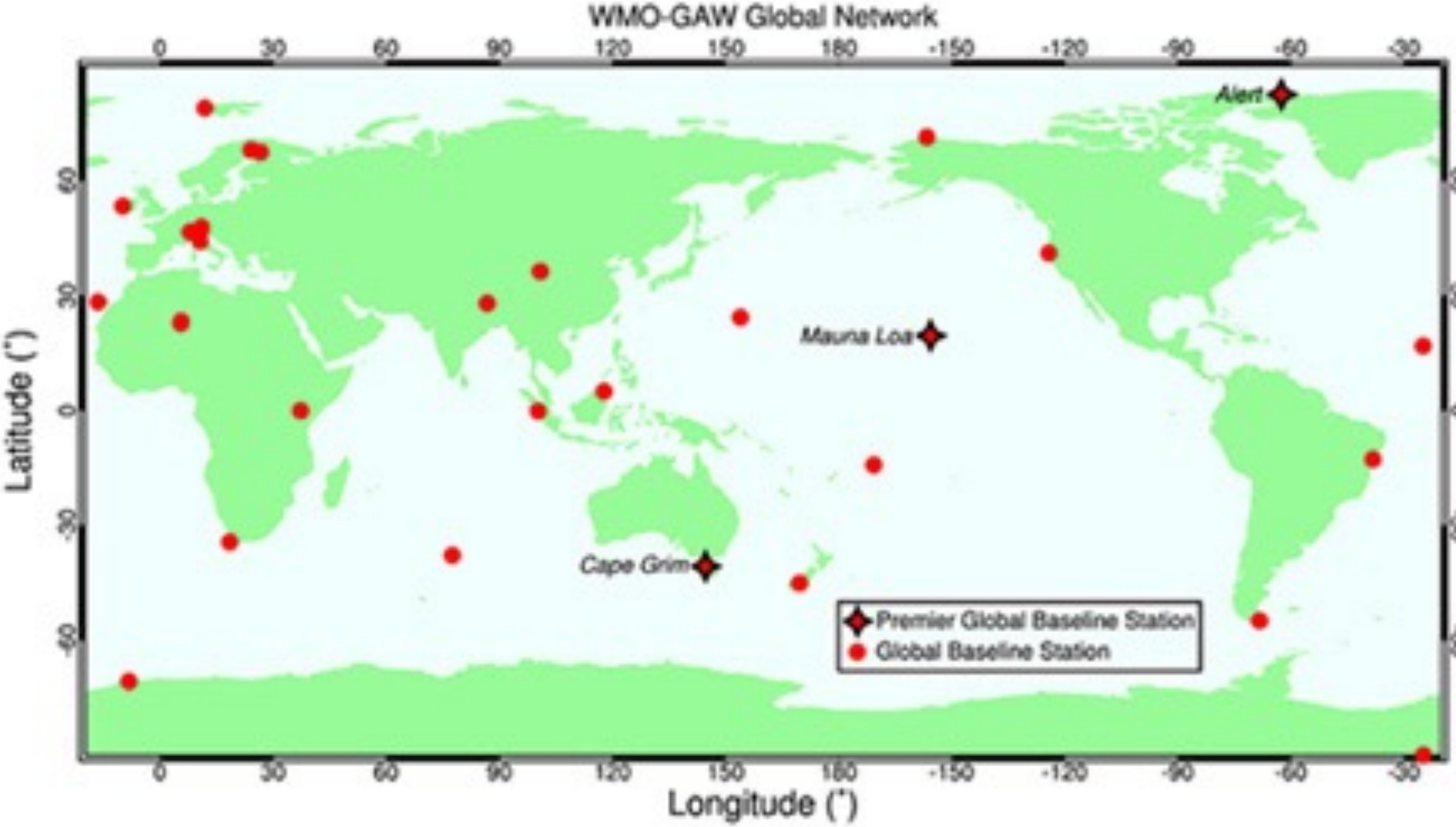
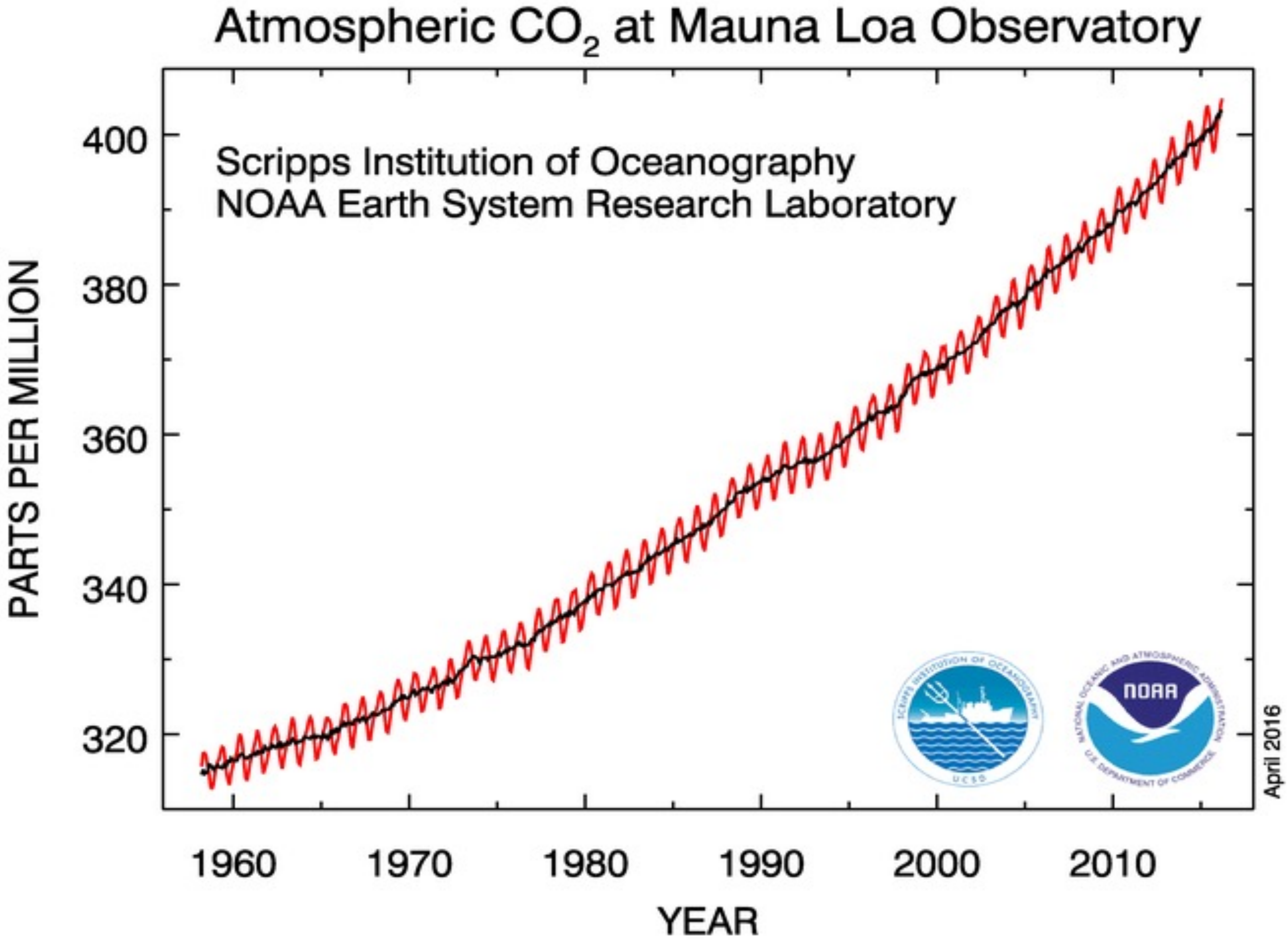
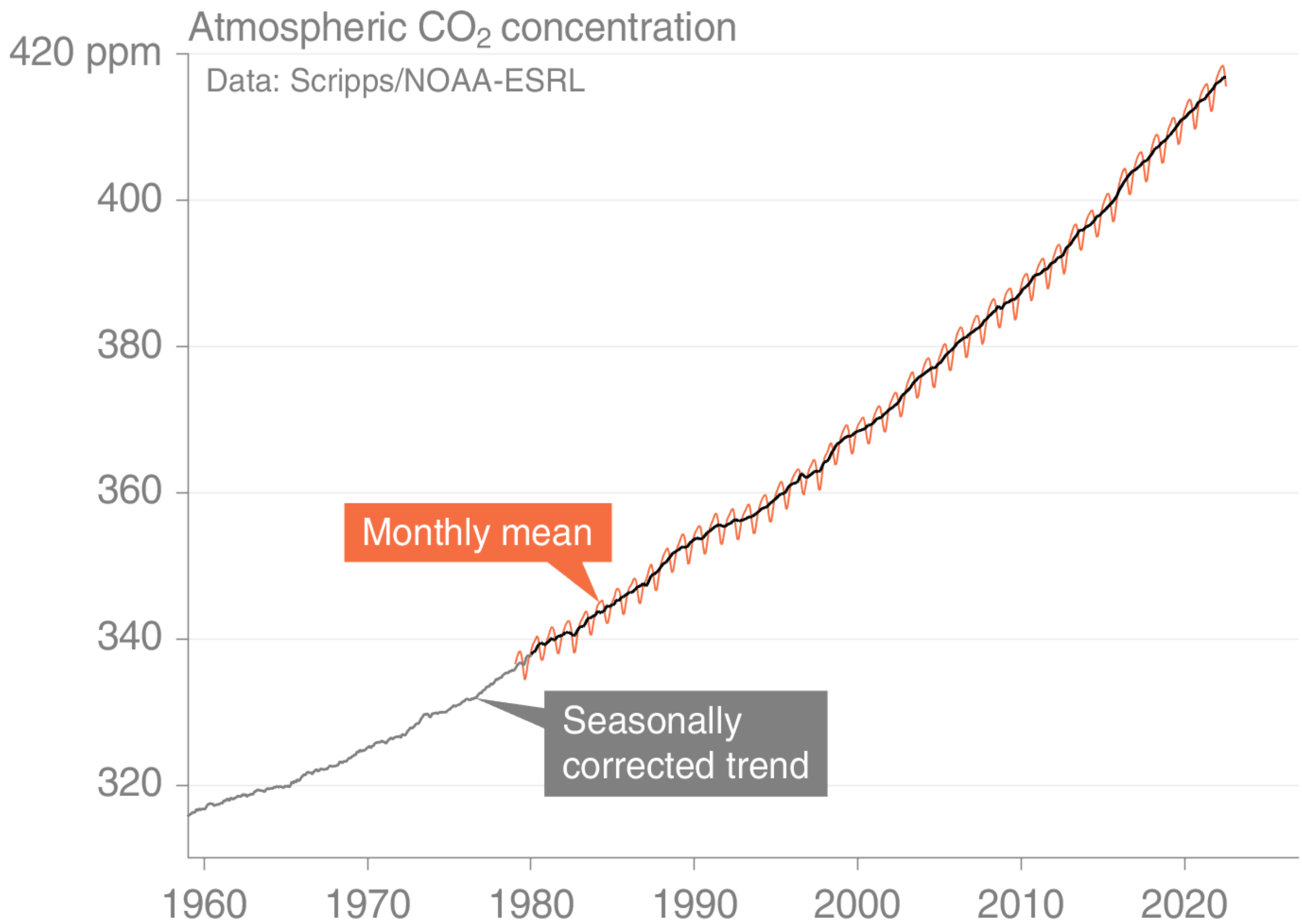
The Global Carbon Cycle

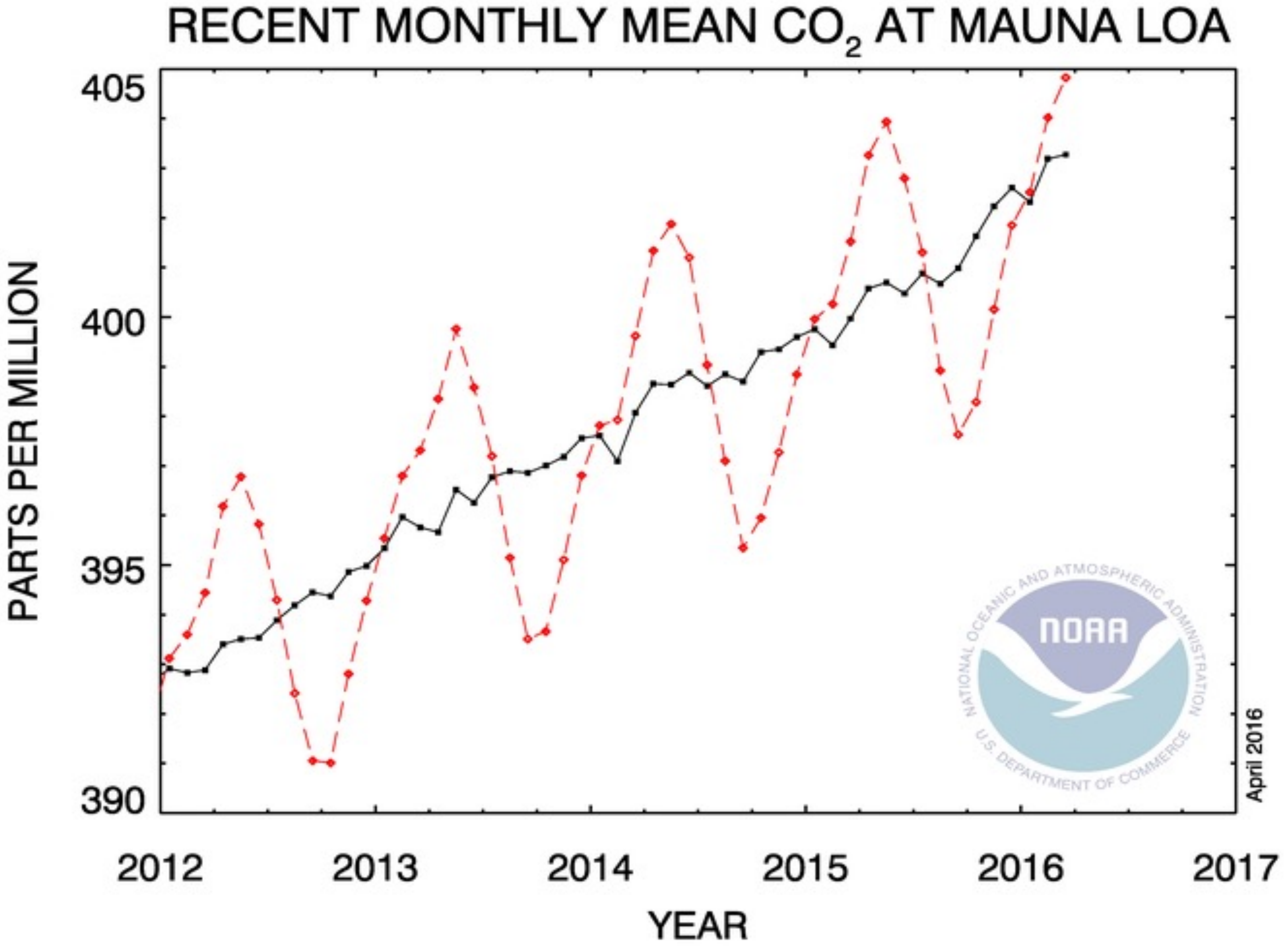


WMO-GAW Global Network
Alert
Mauna Loa
Cape Grim
Premier Global Baseline Station
Global Baseline Station
Latitude (°)
Longitude (°)

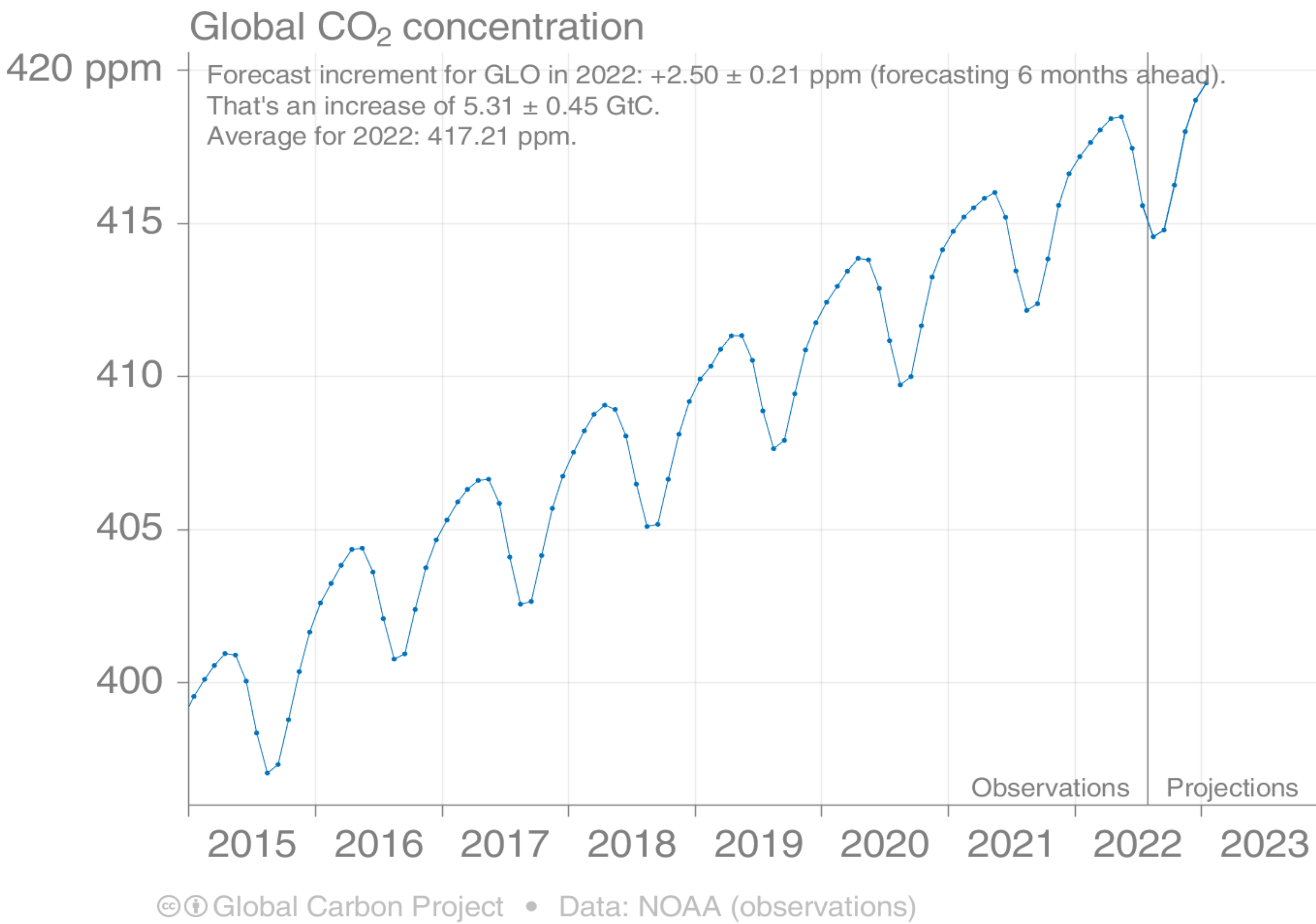

Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
NOAA
April 2016



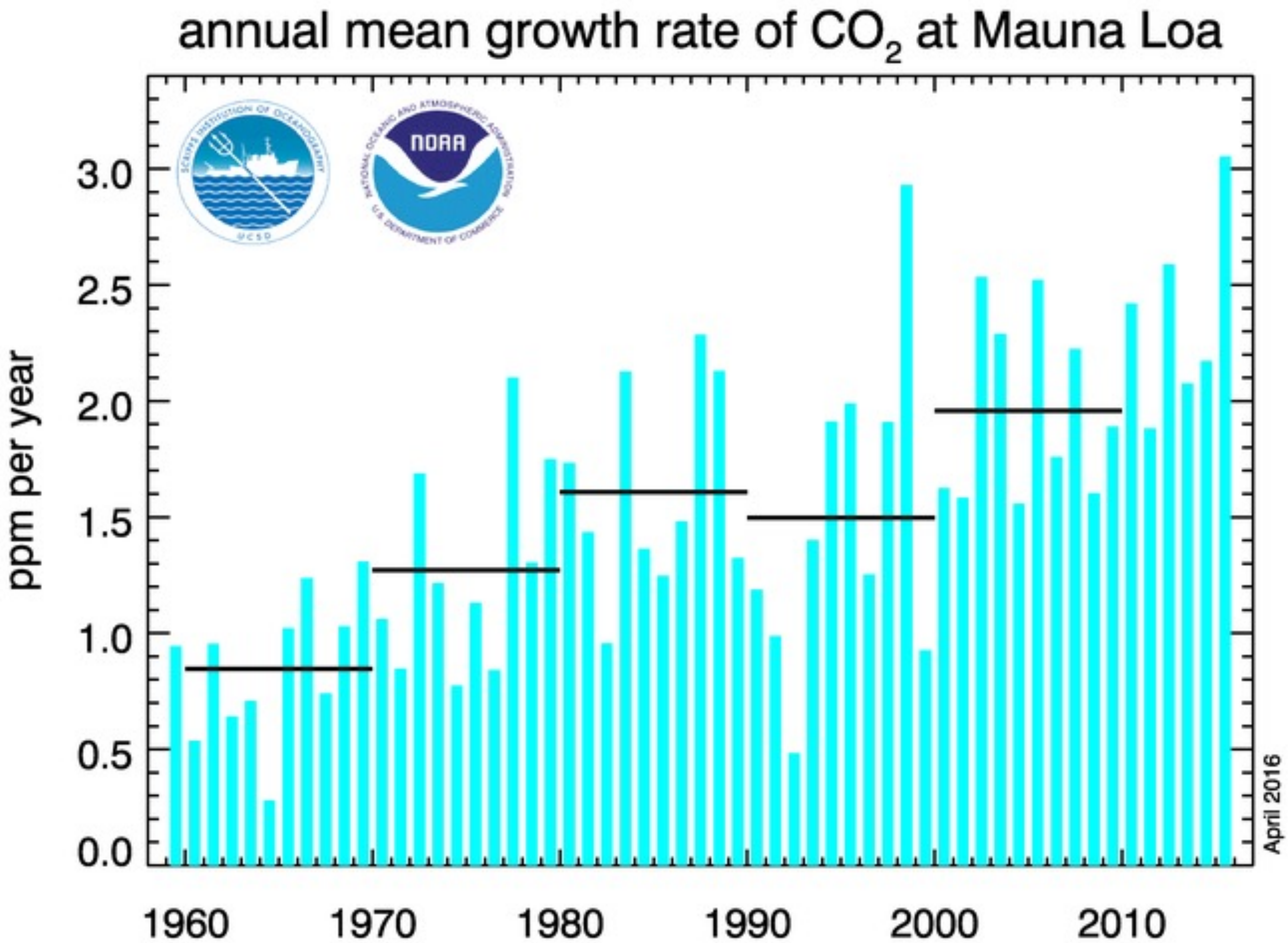
Atmospheric CO_2 concentration
420 ppm
Data: Scripps/NOAA-ESRL
400
380
360
340
320
Monthly mean
Seasonally corrected trend
1960
1970
1980
1990
2000
2010
2020



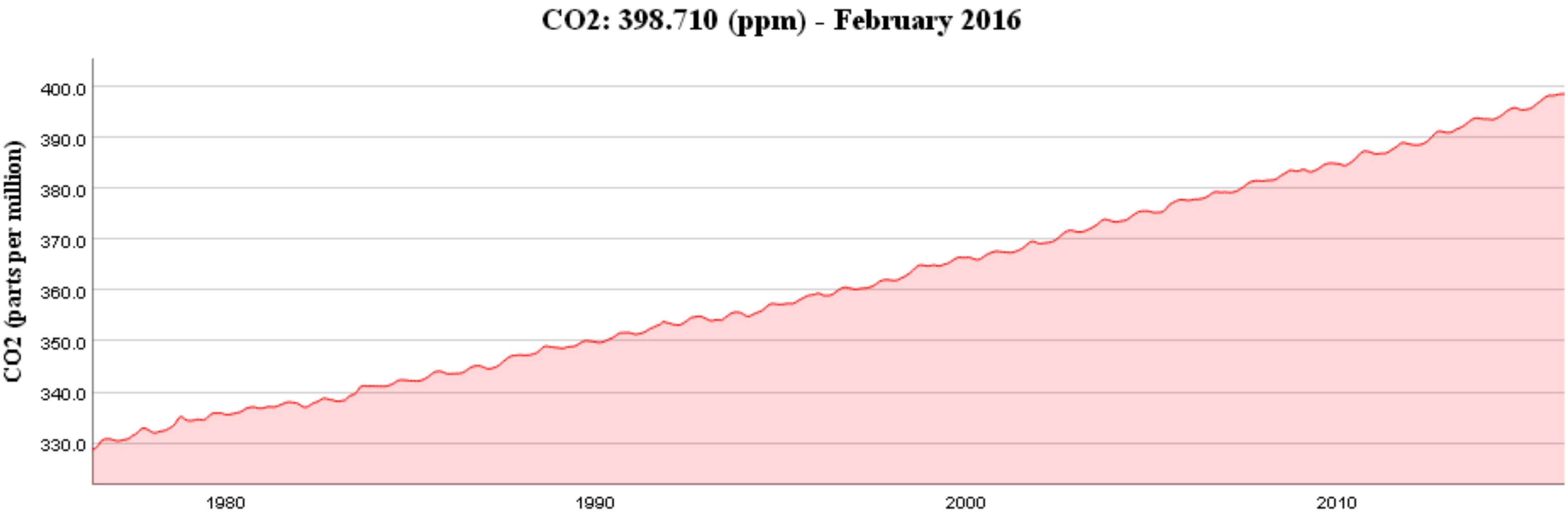
RECENT MONTHLY MEAN CO_2 AT MAUNA LOA
PARTS PER MILLION
405
400
395
390
2012
2013
2014
2015
2016
2017
YEAR
April 2016
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE



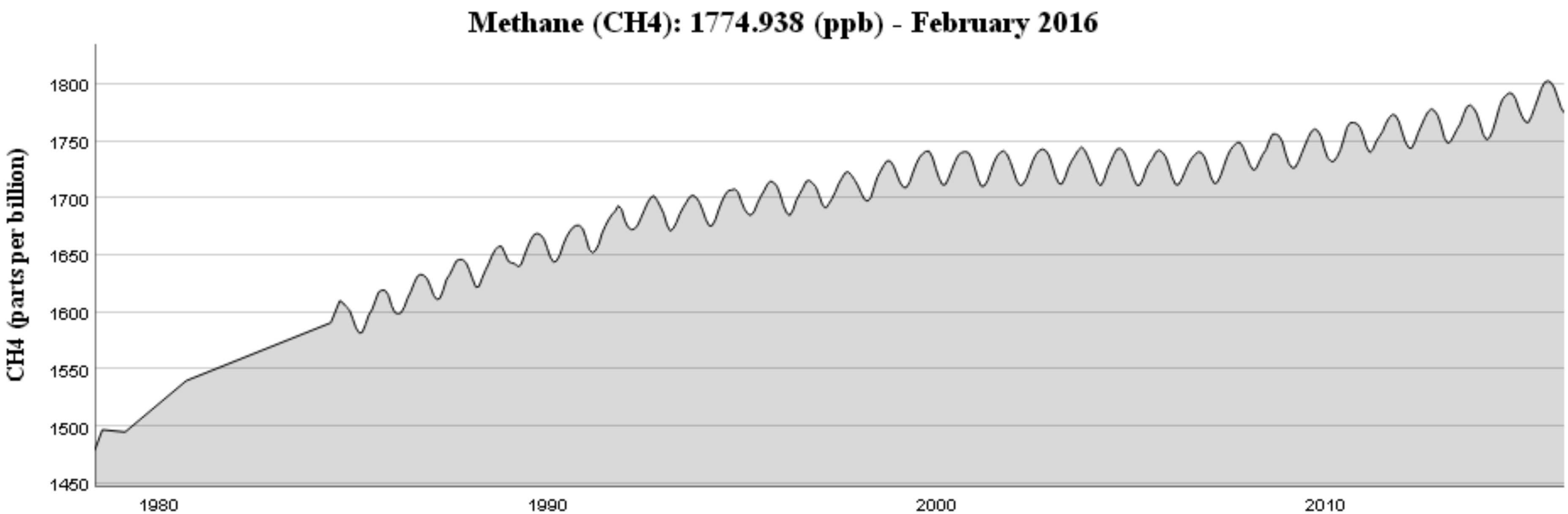
Global CO2 concentration
420 ppm
415
410
405
400
Forecast increment for GLO in 2022: +2.50 ± 0.21 ppm (forecasting 6 months ahead).
That's an increase of 5.31 ± 0.45 GtC.
Average for 2022: 417.21 ppm.
Observations
Projections
2015
2016
2017
2018
2019
2020
2021
2022
2023
Global Carbon Project • Data: NOAA (observations)


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

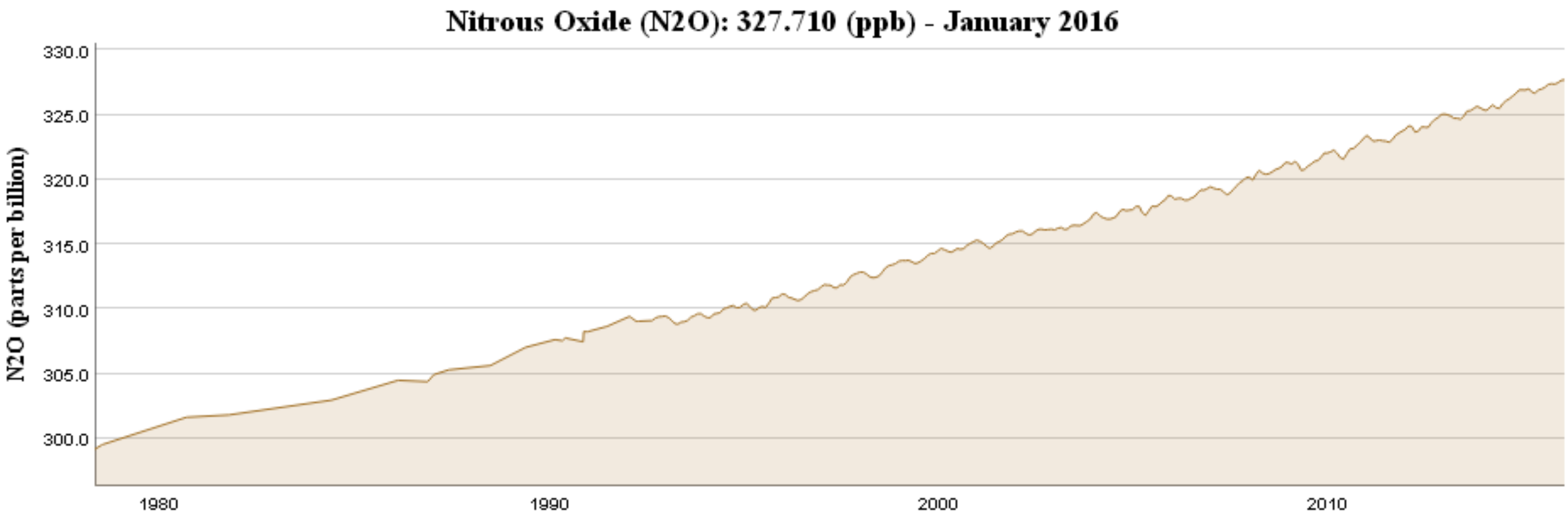
Cape Grim Tasmania CO_2

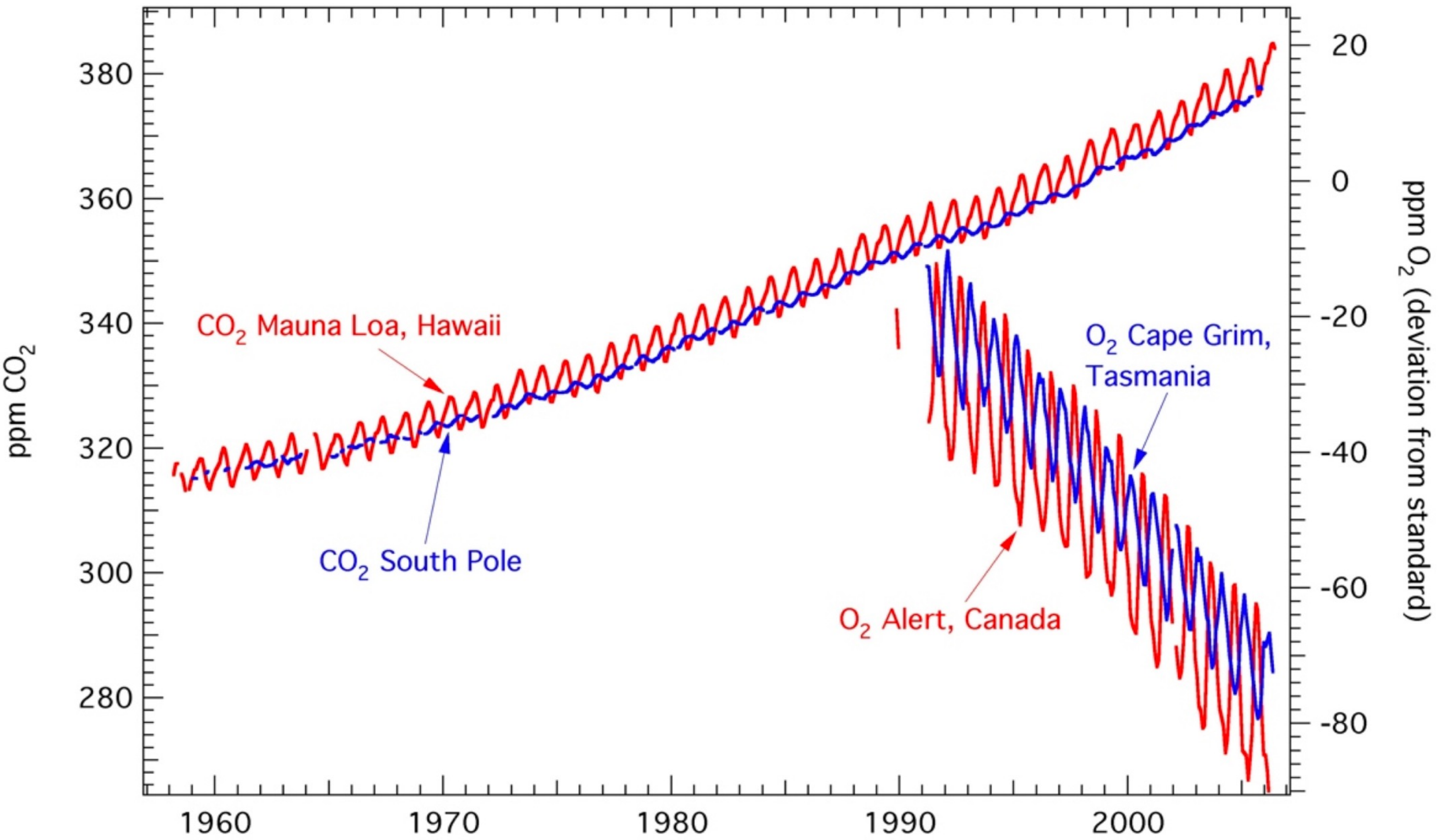


Cape Grim Tasmania CH_4

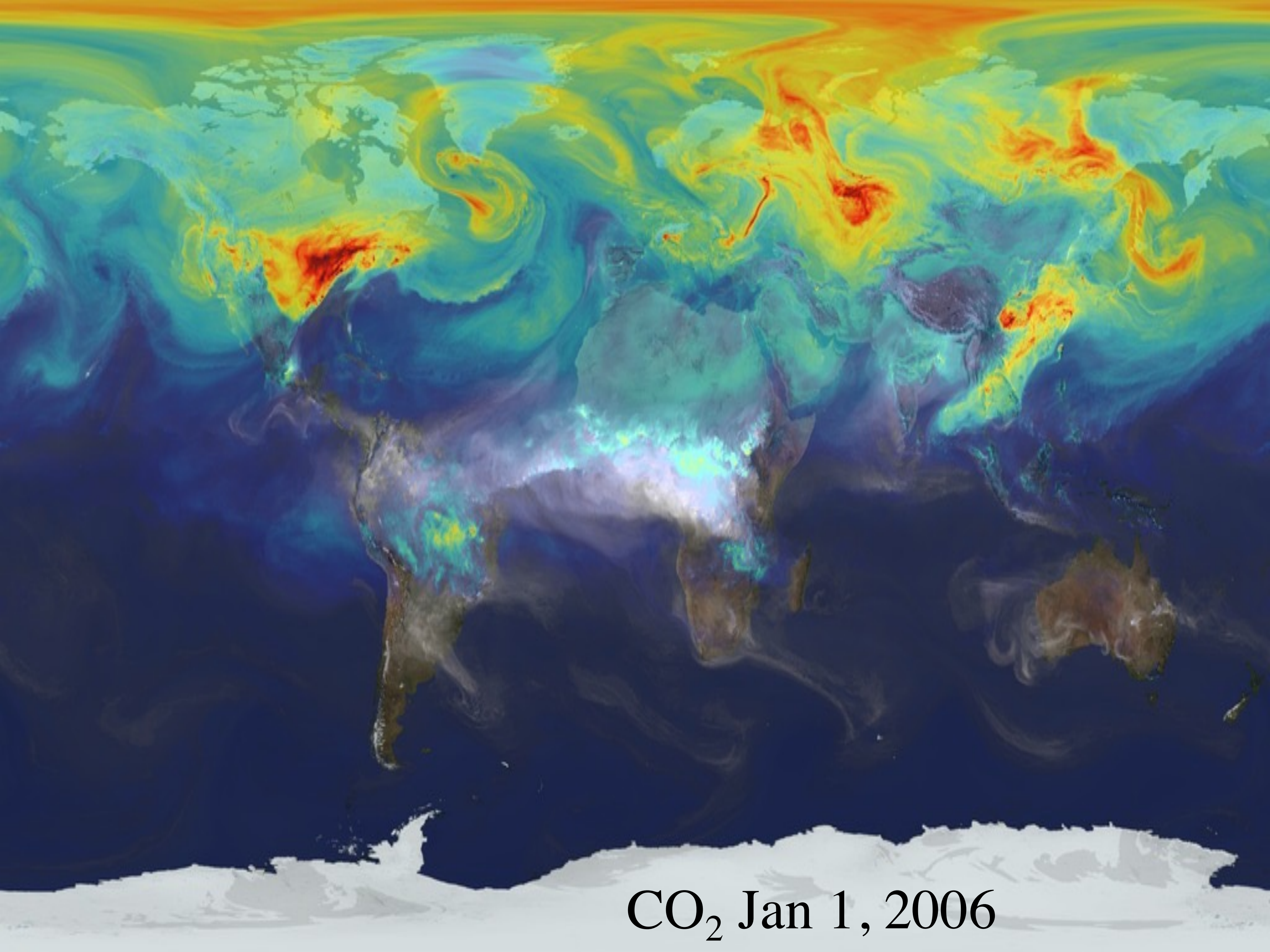


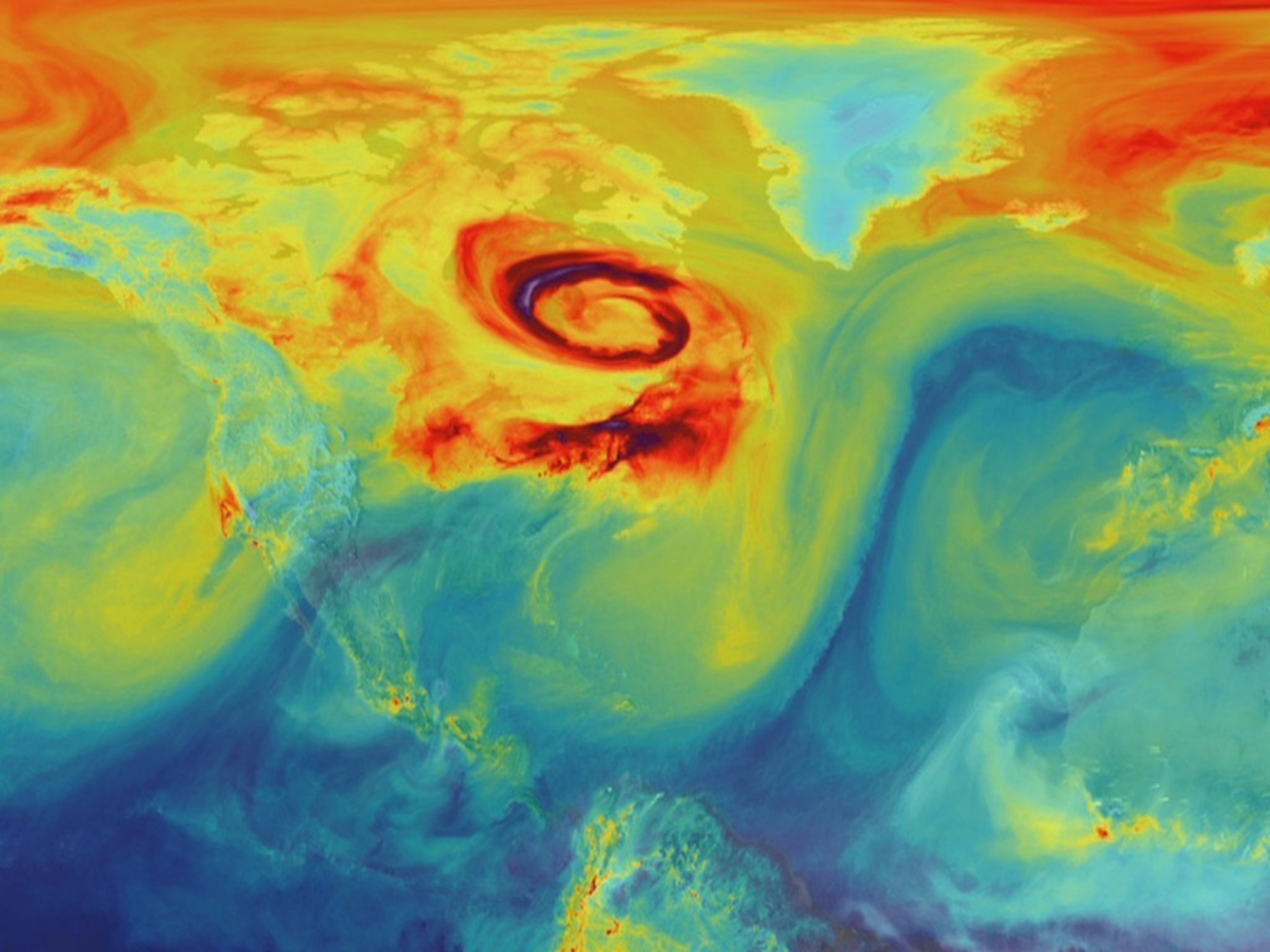
Cape Grim Tasmania N_2O





ppm CO_2
380
360
340
320
300
280
1960
1970
1980
1990
2000
20
0
-20
-40
-60
-80
ppm O_2 (deviation from standard)
CO_2 Mauna Loa, Hawaii
CO_2 South Pole
O_2 Cape Grim, Tasmania
O_2 Alert, Canada


CO_2 Jan 1, 2006

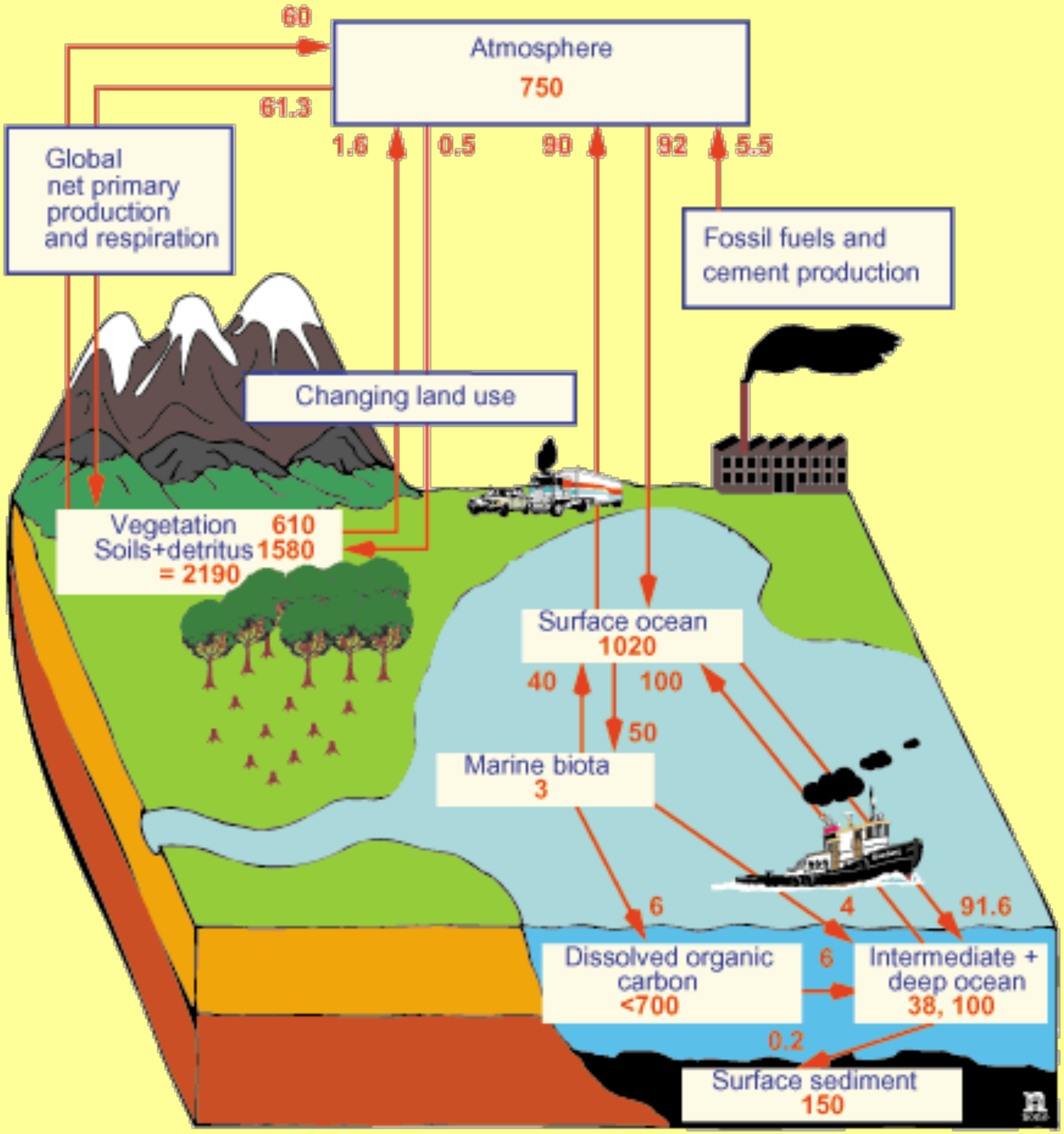


$1\ Pg = 1\ Petagram = 1 \times 10^{15} g = 1 \times 10^{12}\ kg$

$= 1 \times 10^{9}$ metric tonnes = 1 gigatonne = 1 Gt

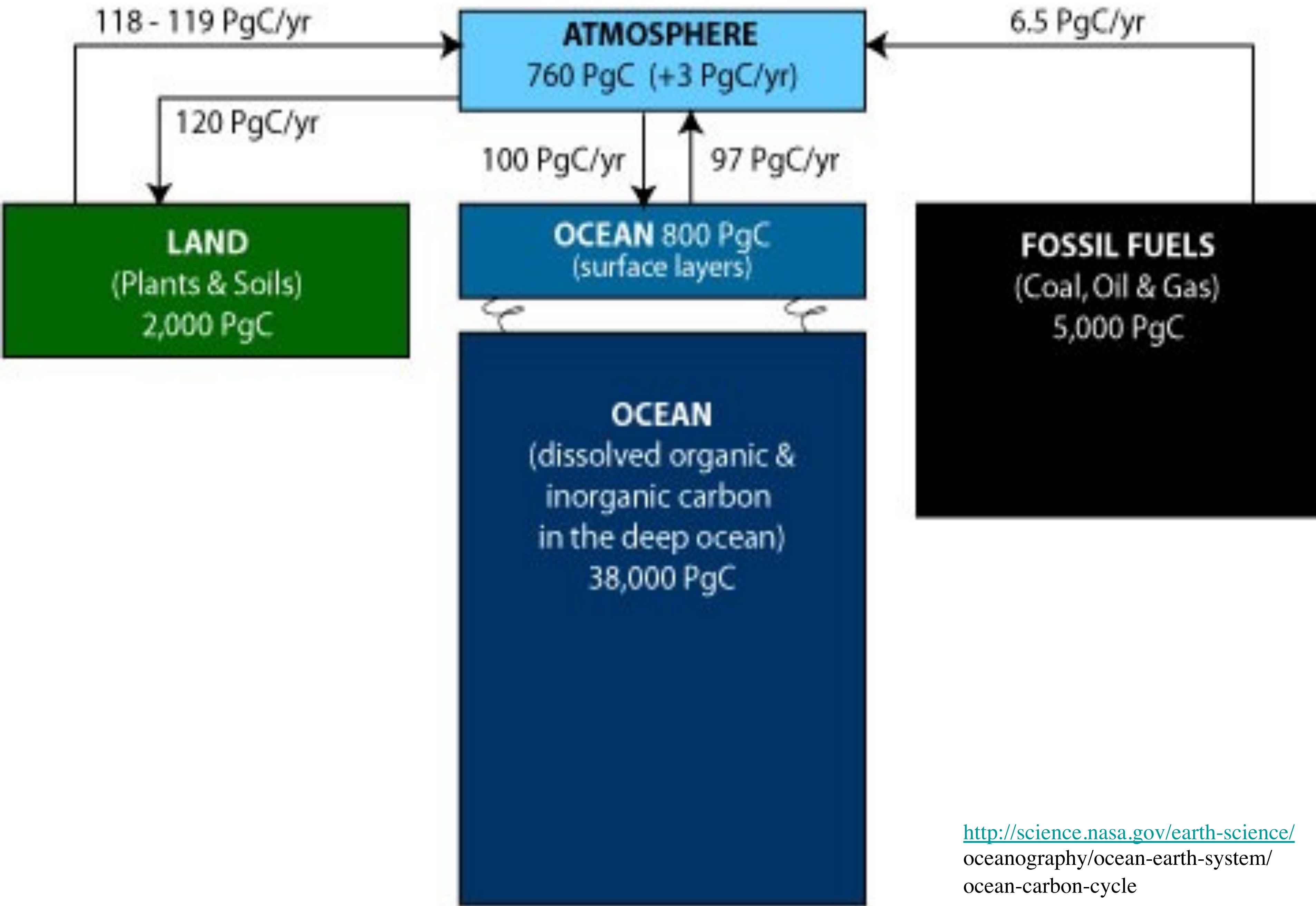
1 kg carbon (C) = 3.67 kg carbon dioxide (CO_2)

1 Pg C = 3.67 Gt CO_2

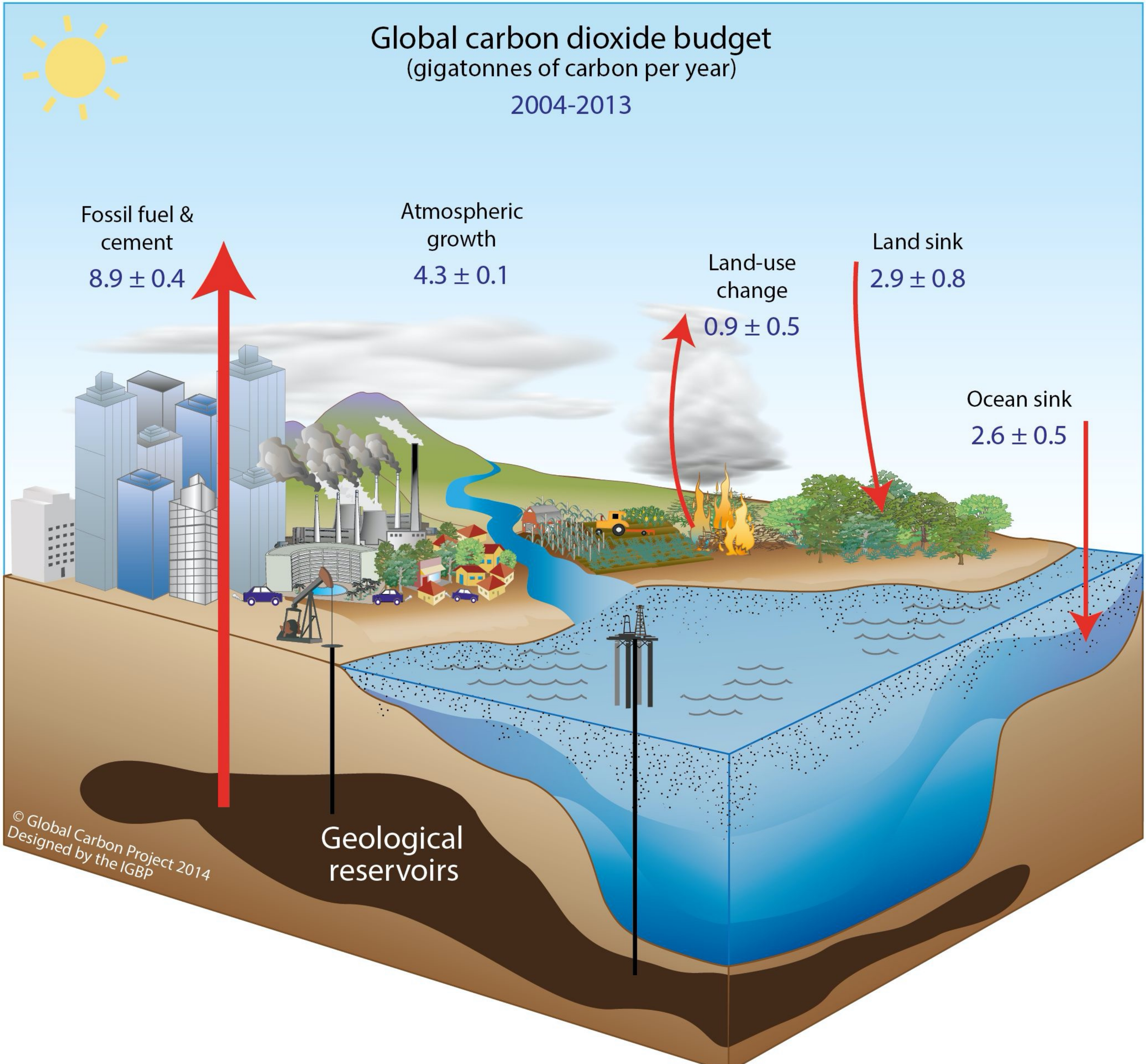


The numbers in boxes indicate the size in GtC of each reservoir.
On each arrow is indicated the magnitude of the flux in GtC/yr.

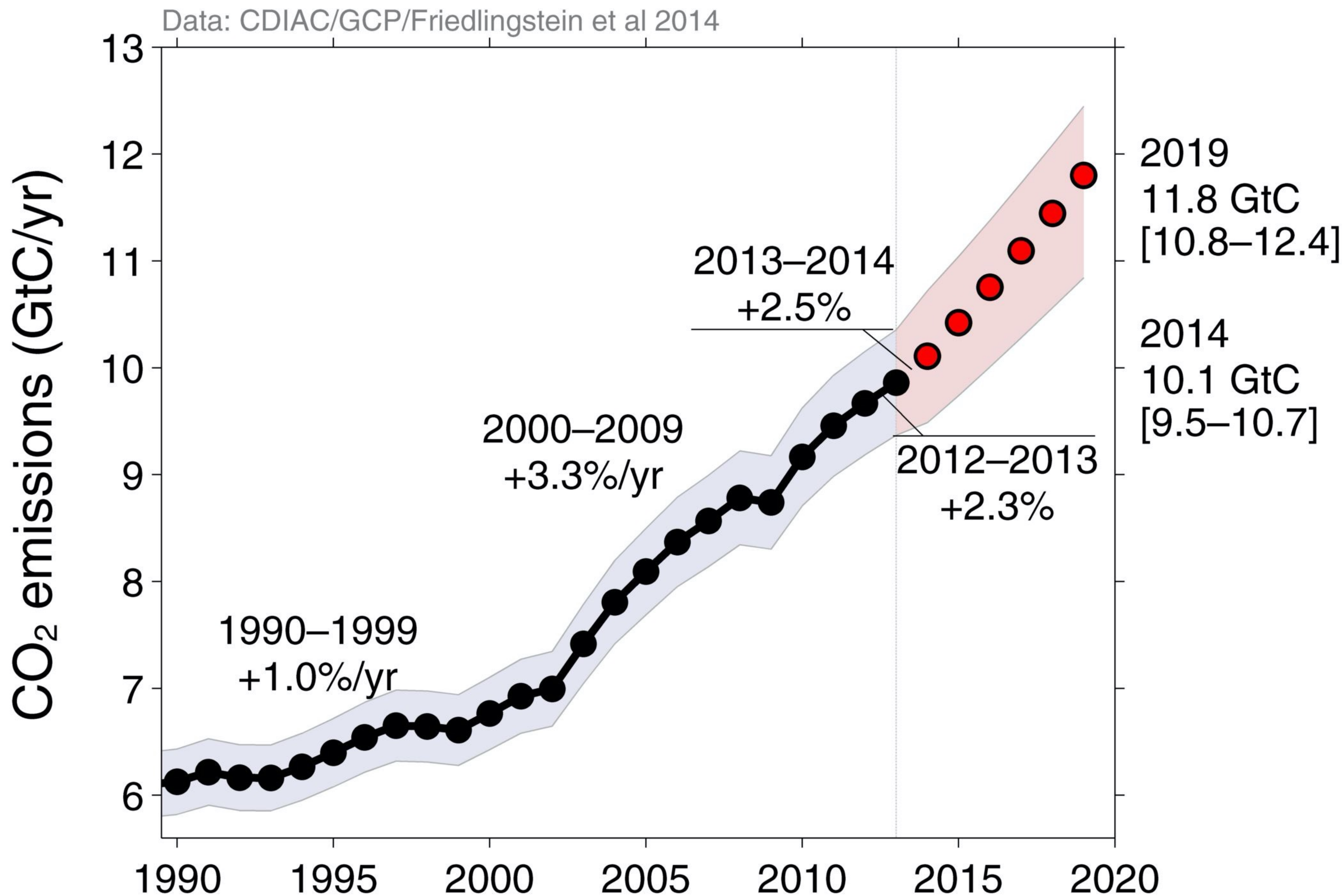
Global Flows of Carbon

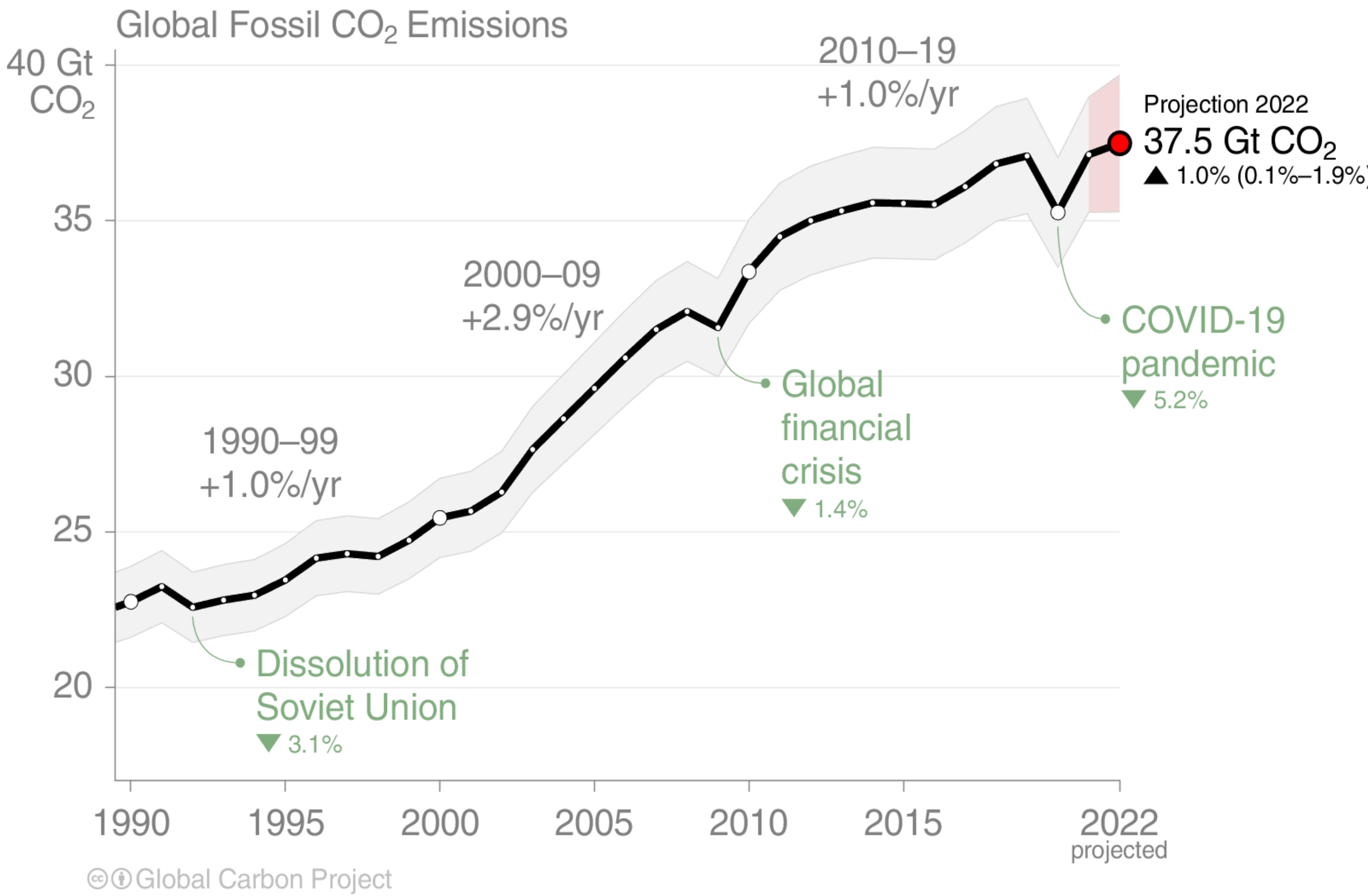


http://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-carbon-cycle

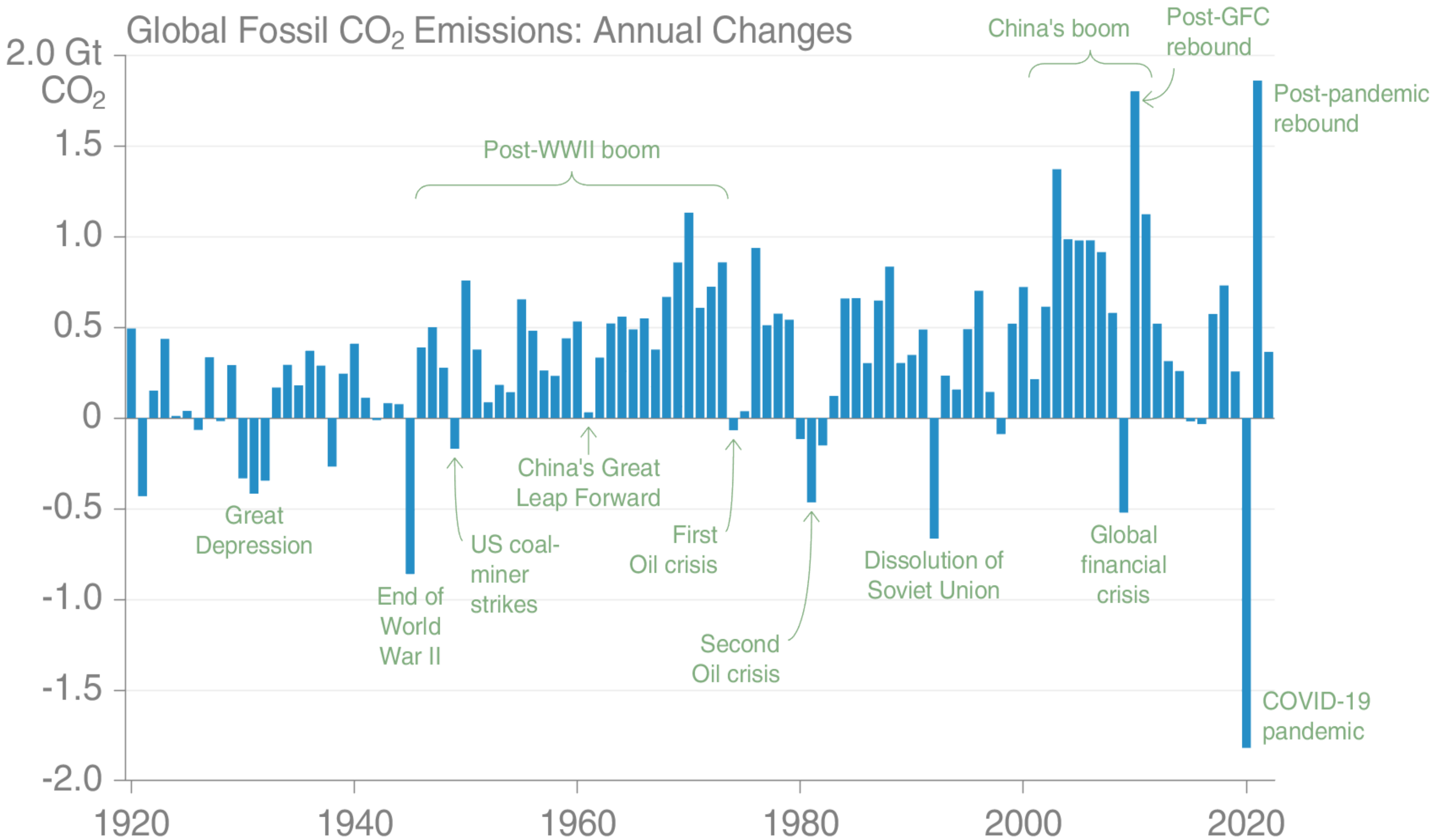

Global carbon dioxide budget
(gigatonnes of carbon per year)
2004-2013
Fossil fuel & cement
8.9 ± 0.4
Atmospheric growth
4.3 ± 0.1
Land-use change
0.9 ± 0.5
Land sink
2.9 ± 0.8
Ocean sink
2.6 ± 0.5
Geological reservoirs
© Global Carbon Project 2014
Designed by the IGBP

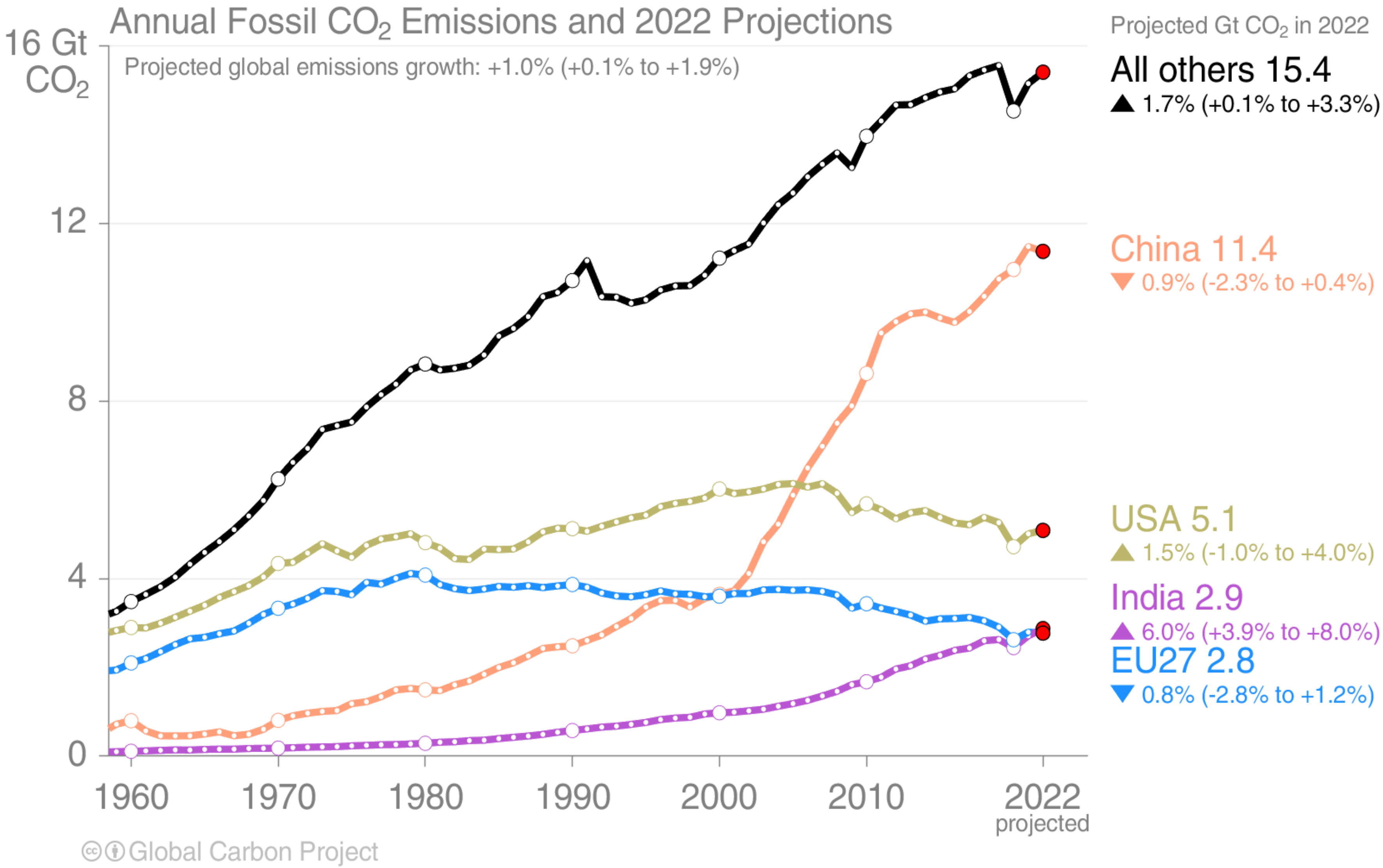
Observed Emissions


Data: CDIAC/GCP/Friedlingstein et al 2014
CO2 emissions (GtC/yr)
13
12
11
10
9
8
7
6
1990
1995
2000
2005
2010
2015
2020
1990–1999
+1.0%/yr
2000–2009
+3.3%/yr
2013–2014
+2.5%
2012–2013
+2.3%
2019
11.8 GtC
[10.8–12.4]
2014
10.1 GtC
[9.5–10.7]

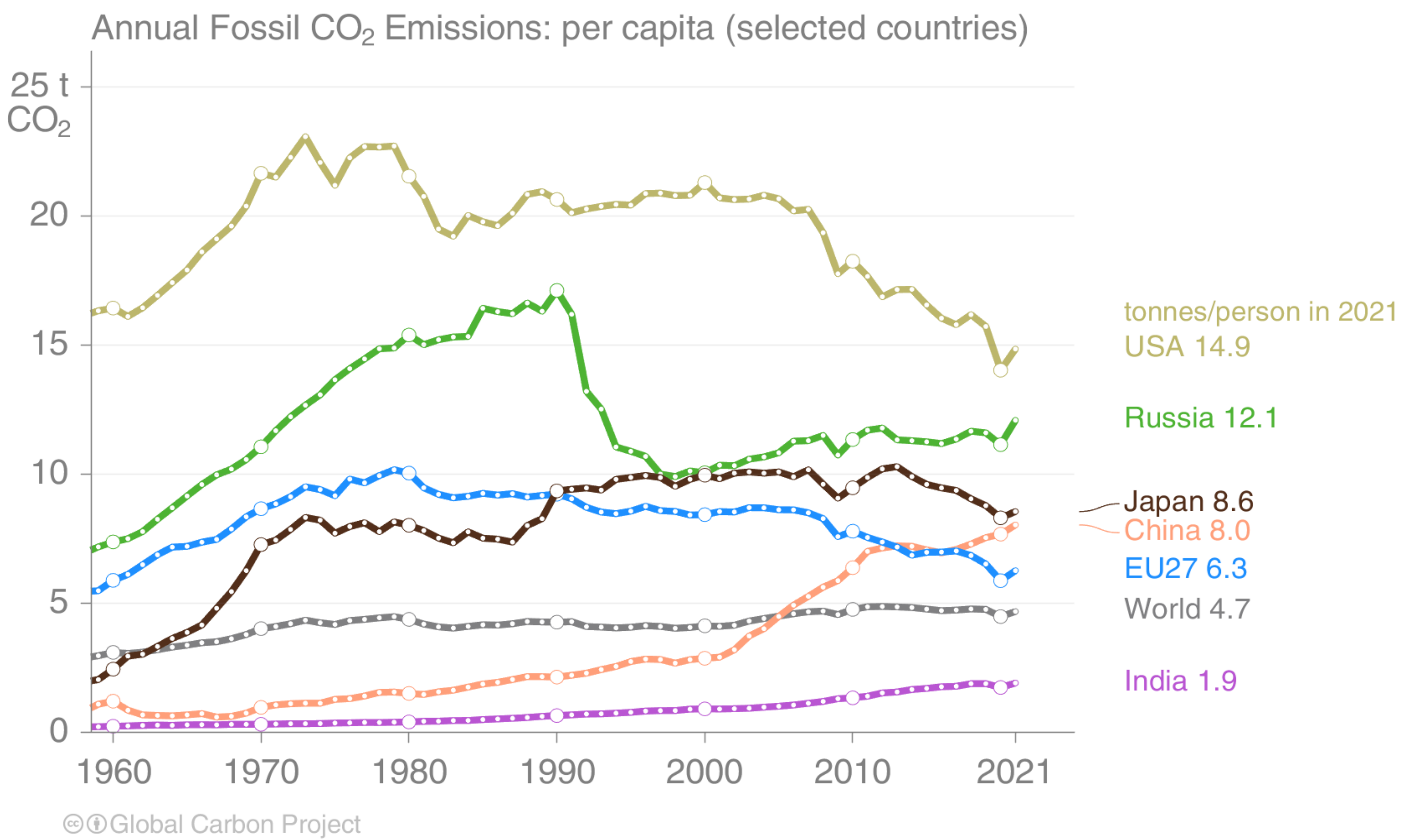


Friedlingstein et al 2022; Global Carbon Project 2022

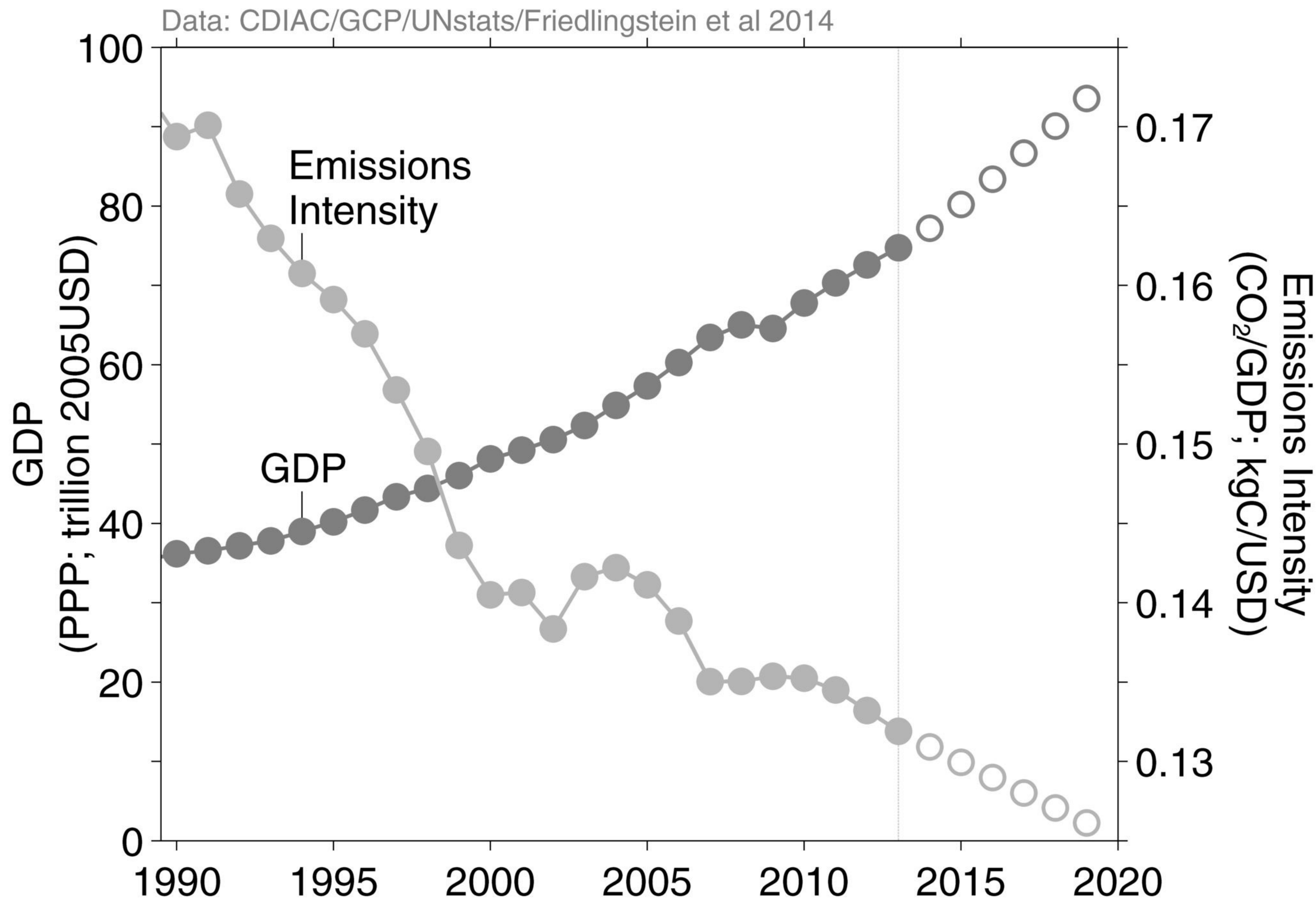

Global Fossil CO_2 Emissions: Annual Changes
2.0 Gt CO_2
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
1920
1940
1960
1980
2000
2020
Post-WWII boom
China's boom
Post-GFC rebound
Post-pandemic rebound
Great Depression
End of World War II
US coal-miner strikes
China's Great Leap Forward
First Oil crisis
Second Oil crisis
Dissolution of Soviet Union
Global financial crisis
COVID-19 pandemic

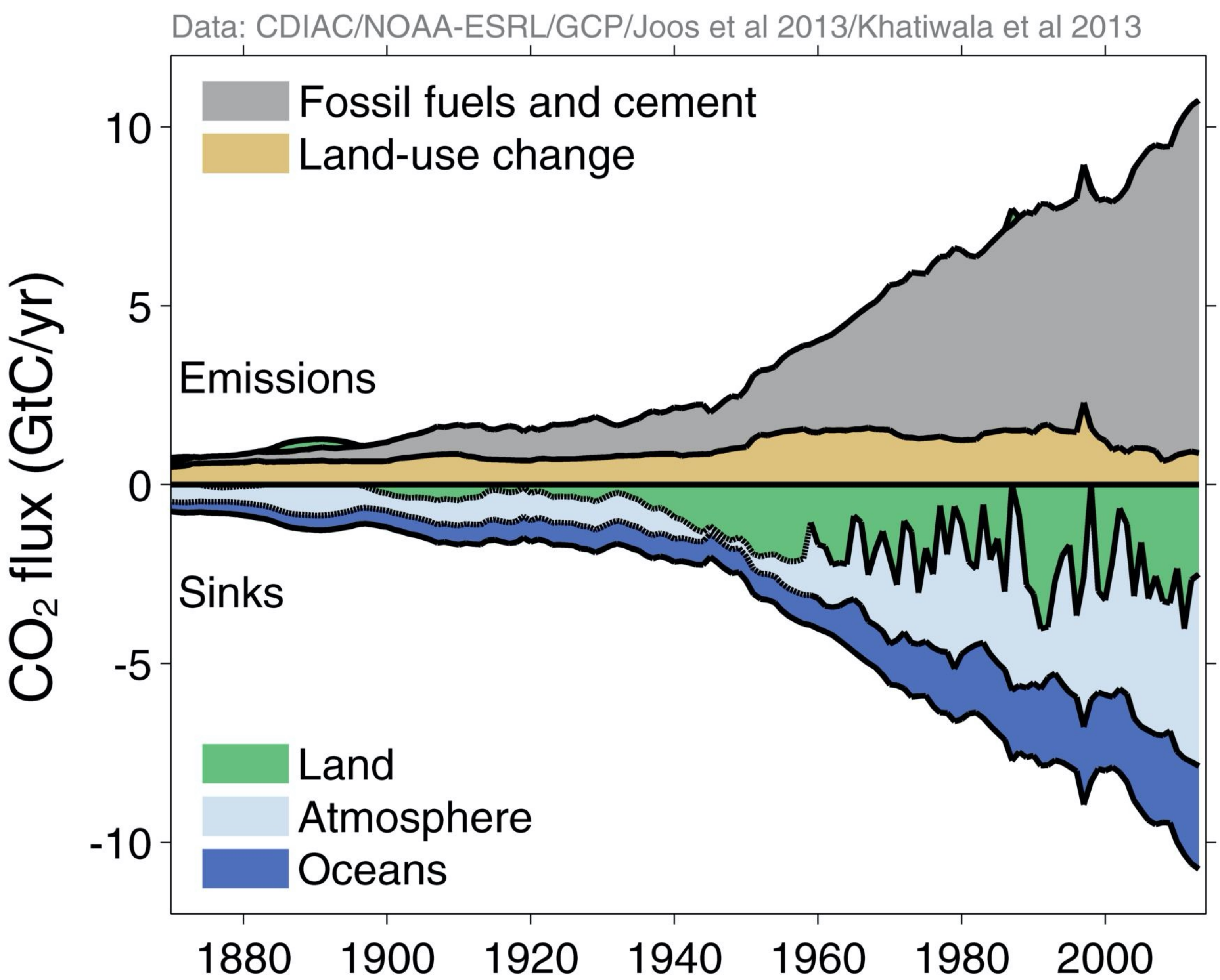


Annual Fossil CO_2 Emissions and 2022 Projections
Projected global emissions growth: +1.0% (+0.1% to +1.9%)
16 Gt CO_2
12
8
4
0
1960
1970
1980
1990
2000
2010
2022
projected
Projected Gt CO_2 in 2022
All others 15.4
▲ 1.7% (+0.1% to +3.3%)
China 11.4
▼ 0.9% (-2.3% to +0.4%)
USA 5.1
▲ 1.5% (-1.0% to +4.0%)
India 2.9
▲ 6.0% (+3.9% to +8.0%)
EU27 2.8
▼ 0.8% (-2.8% to +1.2%)
Global Carbon Project



Annual Fossil CO_2 Emissions: per capita (selected countries)
25 t CO_2
20
15
10
5
0
1960
1970
1980
1990
2000
2010
2021
tonnes/person in 2021
USA 14.9
Russia 12.1
Japan 8.6
China 8.0
EU27 6.3
World 4.7
India 1.9
Global Carbon Project


Data: CDIAC/GCP/UNstats/Friedlingstein et al 2014
100
80
60
40
20
0
GDP
(PPP; trillion 2005USD)
Emissions
Intensity
GDP
1990
1995
2000
2005
2010
2015
2020
0.17
0.16
0.15
0.14
0.13
Emissions Intensity
(CO_2/GDP; kgC/USD)



Data: CDIAC/NOAA-ESRL/GCP/Joos et al 2013/Khatiwala et al 2013
Fossil fuels and cement
Land-use change
Emissions
Sinks
Land
Atmosphere
Oceans
CO_2 flux (GtC/yr)
10
5
0
-5
-10
1880
1900
1920
1940
1960
1980
2000

Fate of Anthropogenic CO_2 Emissions (2002-2011 average)

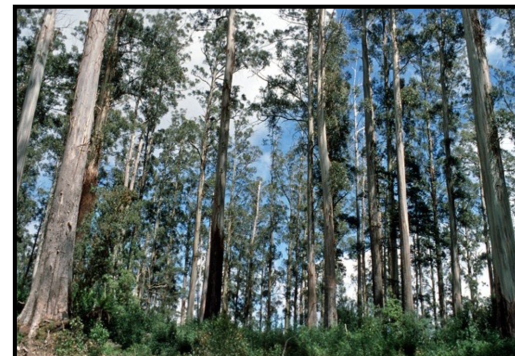
8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

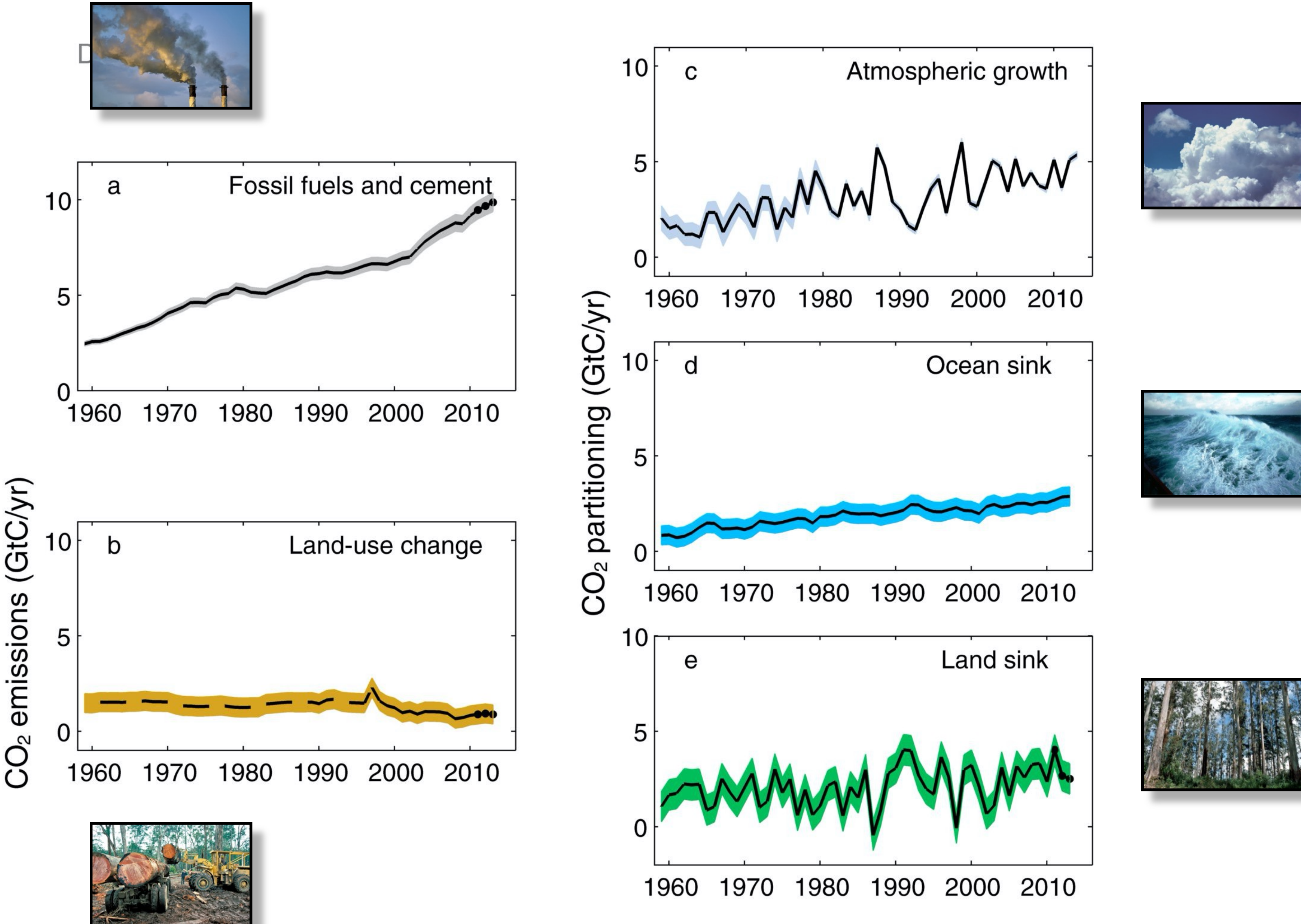
4.3±0.1 PgC/yr
46%

2.6±0.8 PgC/yr
28%
Calculated as the residual of all other flux components

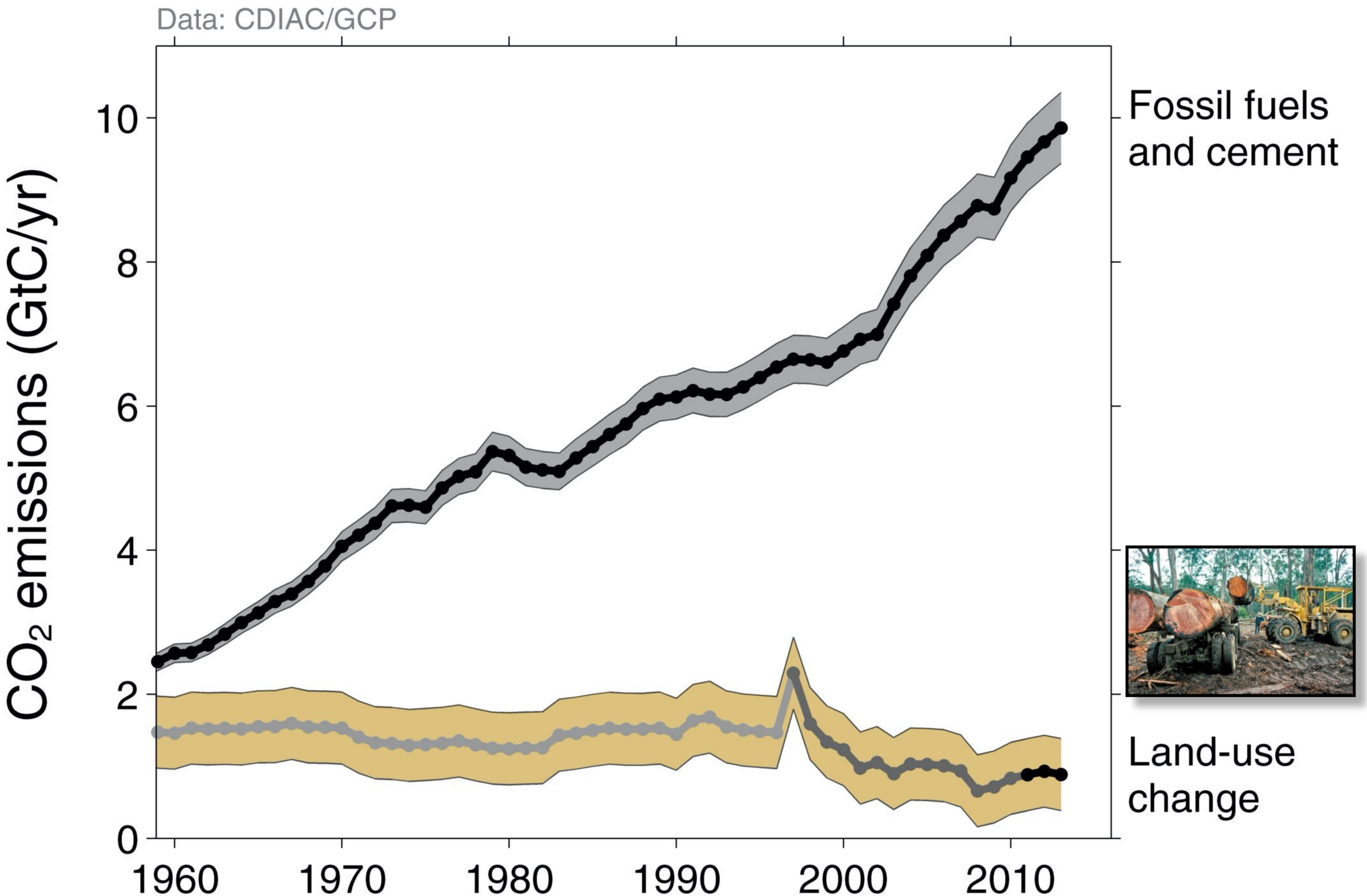


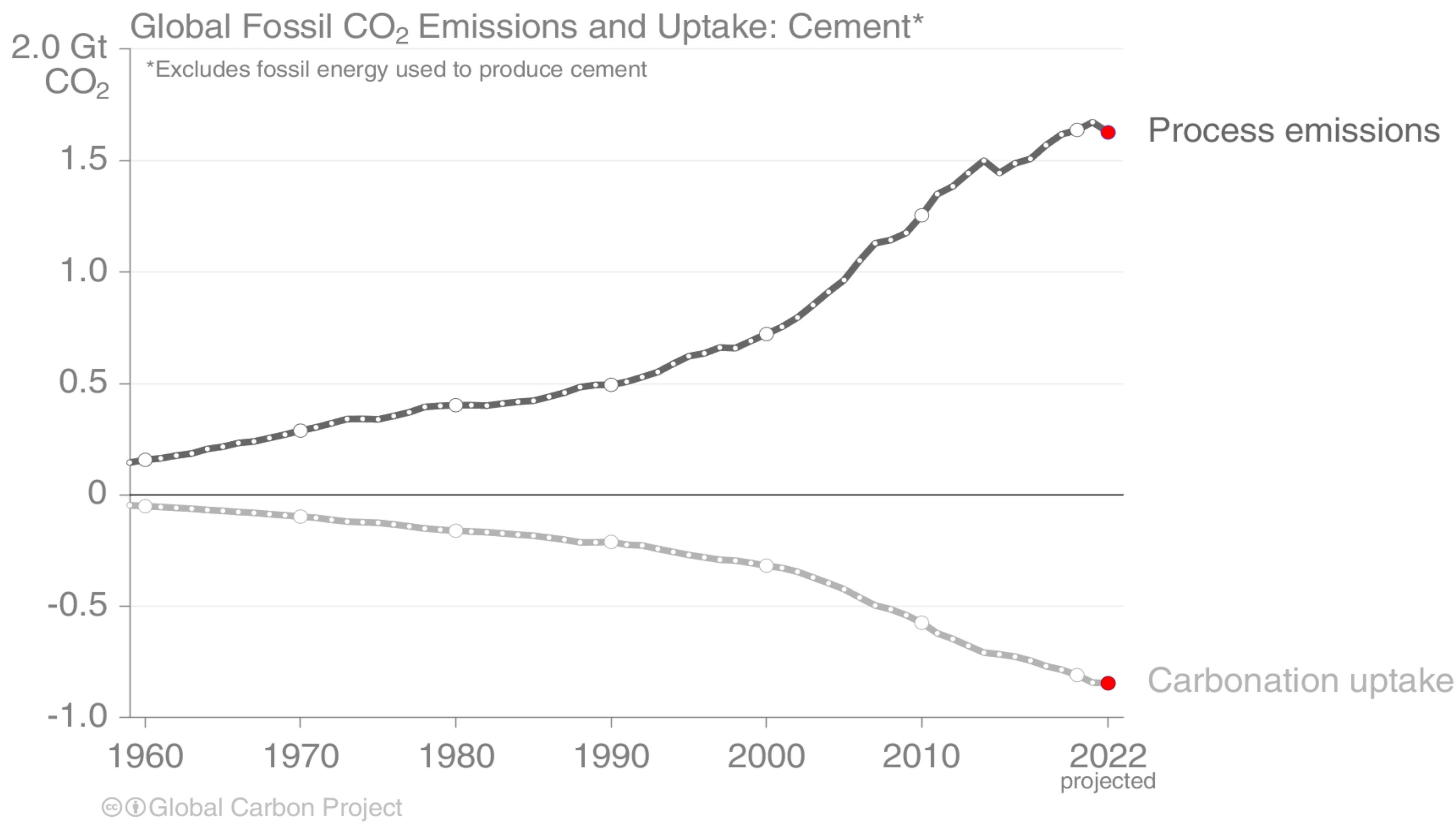
26%
2.5±0.5 PgC/yr

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

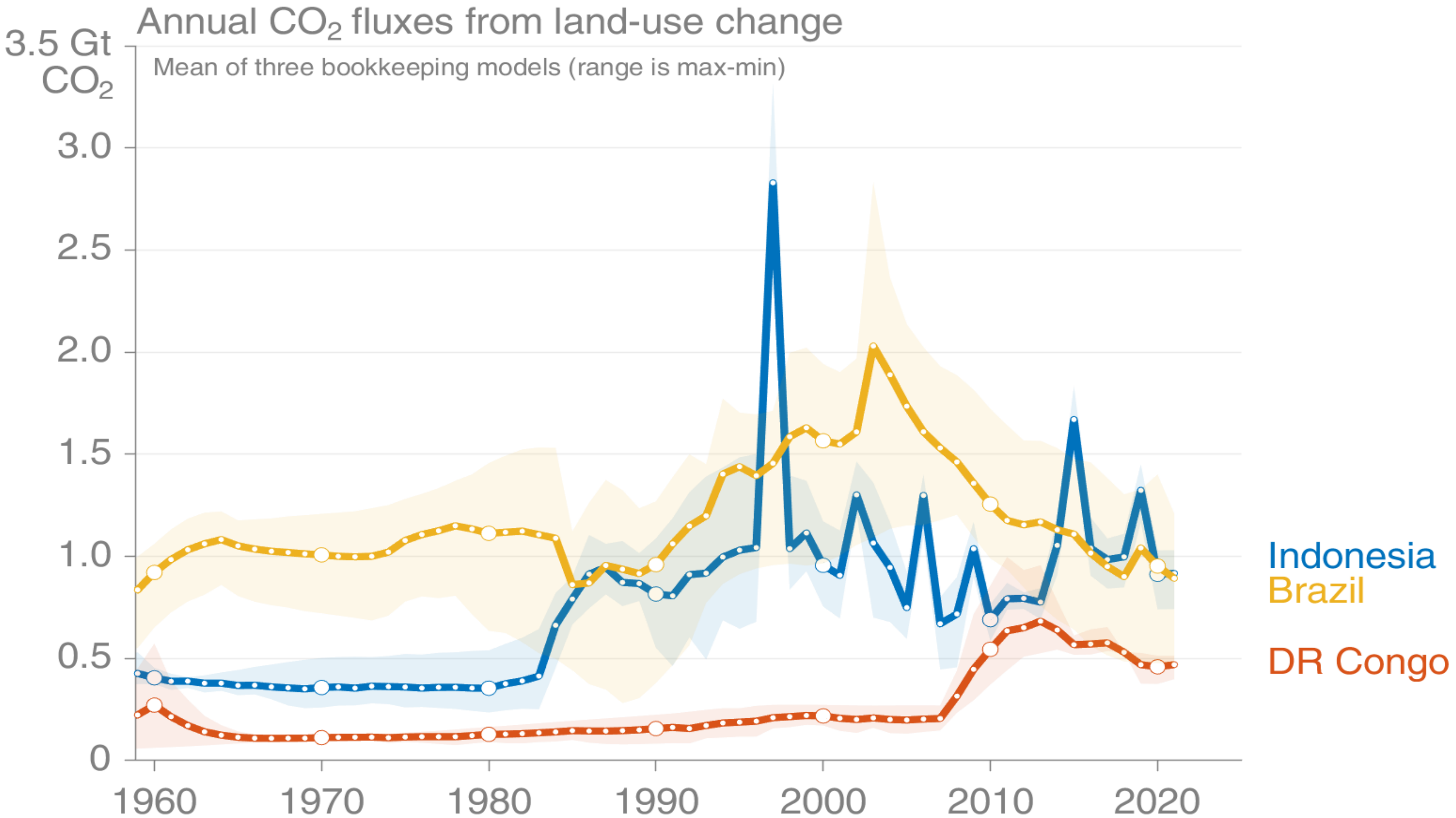


a
Fossil fuels and cement
b
Land-use change
CO2 emissions (GtC/yr)
c
Atmospheric growth
d
Ocean sink
e
Land sink
CO2 partitioning (GtC/yr)
0
5
10
1960
1970
1980
1990
2000
2010

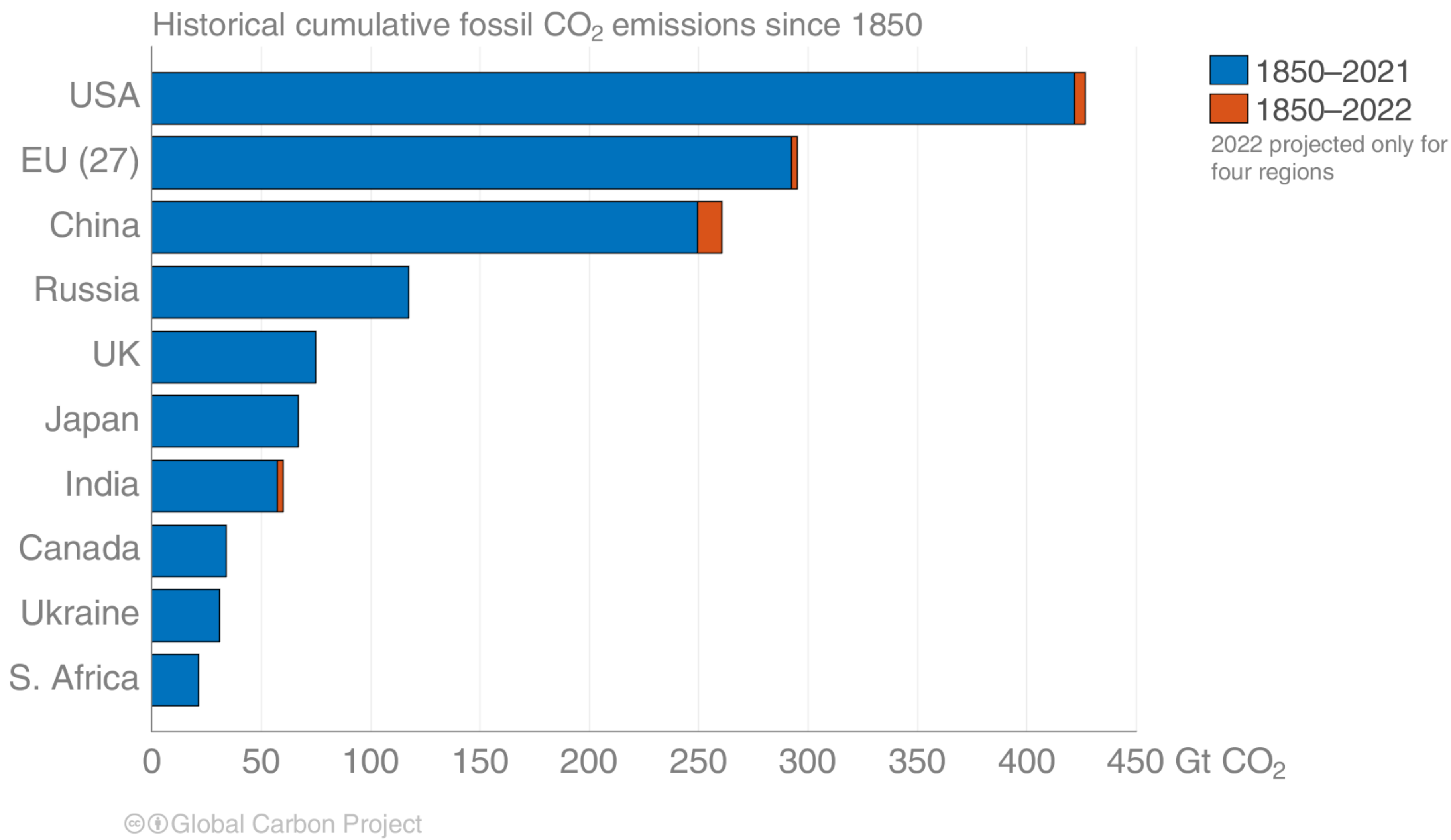

Data: CDIAC/GCP
CO2 emissions (GtC/yr)
0
2
4
6
8
10
1960
1970
1980
1990
2000
2010
Fossil fuels and cement
Land-use change



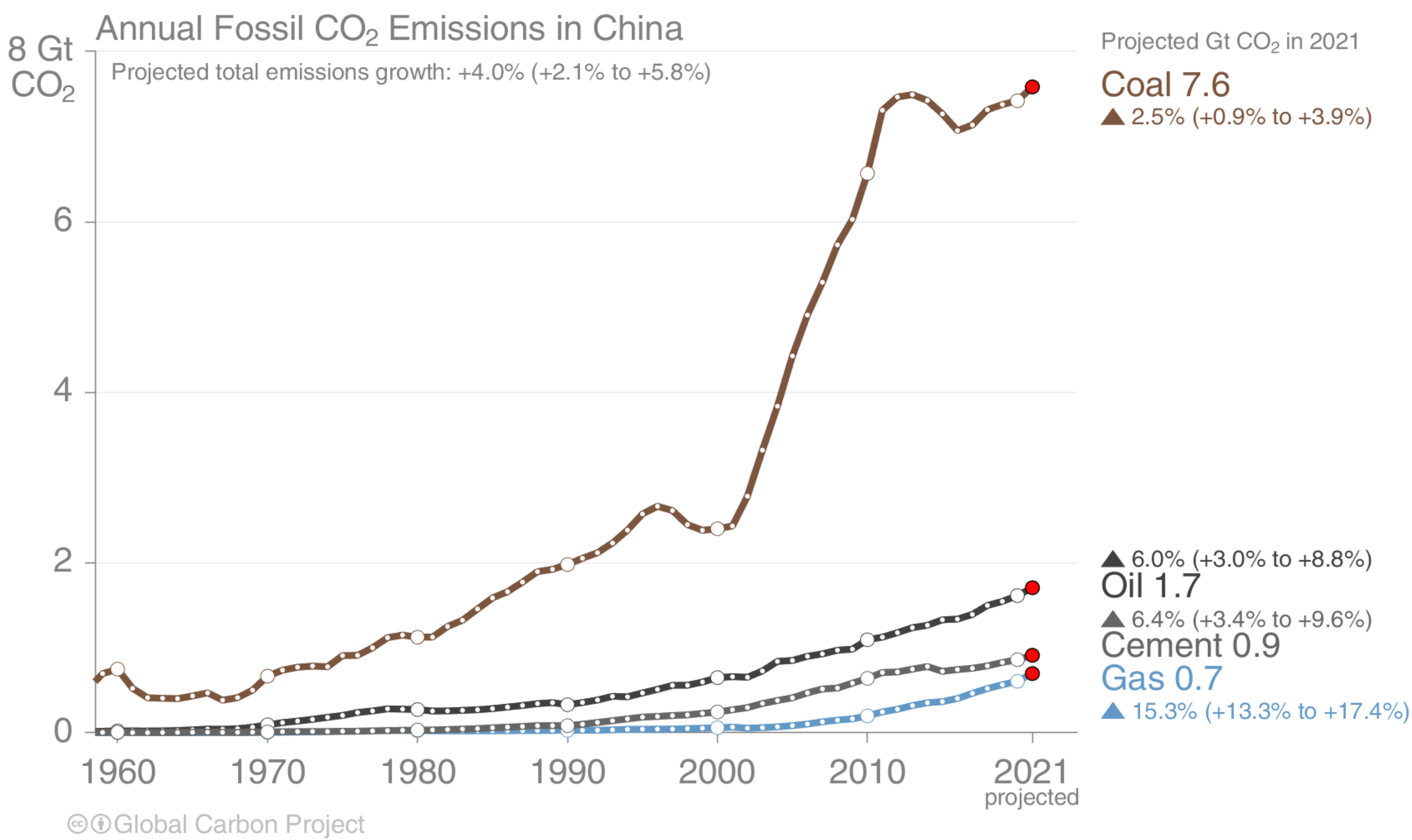
Global Fossil CO2 Emissions and Uptake: Cement*
*Excludes fossil energy used to produce cement
2.0 Gt CO2
1.5
1.0
0.5
0
-0.5
-1.0
Process emissions
Carbonation uptake
1960
1970
1980
1990
2000
2010
2022
projected
Global Carbon Project



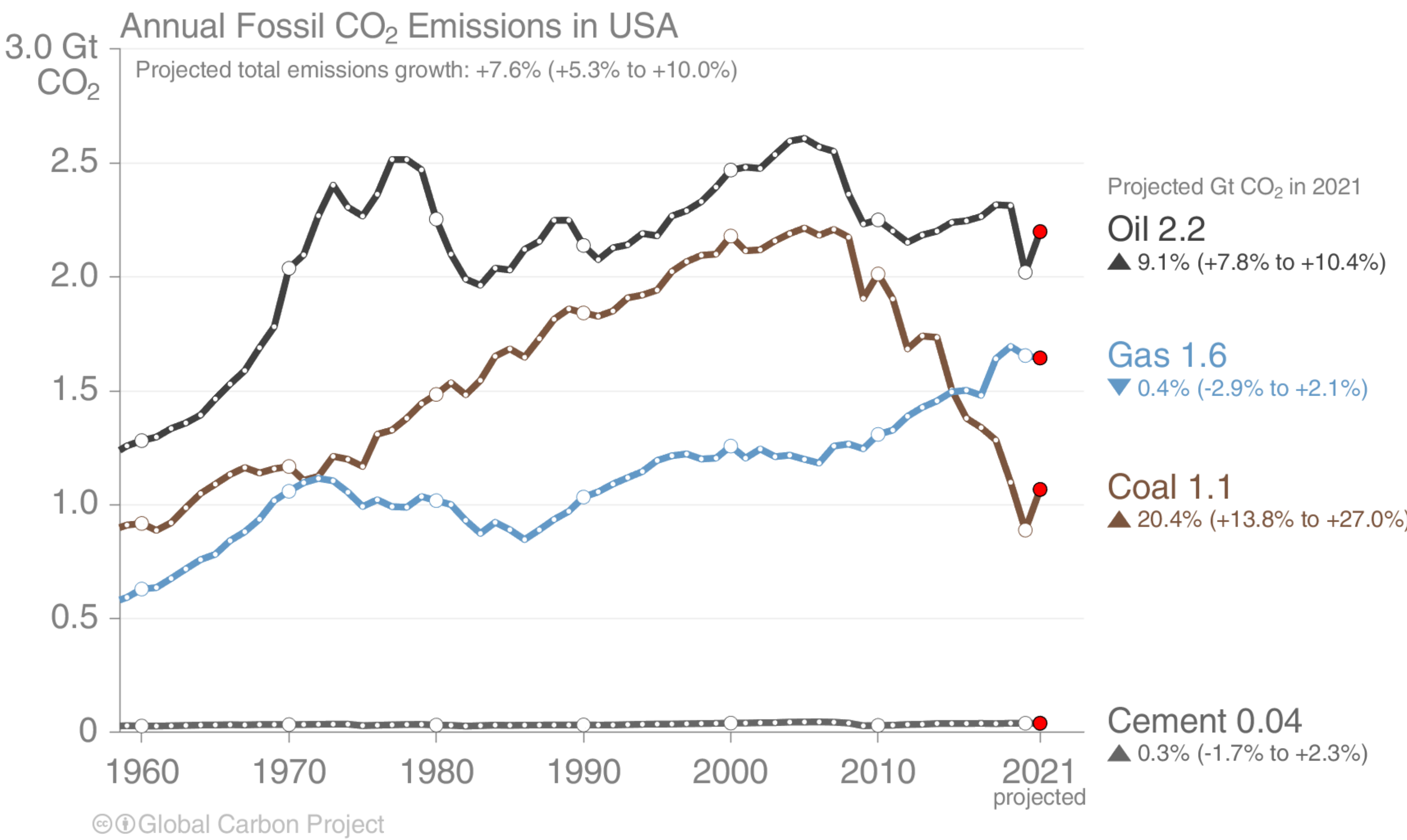
Annual CO2 fluxes from land-use change
Mean of three bookkeeping models (range is max-min)
3.5 Gt CO2
3.0
2.5
2.0
1.5
1.0
0.5
0
1960
1970
1980
1990
2000
2010
2020
Indonesia
Brazil
DR Congo

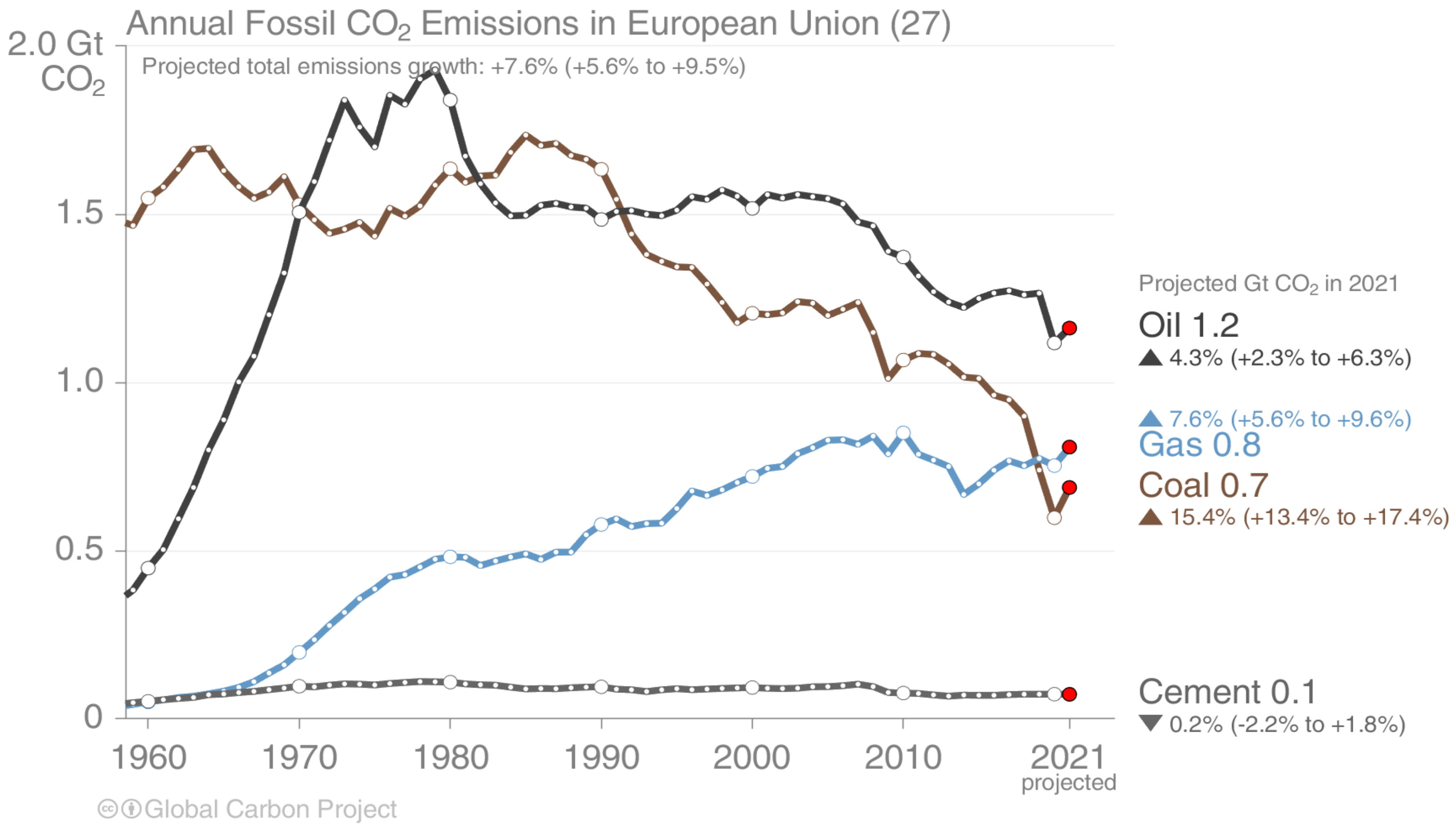


Historical cumulative fossil CO_2 emissions since 1850
USA
EU (27)
China
Russia
UK
Japan
India
Canada
Ukraine
S. Africa
0
50
100
150
200
250
300
350
400
450 Gt CO_2
1850–2021
1850–2022
2022 projected only for four regions
Global Carbon Project

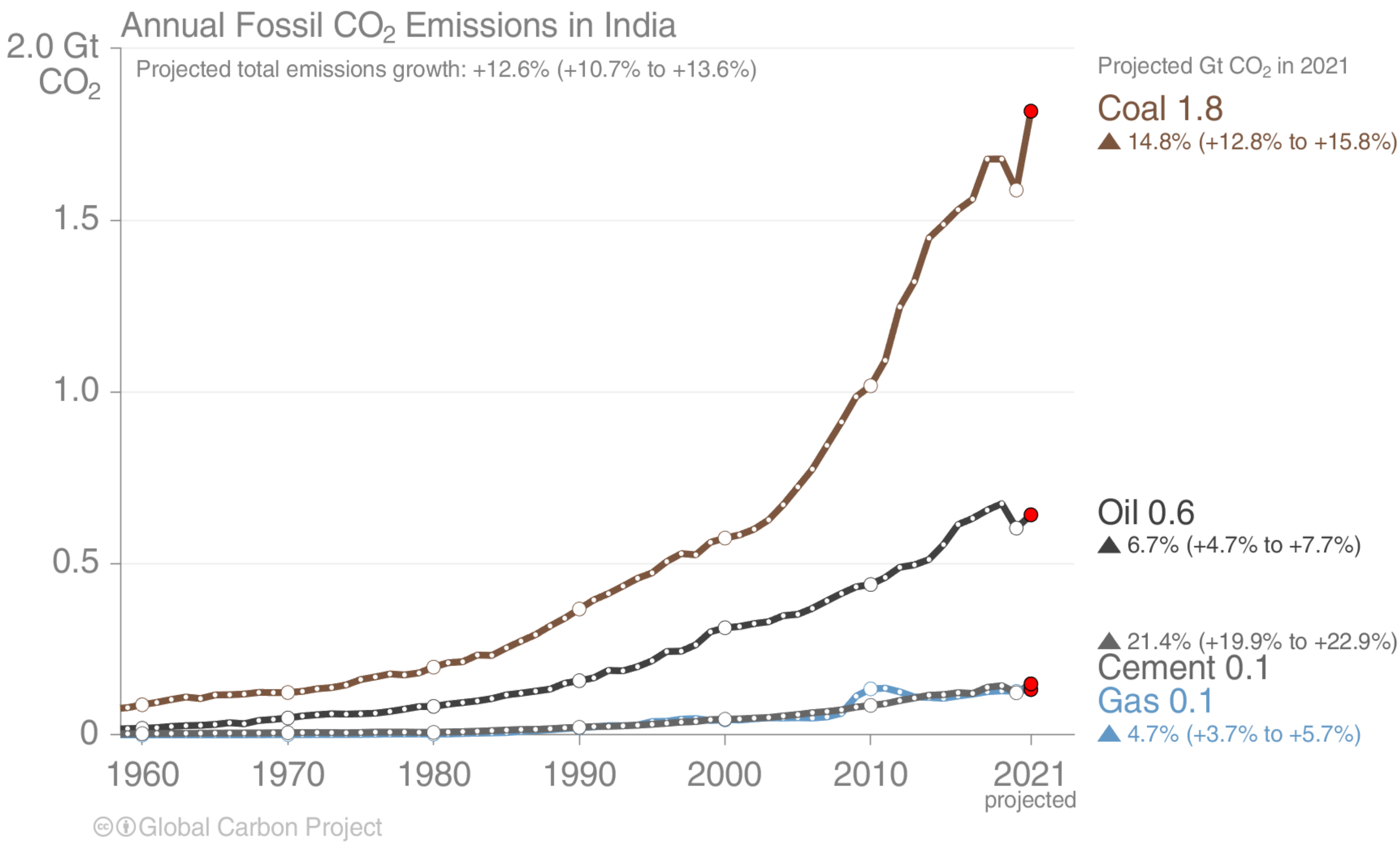


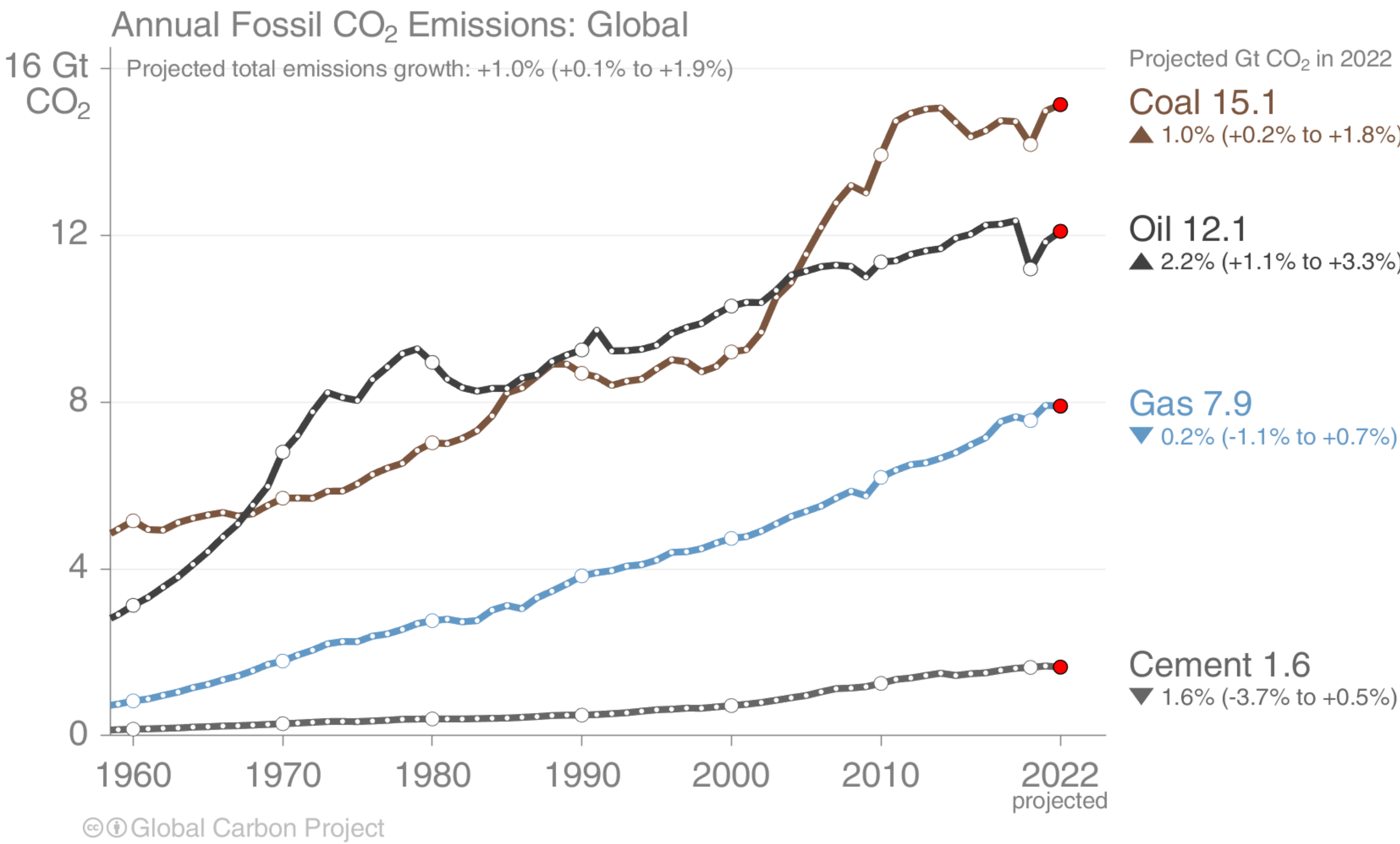
Annual Fossil CO_2 Emissions in China
8 Gt CO_2
Projected total emissions growth: +4.0% (+2.1% to +5.8%)
6
4
2
0
1960
1970
1980
1990
2000
2010
2021
projected
Projected Gt CO_2 in 2021
Coal 7.6
▲ 2.5% (+0.9% to +3.9%)
▲ 6.0% (+3.0% to +8.8%)
Oil 1.7
▲ 6.4% (+3.4% to +9.6%)
Cement 0.9
Gas 0.7
▲ 15.3% (+13.3% to +17.4%)
Global Carbon Project


Annual Fossil CO_2 Emissions in USA
3.0 Gt CO_2
Projected total emissions growth: +7.6% (+5.3% to +10.0%)
2.5
2.0
1.5
1.0
0.5
0
1960
1970
1980
1990
2000
2010
2021
projected
Projected Gt CO_2 in 2021
Oil 2.2
▲ 9.1% (+7.8% to +10.4%)
Gas 1.6
▼ 0.4% (-2.9% to +2.1%)
Coal 1.1
▲ 20.4% (+13.8% to +27.0%)
Cement 0.04
▲ 0.3% (-1.7% to +2.3%)
Global Carbon Project

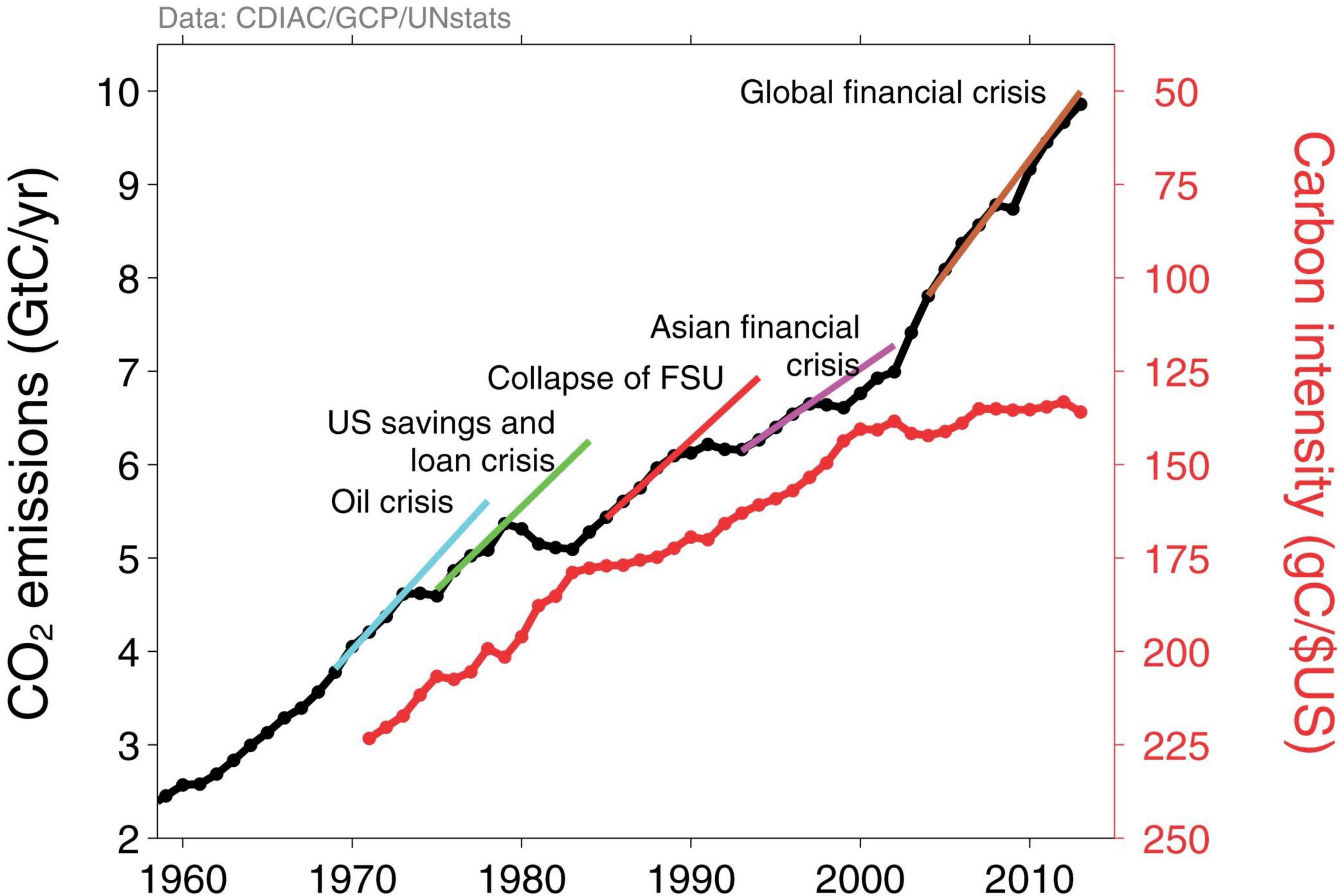


Annual Fossil CO_2 Emissions in European Union (27)
Projected total emissions growth: +7.6% (+5.6% to +9.5%)
2.0 Gt CO_2
1.5
1.0
0.5
0
1960
1970
1980
1990
2000
2010
2021
projected
Projected Gt CO_2 in 2021
Oil 1.2
▲ 4.3% (+2.3% to +6.3%)
▲ 7.6% (+5.6% to +9.6%)
Gas 0.8
Coal 0.7
▲ 15.4% (+13.4% to +17.4%)
Cement 0.1
▼ 0.2% (-2.2% to +1.8%)
Global Carbon Project


Annual Fossil CO2 Emissions in India
2.0 Gt CO2
Projected total emissions growth: +12.6% (+10.7% to +13.6%)
1.5
1.0
0.5
0
1960
1970
1980
1990
2000
2010
2021
projected
Projected Gt CO2 in 2021
Coal 1.8
14.8% (+12.8% to +15.8%)
Oil 0.6
6.7% (+4.7% to +7.7%)
21.4% (+19.9% to +22.9%)
Cement 0.1
Gas 0.1
4.7% (+3.7% to +5.7%)
Global Carbon Project



Annual Fossil CO2 Emissions: Global
16 Gt CO2
12
8
4
0
Projected total emissions growth: +1.0% (+0.1% to +1.9%)
Projected Gt CO2 in 2022
Coal 15.1
▲ 1.0% (+0.2% to +1.8%)
Oil 12.1
▲ 2.2% (+1.1% to +3.3%)
Gas 7.9
▼ 0.2% (-1.1% to +0.7%)
Cement 1.6
▼ 1.6% (-3.7% to +0.5%)
1960
1970
1980
1990
2000
2010
2022
projected
Global Carbon Project

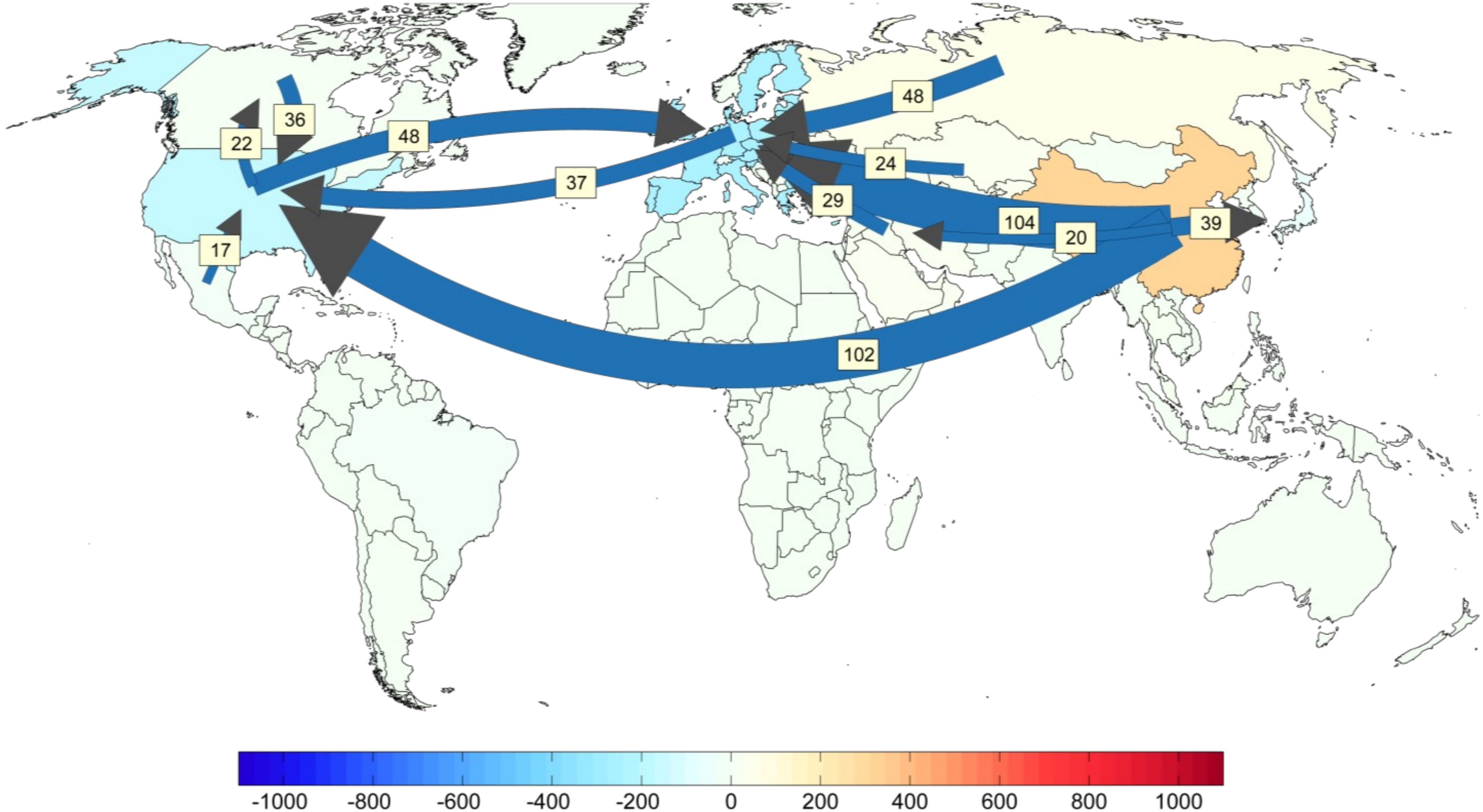


Data: CDIAC/GCP/UNstats
CO2 emissions (GtC/yr)
Carbon intensity (gC/$US)
Global financial crisis
Asian financial crisis
Collapse of FSU
US savings and loan crisis
Oil crisis
10
9
8
7
6
5
4
3
2
50
75
100
125
150
175
200
225
250
1960
1970
1980
1990
2000
2010

Major flows from Production to Consumption

Start of Arrow: fossil-fuel consumption (production)

End of arrow: goods and services consumption

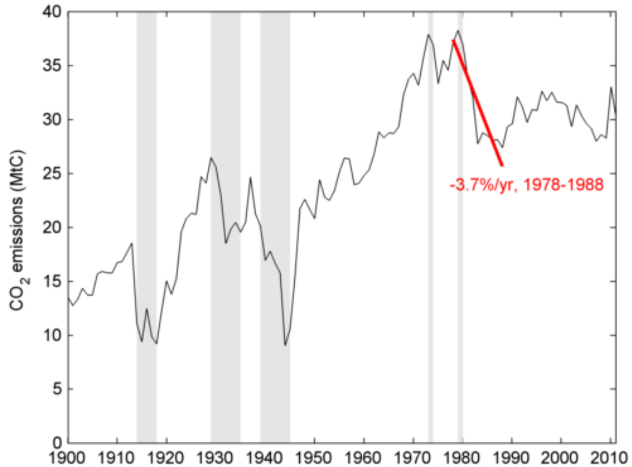


Values for 2007. EU27 is treated as one region. Units: TgC=PgC/1000

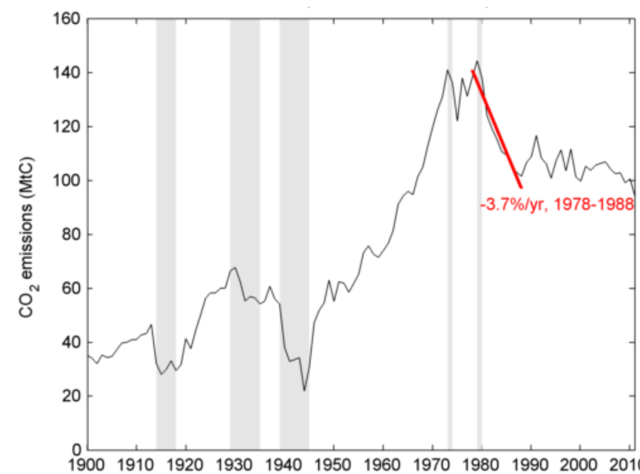
Source: Peters et al 2012b

Previous CO_2 emission reductions

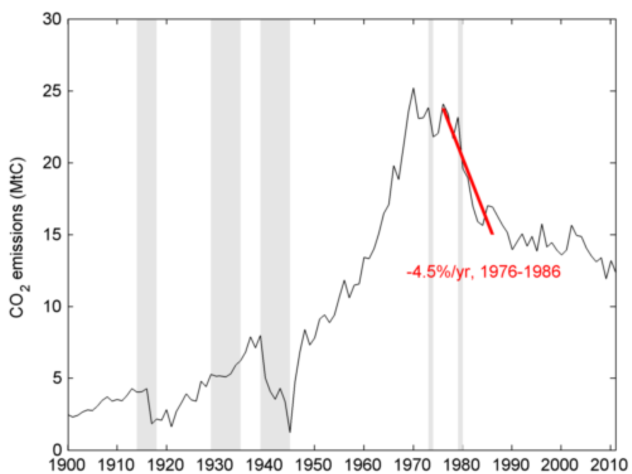
Without climate policies, some countries have reduced emissions at 1-5%/yr
Repeating with modern low-carbon technologies can “kick-start” mitigation



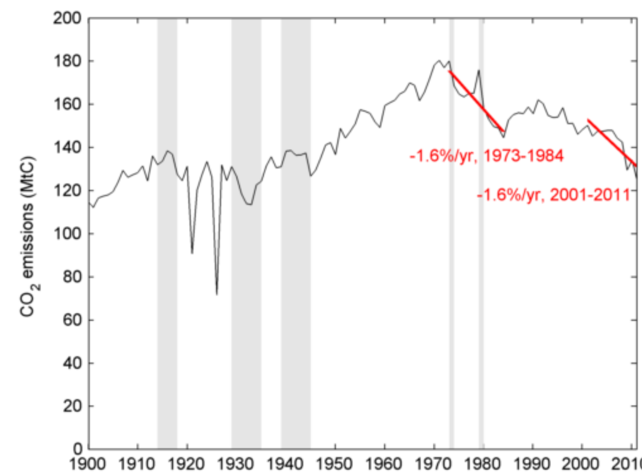
Belgium
Increased Nuclear
Reduced Oil



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

Closing the Global Carbon Budget

GLOBAL CARBON project

Fate of anthropogenic CO_2 emissions (2012–2021)

Sources = Sinks

35.2 $GtCO_2$/yr
89%

11%
4.5 $GtCO_2$/yr

19.1 $GtCO_2$/yr
48%

29%
11.4 $GtCO_2$/yr

26%
10.5 $GtCO_2$/yr

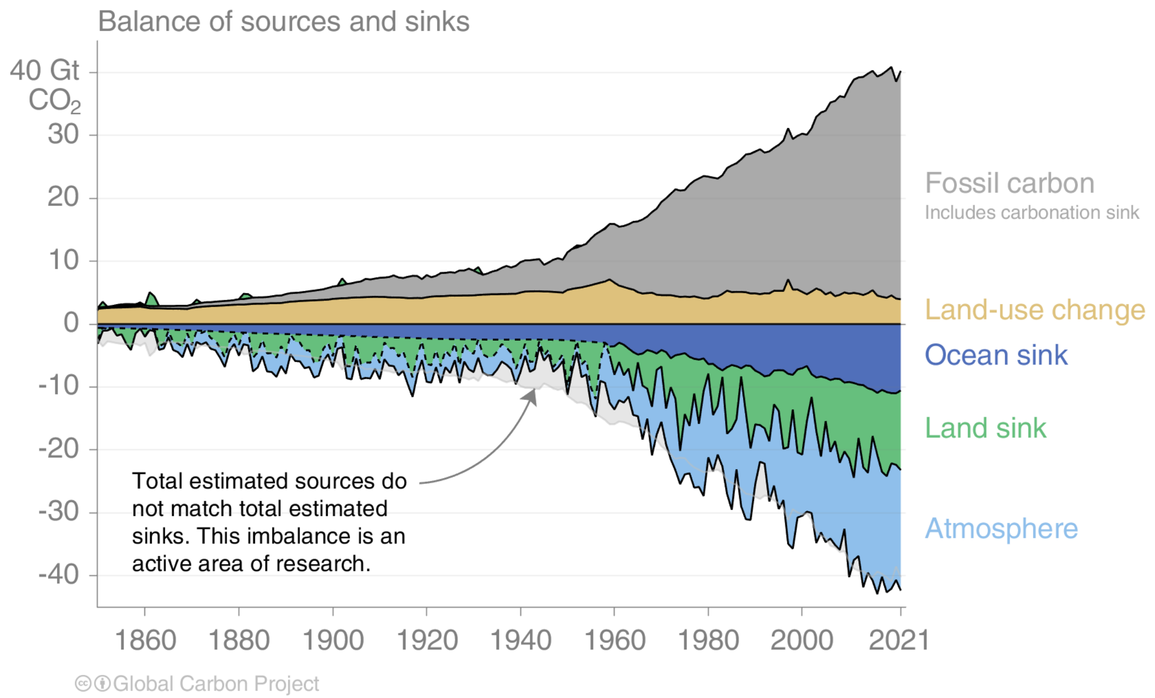
Budget Imbalance:
(the difference between estimated sources & sinks)

3%
-1.2 $GtCO_2$/yr

Source: Friedlingstein et al 2022; Global Carbon Project 2022

Global carbon budget

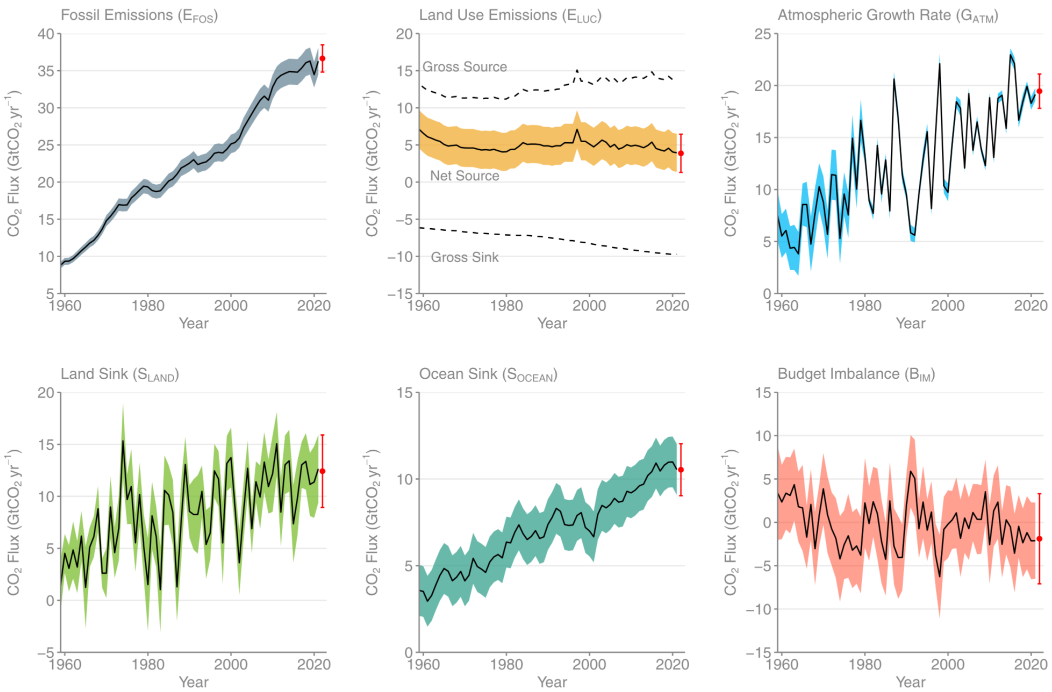
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean
The "imbalance" between total emissions and total sinks is an active area of research



Source: Friedlingstein et al 2022; Global Carbon Project 2022

Changes in the budget over time

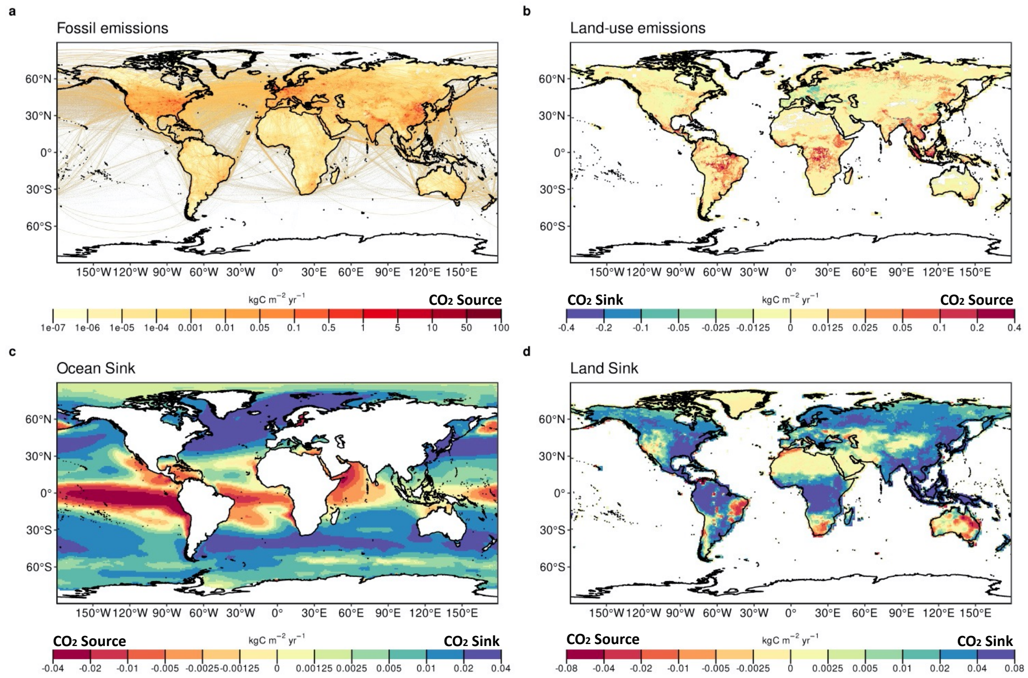
The sinks have continued to grow with increasing emissions, but climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere



The budget imbalance is the total emissions minus the estimated growth in the atmosphere, land and ocean.
It reflects the limits of our understanding of the carbon cycle.
Source: Friedlingstein et al 2022; Global Carbon Project 2022

Global carbon budget

Fossil emissions dominate in the Northern Hemisphere, while land-use emissions are important in the tropics. The North Atlantic and Southern Ocean are carbon sinks while the tropical ocean is a source of CO_2. Tropical, temperate and boreal forest are the main terrestrial carbon sinks

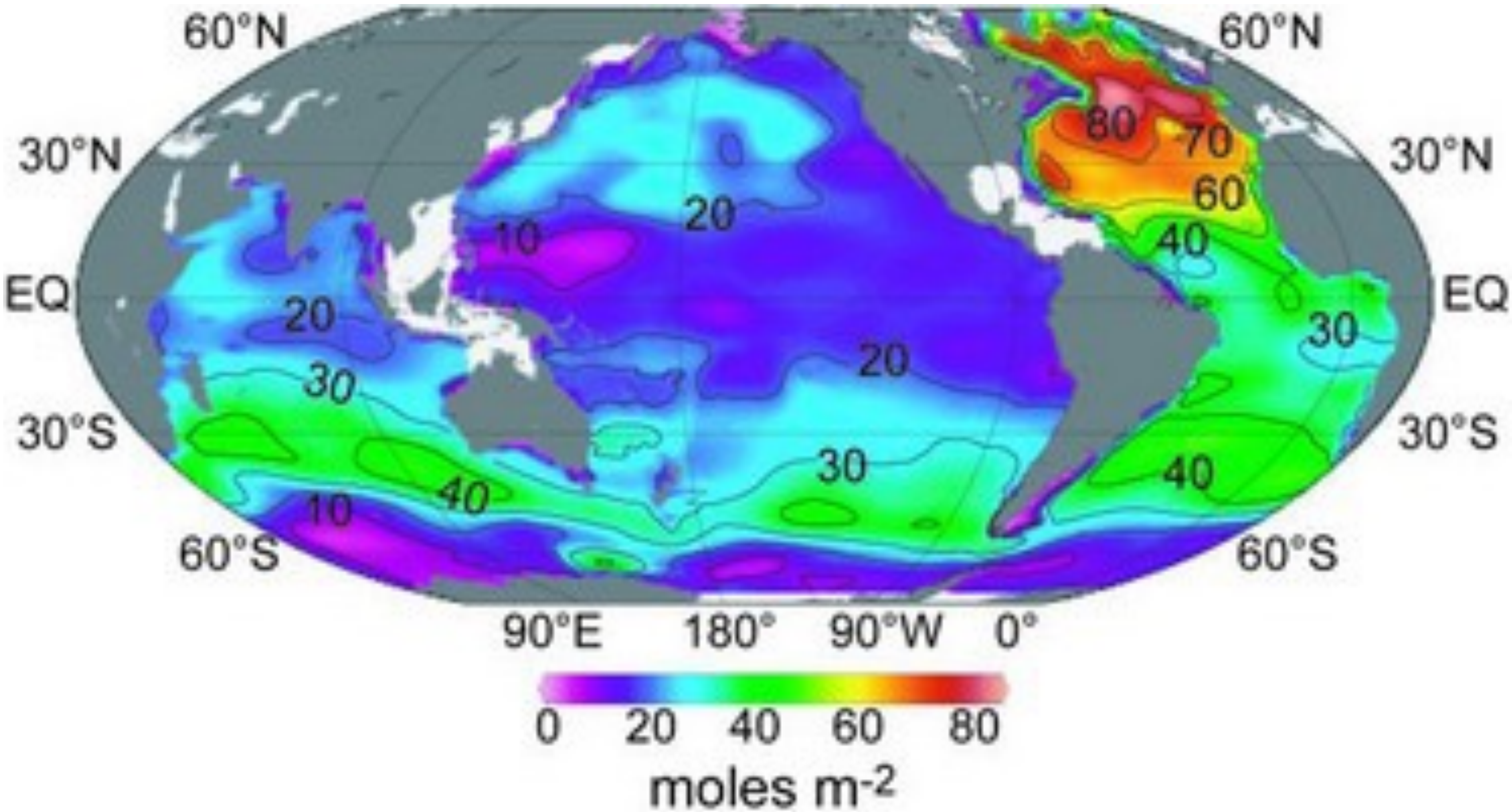


Source: Friedlingstein et al 2022; Global Carbon Budget 2022

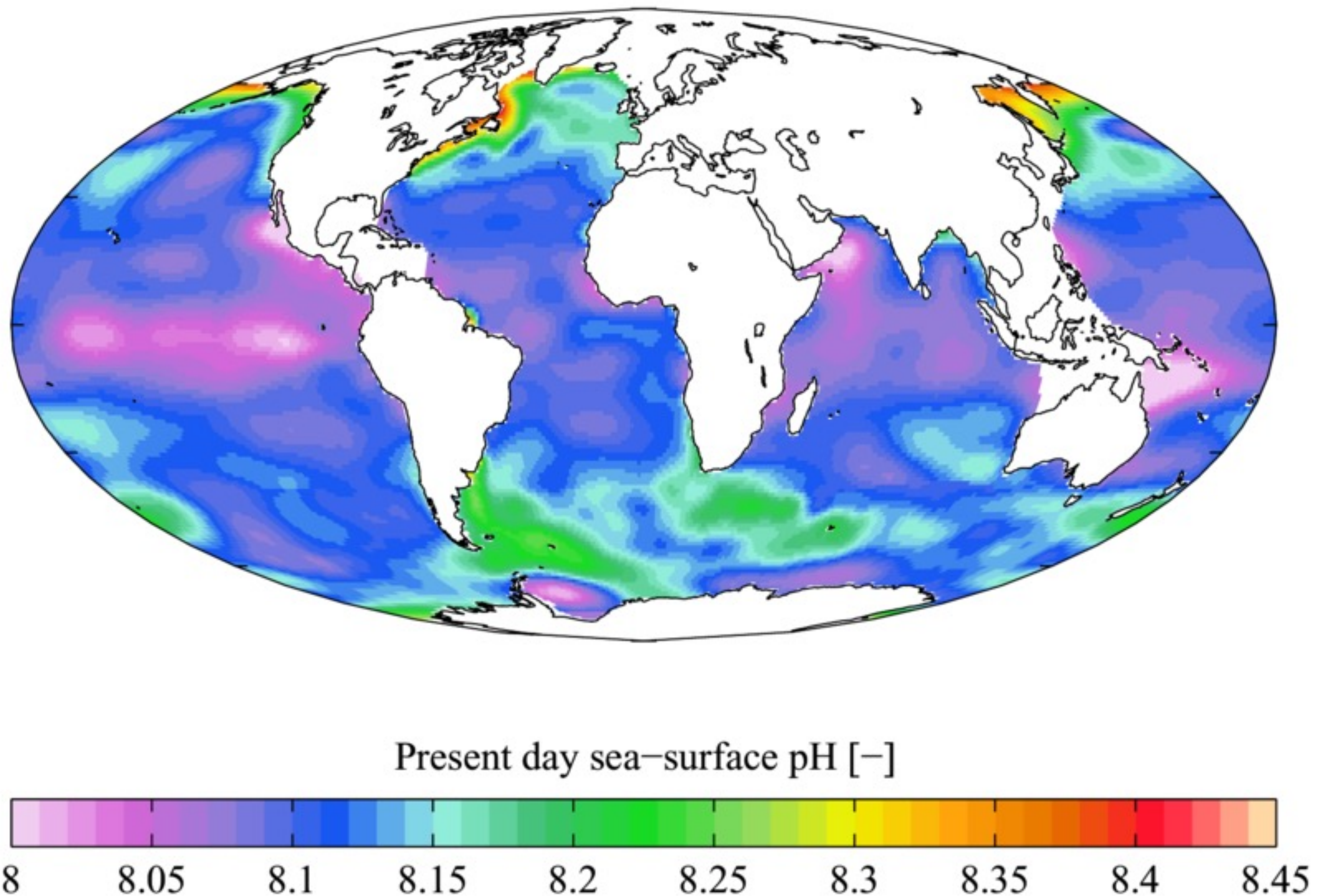
Ocean Acidification

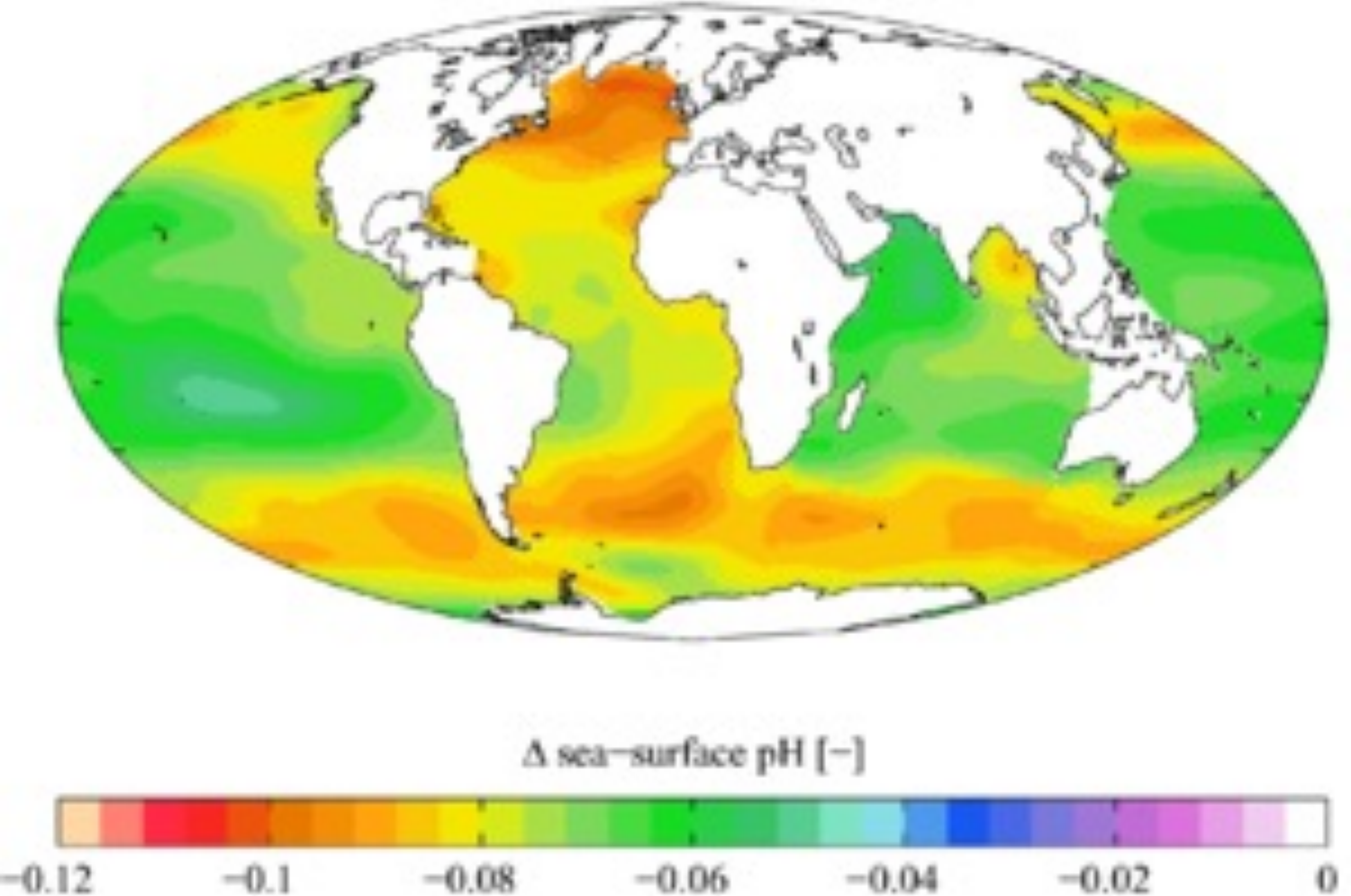
Quantities of Gas in Air and Seawater

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, Inertgases (He, Ar, Ne)	0.95	1.4	1.5

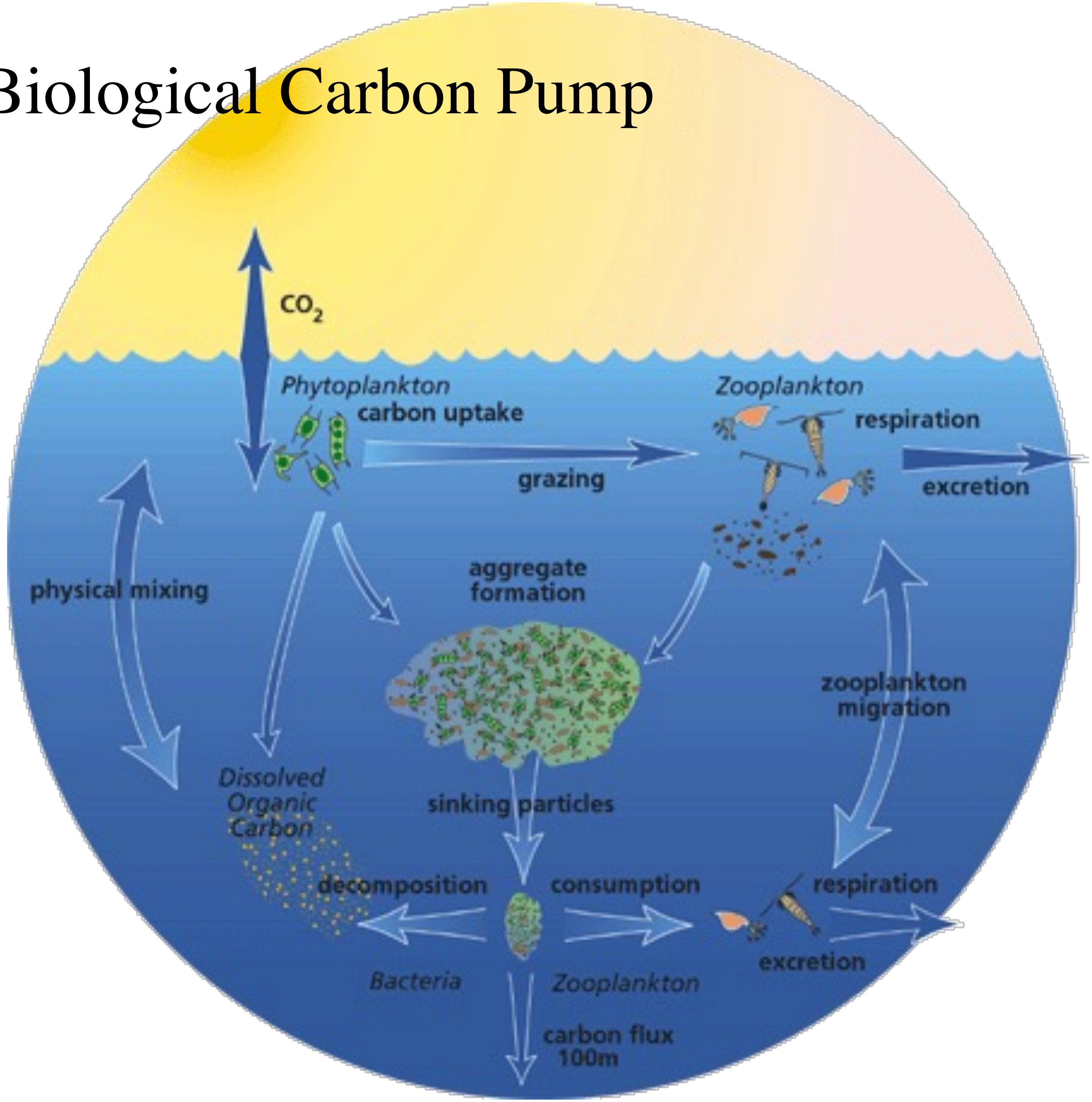


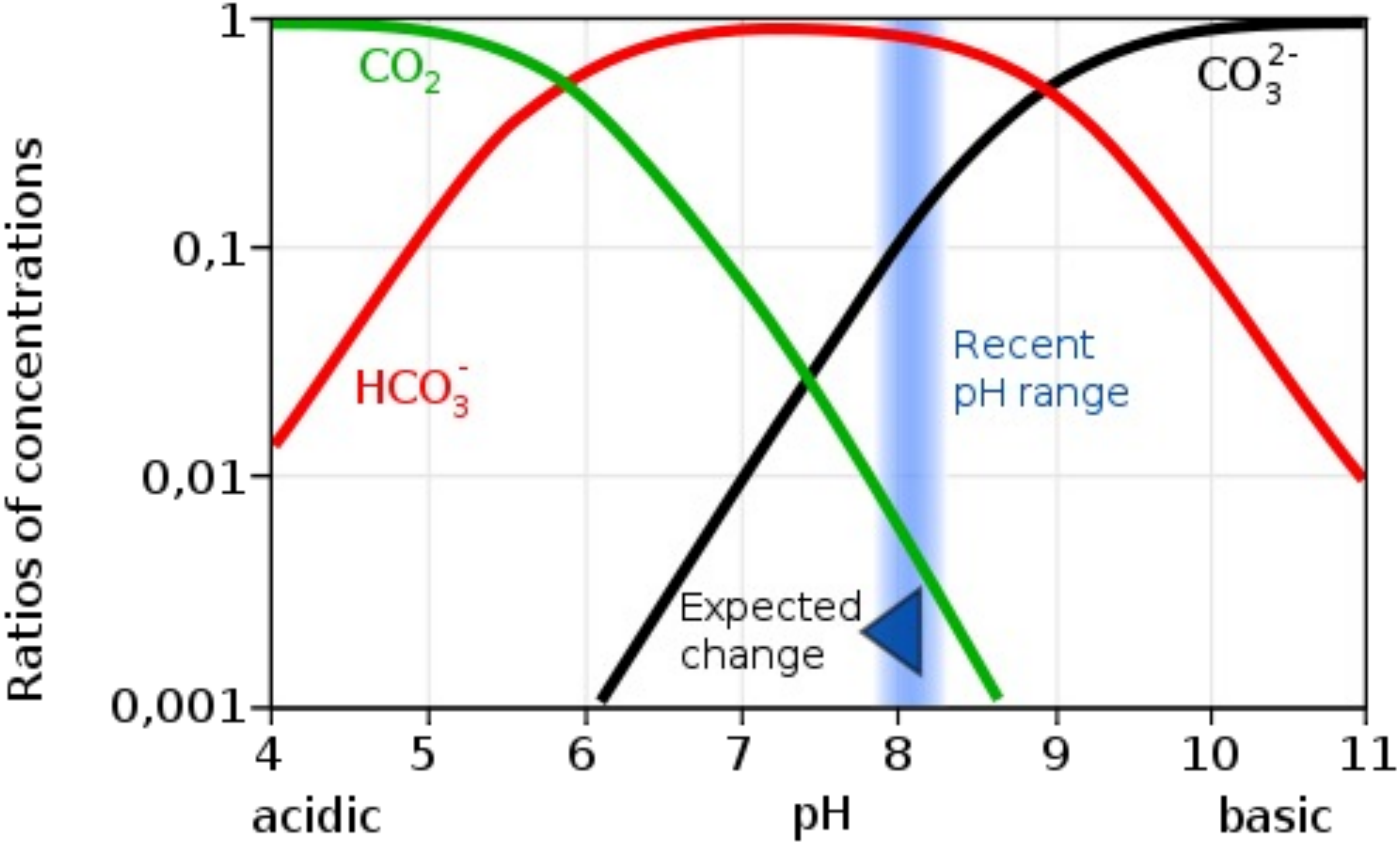
Column Anthropogenic CO_2 (Sabine et al. 2004)


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

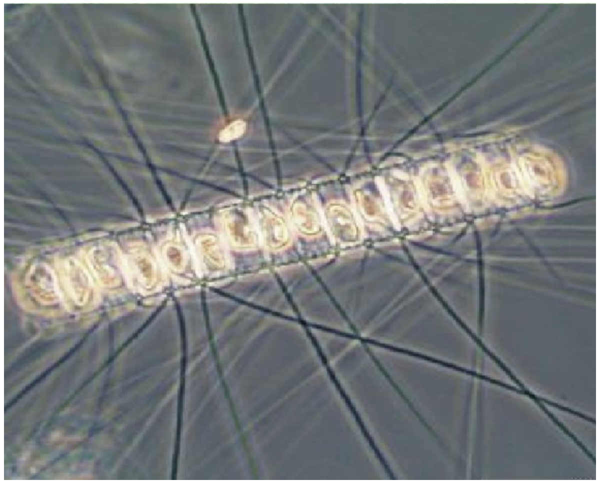

Δ sea−surface pH [−]
−0.12
−0.1
−0.08
−0.06
−0.04
−0.02
0

The Biological Carbon Pump



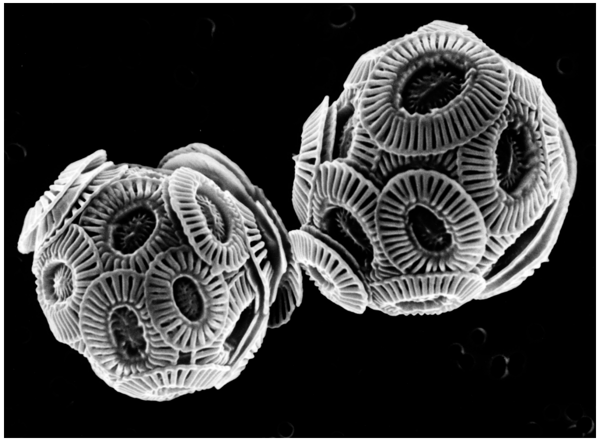

Ratios of concentrations
1
0,1
0,01
0,001
CO_2
HCO_3^-
CO_3^{2-}
Recent
pH range
Expected
change
4
5
6
7
8
9
10
11
acidic
pH
basic

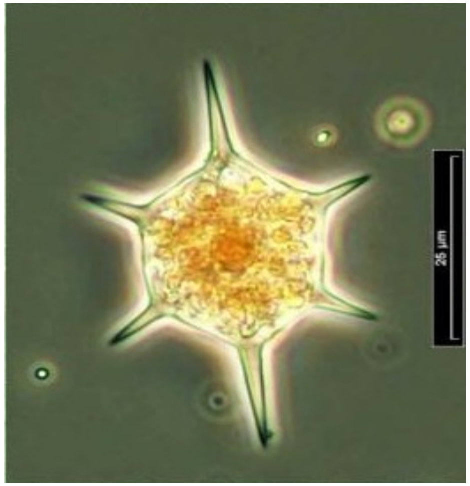
Ocean acidification and species composition



Chaetoceros costatus
(Diatom)

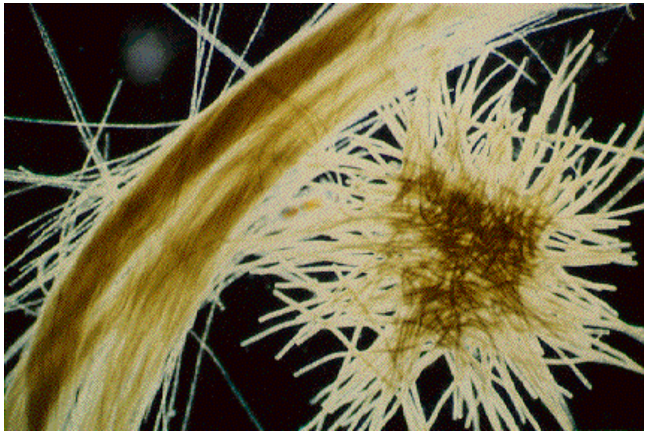
Emiliania huxleii
(Coccolithophorids)

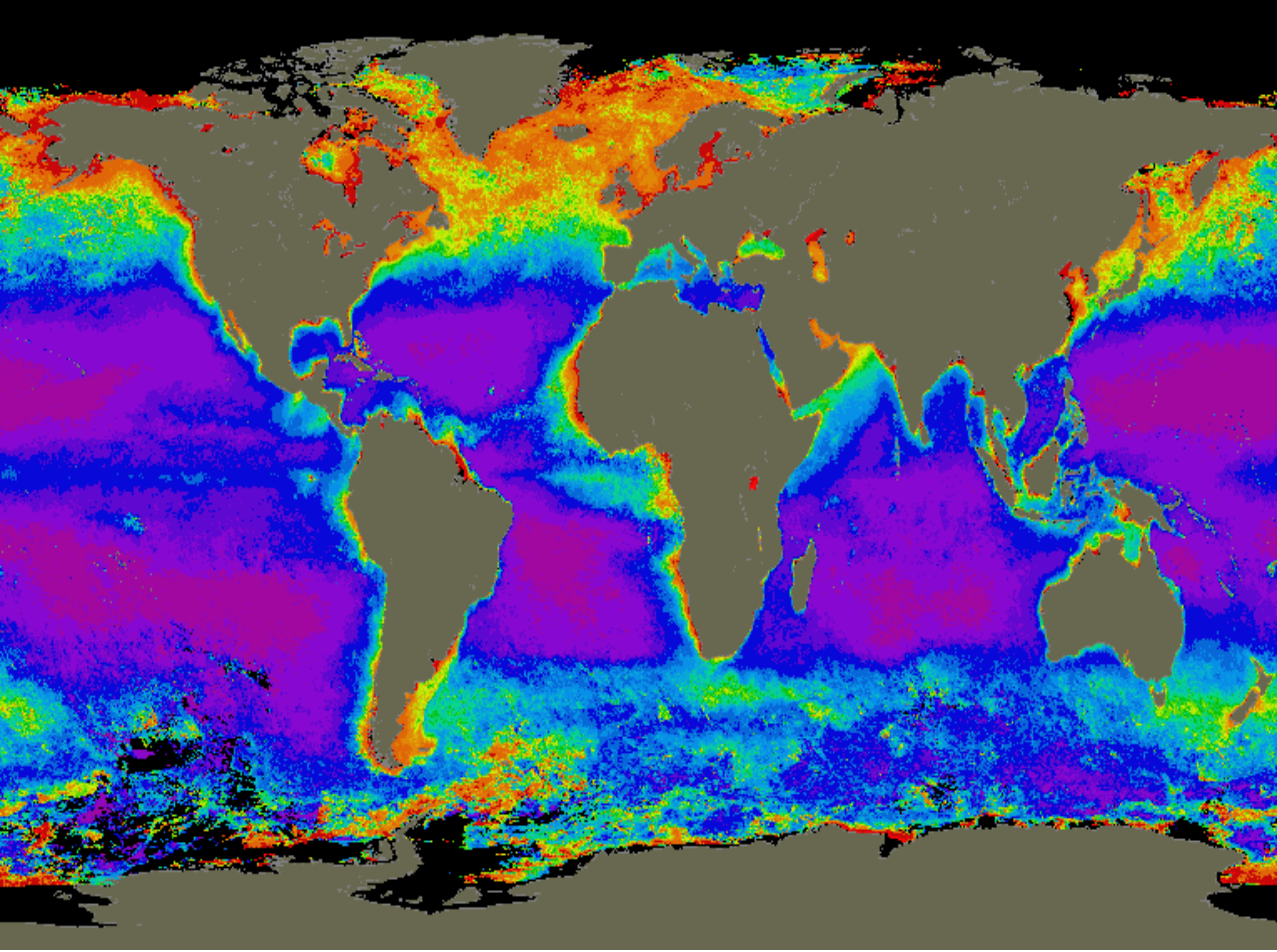


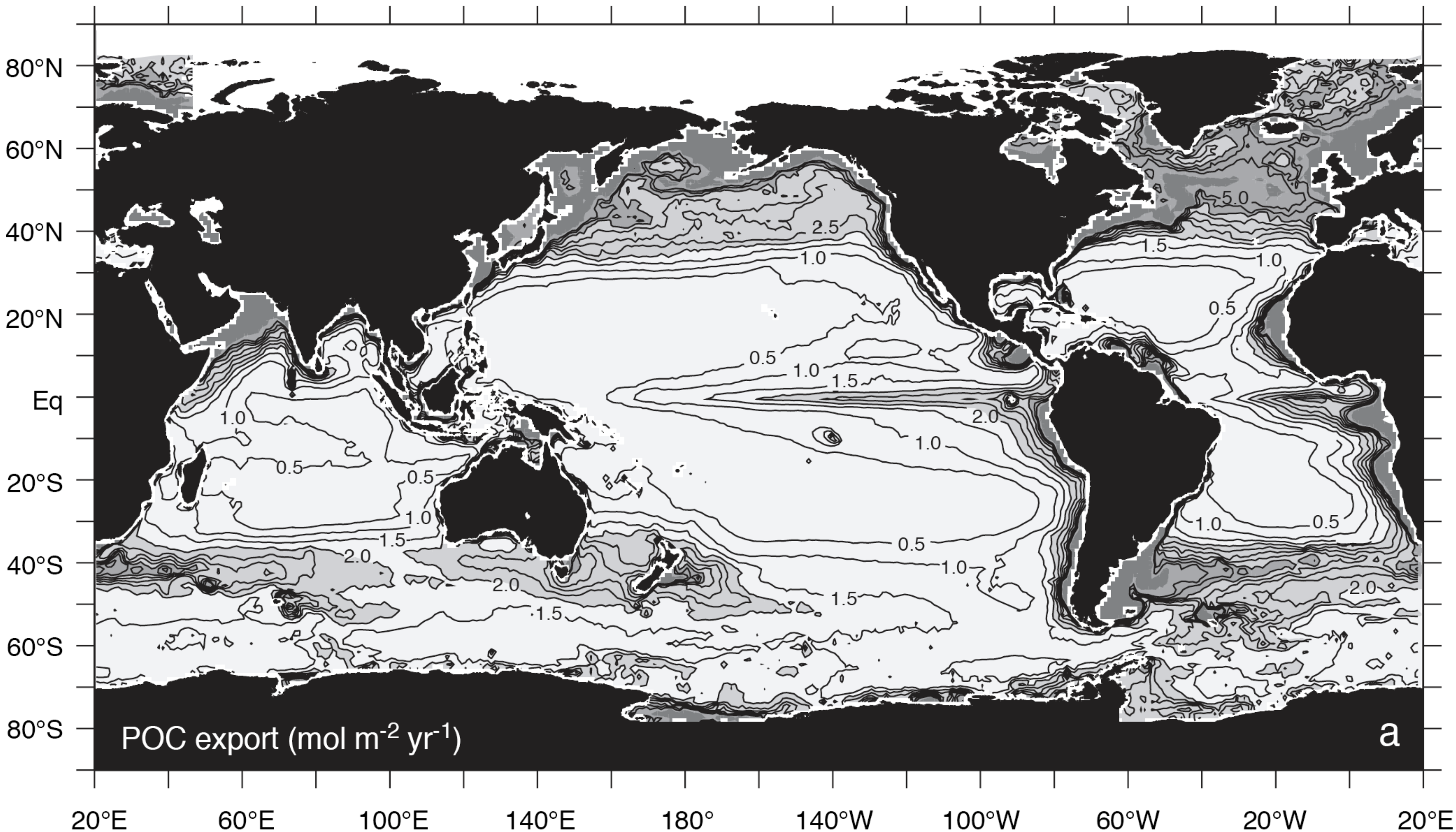


Distephanus speculum
(Silicoflagellate)

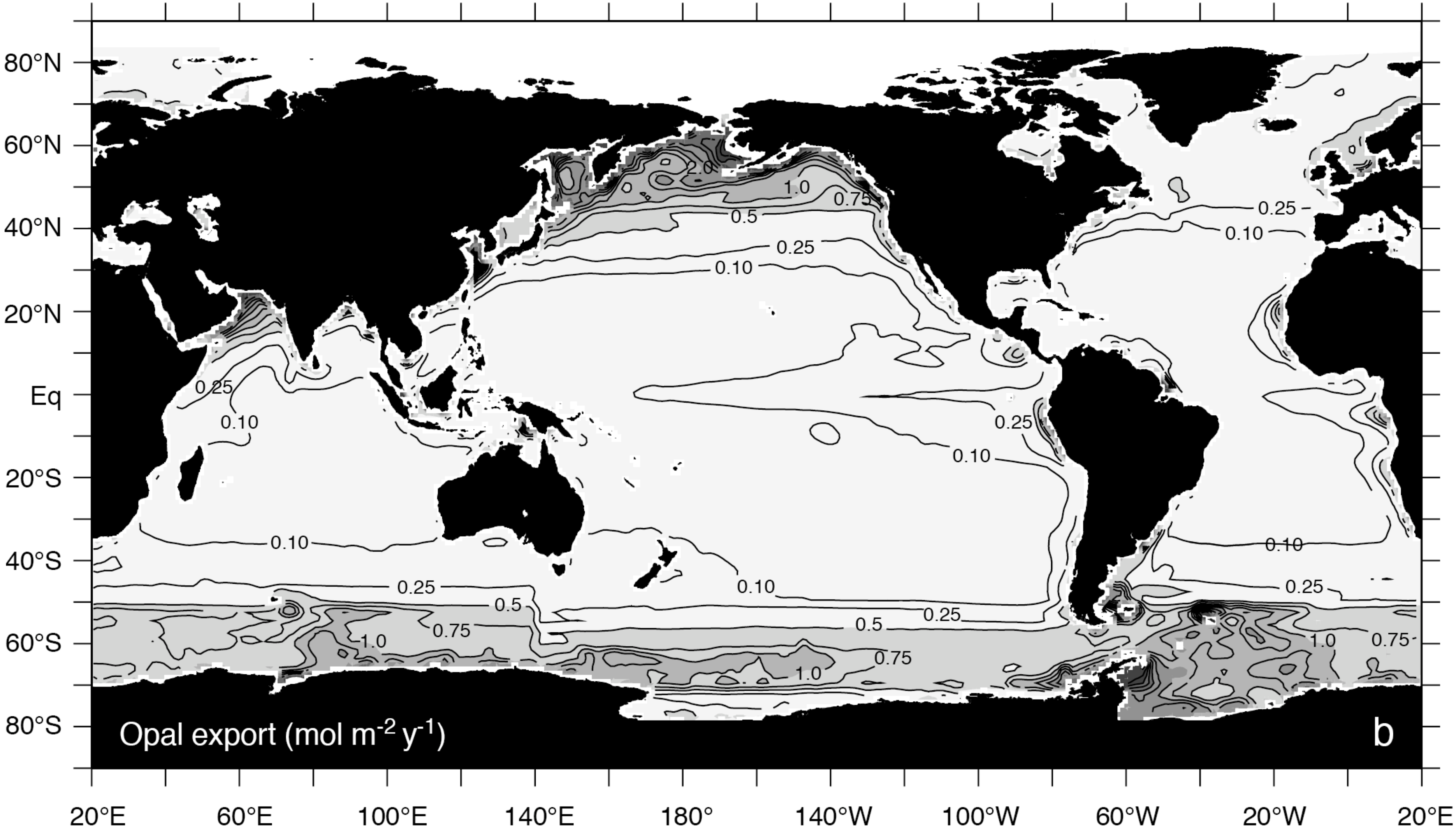
Trichodesmium
(Cyanobacterium)



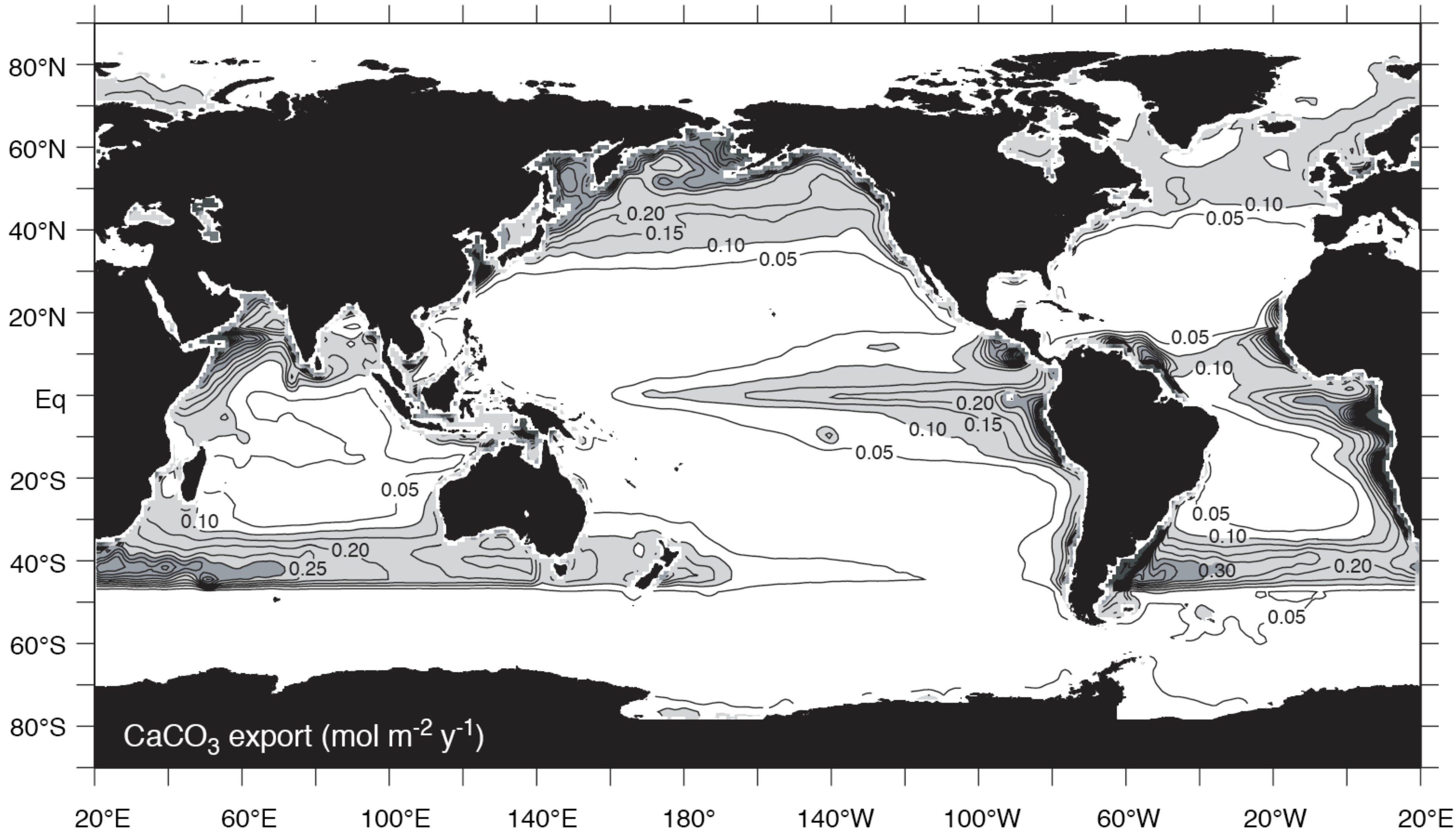




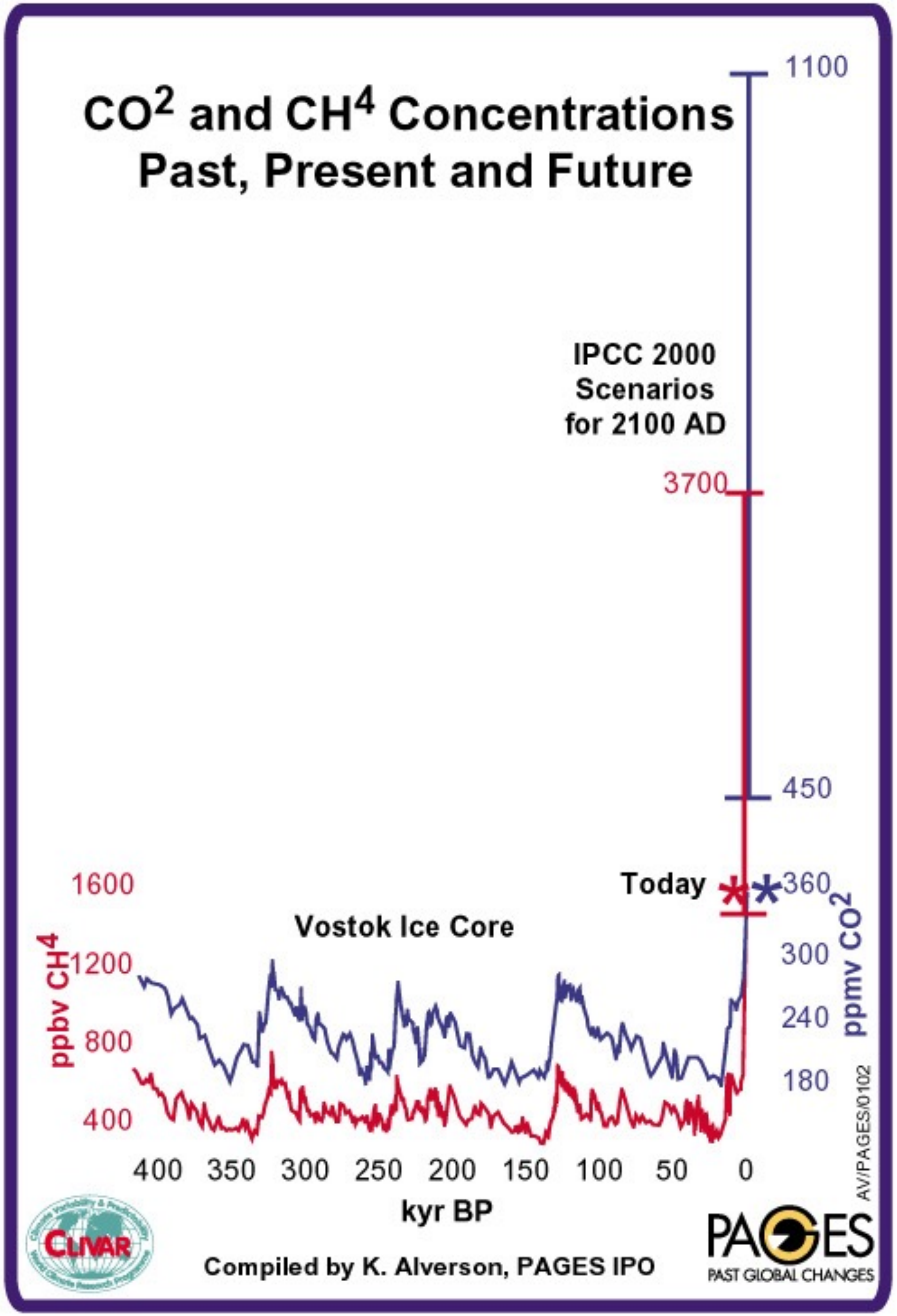
Export of particulate organic carbon (POC) to deep ocean.



Export of SiO_2 to deep ocean by diatom ecosystem.

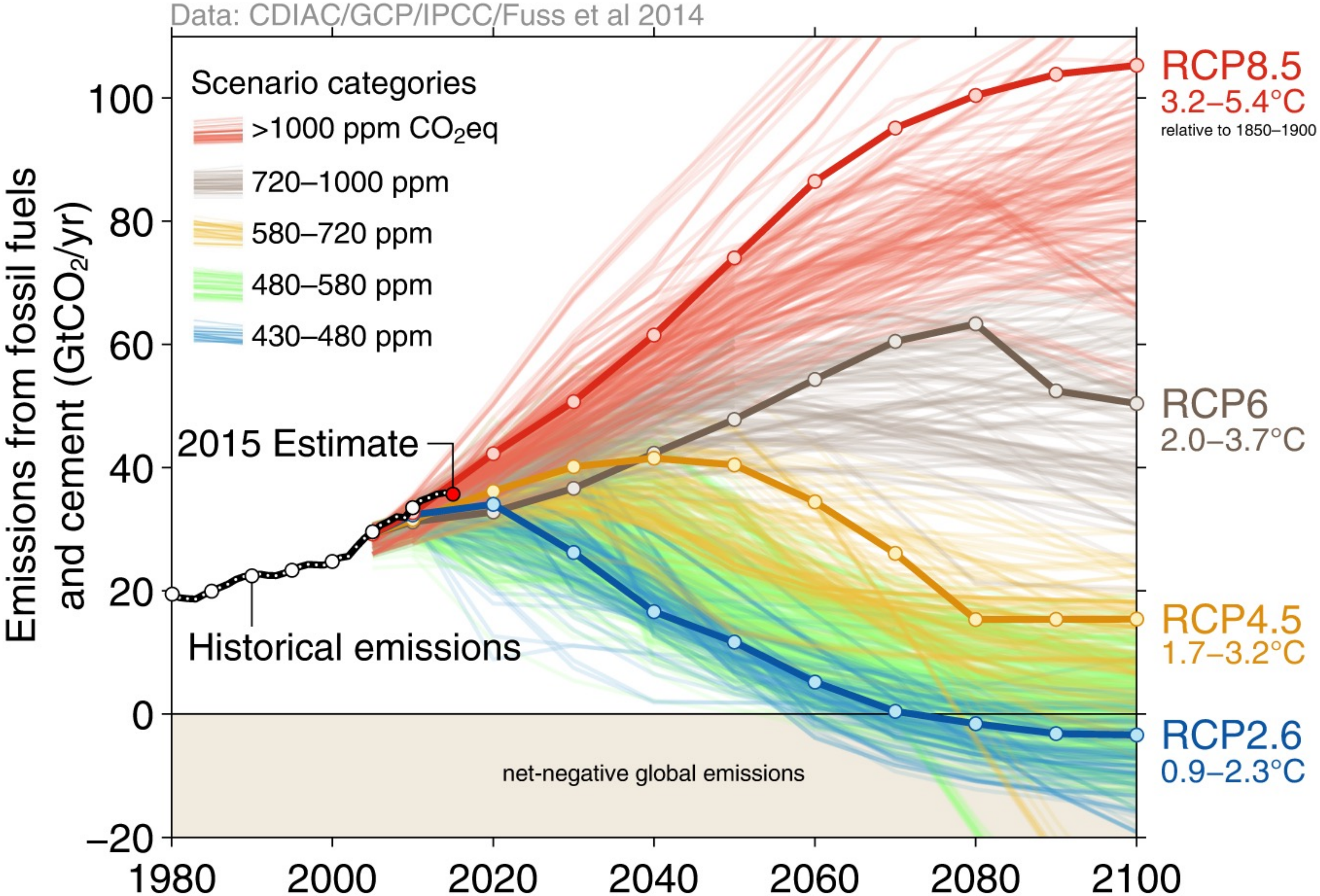


Export of $CaCO_3$ to deep ocean by coccolithophore ecosystem.


CO2 and CH4 Concentrations
Past, Present and Future
1100
IPCC 2000
Scenarios
for 2100 AD
3700
450
Today
360
1600
Vostok Ice Core
1200
300
240
800
180
400
ppbv CH4
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

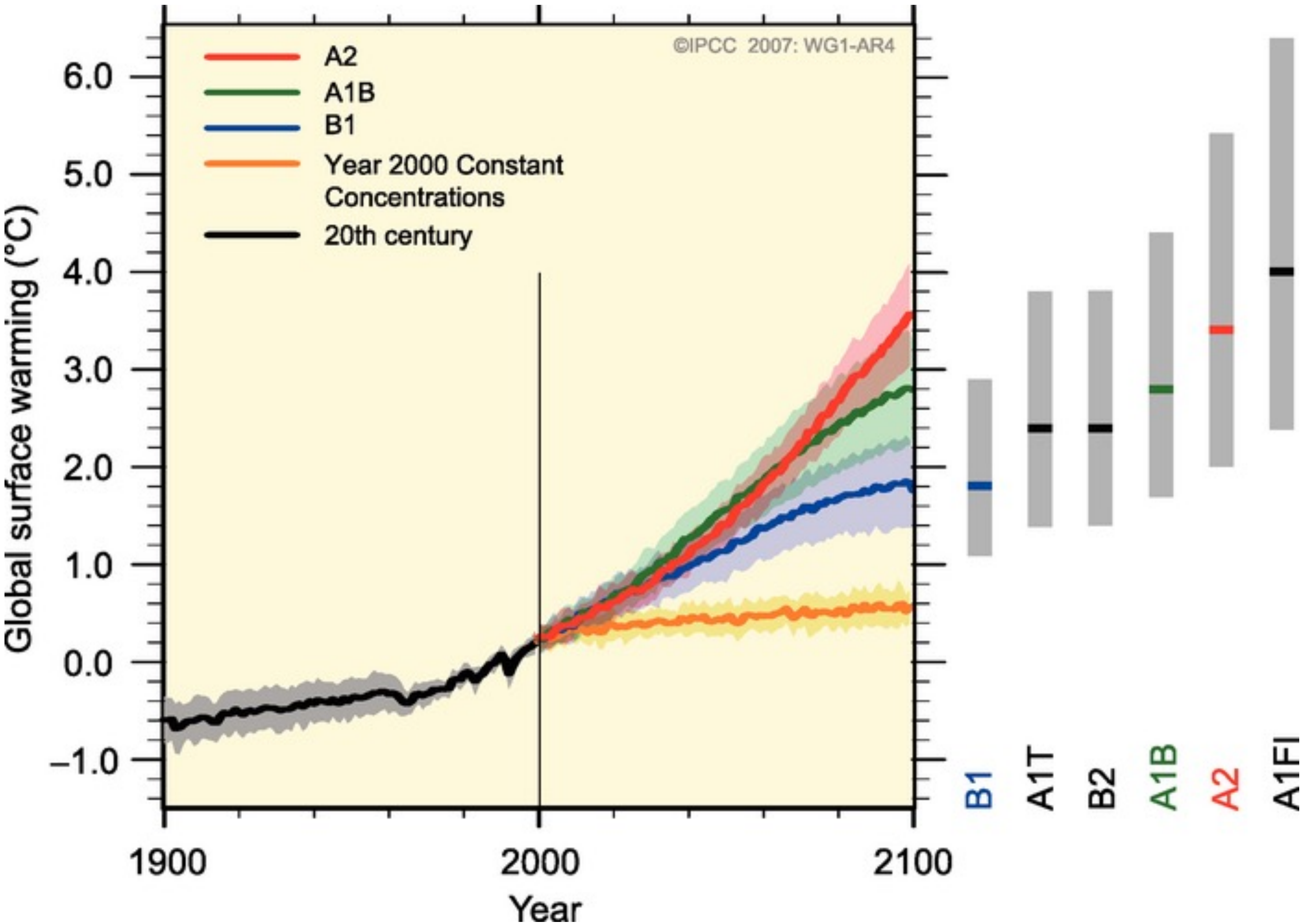
Observed emissions and emissions scenarios

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)



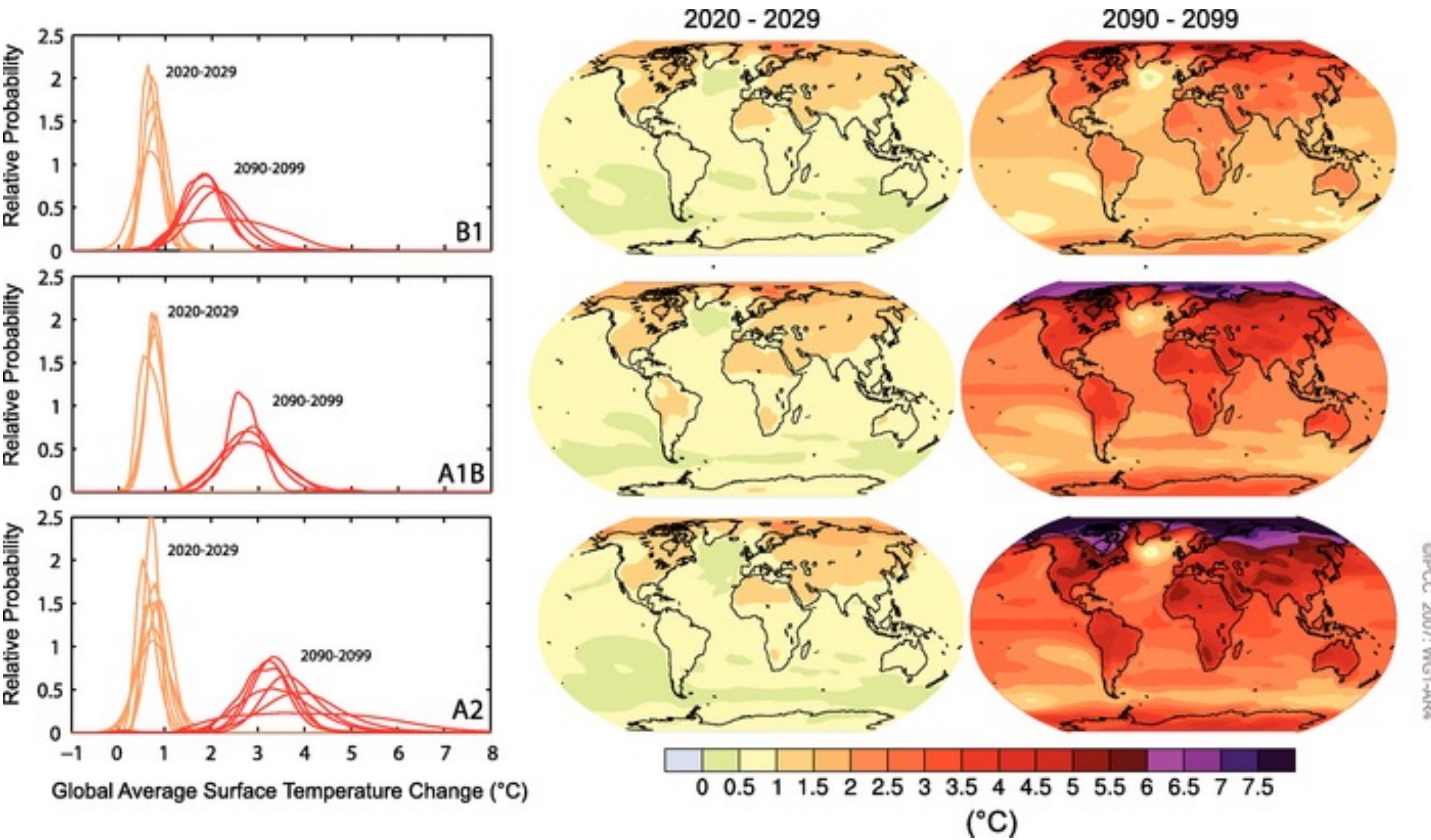
Over 1000 scenarios from the IPCC Fifth Assessment Report are shown

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

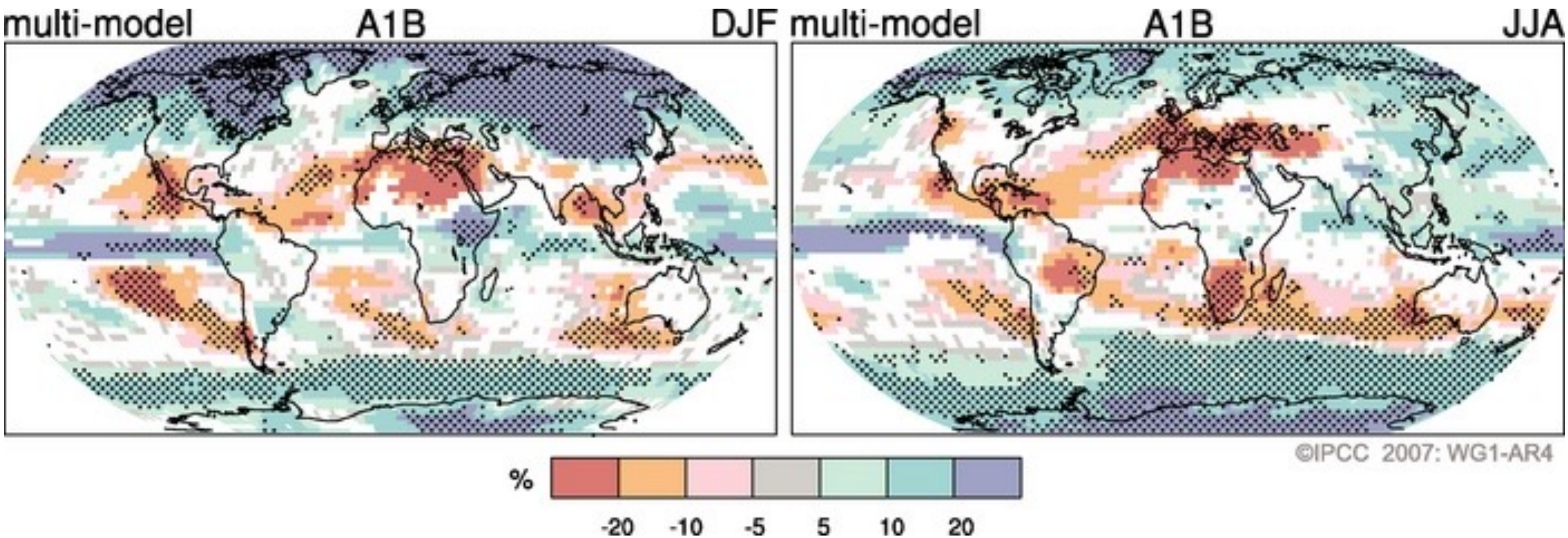


©IPCC 2007: WG1-AR4
A2
A1B
B1
Year 2000 Constant Concentrations
20th century
Global surface warming (°C)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1.0
1900
2000
2100
Year
B1
A1T
B2
A1B
A2
A1FI

Change in Surface Temperature



Change in Precipitation



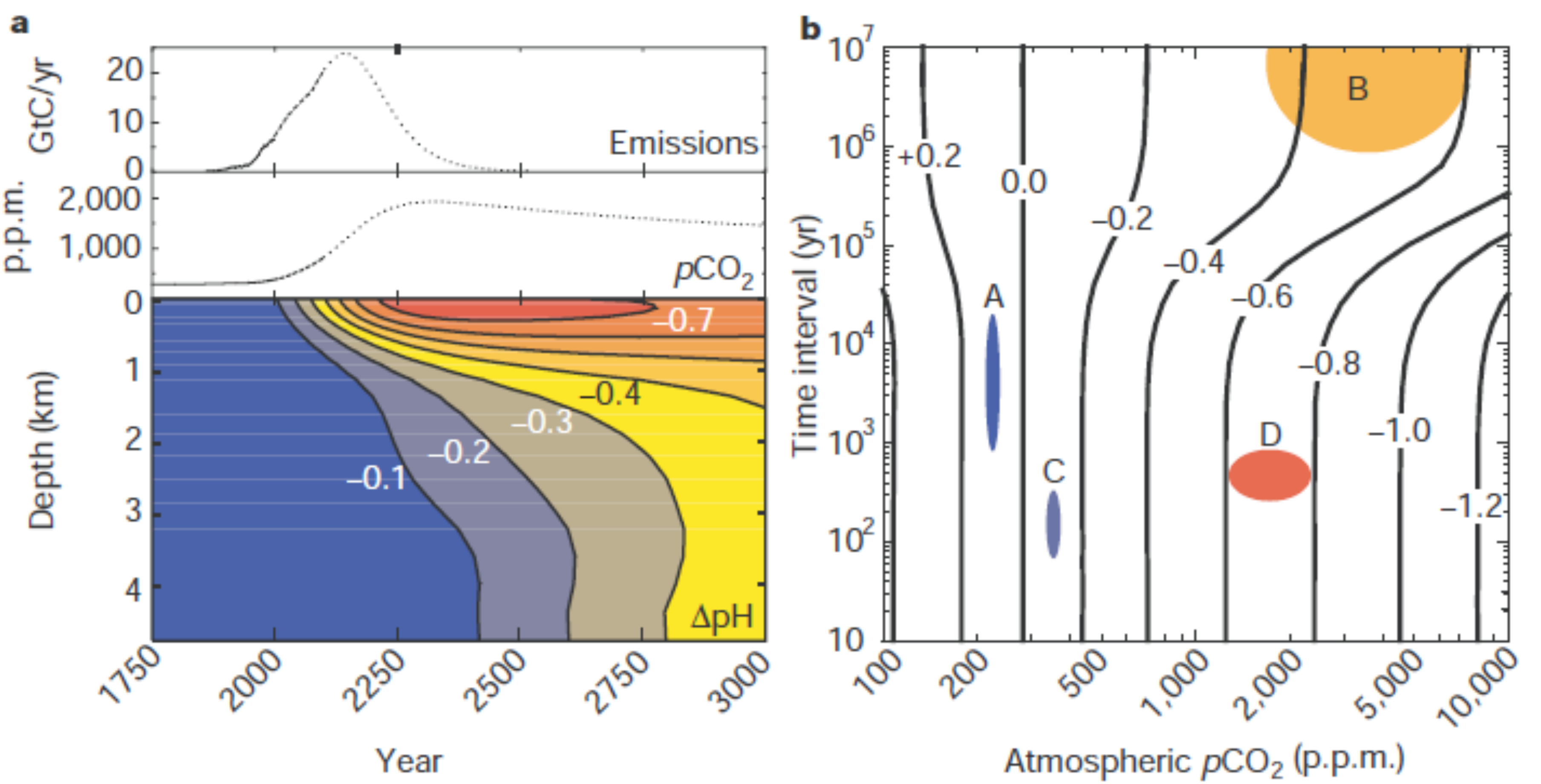
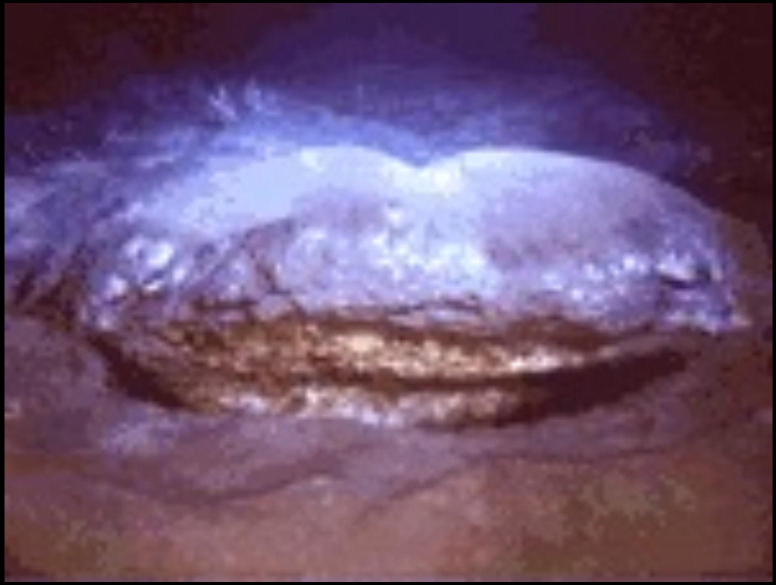
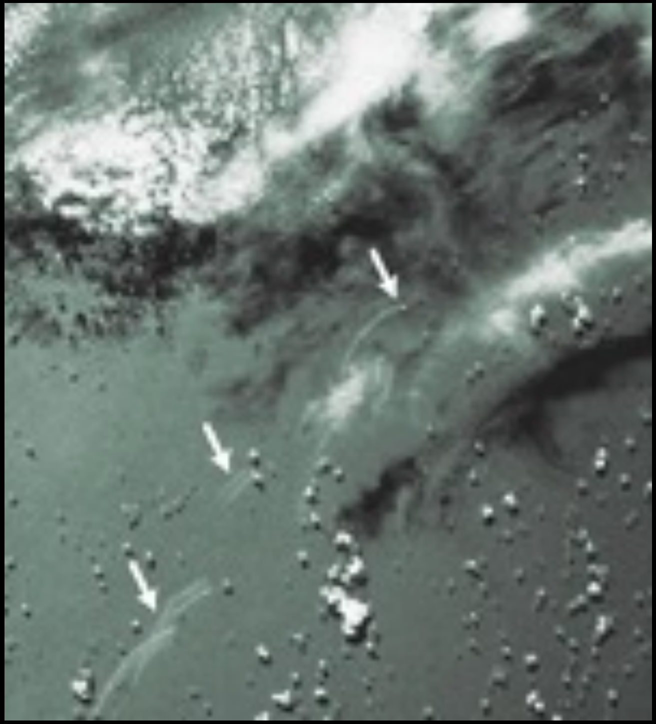


Figure 1 Atmospheric release of CO_2 from the burning of fossil fuels may give rise to a marked increase in ocean acidity. **a,** Atmospheric CO_2 emissions, historical atmospheric CO_2 levels and predicted CO_2 concentrations from this emissions scenario, together with changes in ocean pH based on horizontally 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.

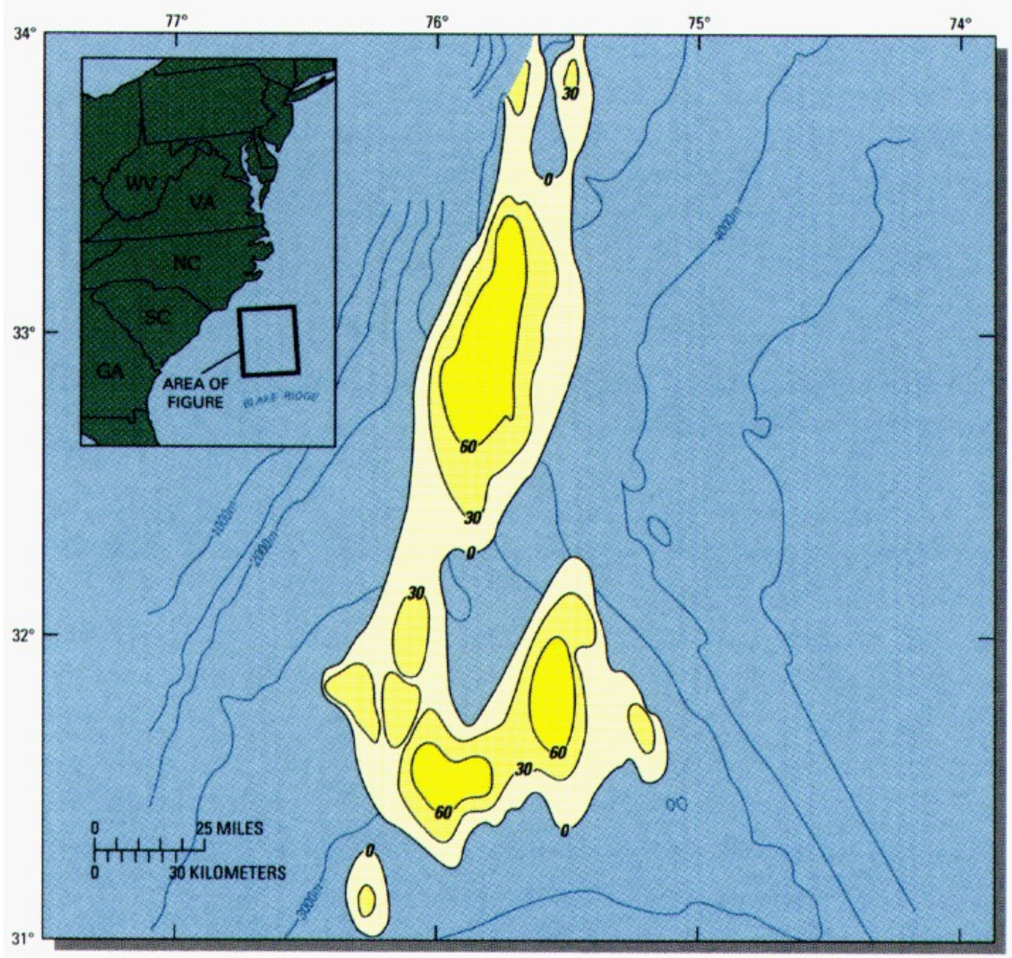
Caldeira 2003

GAS HYDRATES

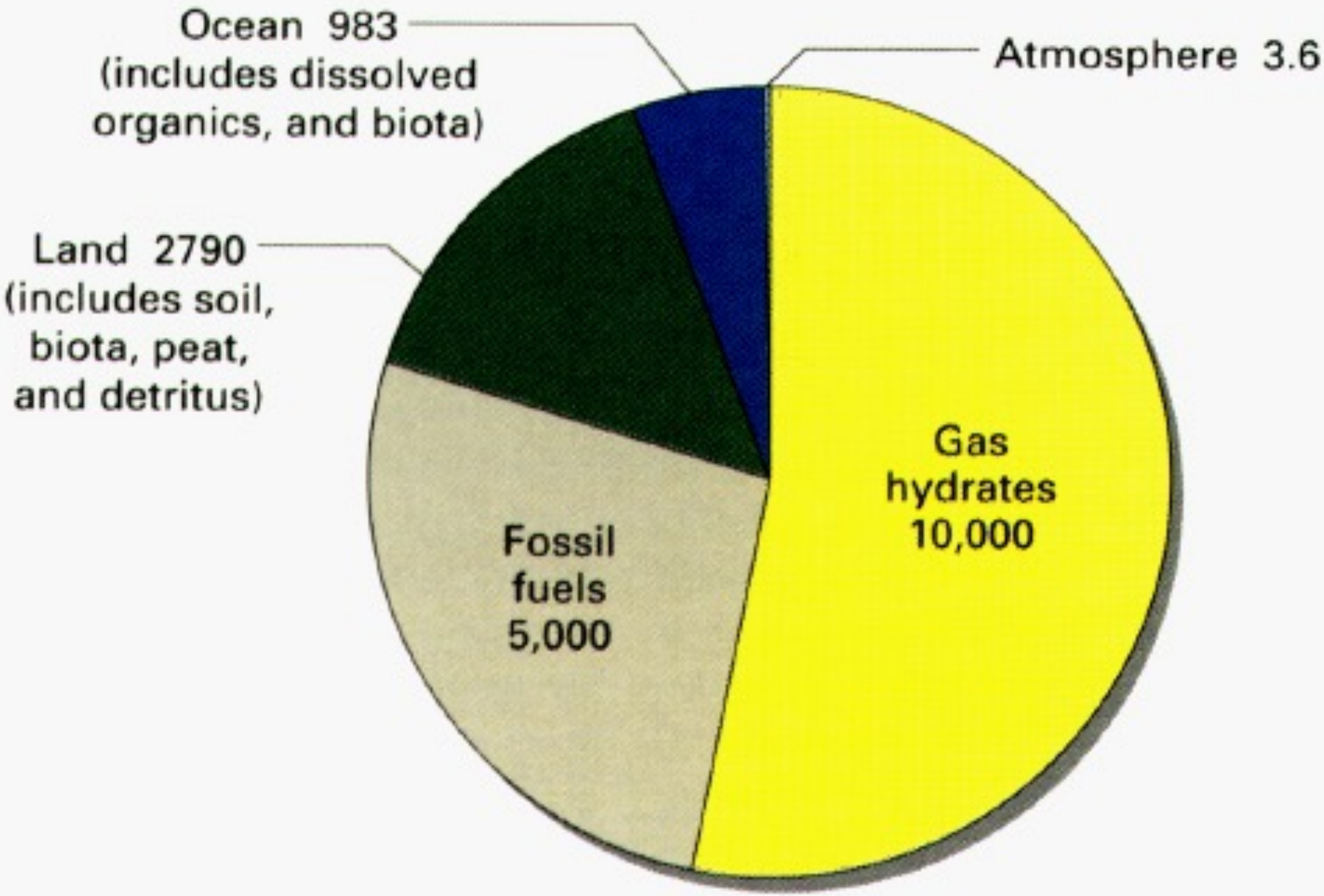




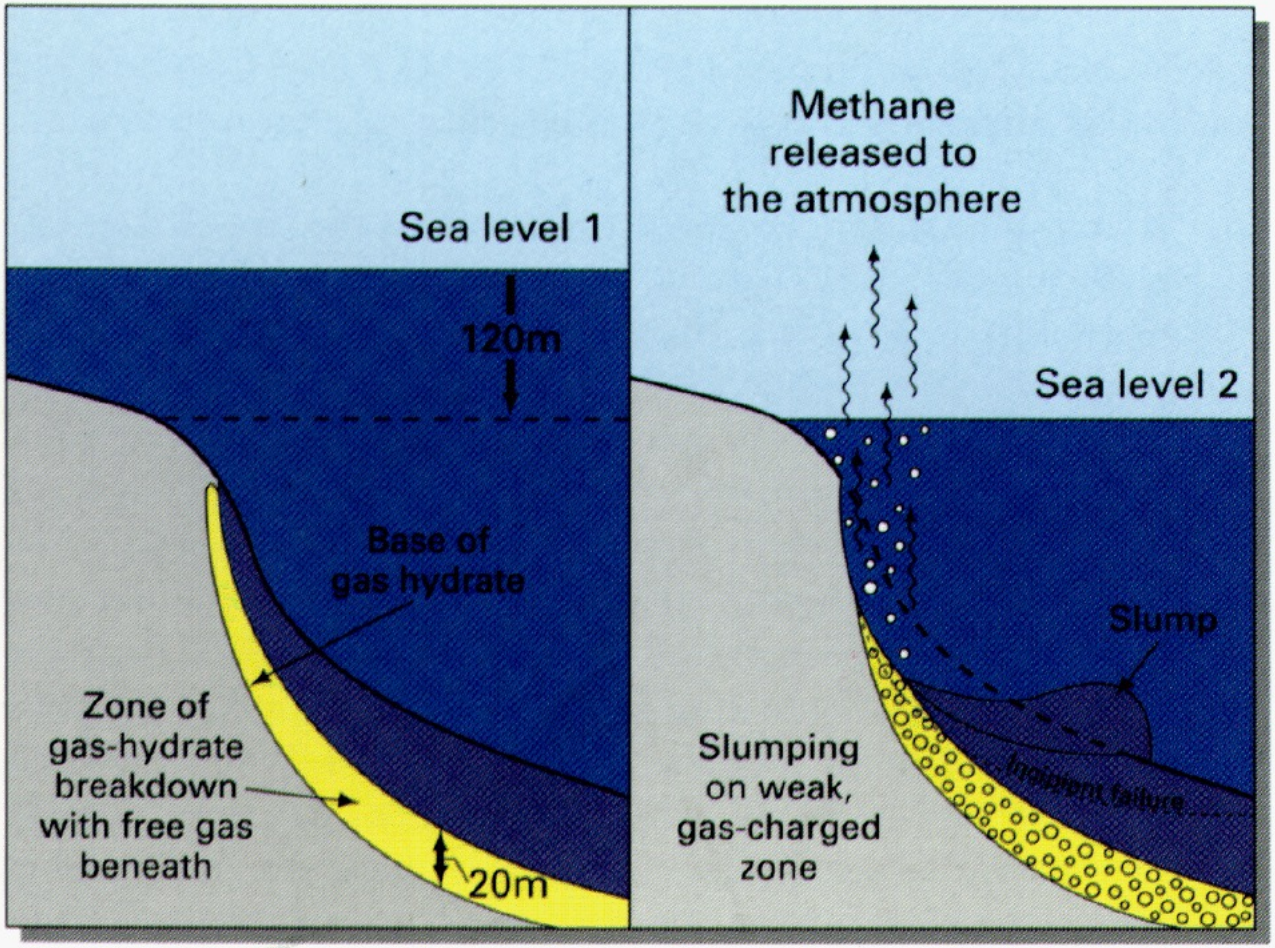
GAS HYDRATES



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



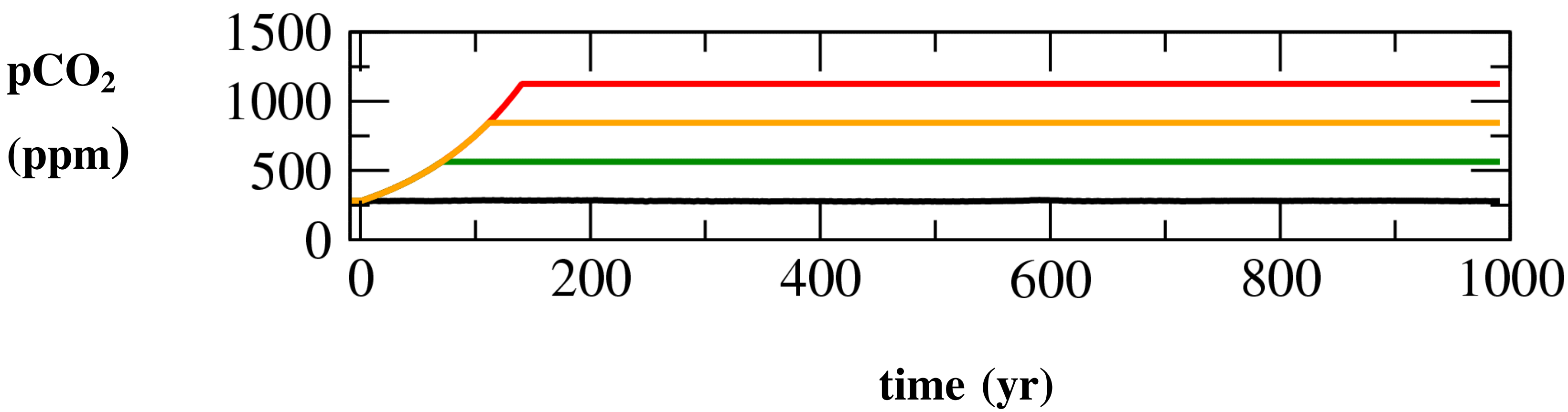
Distribution of organic carbon in Earth reservoirs (excluding dispersed carbon in rocks and sediments, which equals nearly 1,000 times this total amount). Numbers in gigatons (10^{15} tons) of carbon.


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

Future Climate Change Experiments

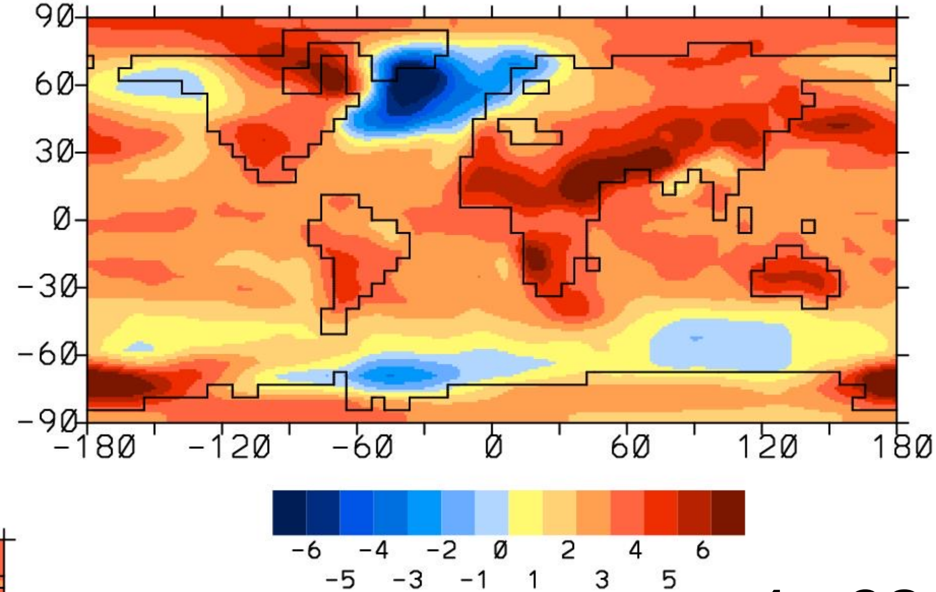
- atmosphere – ocean – ice sheets – vegetation – ocean biogeochemistry
- CO_2 concentration increased from pre-industrial (280 ppm) to 2 x, 3 x, or 4 x pre-industrial concentration with an increase of 1% per year

control run
2 x CO_2
3 x CO_2
4 x CO_2

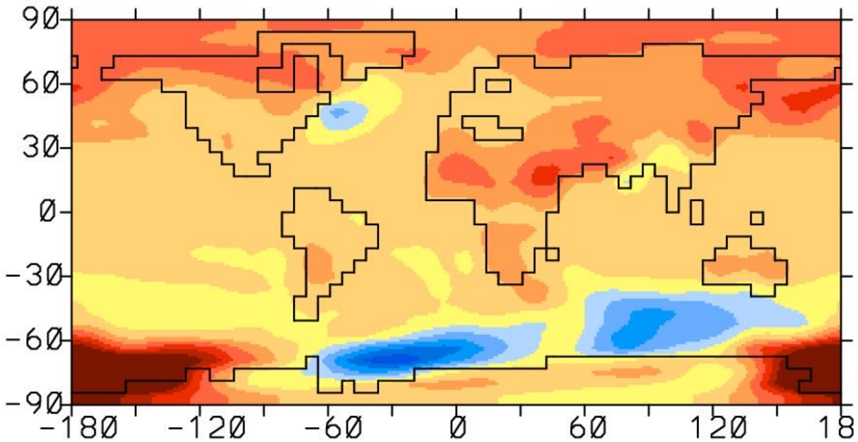


Change in surface air temperature

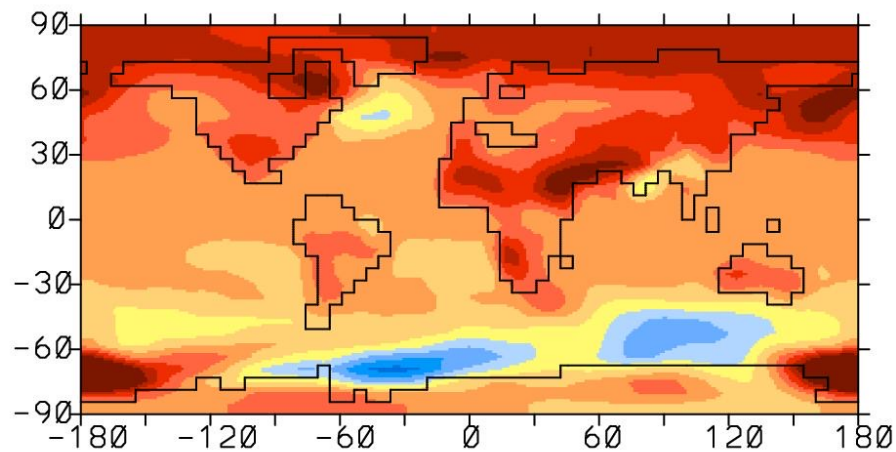
Average over years 300 to 399 relative to climate of control run



4 x CO_2

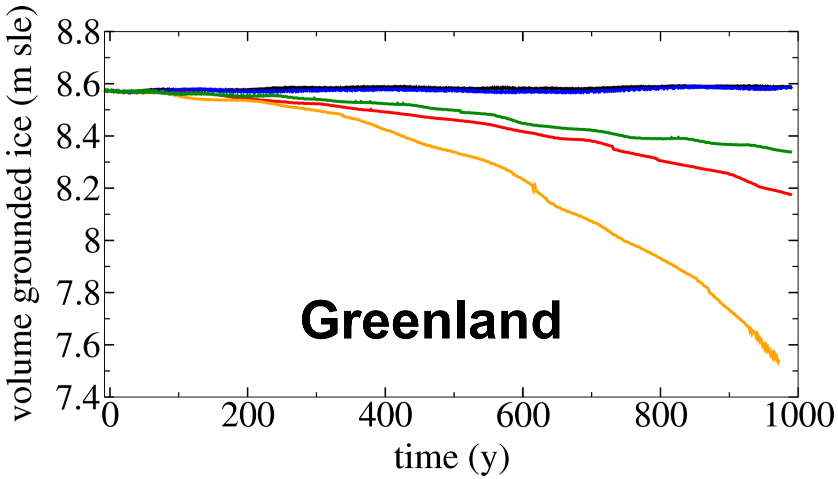


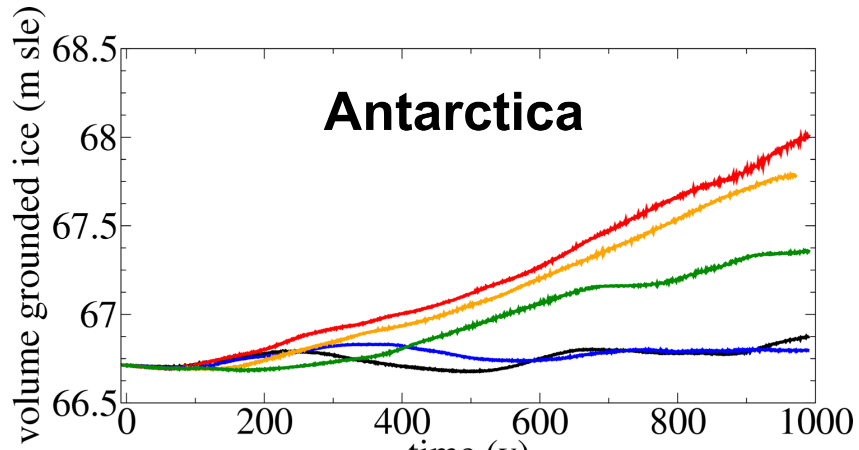
2 x CO_2



3 x CO_2

Change in glaciervolume (m sea level equivalent)





Change in ice thickness after 1000 years Greenland (m)