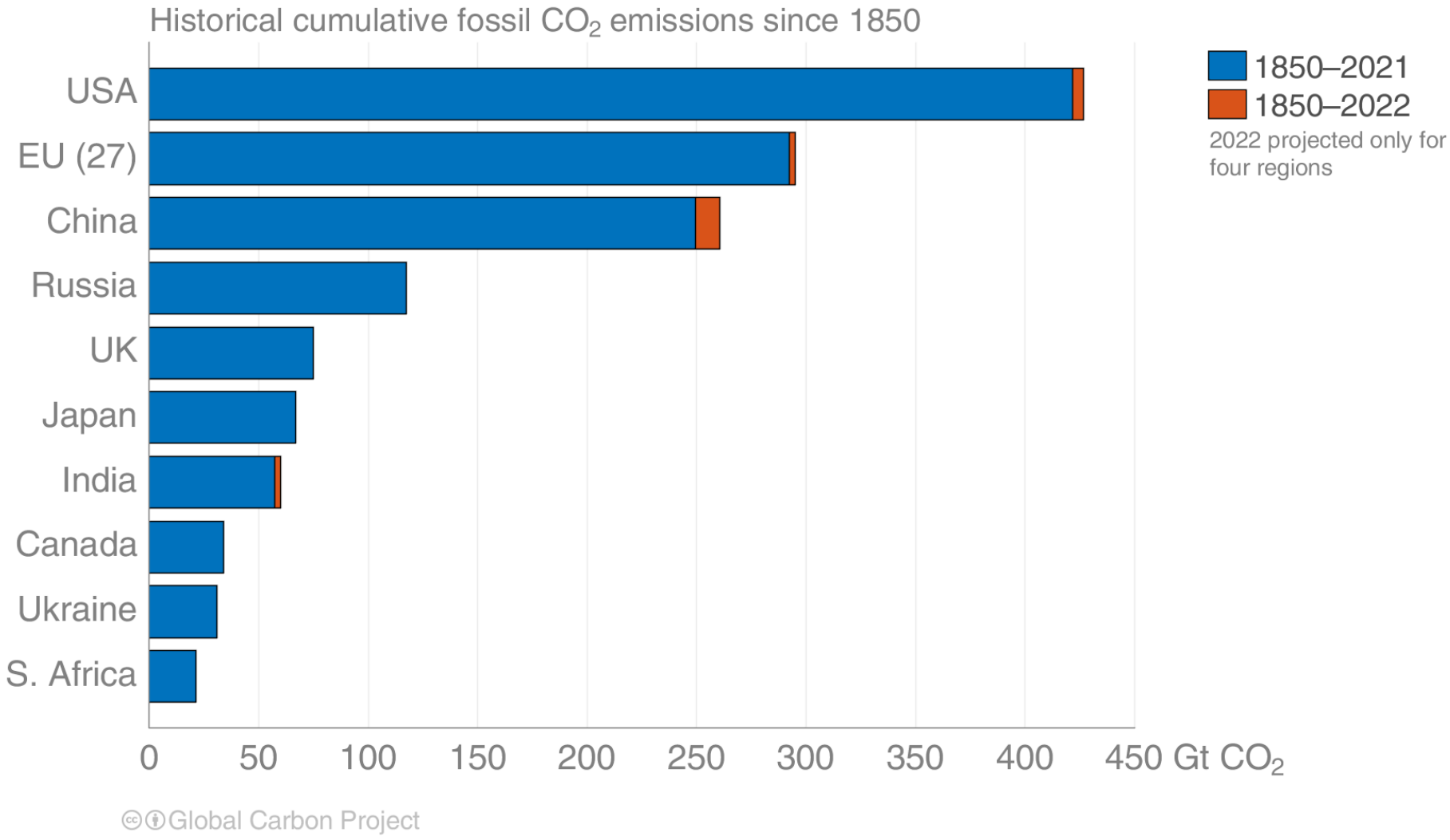
Process models suggest that increasing atmospheric CO_2 drives the land and ocean sinks while climate change reduces the carbon sinks; the climate effect is largest in tropical and semi-arid land ecosystems.

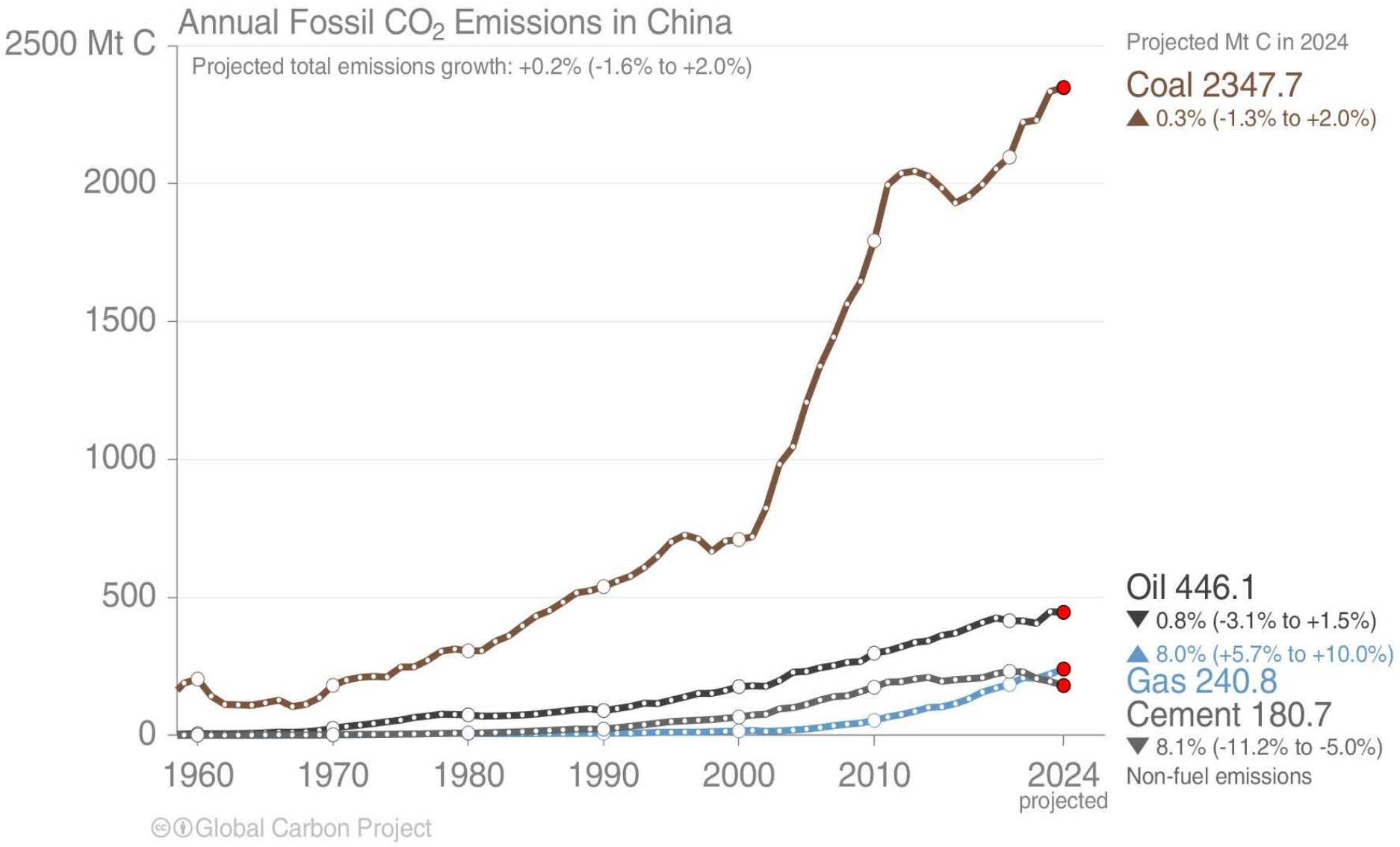
Globally during 2014–2023, climate change reduced the land sink by ~27% and the ocean sink by 6%.

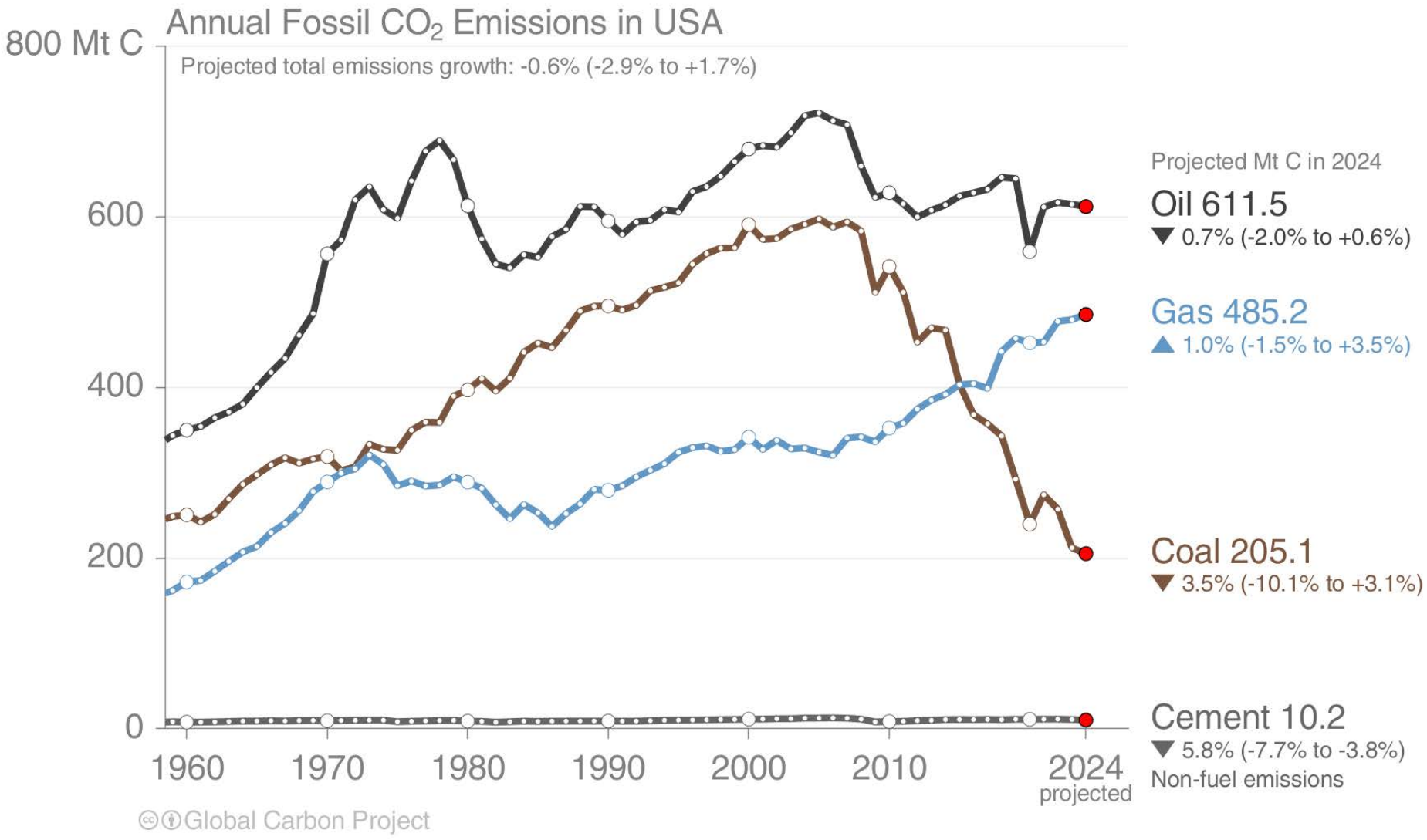

b
Atmospheric Growth Rate (G_{ATM})
CO_2 Flux (GtC yr^{-1})
0
2
4
6
1960
1980
2000
2020
Year

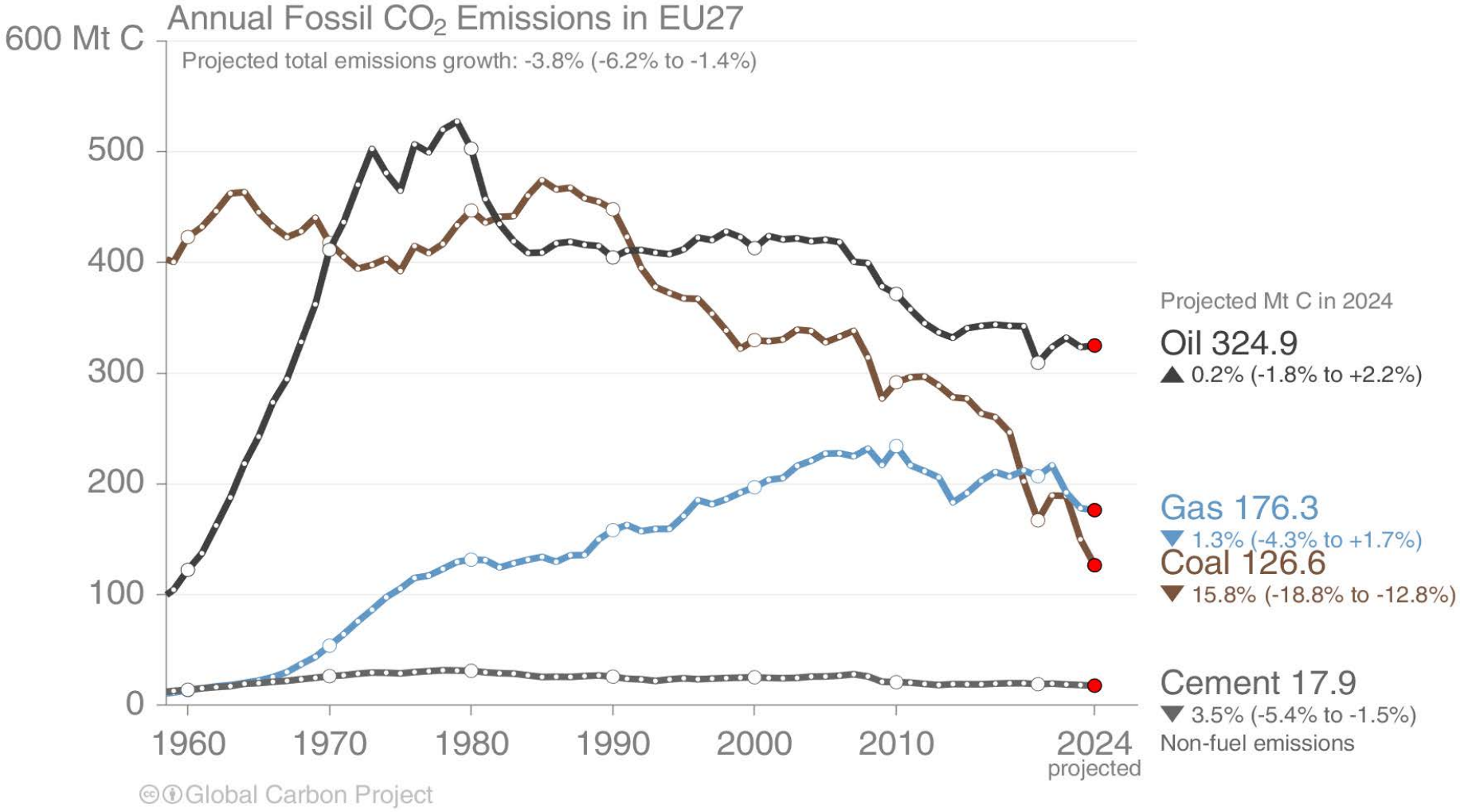

Annual CO_2 Emissions
12 Gt C
8
4
0
1960
1970
1980
1990
2000
2010
2024
projected
Global Carbon Project
Total
Fossil carbon
Includes cement carbonation sink
Land-use change

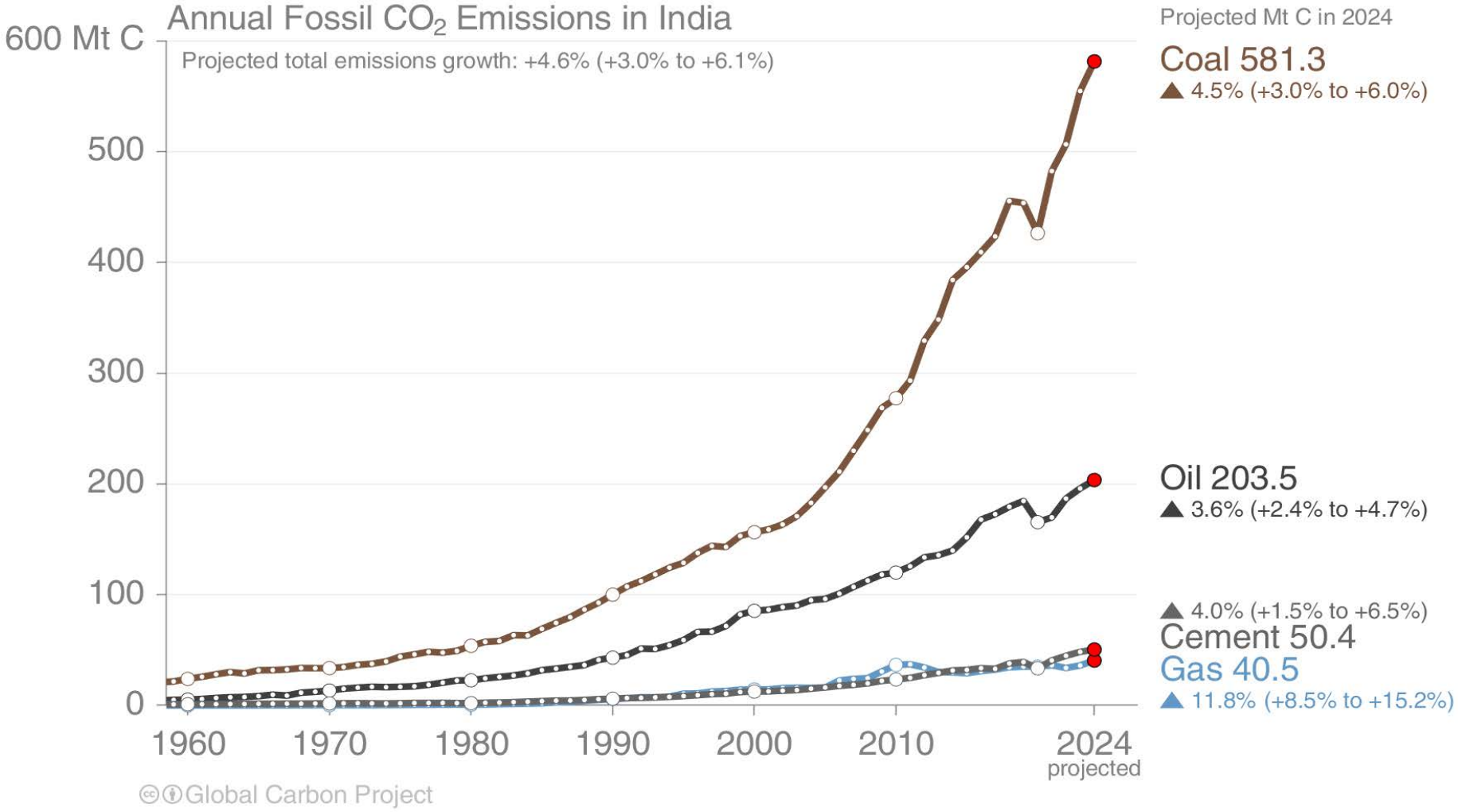

Global Fossil CO_2 Emissions and Uptake: Cement*
*Excludes fossil energy used to produce cement
0.4 Gt C
0.2
0
-0.2
Process emissions
Carbonation uptake
1960
1970
1980
1990
2000
2010
2024
projected
Global Carbon Project

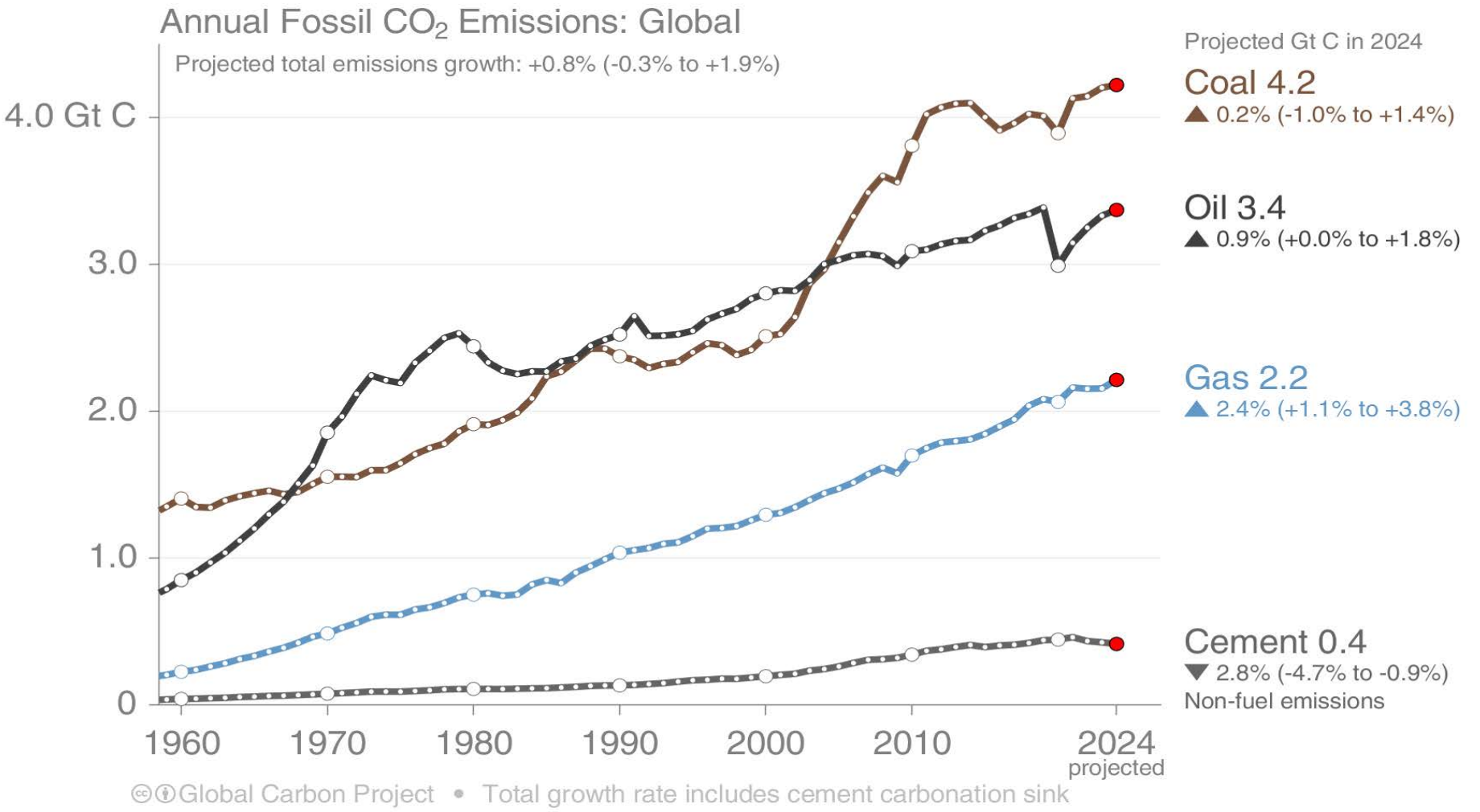

Historical cumulative fossil CO_2 emissions since 1850
USA
EU (27)
China
Russia
UK
Japan
India
Canada
Ukraine
S. Africa
1850–2021
1850–2022
2022 projected only for four regions
0
50
100
150
200
250
300
350
400
450 Gt CO_2
Global Carbon Project

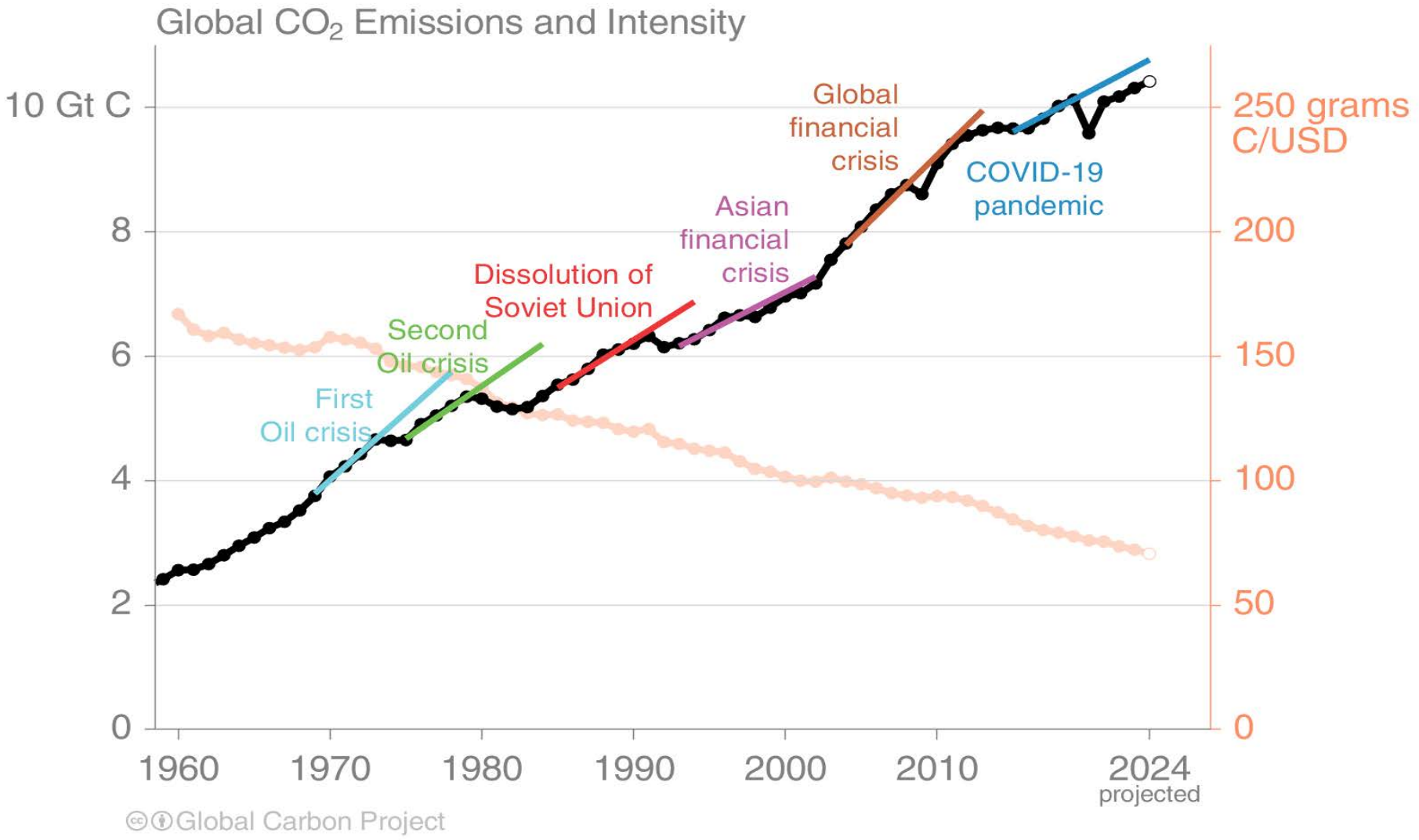

Annual Fossil CO_2 Emissions in China
Projected total emissions growth: +0.2% (-1.6% to +2.0%)
2500 Mt C
2000
1500
1000
500
0
1960
1970
1980
1990
2000
2010
2024
projected
Projected Mt C in 2024
Coal 2347.7
▲ 0.3% (-1.3% to +2.0%)
Oil 446.1
▼ 0.8% (-3.1% to +1.5%)
▲ 8.0% (+5.7% to +10.0%)
Gas 240.8
Cement 180.7
▼ 8.1% (-11.2% to -5.0%)
Non-fuel emissions
Global Carbon Project


Annual Fossil CO_2 Emissions in USA
Projected total emissions growth: -0.6% (-2.9% to +1.7%)
800 Mt C
600
400
200
0
1960
1970
1980
1990
2000
2010
2024
projected
Projected Mt C in 2024
Oil 611.5
▼ 0.7% (-2.0% to +0.6%)
Gas 485.2
▲ 1.0% (-1.5% to +3.5%)
Coal 205.1
▼ 3.5% (-10.1% to +3.1%)
Cement 10.2
▼ 5.8% (-7.7% to -3.8%)
Non-fuel emissions
Global Carbon Project


Annual Fossil CO_2 Emissions in EU27
Projected total emissions growth: -3.8% (-6.2% to -1.4%)
600 Mt C
500
400
300
200
100
0
1960
1970
1980
1990
2000
2010
2024
projected
Projected Mt C in 2024
Oil 324.9
▲ 0.2% (-1.8% to +2.2%)
Gas 176.3
▼ 1.3% (-4.3% to +1.7%)
Coal 126.6
▼ 15.8% (-18.8% to -12.8%)
Cement 17.9
▼ 3.5% (-5.4% to -1.5%)
Non-fuel emissions
Global Carbon Project


Annual Fossil CO_2 Emissions in India
Projected total emissions growth: +4.6% (+3.0% to +6.1%)
600 Mt C
500
400
300
200
100
0
1960
1970
1980
1990
2000
2010
2024
projected
Projected Mt C in 2024
Coal 581.3
▲ 4.5% (+3.0% to +6.0%)
Oil 203.5
▲ 3.6% (+2.4% to +4.7%)
▲ 4.0% (+1.5% to +6.5%)
Cement 50.4
Gas 40.5
▲ 11.8% (+8.5% to +15.2%)
Global Carbon Project

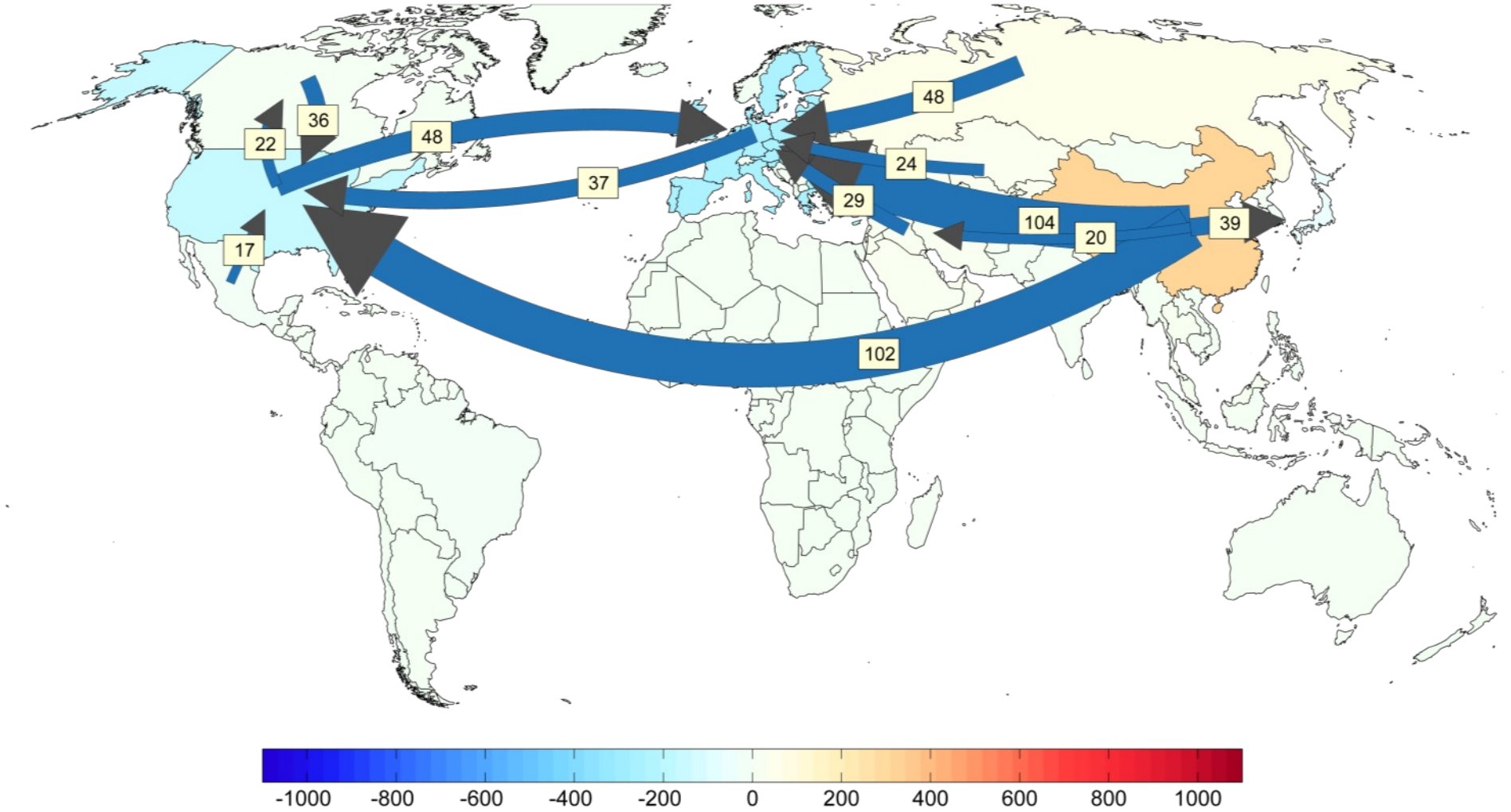

Annual Fossil CO_2 Emissions: Global
Projected total emissions growth: +0.8% (-0.3% to +1.9%)
4.0 Gt C
3.0
2.0
1.0
0
1960
1970
1980
1990
2000
2010
2024
projected
Projected Gt C in 2024
Coal 4.2
▲ 0.2% (-1.0% to +1.4%)
Oil 3.4
▲ 0.9% (+0.0% to +1.8%)
Gas 2.2
▲ 2.4% (+1.1% to +3.8%)
Cement 0.4
▼ 2.8% (-4.7% to -0.9%)
Non-fuel emissions
Global Carbon Project • Total growth rate includes cement carbonation sink


Global CO_2 Emissions and Intensity
10 Gt C
8
6
4
2
0
250 grams C/USD
200
150
100
50
0
1960
1970
1980
1990
2000
2010
2024
projected
First Oil crisis
Second Oil crisis
Dissolution of Soviet Union
Asian financial crisis
Global financial crisis
COVID-19 pandemic
Global Carbon Project

Major flows from Production to Consumption

Start of Arrow: fossil-fuel consumption (production)

End of arrow: goods and services consumption



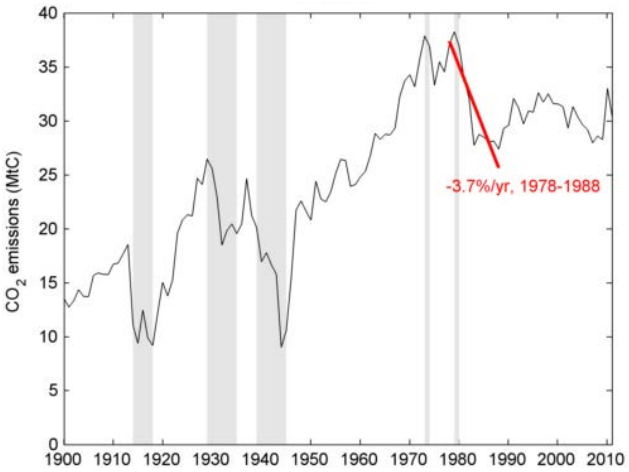
Values for 2007. EU27 is treated as one region. Units: TgC=PgC/1000

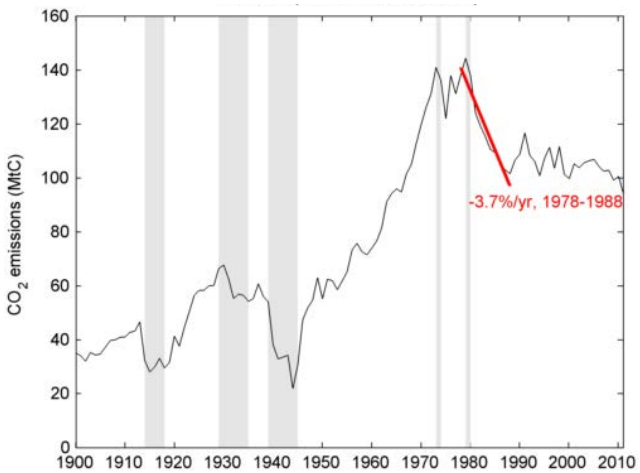
Source: Peters et al 2012b

Previous CO_2 emission reductions

Without climate policies, some countries have reduced emissions at 1-5%/yr
Repeating with modern low-carbon technologies can "kick-start" mitigation

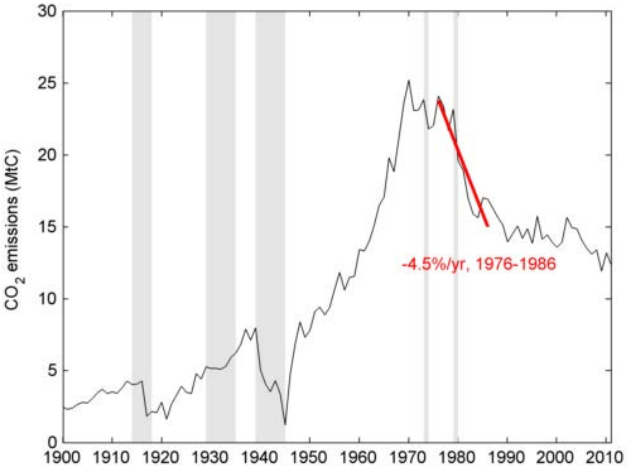
Belgium
Increased Nuclear
Reduced Oil

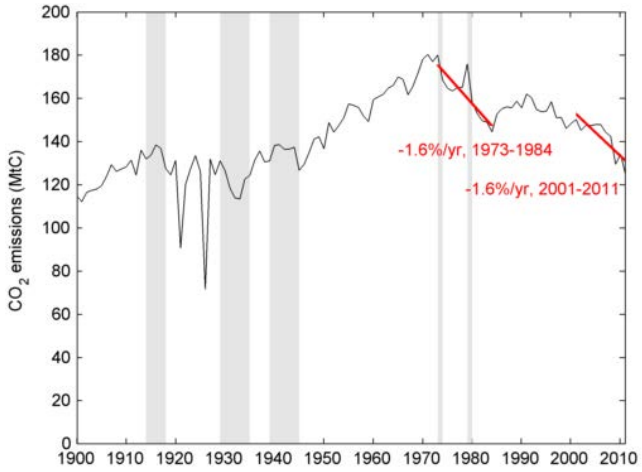




France
Increased Nuclear
Reduced Oil & Coal

Sweden
Increased Nuclear
Reduced Oil





United Kingdom
Coal to gas
Reduced Oil
Increased Nuclear

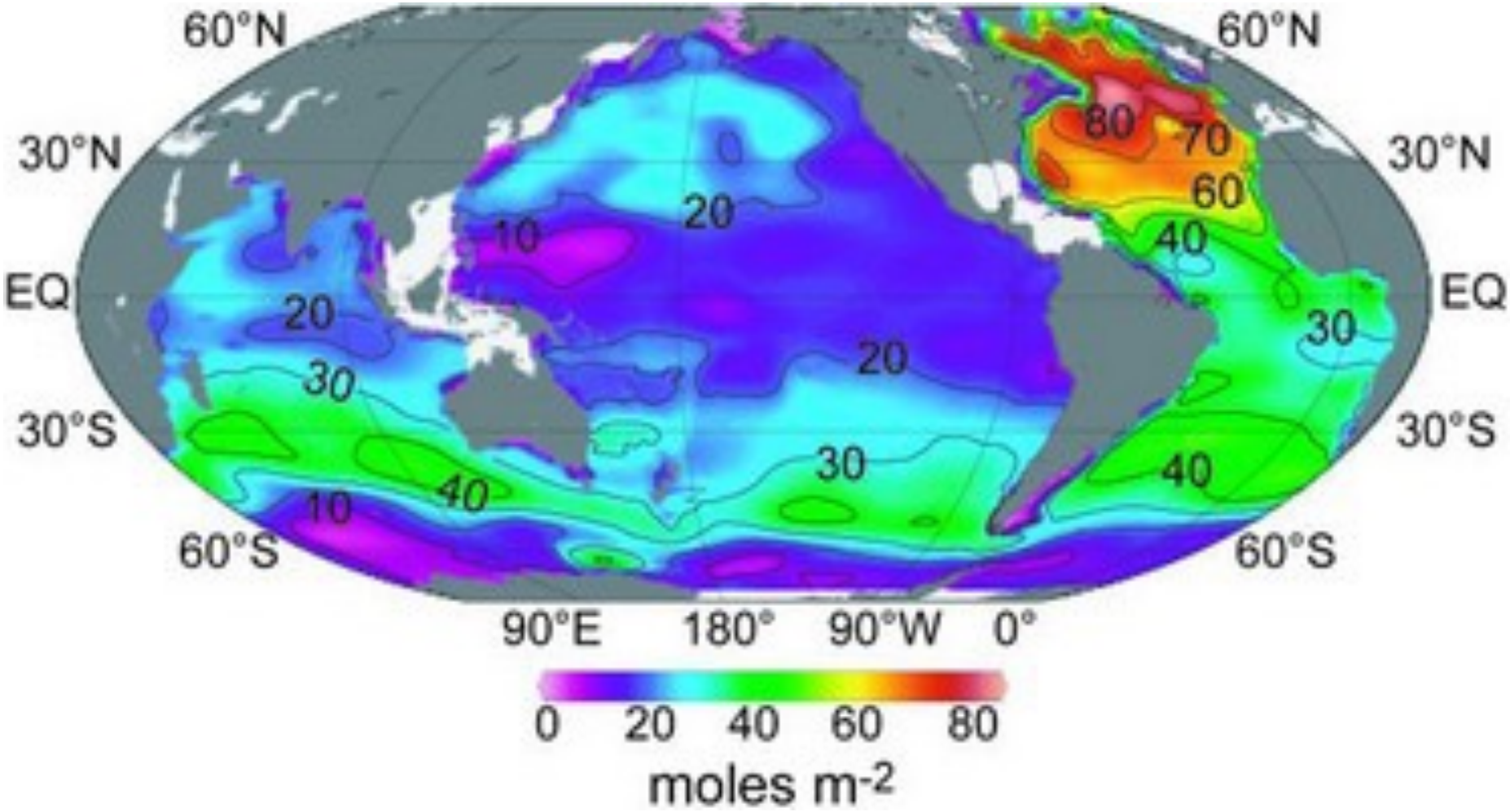
Grey areas are: World War I, Great Depression, World War II, oil shocks

Source: Peters et al. 2012a; CDIAC Data; Global Carbon Project 2012

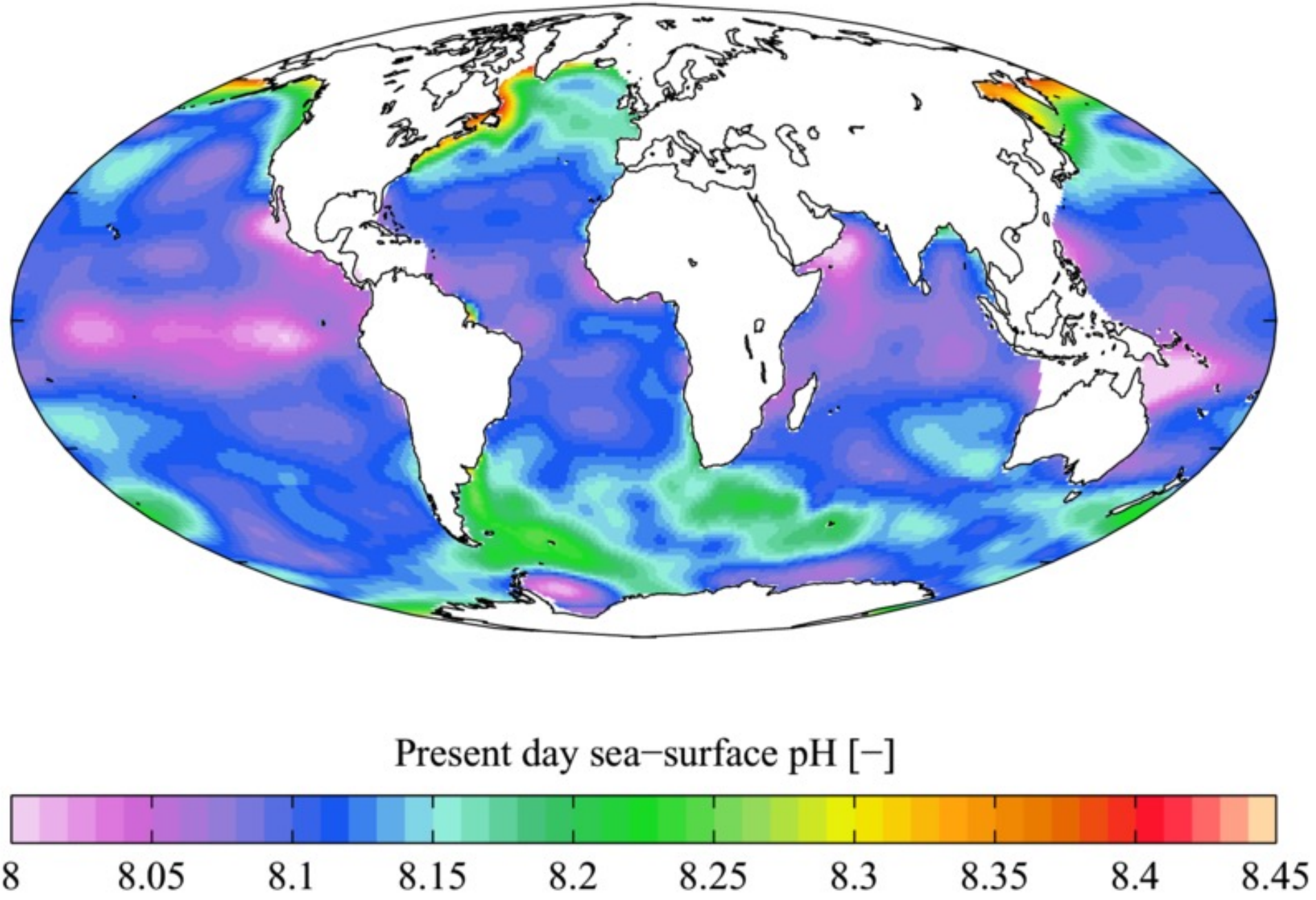
Ocean Acidification

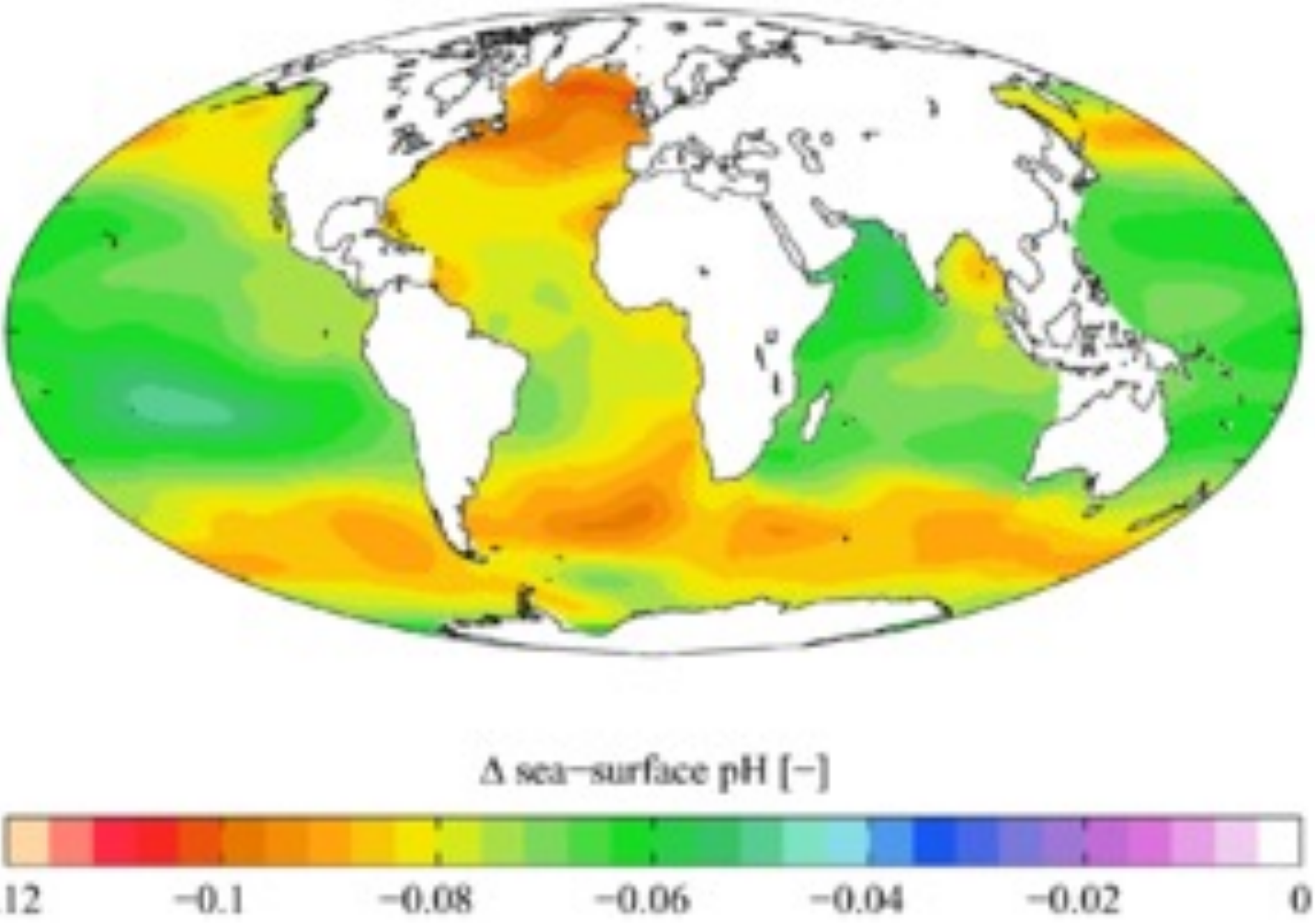
Quantities of Gas in Air and Seawater

Gas	In Dry Air (%)	In Surface Water (%)	Water-Air Ratio
Nitrogen (N_2)	78.03	47.5	0.6
Oxygen (O_2)	20.99	36.0	1.7
Carbon Dioxide (CO_2)	0.03	15.1	503.3
H_2, Inert gases (He, Ar, Ne)	0.95	1.4	1.5

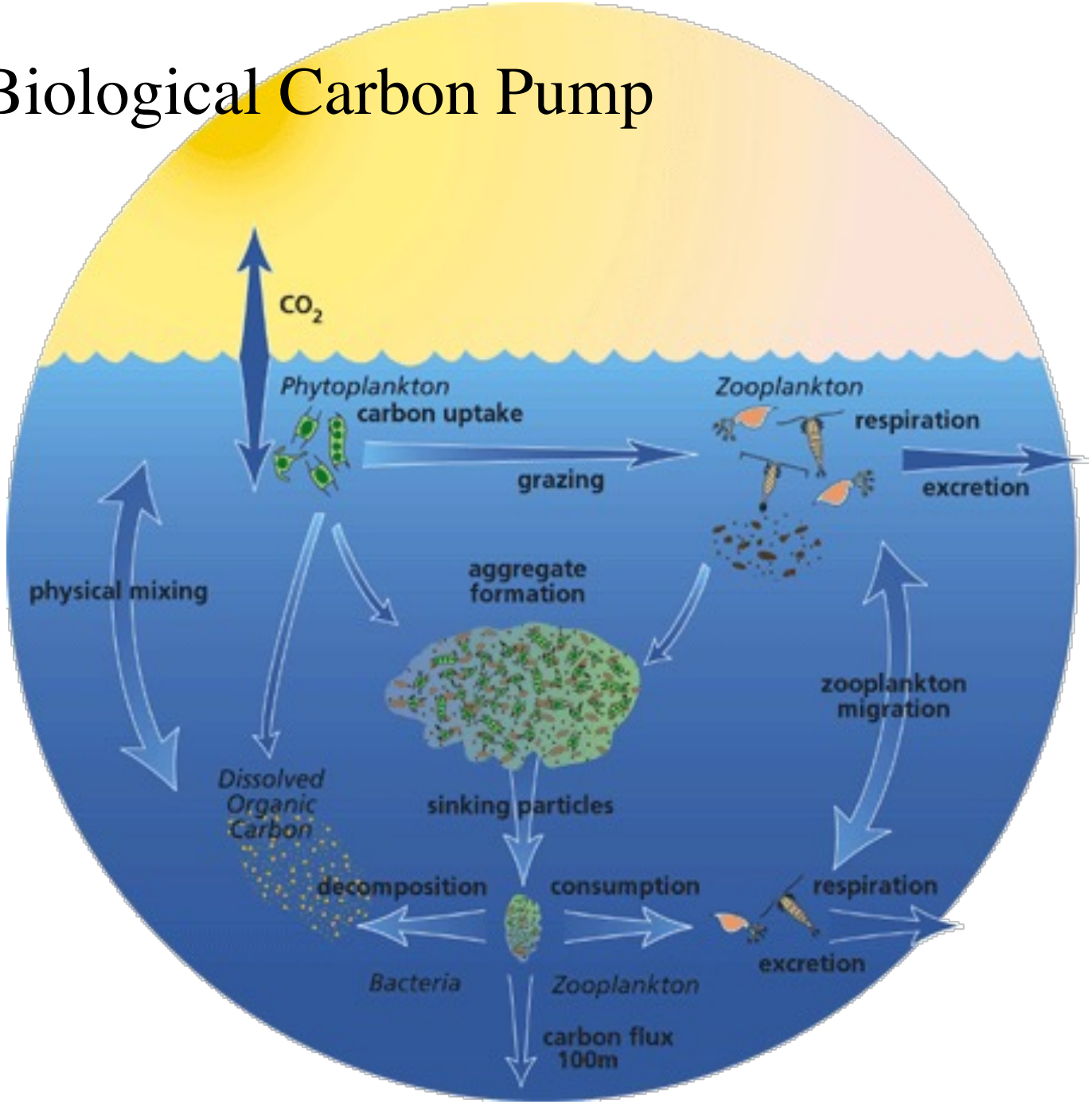


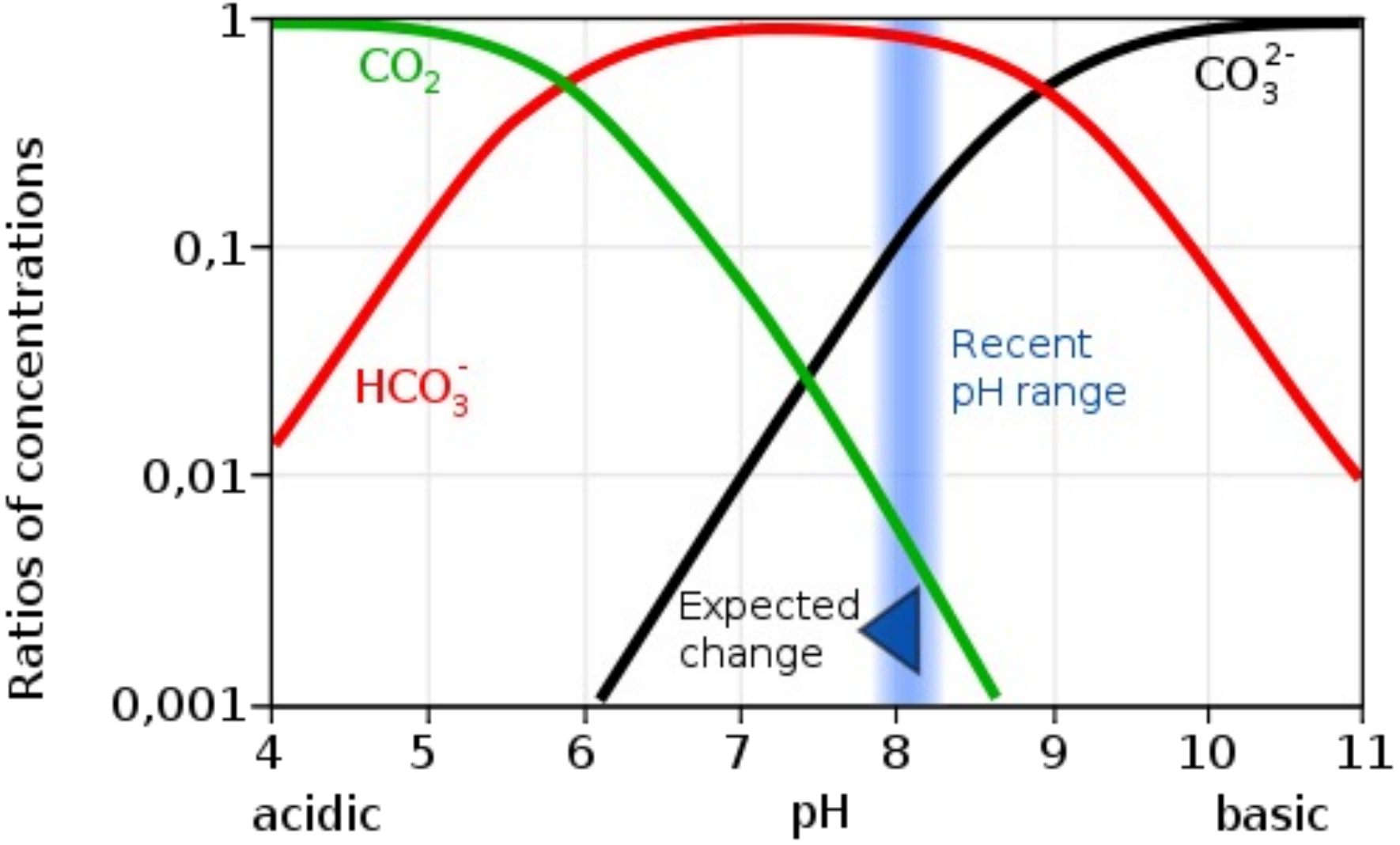
Column Anthropogenic CO_2 (Sabine et al. 2004)


Present day sea−surface pH [−]
8
8.05
8.1
8.15
8.2
8.25
8.3
8.35
8.4
8.45

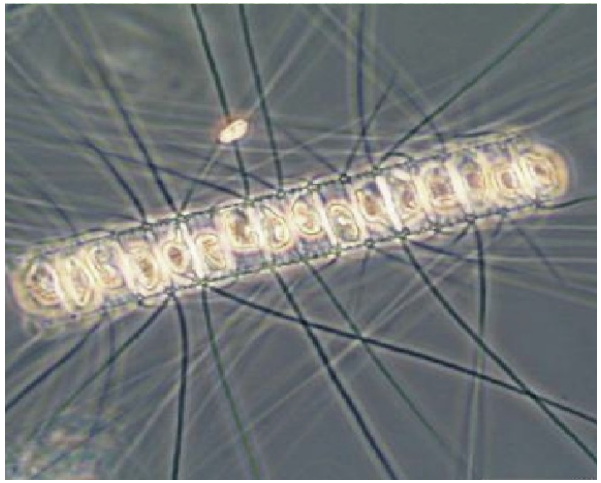

Δ sea−surface pH [−]
−0.12
−0.1
−0.08
−0.06
−0.04
−0.02
0

The Biological Carbon Pump

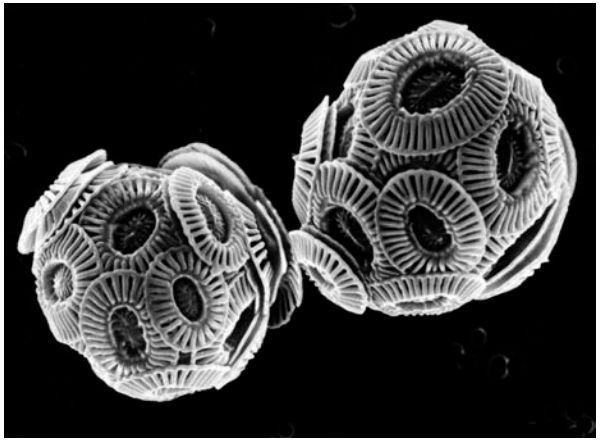



Ratios of concentrations
1
0,1
0,01
0,001
CO_2
HCO_3^-
CO_3^{2-}
Recent
pH range
Expected
change
4
5
6
7
8
9
10
11
acidic
pH
basic

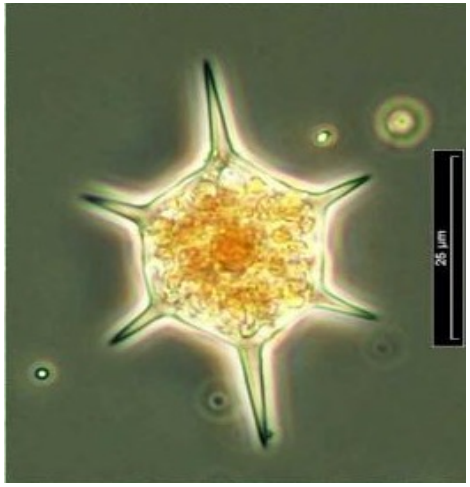
Ocean acidification and species composition



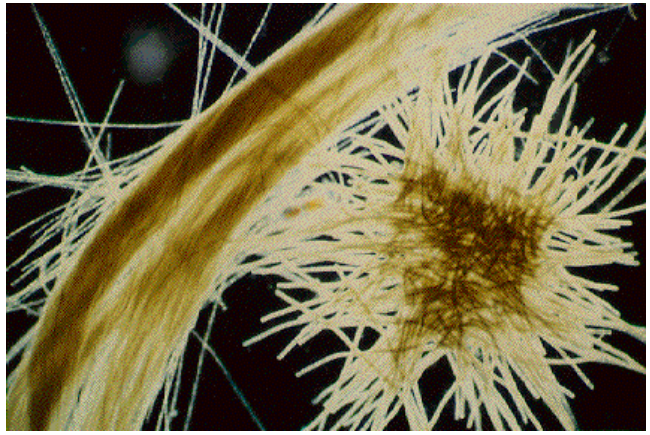
Chaetoceros costatus
(Diatom)



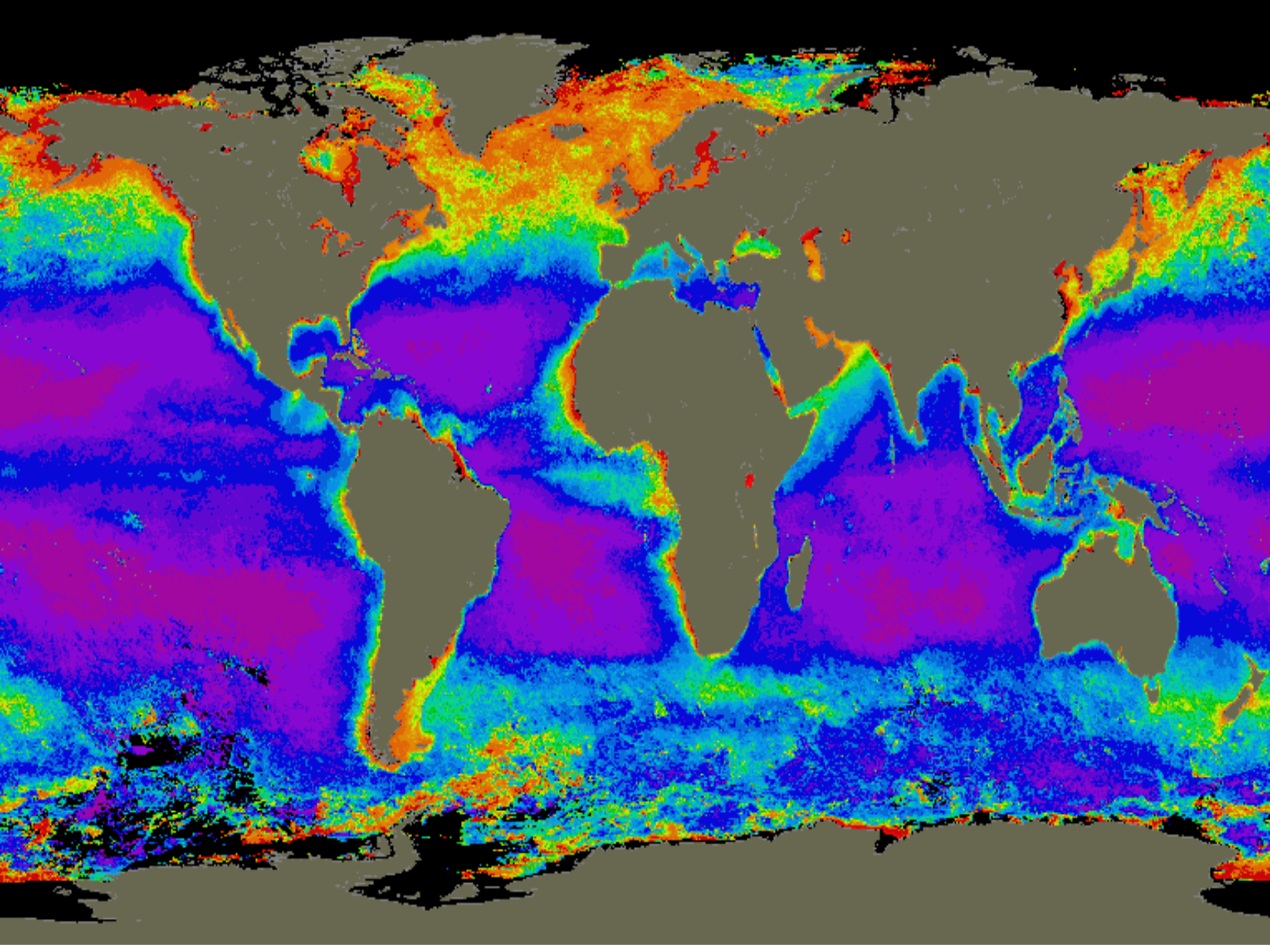
Emiliania huxleii
(Coccolithophorids)

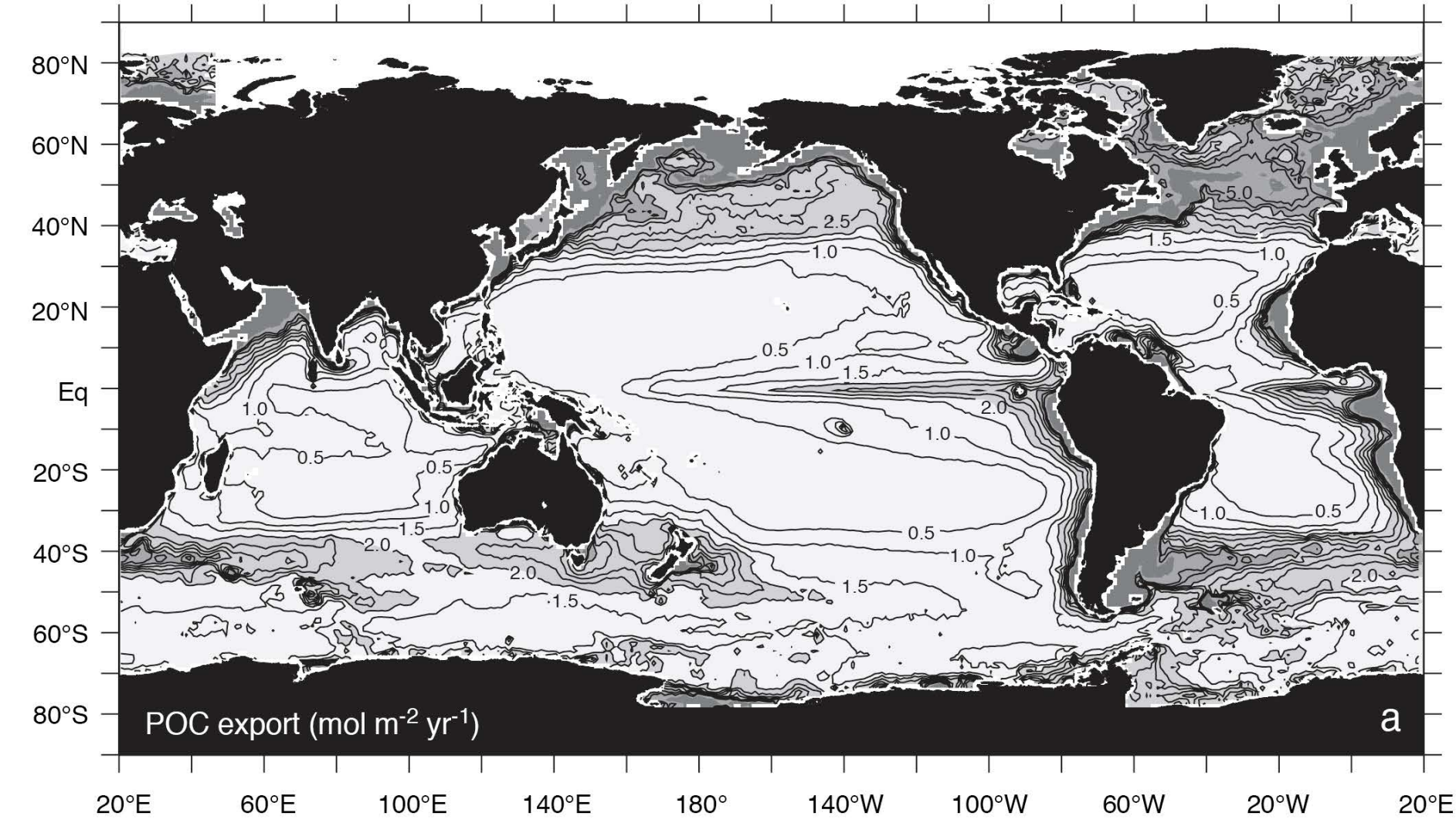


Distephanus speculum
(Silicoflagellate)

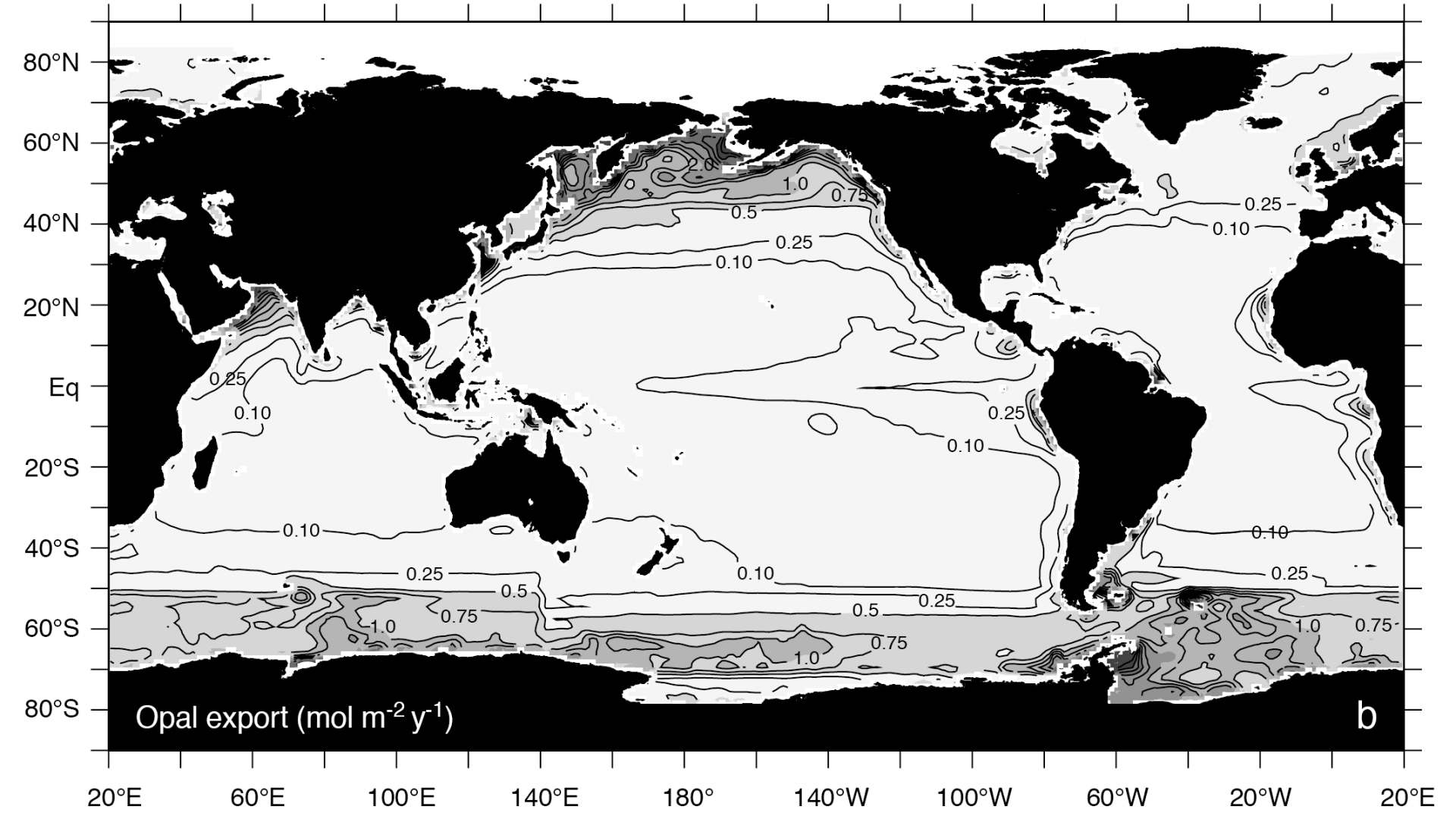


Trichodesmium
(Cyanobacterium)

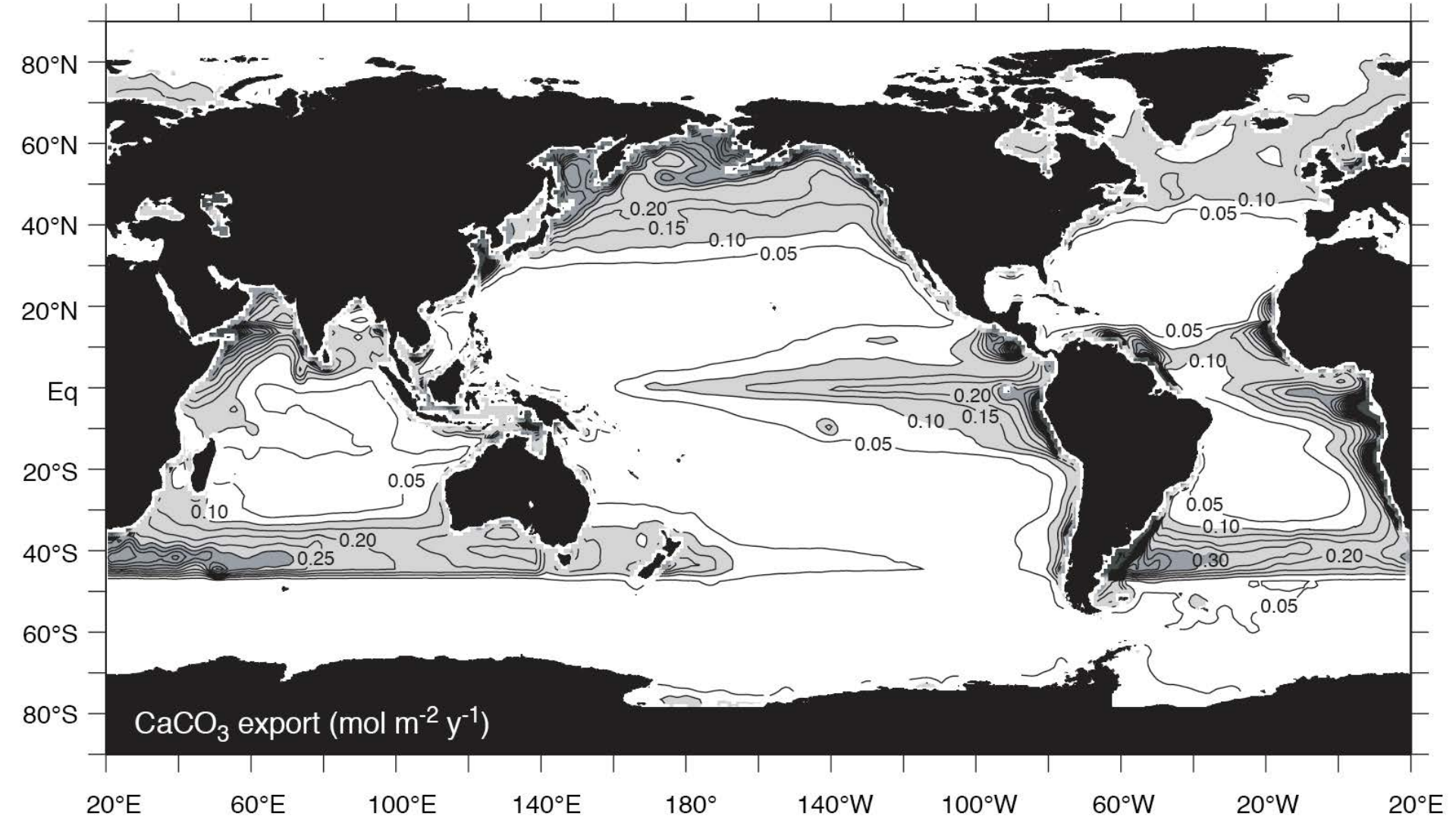




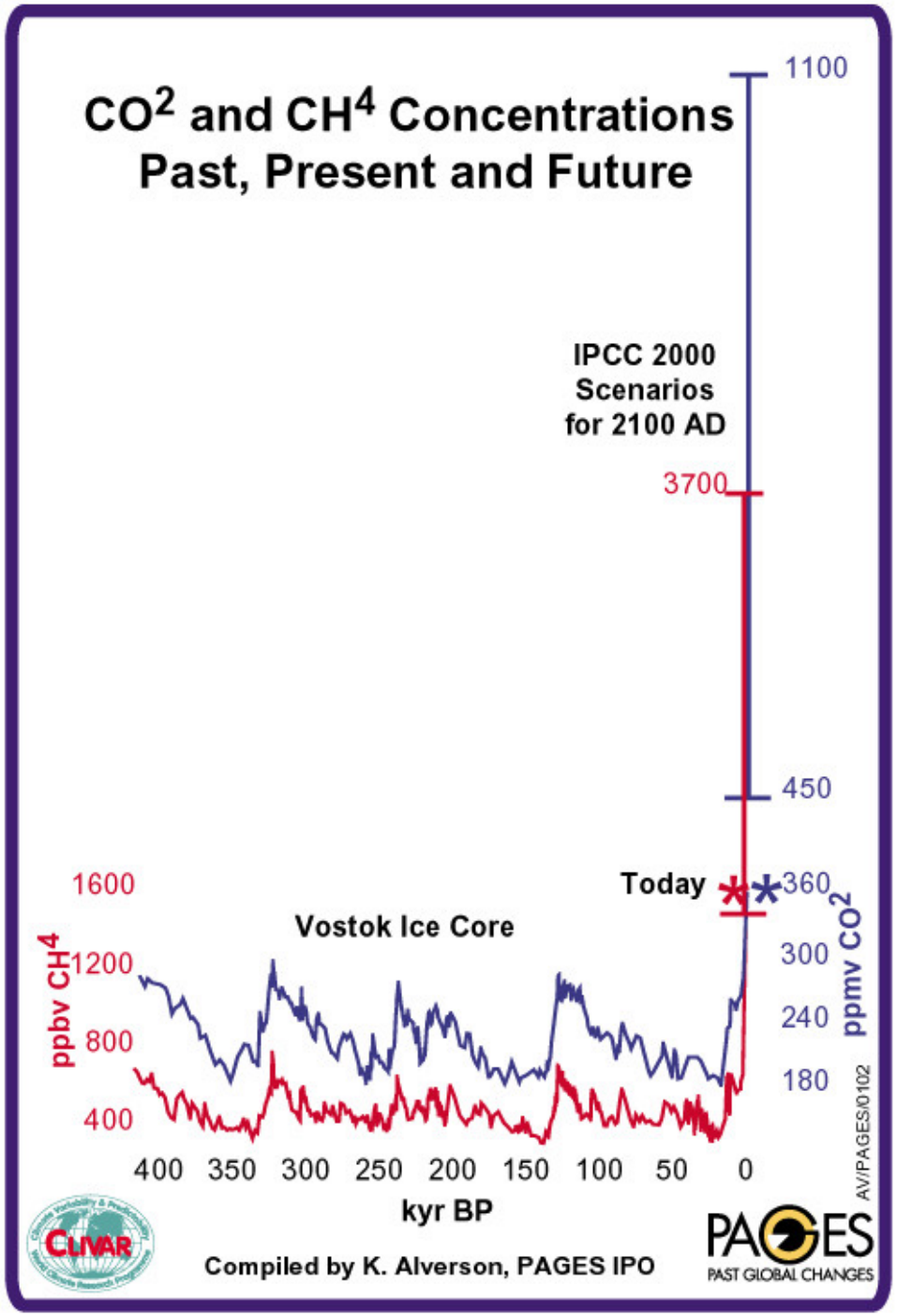
Export of particulate organic carbon (POC) to deep ocean.



Export of SiO_2 to deep ocean by diatom ecosystem.

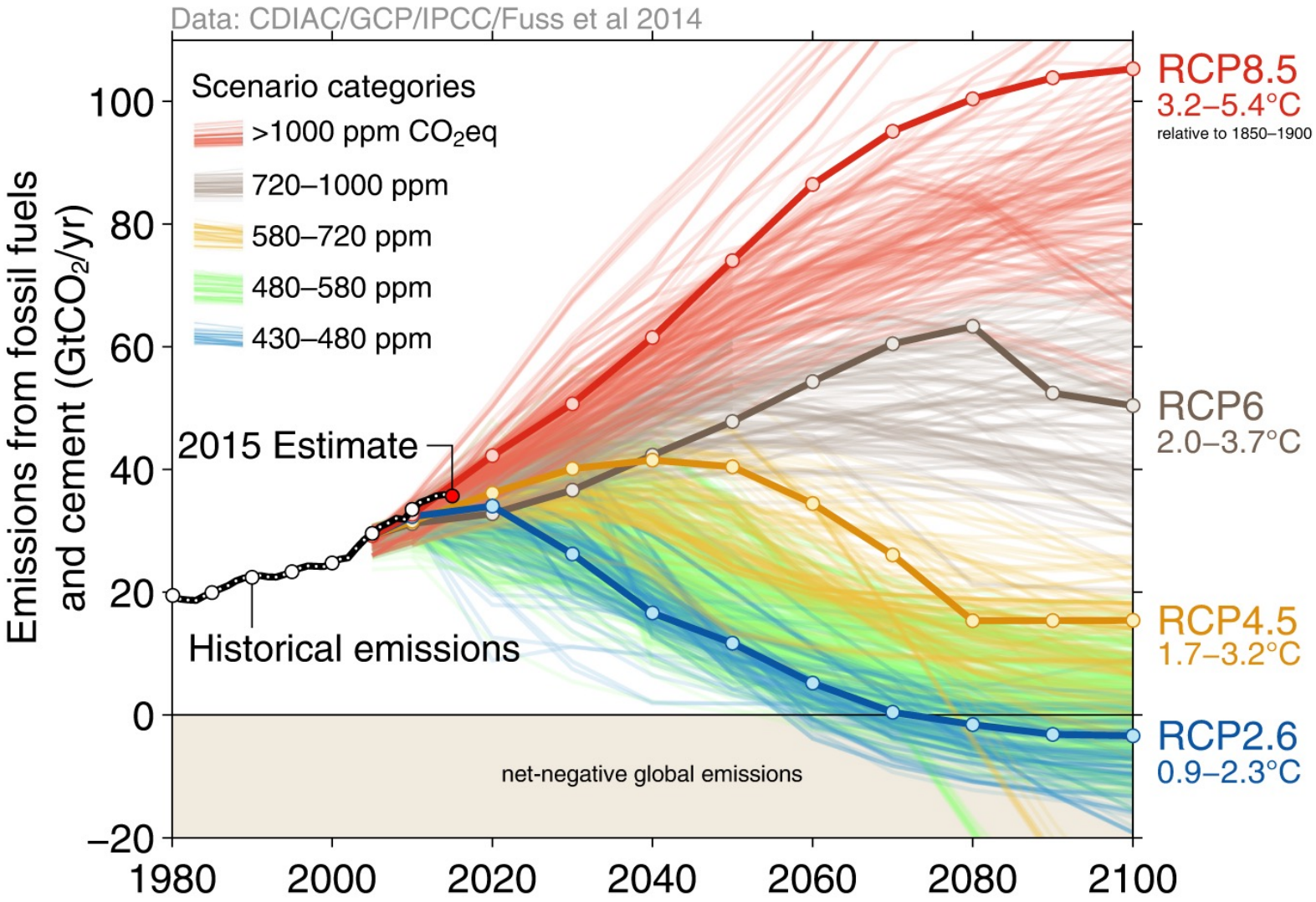


Export of $CaCO_3$ to deep ocean by coccolithophore ecosystem.


CO2 and CH4 Concentrations
Past, Present and Future
1100
IPCC 2000
Scenarios
for 2100 AD
3700
450
Today
360
1600
Vostok Ice Core
ppbv CH4
1200
800
400
300
240
180
ppmv CO2
400 350 300 250 200 150 100 50 0
kyr BP
AV/PAGES/0102
CLIVAR
Compiled by K. Alverson, PAGES IPO
PAGES
PAST GLOBAL CHANGES

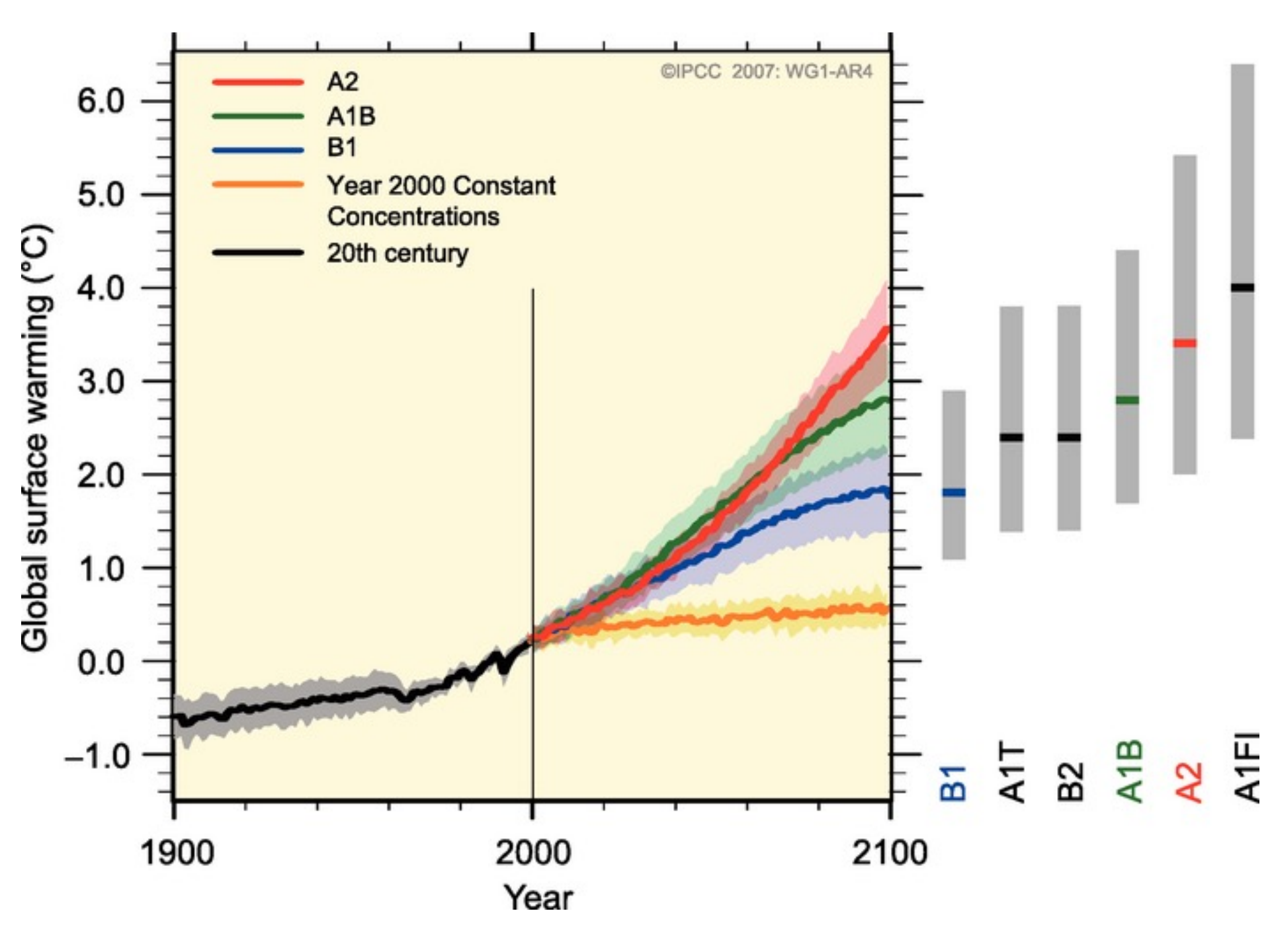
Observed emissions and emissions scenarios

The emission pledges submitted to the Paris climate summit avoid the worst effects of climate change (red), most studies suggest a likely temperature increase of about 3°C (brown)

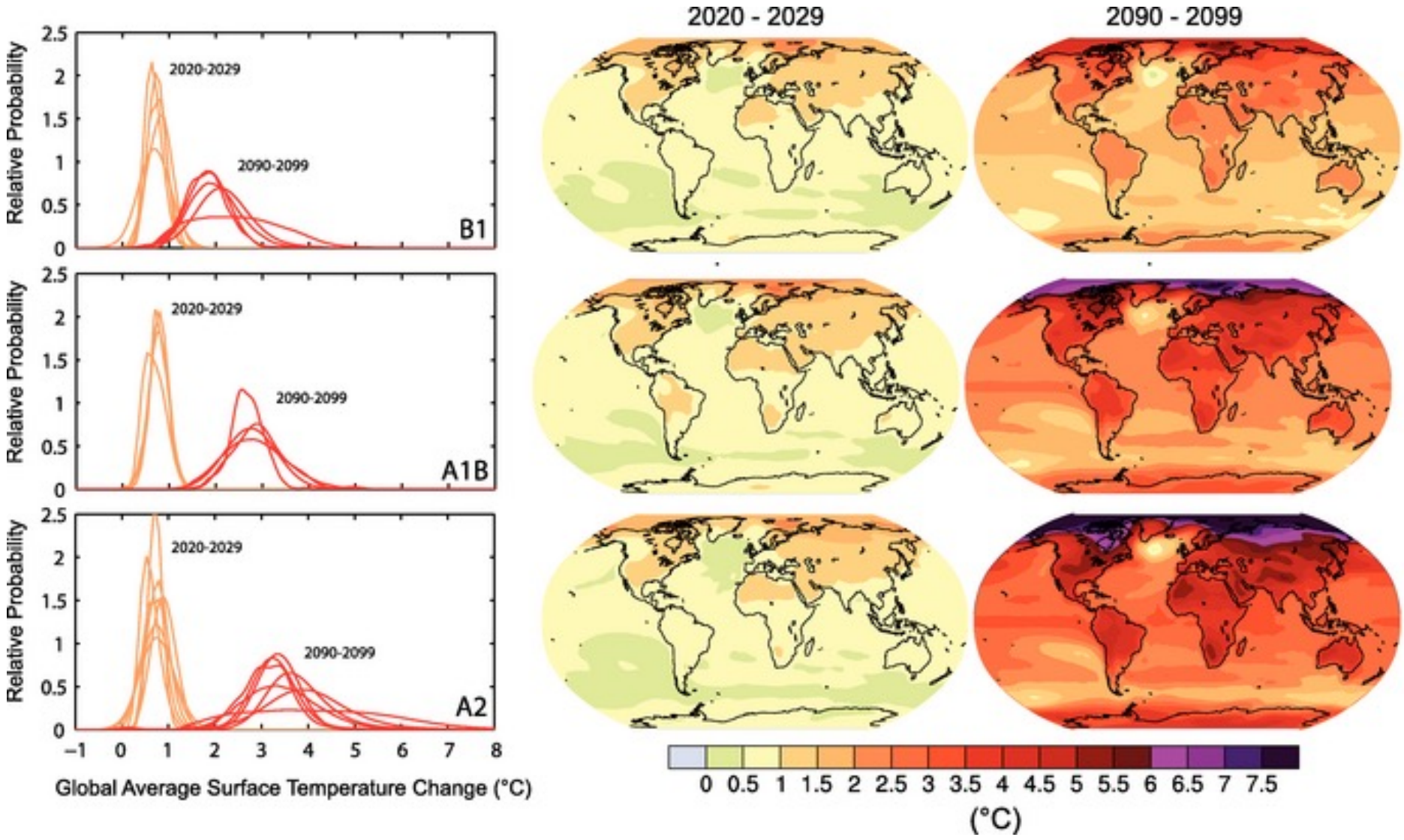


Over 1000 scenarios from the IPCC Fifth Assessment Report are shown

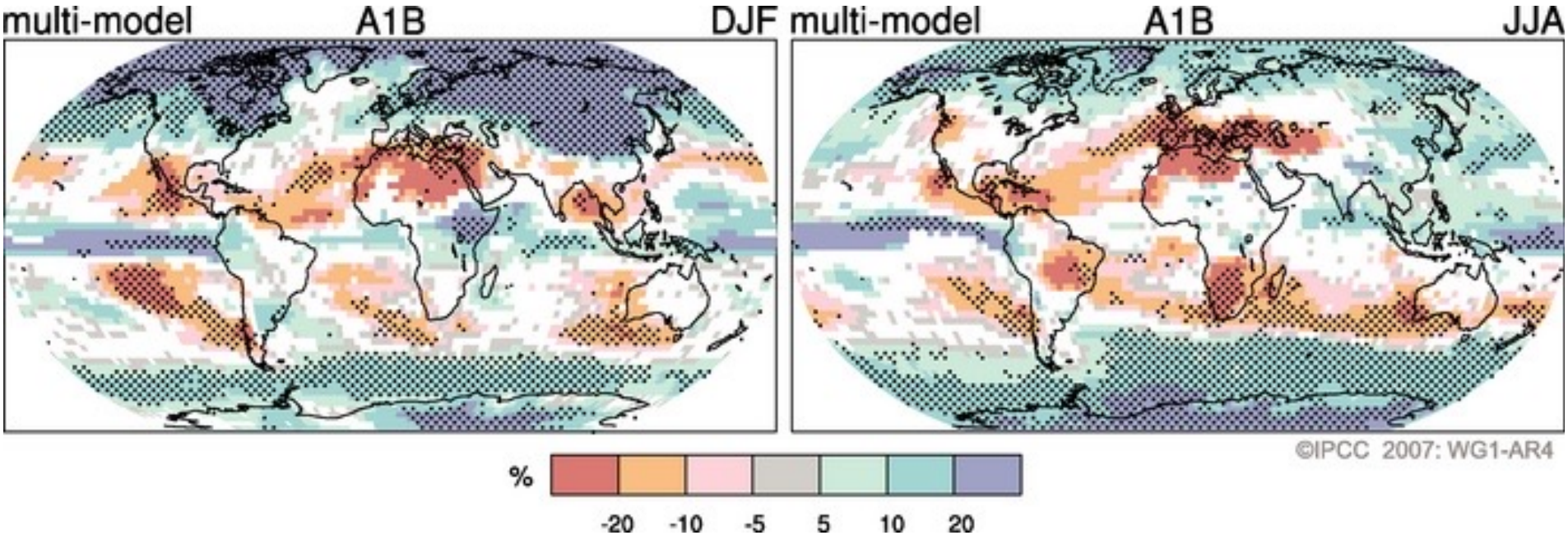
Source: Fuss et al 2014; CDIAC; Global Carbon Budget 2015


©IPCC 2007: WG1-AR4
A2
A1B
B1
Year 2000 Constant Concentrations
20th century
Global surface warming (°C)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
1900
2000
2100
Year
B1
A1T
B2
A1B
A2
A1FI

Change in Surface Temperature



Change in Precipitation



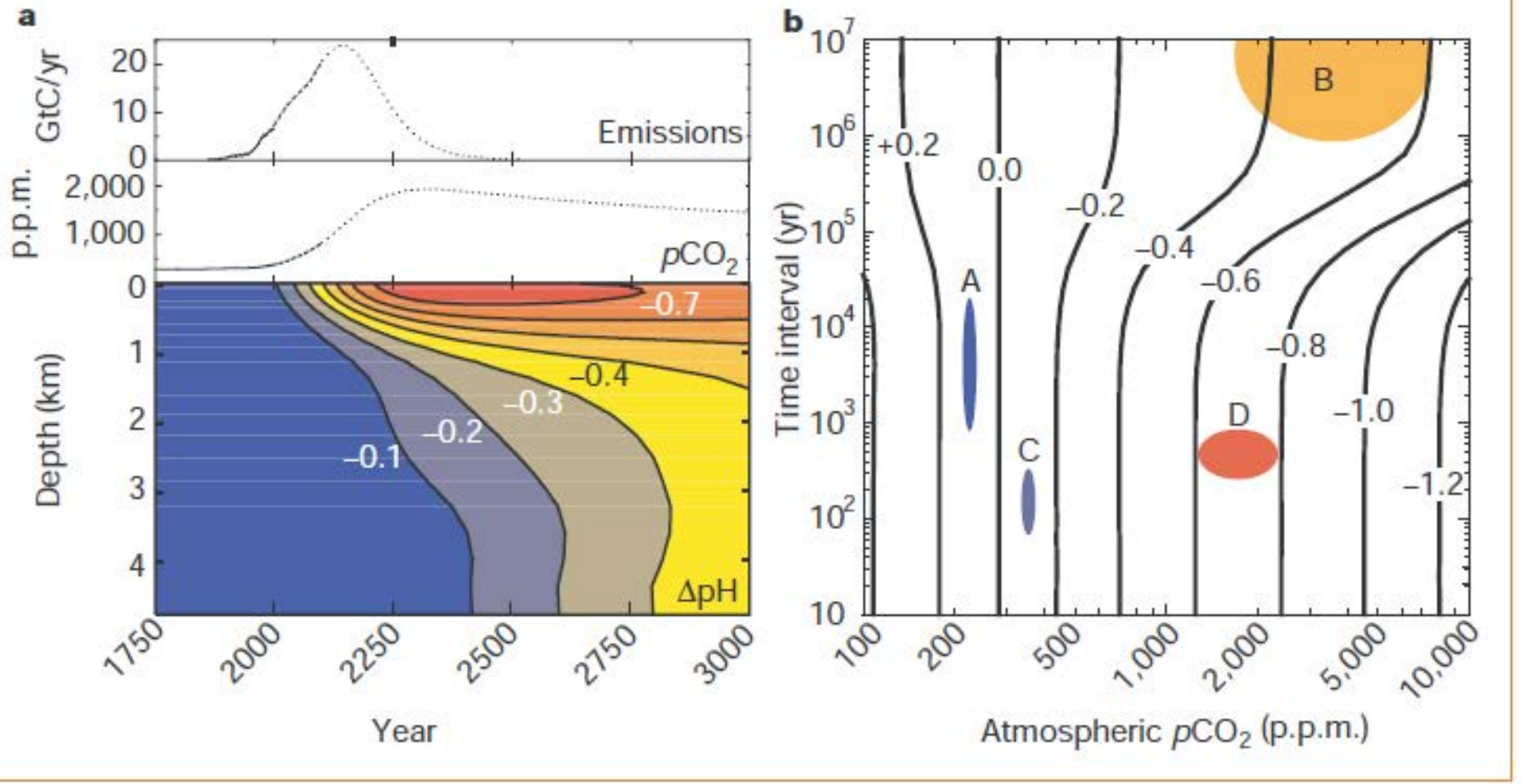
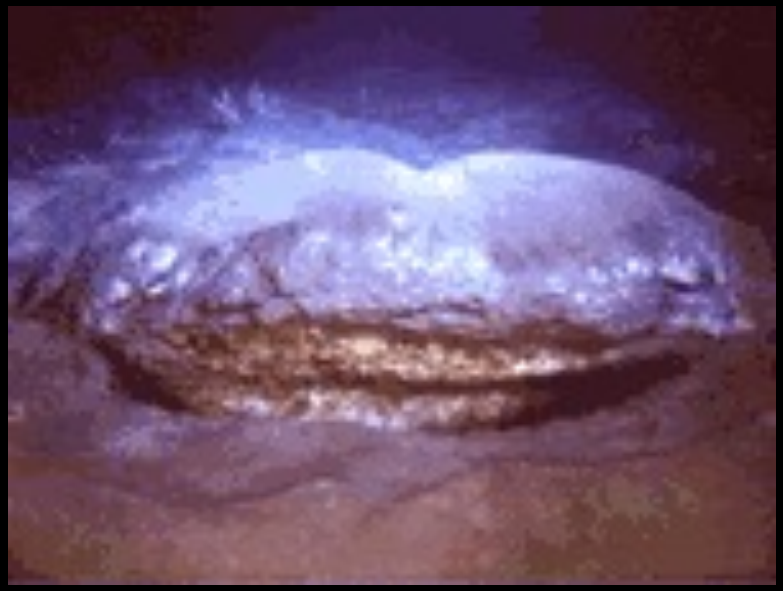
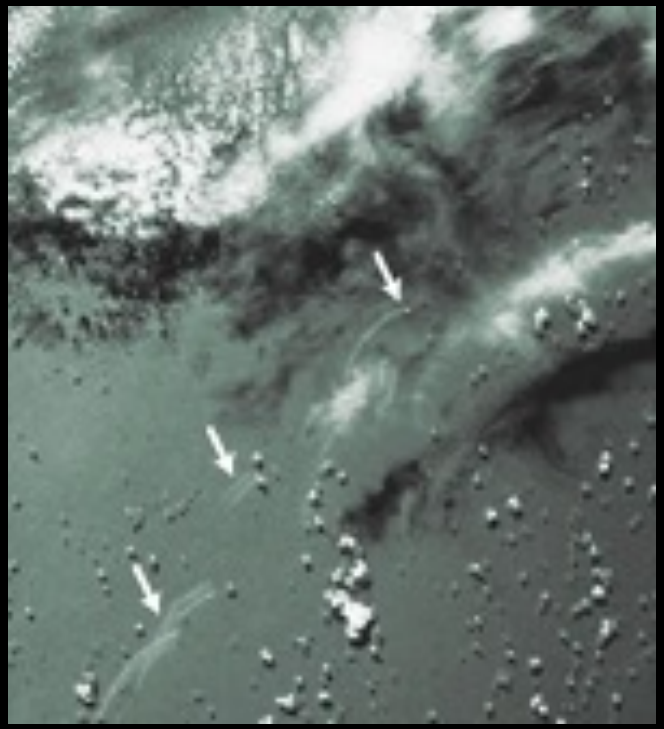


Figure 1 Atmospheric release of CO_2 from the burning of fossil fuels may give rise to a marked increase in ocean acidity. **a,** Atmospheric CO_2 emissions, historical atmospheric CO_2 levels and predicted CO_2 concentrations from this emissions scenario, together with changes in ocean pH based on horizontally averaged chemistry. **b,** Estimated maximum change in surface ocean pH as a function of final atmospheric CO_2 pressure, and the transition time over which this CO_2 pressure is linearly approached from 280 p.p.m. A, glacial–interglacial CO_2 changes[13]; B, slow changes over the past 300 Myr; C, historical changes[1] in ocean surface waters; D, unabated fossil-fuel burning over the next few centuries.

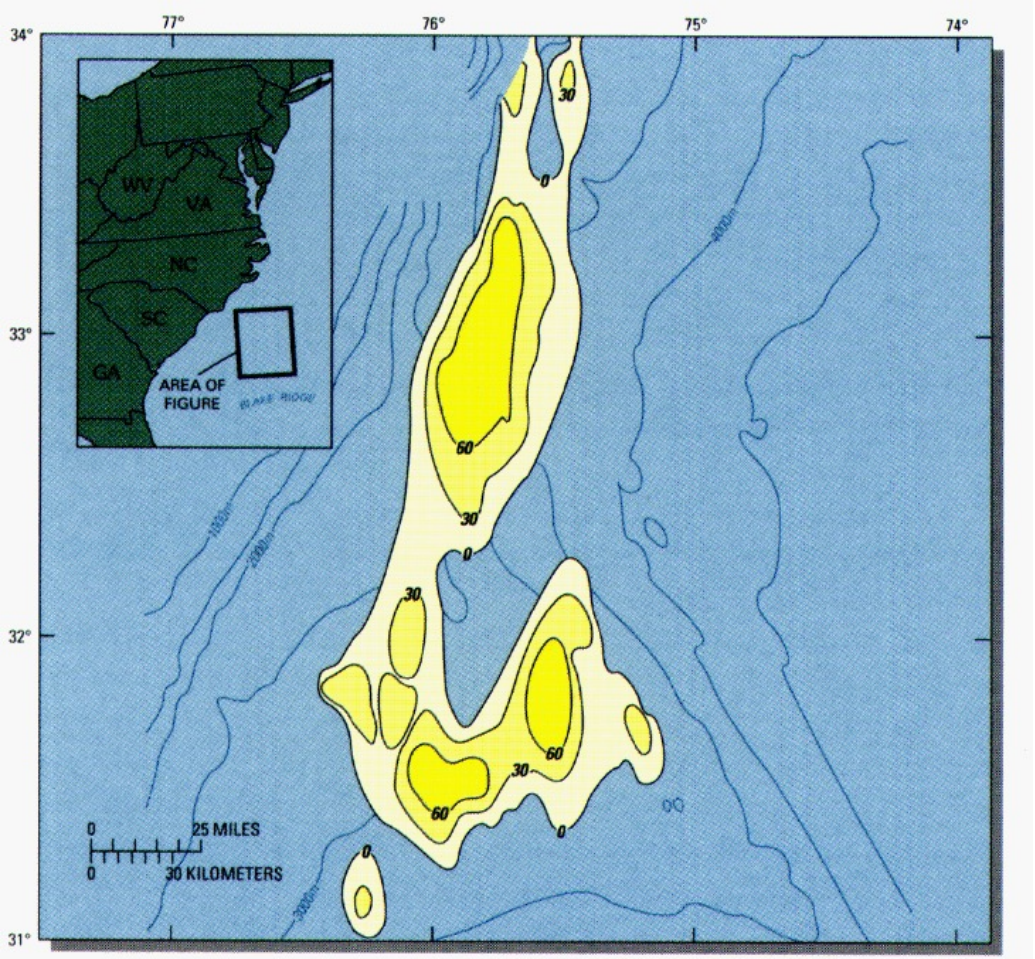
Caldeira 2003

GAS HYDRATES

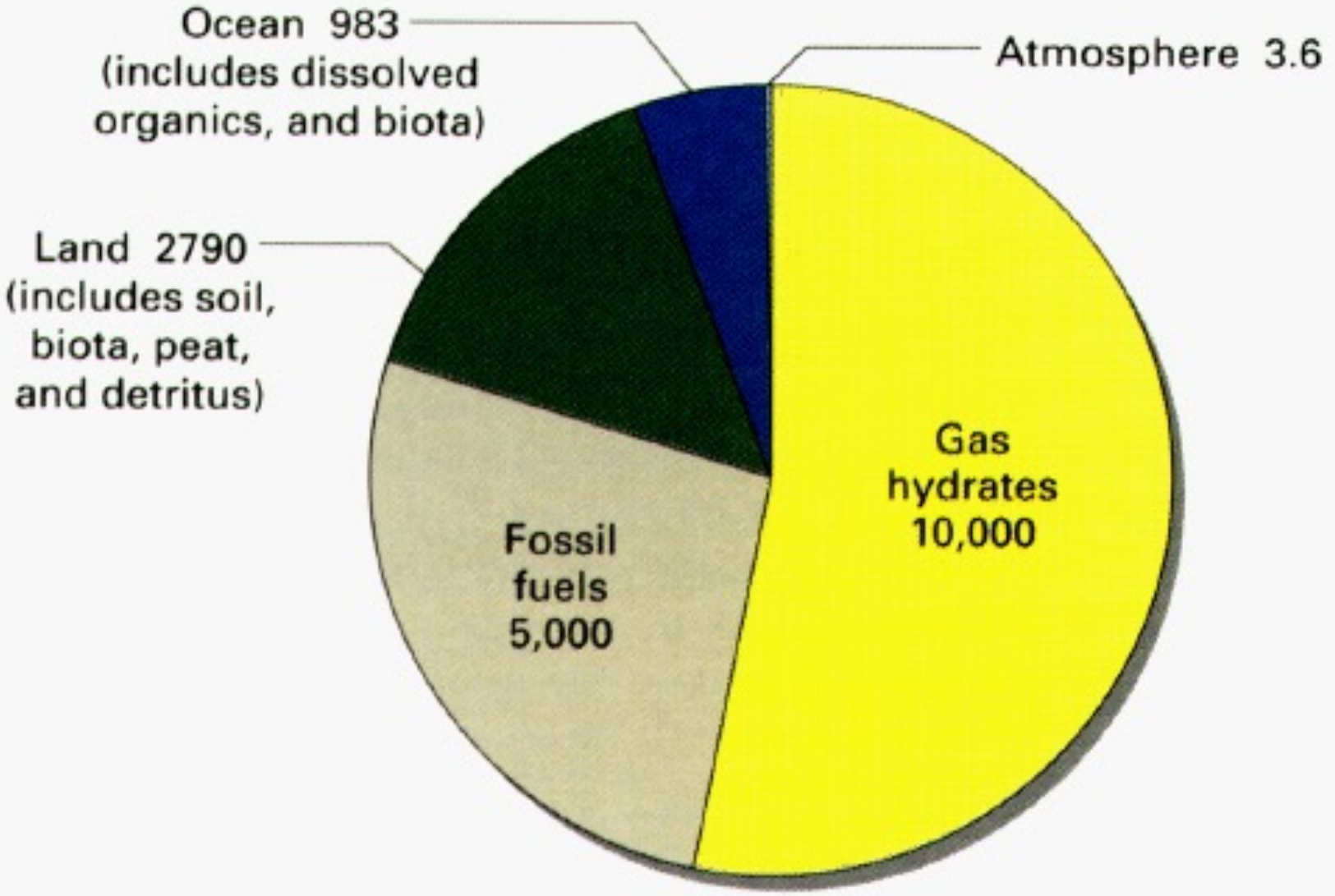




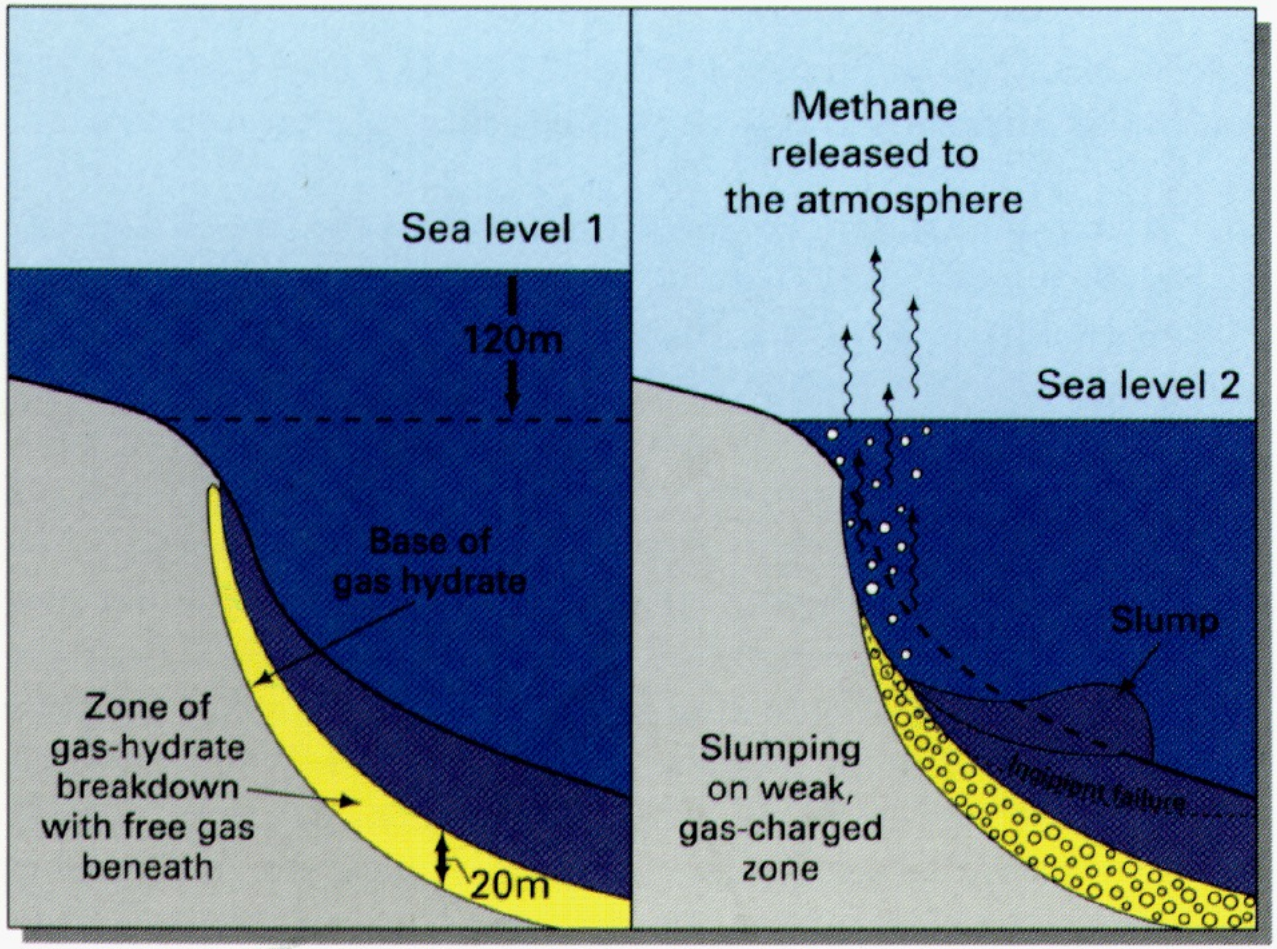
GAS HYDRATES



Map showing location and inferred thickness (in meters) of hydrates within sediments in the high concentration area off North Carolina and South Carolina.



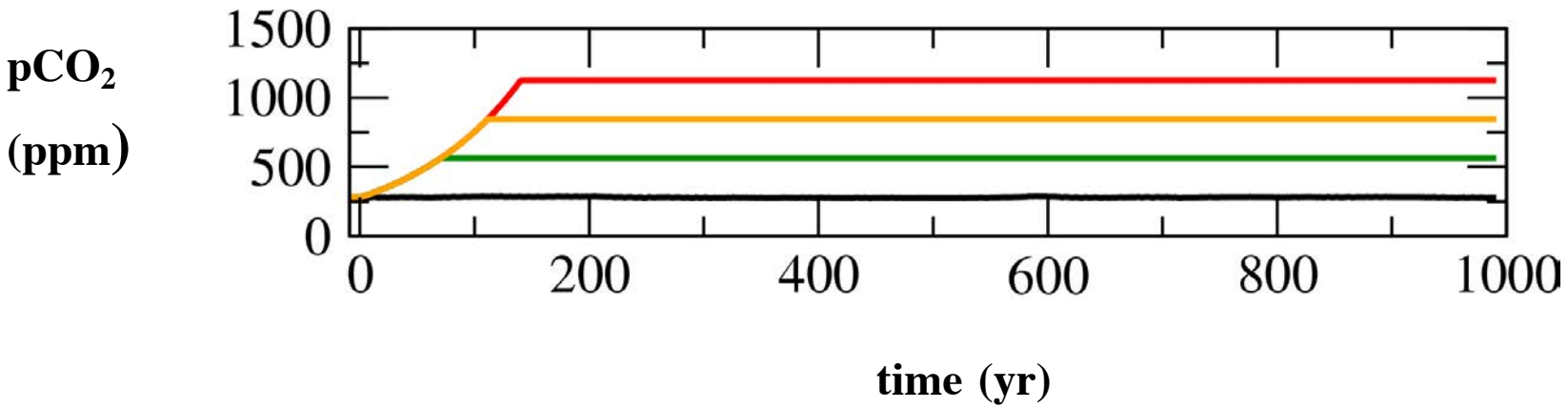
Distribution of organic carbon in Earth reservoirs (excluding dispersed carbon in rocks and sediments, which equals nearly 1,000 times this total amount). Numbers in gigatons (10^{15} tons) of carbon.


Sea level 1
120m
Base of
gas hydrate
Zone of
gas-hydrate
breakdown
with free gas
beneath
20m
Methane
released to
the atmosphere
Sea level 2
Slump
Slumping
on weak,
gas-charged
zone
Incipient failure

Future Climate Change Experiments

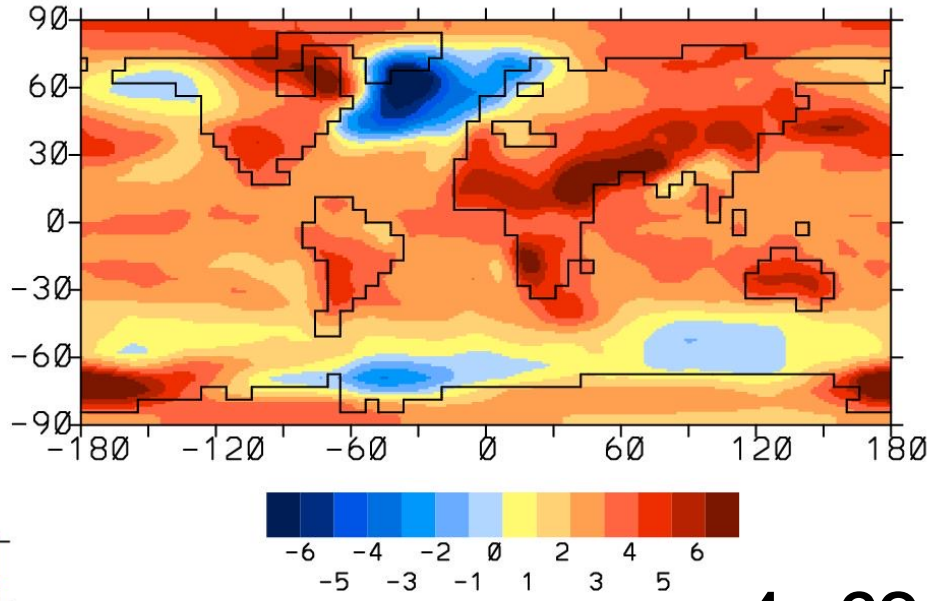
- atmosphere – ocean – ice sheets – vegetation – ocean biogeochemistry
- CO_2 concentration increased from pre-industrial (280 ppm) to 2 x, 3 x, or 4 x pre-industrial concentration with an increase of 1% per year

control run
2 x CO_2
3 x CO_2
4 x CO_2

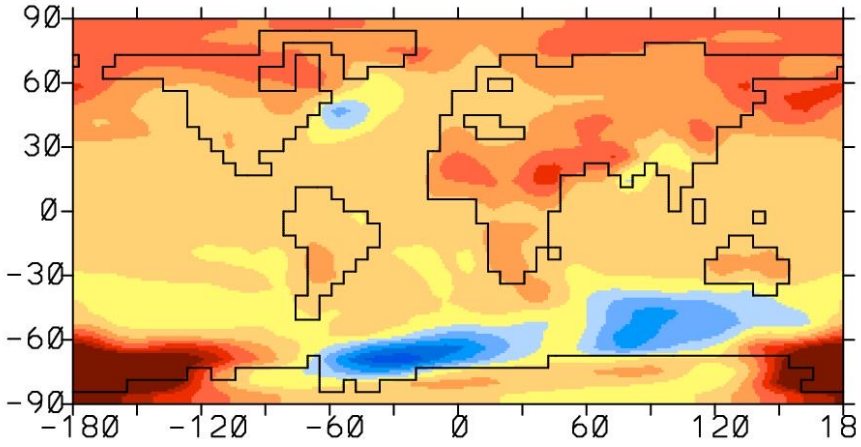


Change in surface air temperature

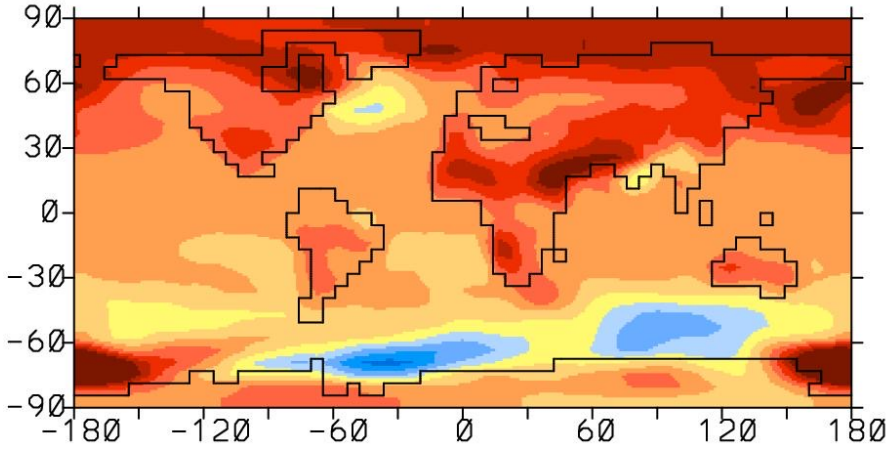
Average over years 300 to 399 relative to climate of control run



4 x CO_2

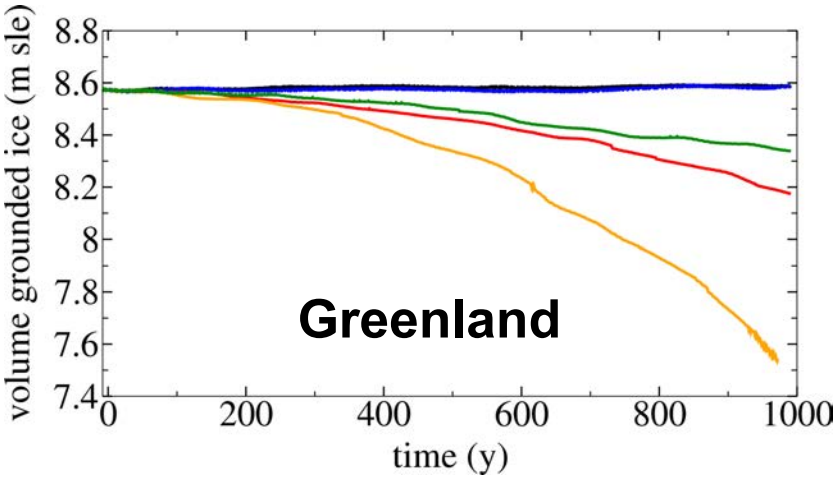


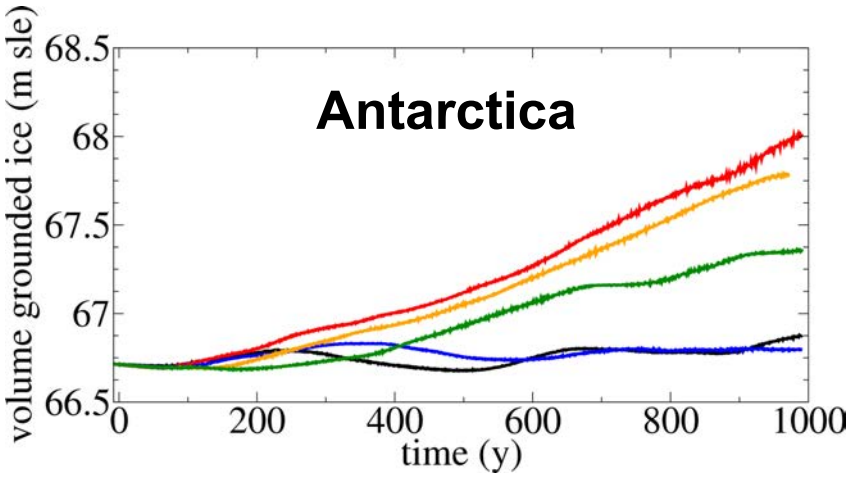
2 x CO_2



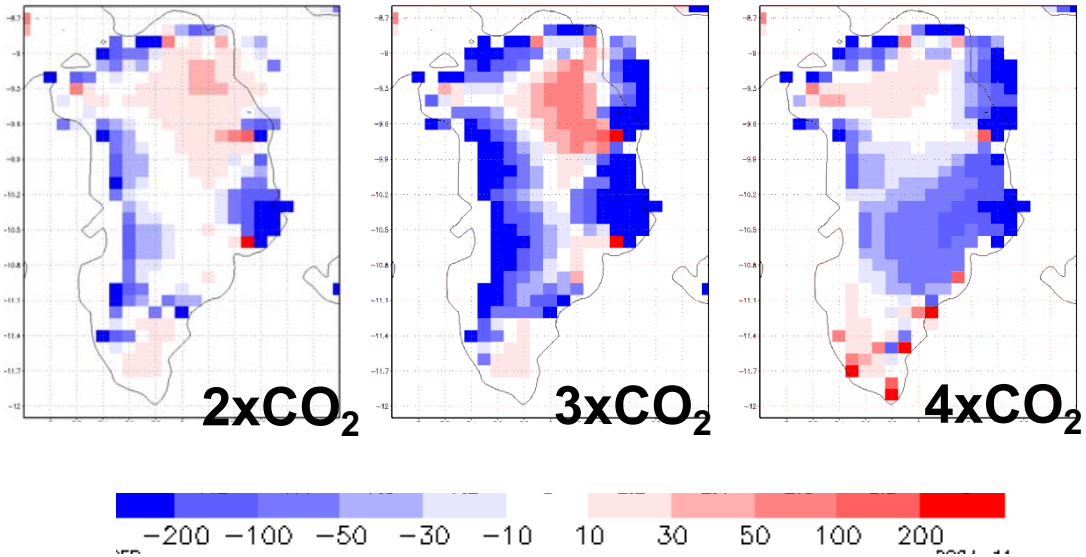
3 x CO_2

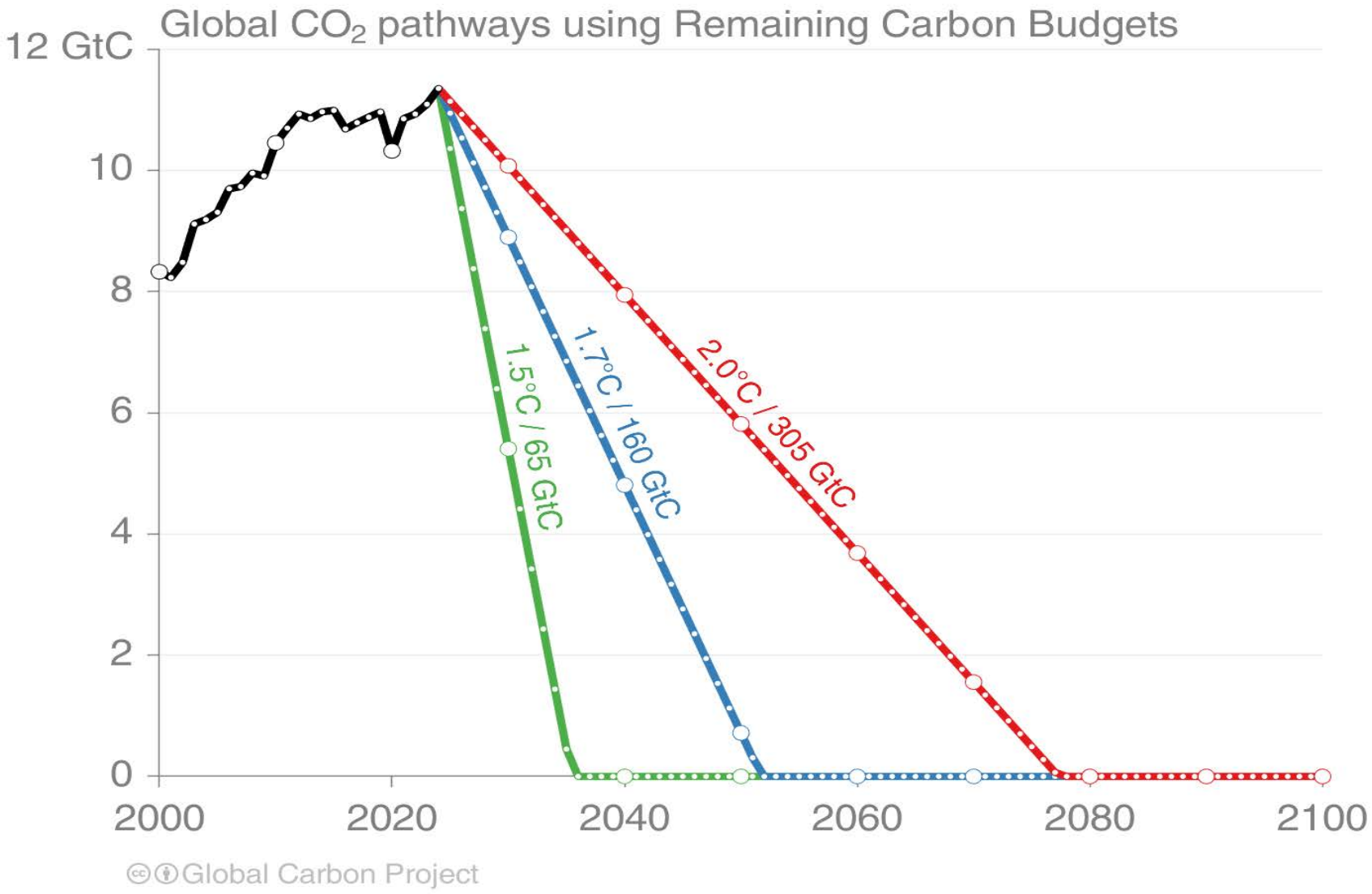
Change in glaciervolume (m sea level equivalent)





Change in ice thickness after 1000 years Greenland (m)




Global CO_2 pathways using Remaining Carbon Budgets
12 GtC
10
8
6
4
2
0
2000
2020
2040
2060
2080
2100
1.5°C / 65 GtC
1.7°C / 160 GtC
2.0°C / 305 GtC
Global Carbon Project