GEF4400 “The Earth System”

Prof. Dr. Jon Egill Kristjansson,

Prof. Dr. Kirstin Krüger (UiO)

- **Lecture/ interactive seminar/ field excursion**
  Teaching language: English
  Time and location: Monday 12:15-14:00
  Thursday 14:15-16:00, CIENS Glasshallen 2.
- **Study program**

  Master of meteorology and oceanography
  PhD course for meteorology and oceanography students

- **Credits and conditions:**
  The successful completion of the course includes an **oral presentation (weight 50%)**, a **successful completion of the Andøya field excursion** (mandatory), a **field report**, as well as a final **oral examination (50%)**. Student presentations will be part of the course.

GEF4400/9400 changed time schedule

Changed GEF4400/9400 time schedule during November 2015:

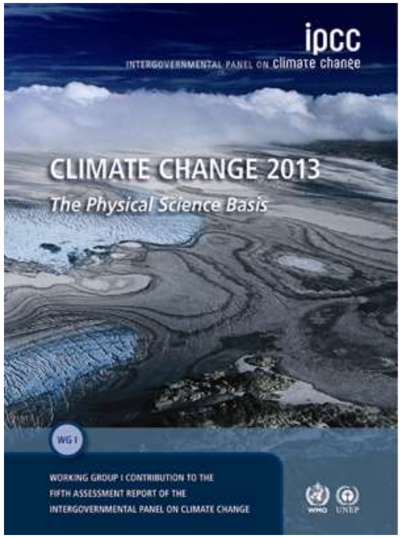
Mo. 02.11.15: 10:00-12:30, Wed 04.11.15 10:15-12:00

Mo. 09.11.15: 10:00-12:30, Wed 11.11.15 10:15-12:00

Mo. 16.11.15: 10:00-12:30, Wed 18.11.15 10:15-12:00

Mo. 23.11.15: 10:00-12:30, Wed 25.11.15 10:15-12:00

IPCC Chapter 6: **Carbon and other biogeochemical cycles**



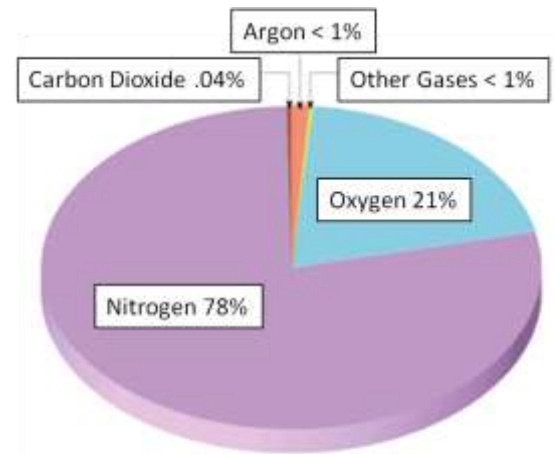
- Background
- Introduction: Global Carbon Cycle *(Section 6.1)*
- Evolution of biogeochemical cycles since industrial era *(Section 6.3)*
- Variations in Carbon cycle before the fossil fuel era *(Section 6.2)*
- Projections of future carbon cycles *(Section 6.4)*
- Global Carbon Budget in 2014
- Executive Summary (Ch. 6)

Ciais, P., Cet al., 2013: Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Carbon dioxide (CO_2) in the atmosphere

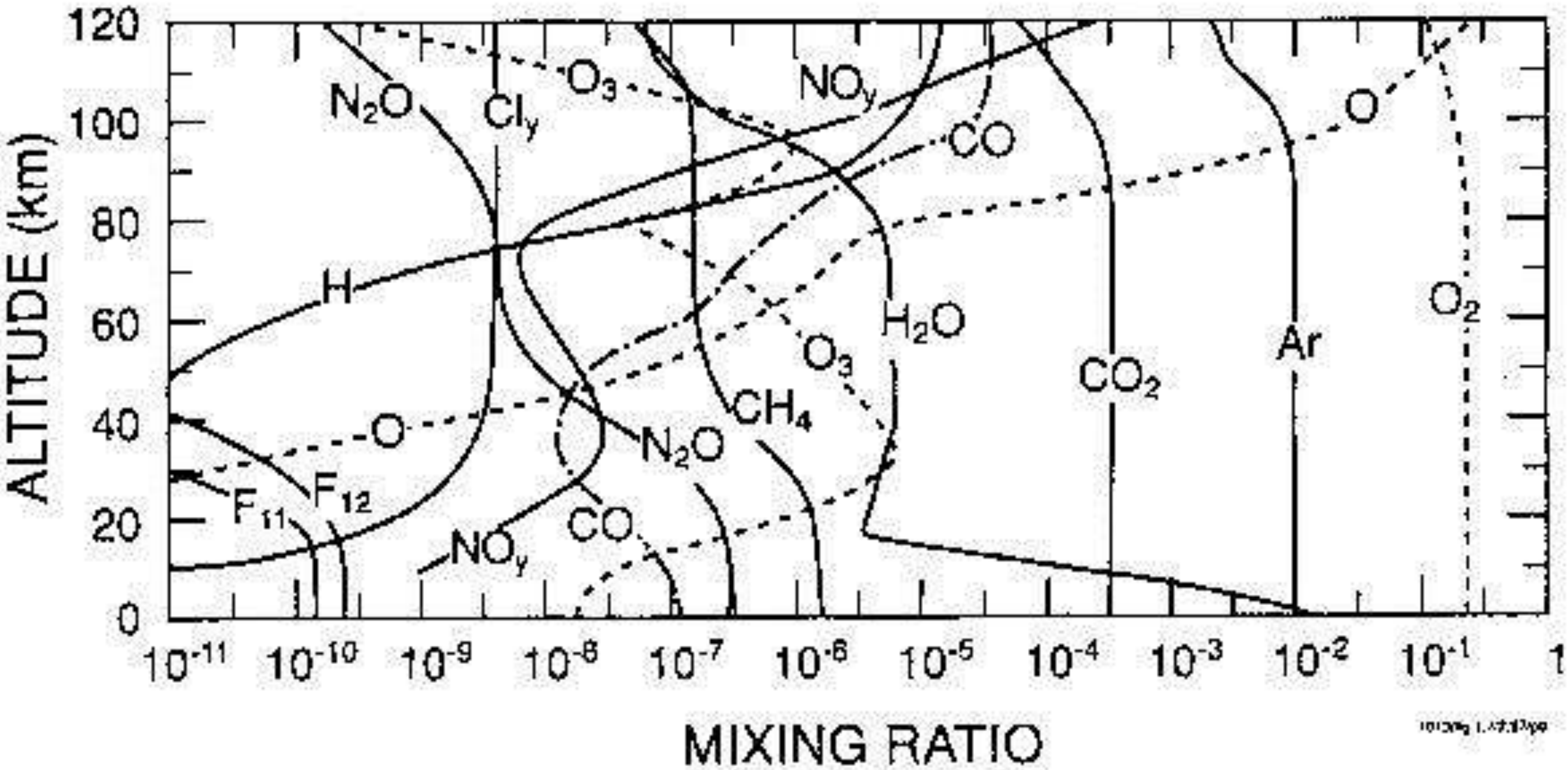
Content of air

Nitrogen N_2	78	Percent of volume (%)
Oxygen O_2	21	
Inert gases (Ar)	0.9	
	99.9	



Carbon dioxide CO_2	0.04, varying
Ozone O_3	0.00005, varying
Water vapour H_2O	highly varying
+ other trace gases	

Background



Typical vertical distribution of chemical species within the air [Brasseur, 1999].

Mixing ratios of trace gases

1 ppm (1 part per million) 1 particle CO_2 per 10^6 particles air
1 ppb (1 part per billion): 1 particle CO_2 per 10^9 particles air
1 ppt (1 part per trillion): 1 particle CO_2 per 10^{12} particles air

"v": per volume
"m": per mass

Mixing ratio is a relative unit → taking the air density into account

Absolute unit: concentration of a trace gas (e.g. given in mPa, nbar, Dobson units for ozone)

Background

Carbon dioxide

Molecular formula	CO_2
Molar mass	44.010 g/mol
Appearance	colorless, odorless gas (gas at 1 atm and 0 °C; 1 atm =1013.25 hPa) (solid at 1 atm and −78.5 °C) (liquid at 56 atm and 20 °C)
Dipole moment	zero
Molecular shape	linear
Spectral data	UV, IR

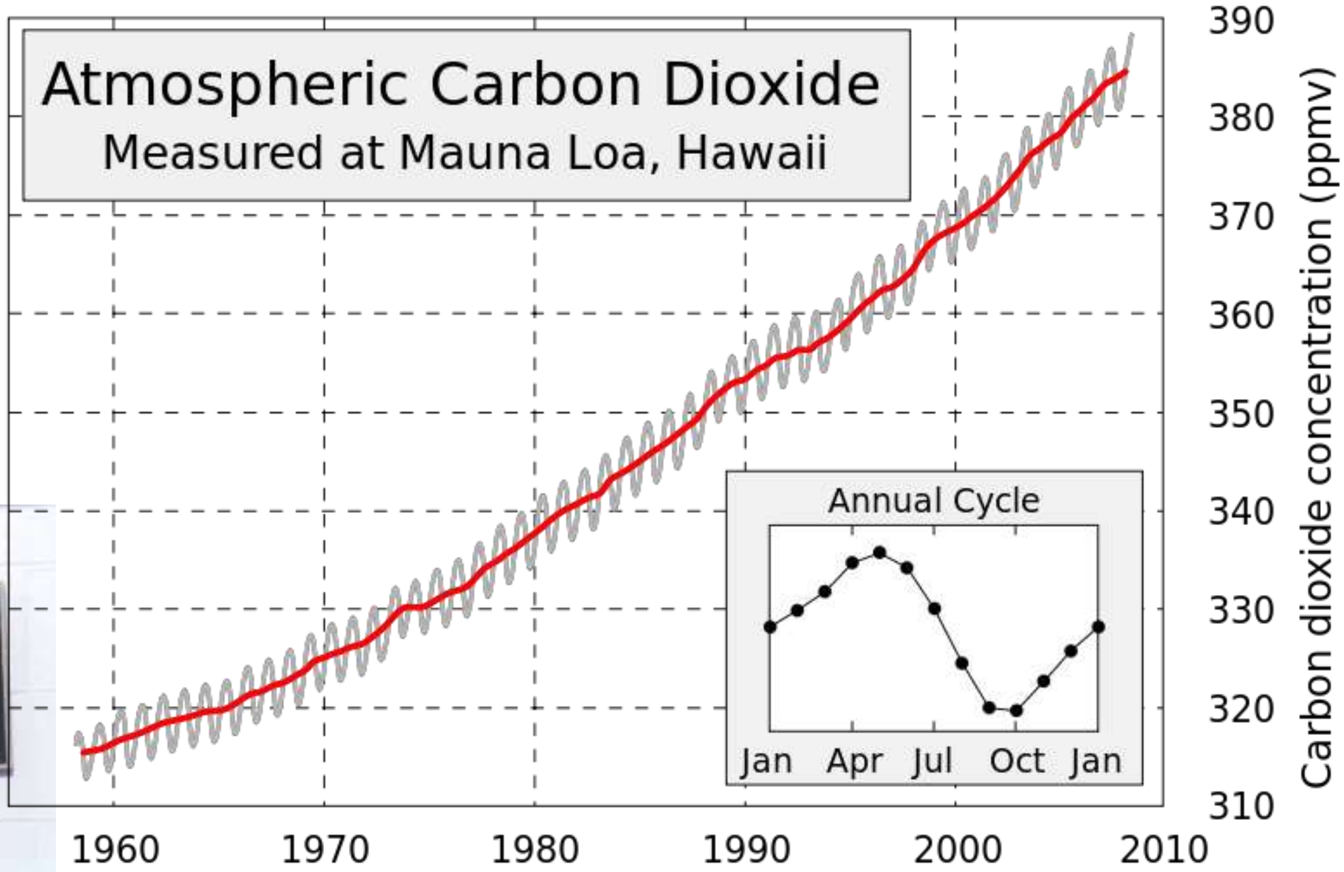
O=C=O

CO_2: **trace gas, 0.0398%** concentration of the atmosphere,
sources and sinks are at the surface, uniform distribution up to 90 km.

Sources: combustion of fossil fuels, burning of vegetable matter, chemical processes, respiration, volcanoes , geothermal processes, dissolution of carbonates in crustal rocks.

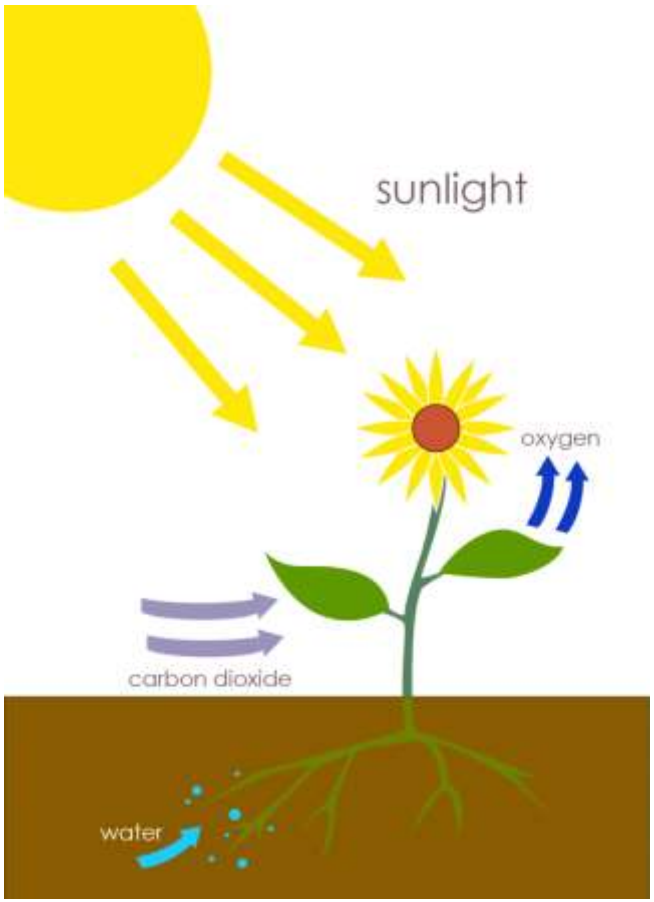
Sinks: ocean, sediments, biosphere(photosynthesis)

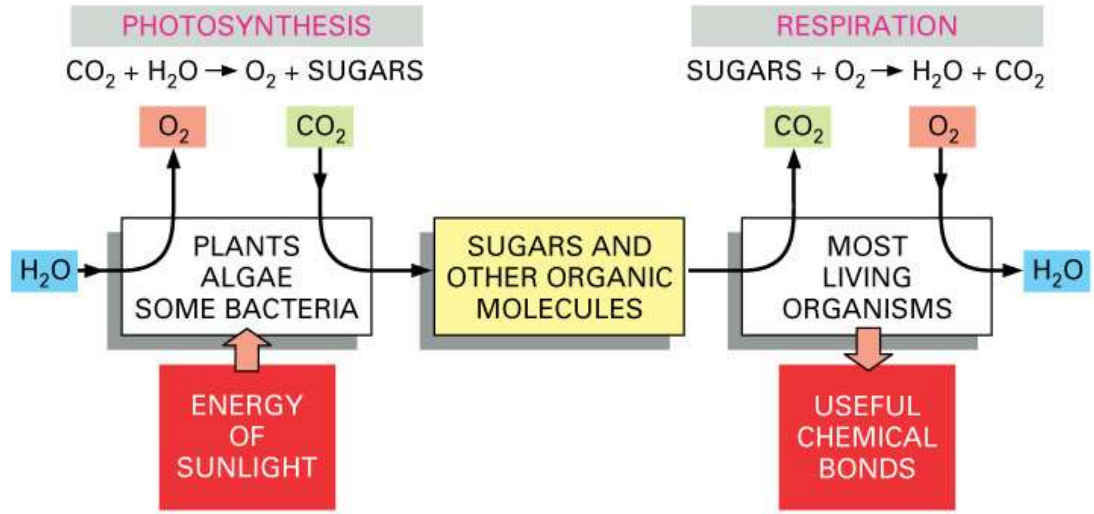
Mauna loa curve (Keeling curve)



Charles D. Keeling
1928-2005

Photosynthesis + Respiration

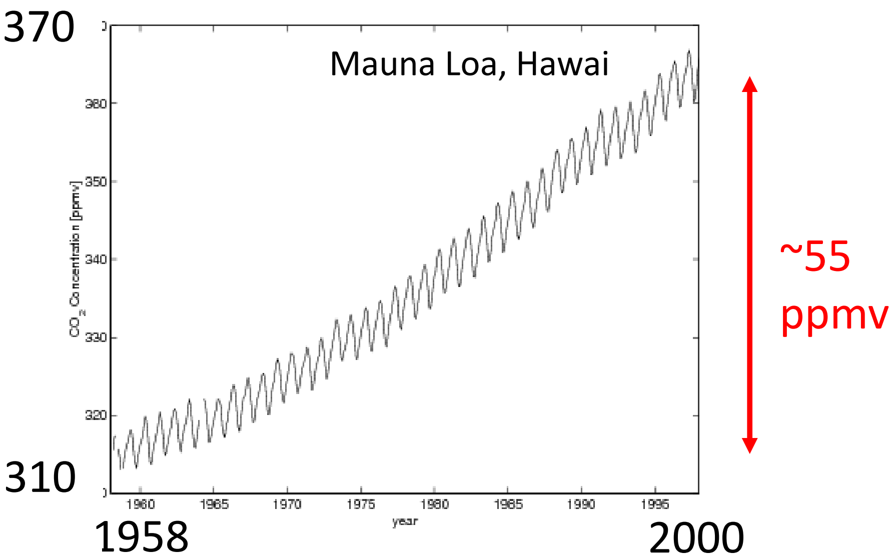


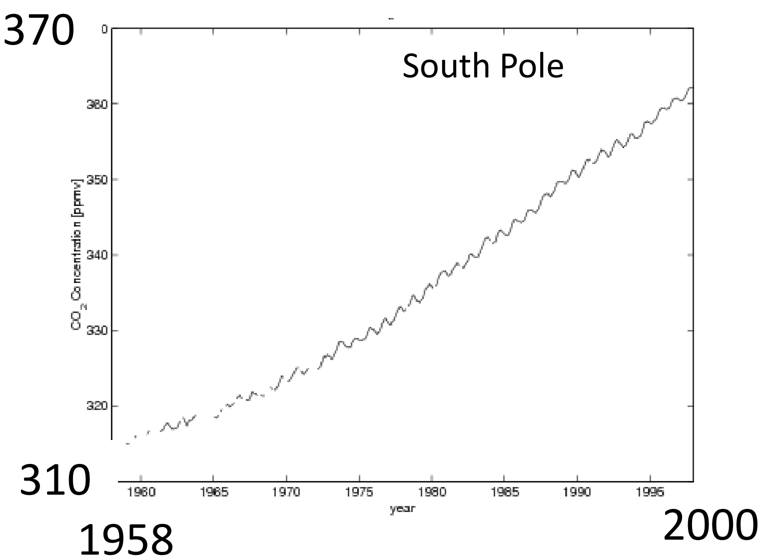


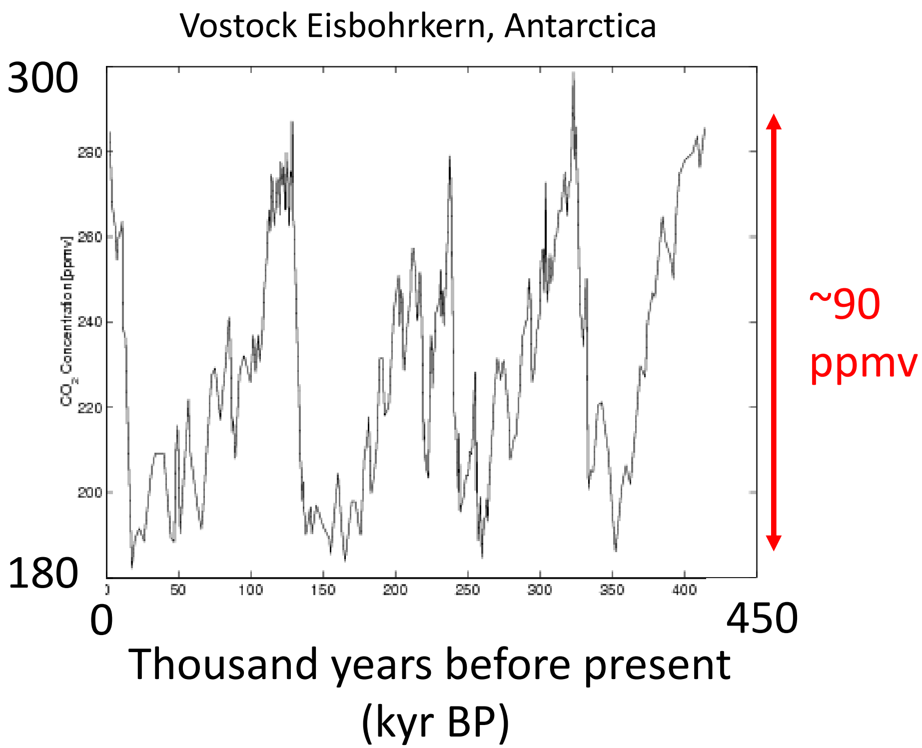
$$6CO_2 + 6H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6O_2$$

Carbon dioxide + Water → Sugar + Oxygen

Past and present CO_2 mixing ratio (ppmv)

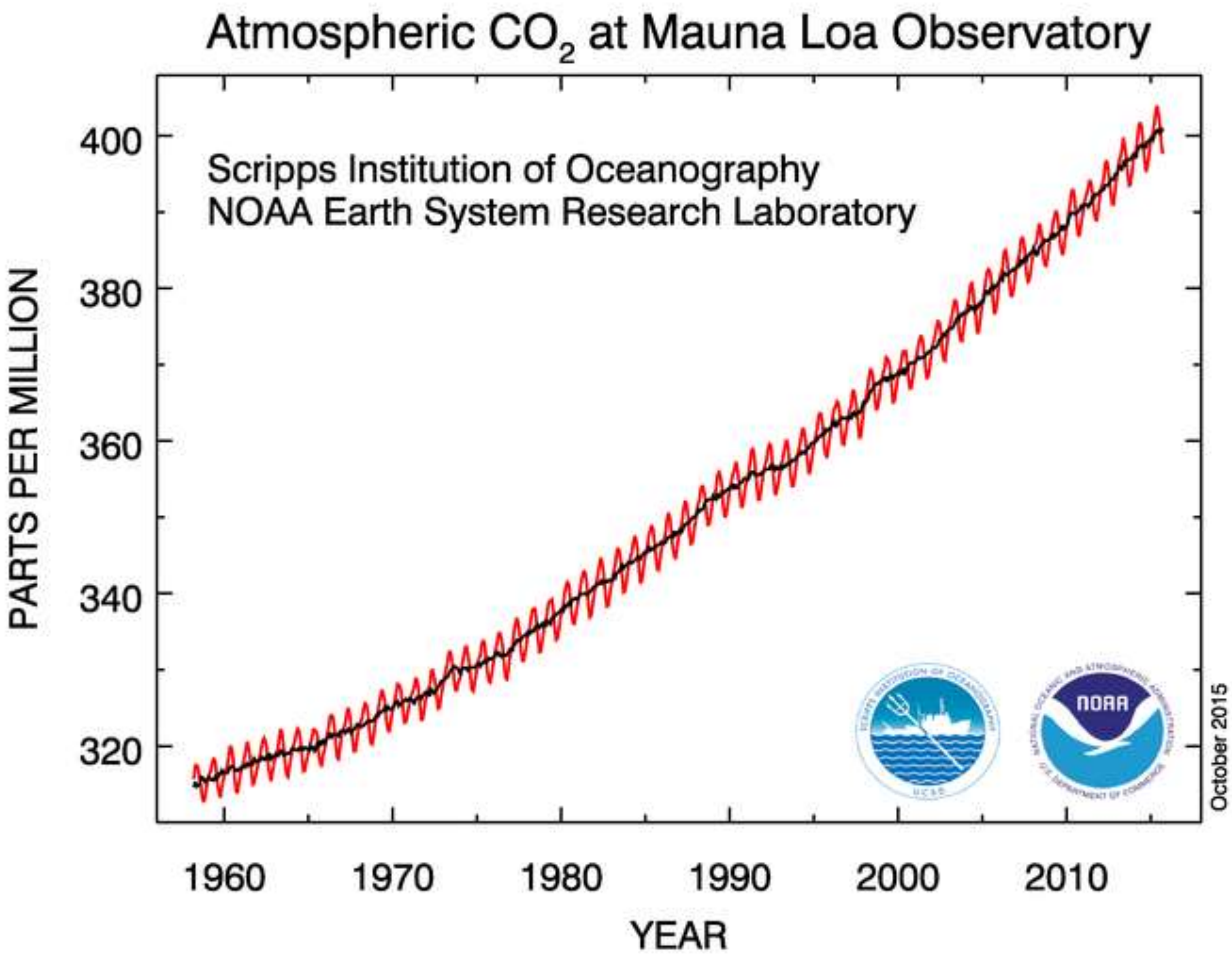






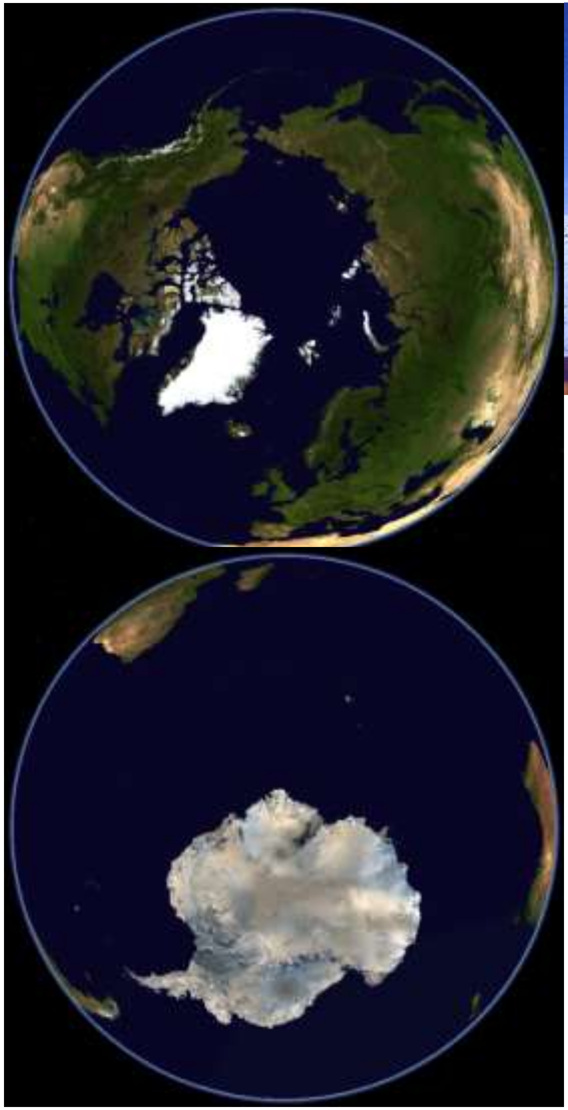
(Macke, 2004)

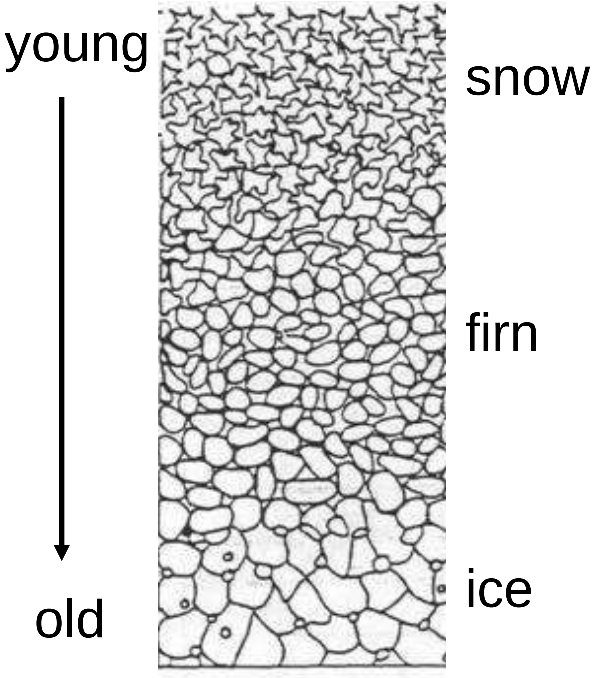
Background



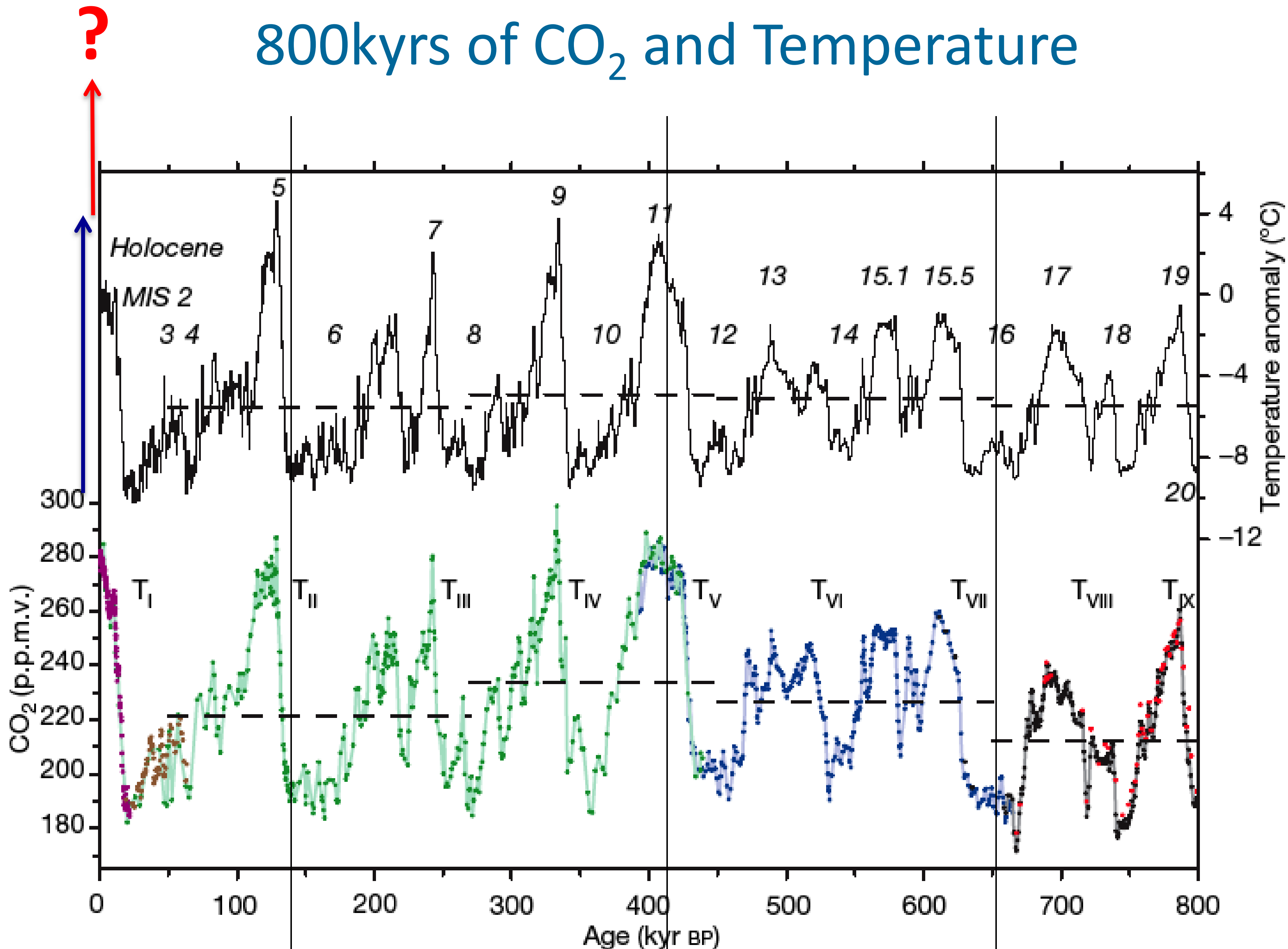
www.esrl.noaa.gov

Ice cores as climate archives

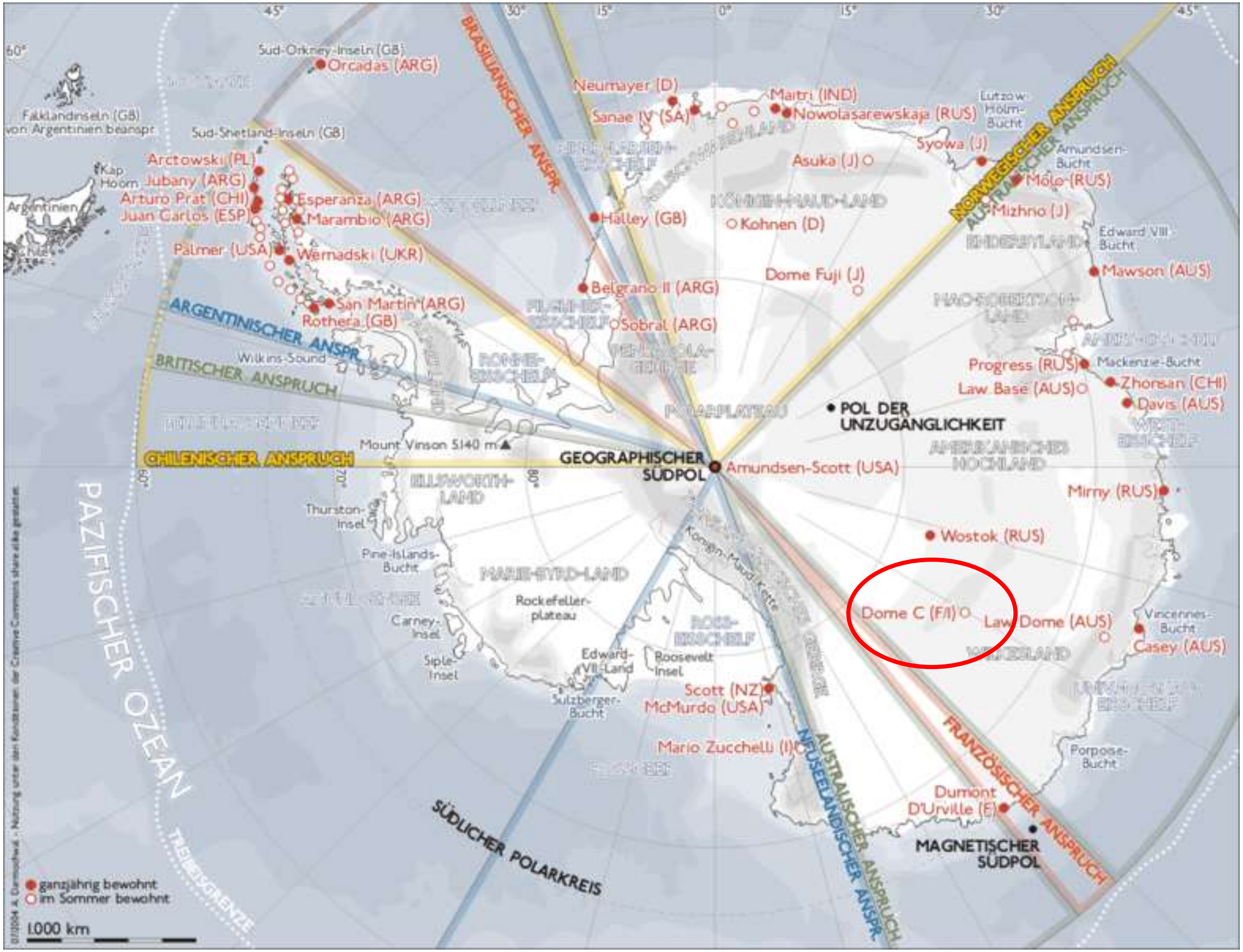




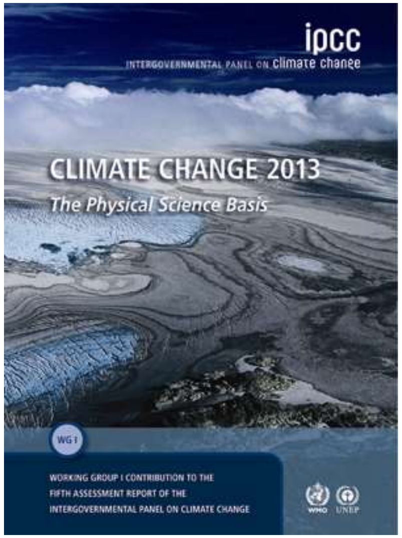
800kyrs of CO_2 and Temperature



Barnola et al., 1987 | Petit et al., 1999 | Siegenthaler et al., 2005 | Lüthi et al., 2008


Süd-Orkney-Inseln (GB)
Orcadas (ARG)
Falklandinseln (GB) von Argentinien beanspr.
Süd-Shetland-Inseln (GB)
Kap Hoorn
Argentinien
Chile
Arctowski (PL)
Jubany (ARG)
Arturo Prat (CHI)
Juan Carlos (ESP)
Esperanza (ARG)
Marambio (ARG)
Palmer (USA)
Wernadski (UKR)
San Martin (ARG)
Rothera (GB)
ARGENTINISCHER ANSPR.
BRITISCHER ANSPRUCH
CHILENISCHER ANSPRUCH
BRASILIANISCHER ANSPR.
Wilkins-Sound
Neumayer (D)
Sanae IV (SA)
Maitri (IND)
Nowolasarewskaja (RUS)
Lützow-Holm-Bucht
Syowa (J)
Asuka (J)
Amundsen-Bucht
Molo (RUS)
Mizhno (J)
NORWEGISCHER ANSPRUCH
AUSTRALISCHER ANSPRUCH
Halley (GB)
Kohnen (D)
Edward VIII Bucht
Mawson (AUS)
Dome Fuji (J)
Belgrano II (ARG)
Sobral (ARG)
Progress (RUS)
Mackenzie-Bucht
Zhongsan (CHI)
Law Base (AUS)
Davis (AUS)
POL DER UNZUGÄNGLICHKEIT
Mount Vinson 5140 m
GEOGRAPHISCHER SÜDPOL
Amundsen-Scott (USA)
Mirny (RUS)
Thurston-Insel
Pine-Islands-Bucht
Wostok (RUS)
Rockefeller-plateau
Carney-Insel
Siple-Insel
Dome C (F/I)
Law Dome (AUS)
Vincennes-Bucht
Casey (AUS)
Edward-VII-Land
Roosevelt Insel
Sulzberger-Bucht
Scott (NZ)
McMurdo (USA)
Königin-Maud-Kette
Mario Zucchelli (I)
Porpoise-Bucht
Dumont D'Urville (F)
MAGNETISCHER SÜDPOL
FRANZÖSISCHER ANSPRUCH
AUSTRALISCHER ANSPRUCH
NEUSEELÄNDISCHER ANSPR.
PAZIFISCHER OZEAN
SÜDLICHER POLARKREIS
TREIBEISGRENZE
ganzjährig bewohnt
im Sommer bewohnt
1.000 km

IPCC Chapter 6:
Carbon and other biogeochemical cycles



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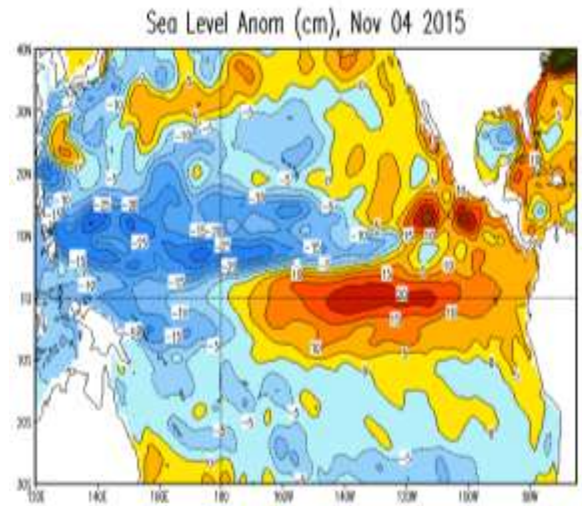
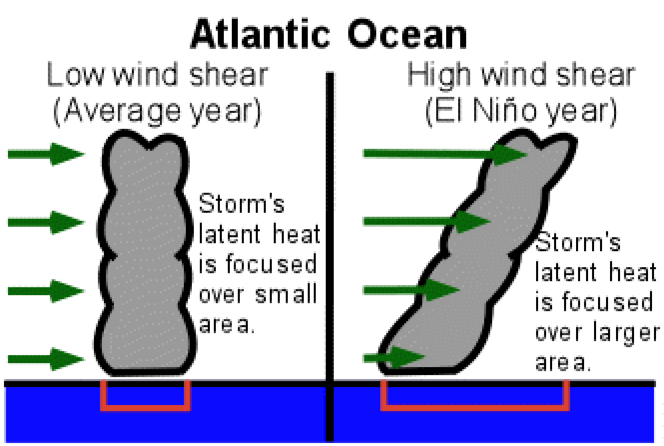
Questions



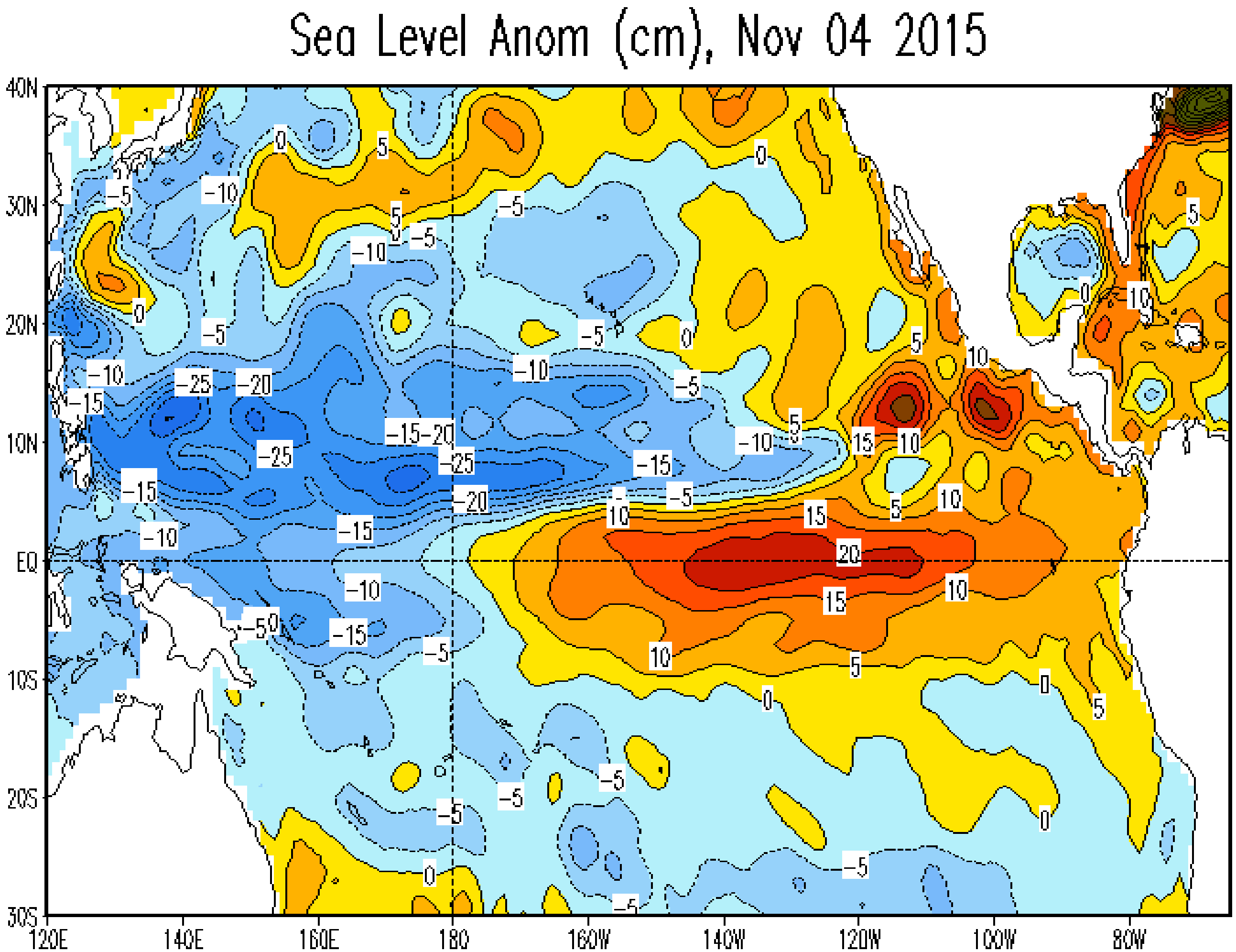
- El Nino SLH anomaly between East and West Pacific? > 20 to 50 cm
- to respire, see-saw (in air pressure)
- Hurricane increase during El Nino?

	Atlantic		Eastern Pacific	
	Average	El Niño Avg.	Average	El Niño Avg.
Named storms	9.4	7.1	16,7	17.6
Hurricanes	5.8	4.0	9.8	10.0
Intense Hurricanes	2.5	1.5	4.8	5.5

ww2010.atmos.uiuc.edu/



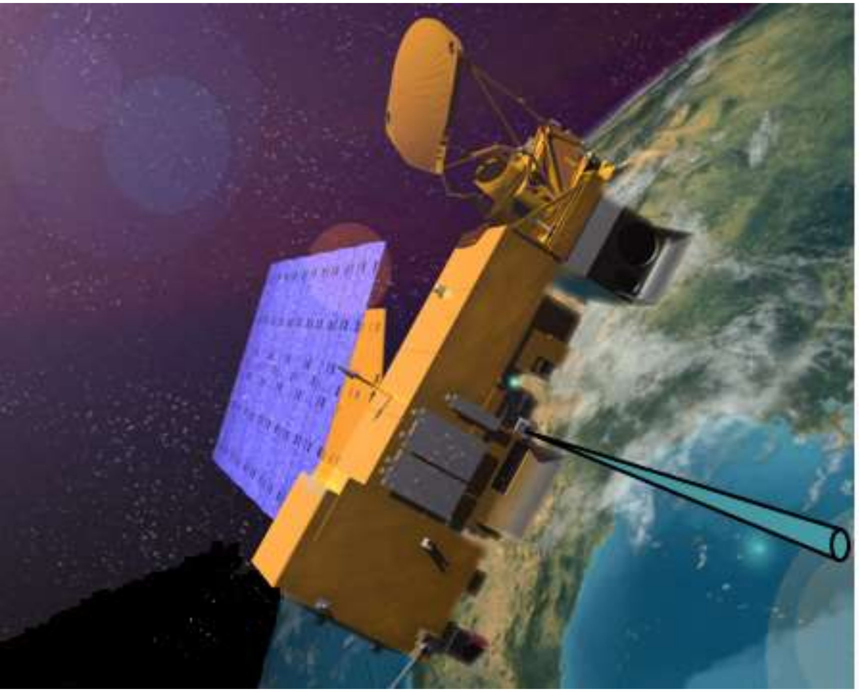
SLH anomalies (cm) Nov, 04, 2015



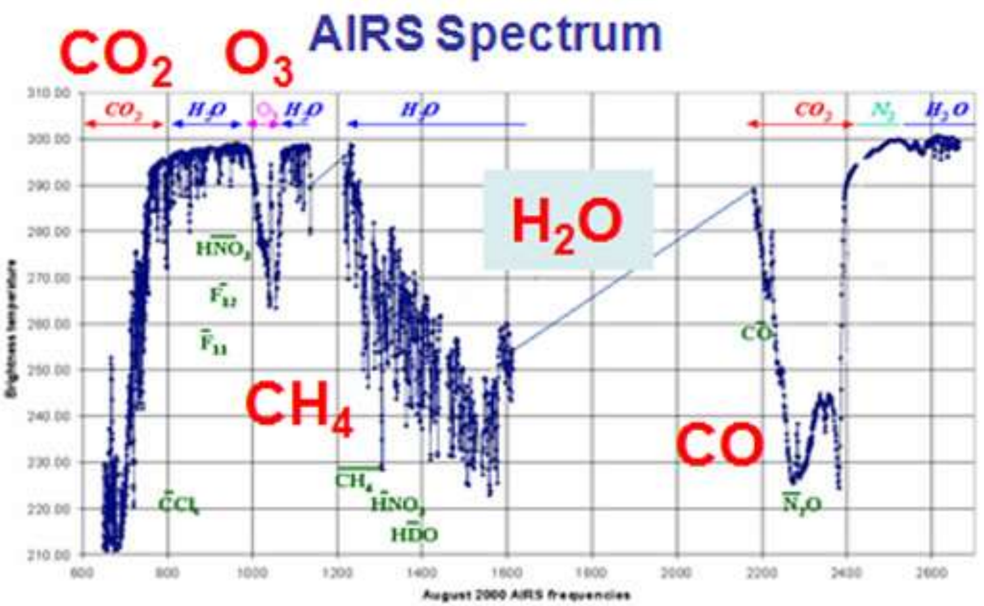
NCEP-CPC

Carbon dioxide (CO_2) in the atmosphere

The Atmospheric Infrared Sounder (AIRS) instrument



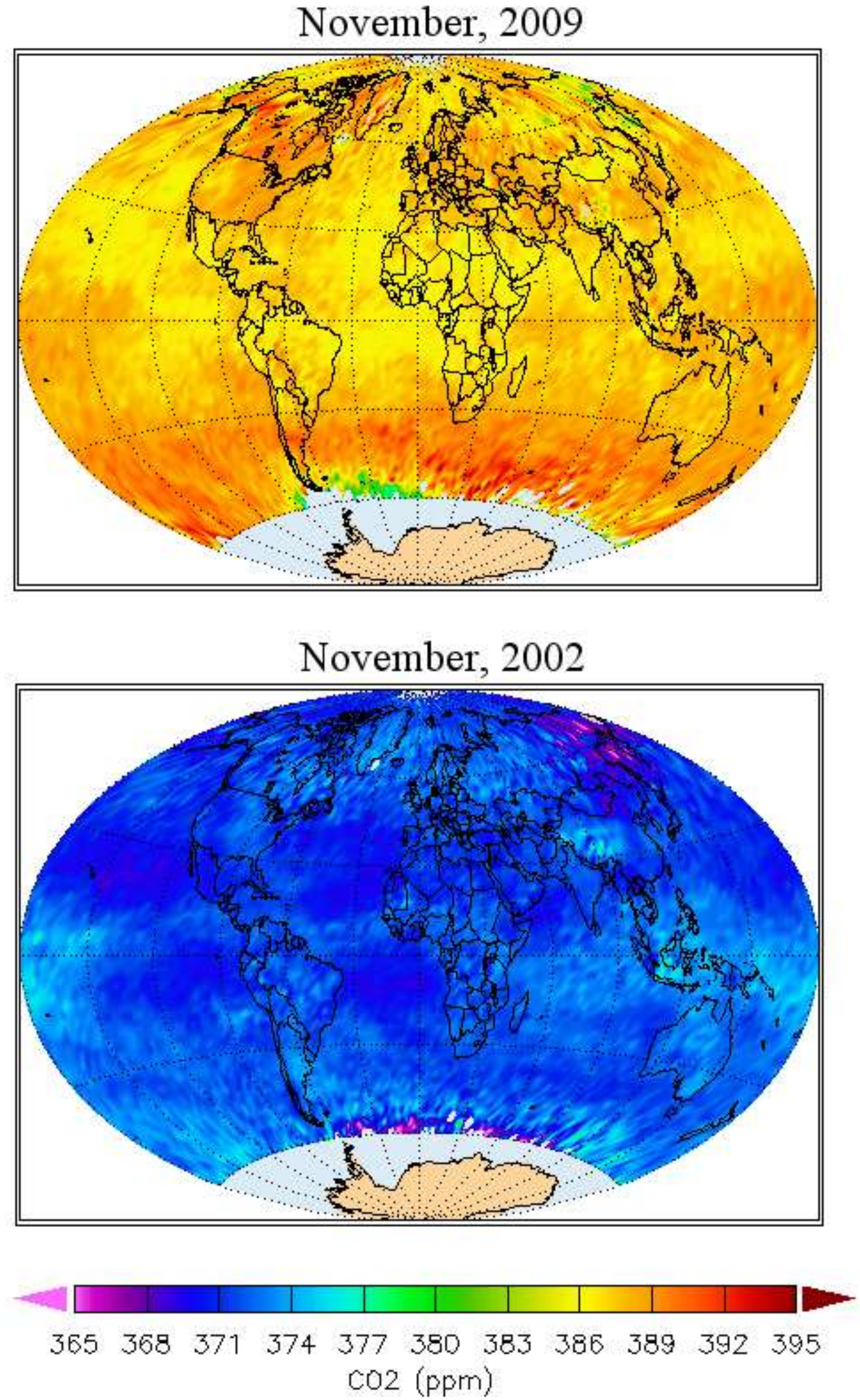
on NASA's Aqua satellite



- Launched on May 4, 2002,
- still operational (http://airs.jpl.nasa.gov/data/near-real-time)
- cross-track scanning instrument,
- scan mirror rotates around an axis along the line of flight and directs infrared energy from the Earth into the instrument,
- ground scan ~800 km from either side.

CO_2 Increase

+17 ppm/7 years



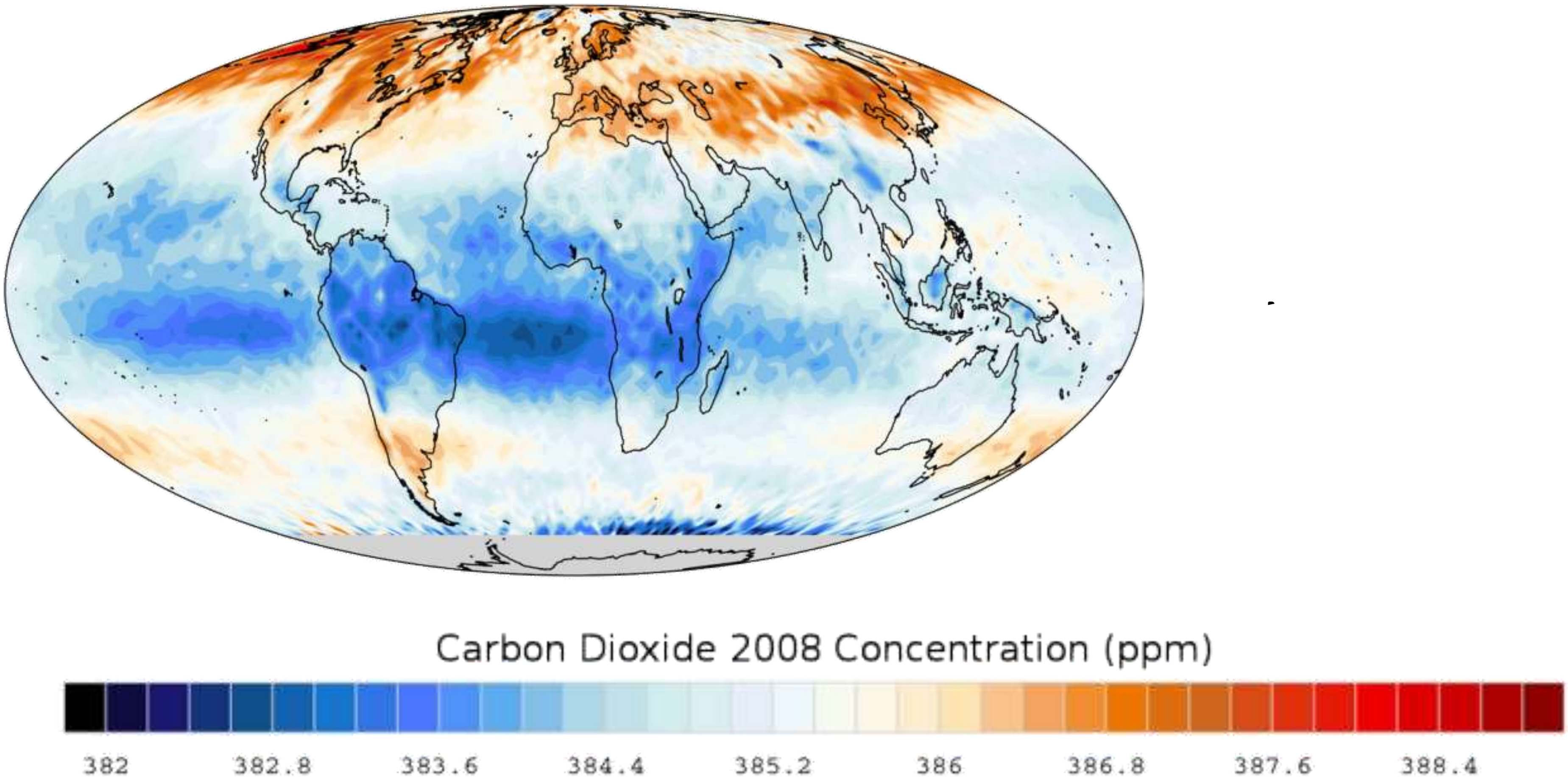
Global averaged annual mean
Marine station data:
-2002: 372 ppm
-2009: 386 ppm
-2014: 397 ppm

(www.esrl.noaa.gov/gmd/ccgg/trends/)

http://disc.sci.gsfc.nasa.gov/AIRS

CO_2 seasonal and hemispheric variations

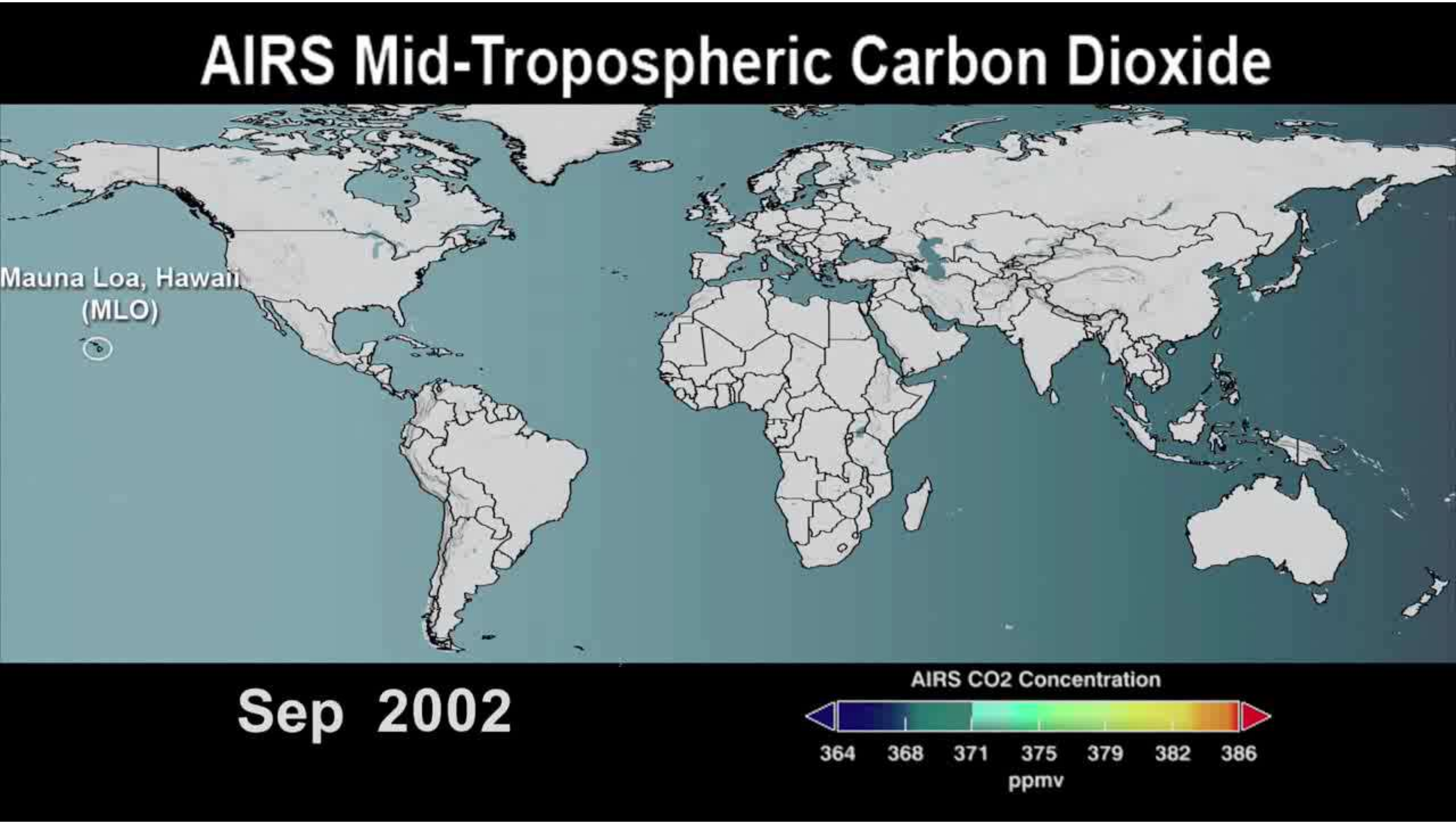
CO_2 mid-troposphere (3-7 km) AIRS instrument
Annual mean 2008



http://mirador.gsfc.nasa.gov

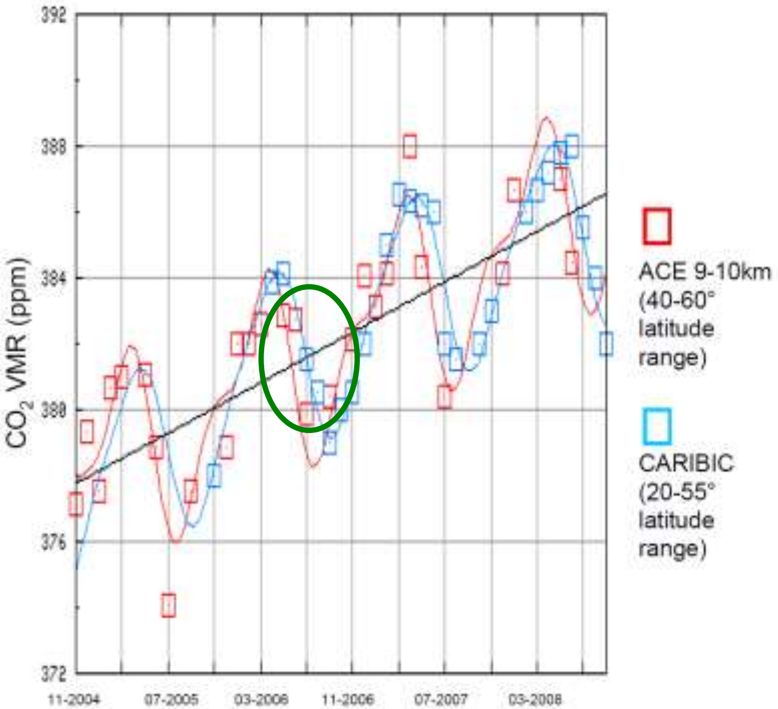
→ seasonal cycle in CO_2 uptake by vegetation
→ maximum in NH due to more emitters and higher fraction of vegetation

CO_2: Sept 2002 - July 2008



http://www.nasa.gov

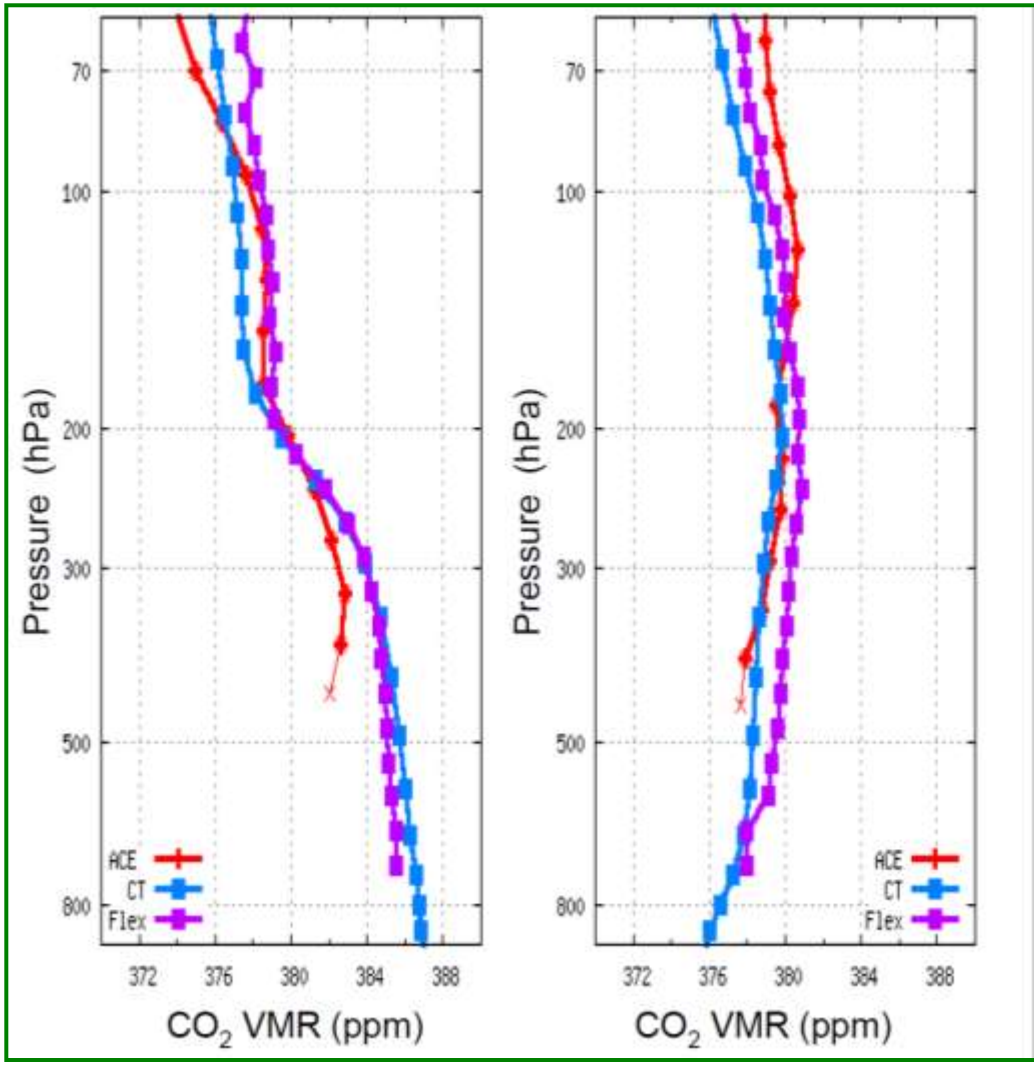
CO_2 as a time distribution tracer - troposphere



11-2004 07-2008

- ACE: Atmospheric Chemistry Experiment (satellite)
- CARIBIC (aircraft)
- CT: Carbon Tracker (model)
- FLEXPART (model)

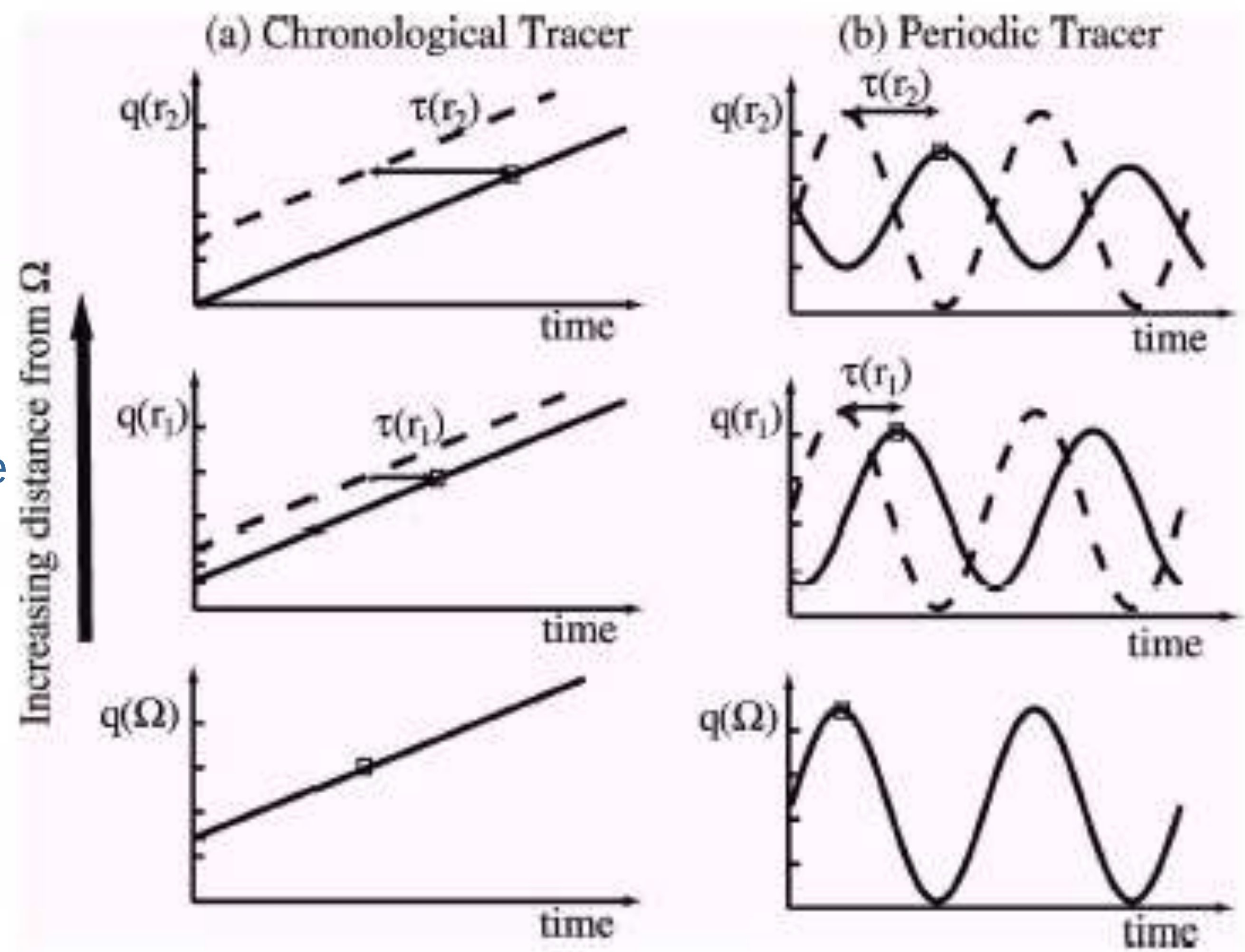
May 2006 July 2006



Foucher et al 2011 ACP

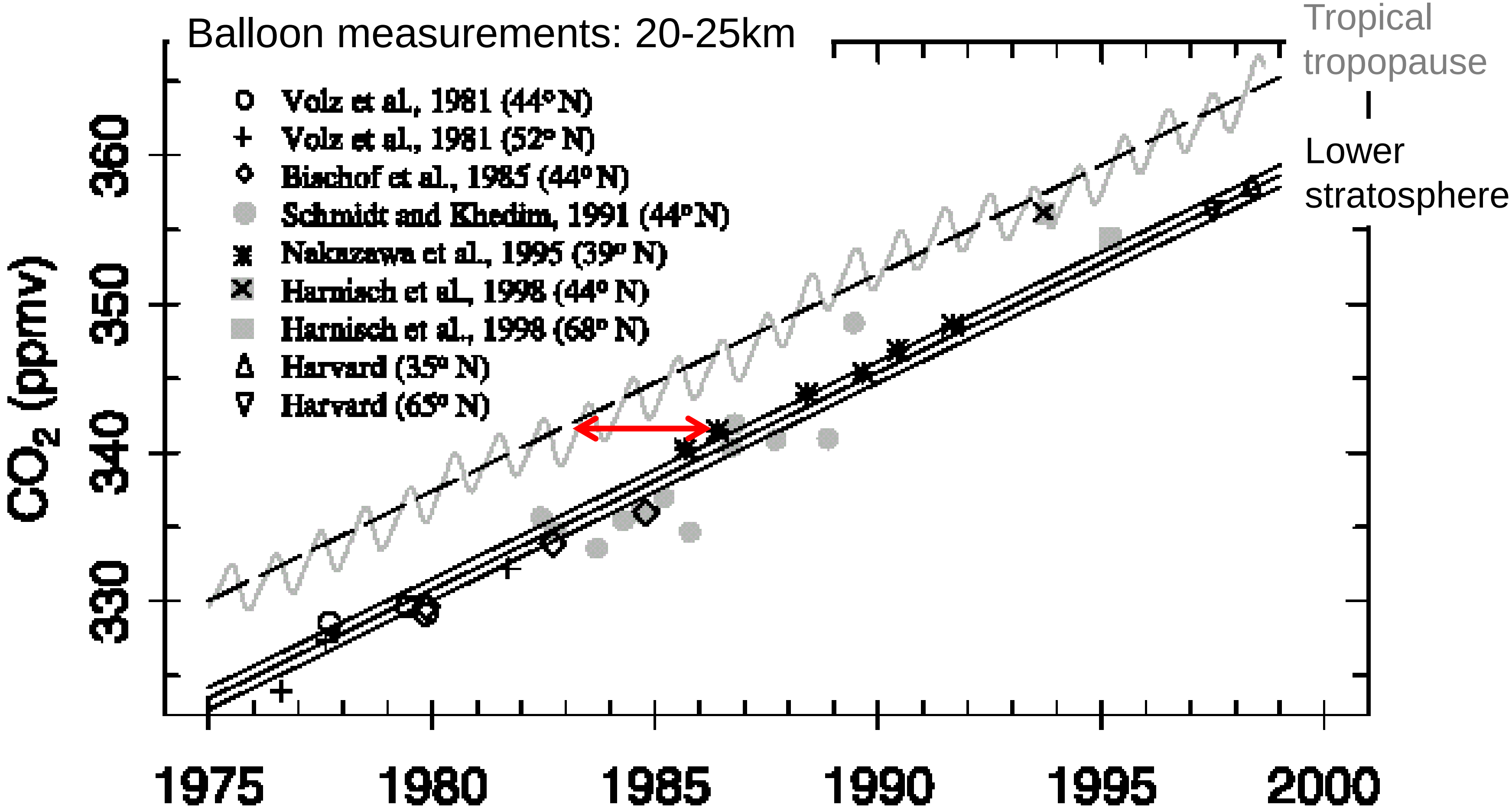
Tracer-distribution in the stratosphere

Increasing distance of the tropical tropopause



[Waugh et al., GR 2002]

CO_2 as a time distribution tracer - stratosphere



The transport from the tropical tropopause towards mid-latitudes, at 20-25 km altitude takes more than 4 years.

Andrews et al. (2001)

Carbon Cycle

Gas		Mixing ratio in ppm	Residence Time	Increase in % per year
Carbon dioxide	CO_2	398	5 – 200 a	0,4
Methane	CH_4	1.8	12 a	1,5
Carbon monoxide	CO	0.05 – 0.2	60 – 180 d	
Chlorofluorocarbon	CFC	10^{-3}	70 – 100 a	

+ many more Halocarbons

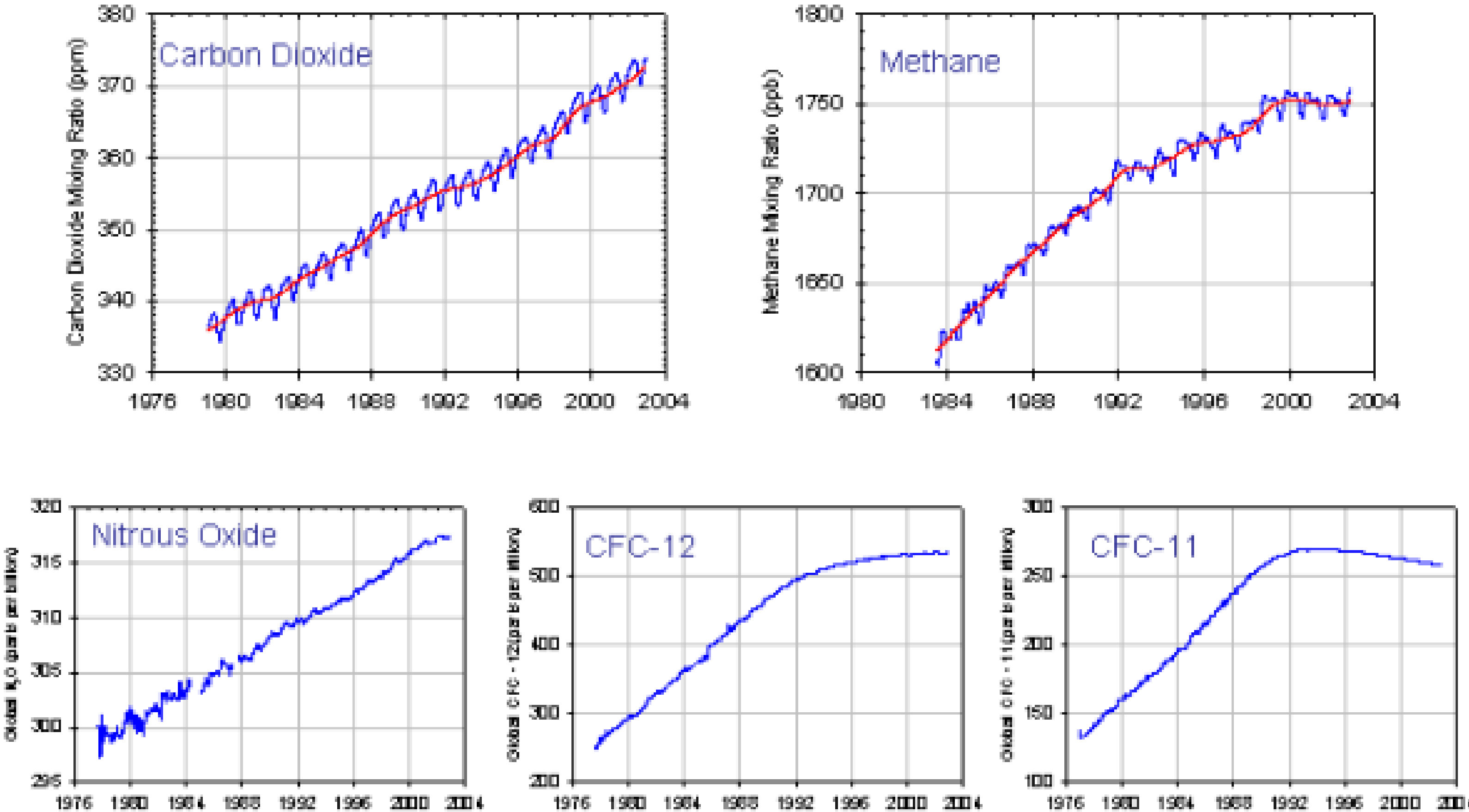
Greenhouse Gas Concentrations

GAS	Pre-1750 tropospheric concentration[1]	Recent tropospheric concentration[2]	GWP*(100-yr time horizon)	Atmospheric lifetime[4](years)	Increased radiative forcing [5] (W/m^2)
Mixing ratios in parts per million (ppm)					
Carbon dioxide (CO_2)	280[6]	384.8[7]	**1**	~ 100[4]	1.66
Mixing ratios in parts per billion (ppb)					
Methane (CH_4)	700[8]	1865[9]/1741[9]	**25**	12[4]	0.48
Nitrous oxide (N_2O)	270[10]	322[9]/321[9]	**298**	114[4]	0.16
Tropospheric ozone (O_3)	25[1]	34[4,1]	n.a.[4]	hours-days	0.35[4]

*Global Warming Potential is the ratio of the radiative forcing of a trace gas relative to that of CO_2.

http://cdiac.ornl.gov

Global Trends in Major Greenhouse Gases to 1/2003



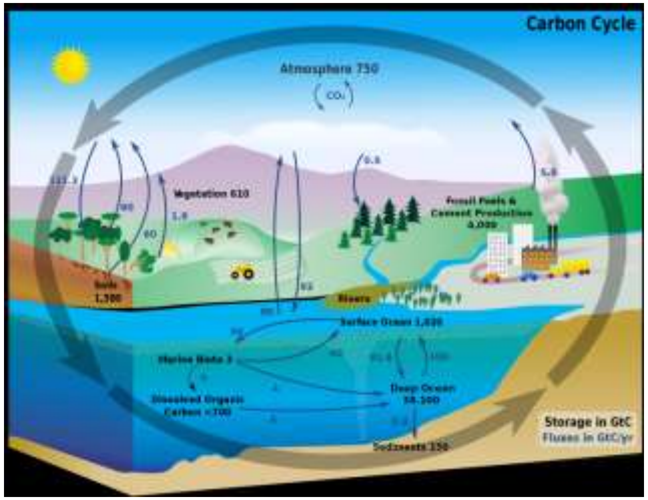
Global trends in major long-lived greenhouse gases through the year 2002. These five gases account for about 97% of the direct climate forcing by long-lived greenhouse gas increases since 1750. The remaining 3% is contributed by an assortment of 10 minor halogen gases, mainly HCFC-22, CFC-113 and CCl_4.

IPCC-AR models: WMGHG

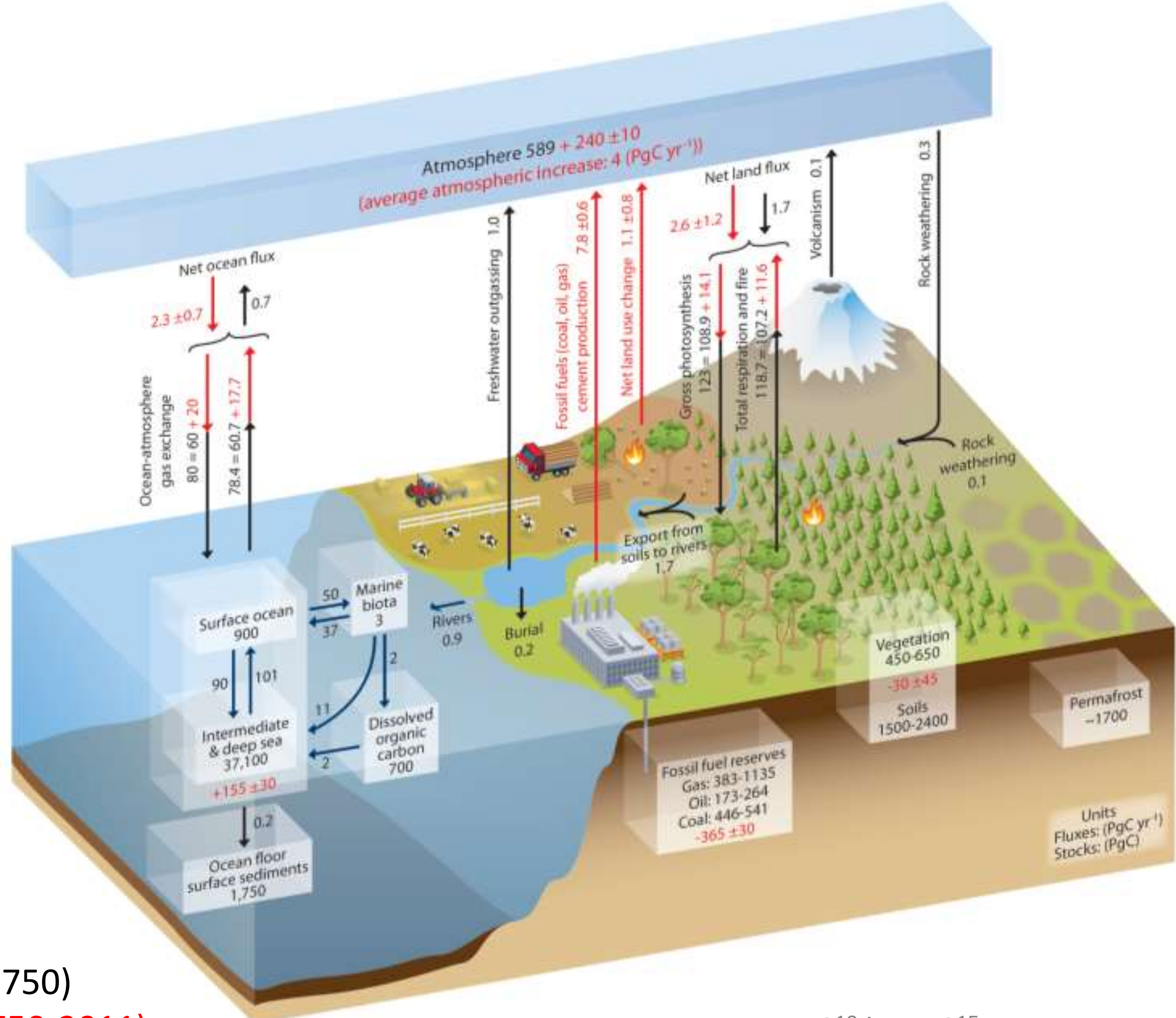
http://cdiac.ornl.gov

The Carbon Cycle in the IPCC FAR

- Introduction: Carbon Cycle *(Section 6.1)*



Global Carbon Cycle



→ Fluxes: PgC yr^{-1}

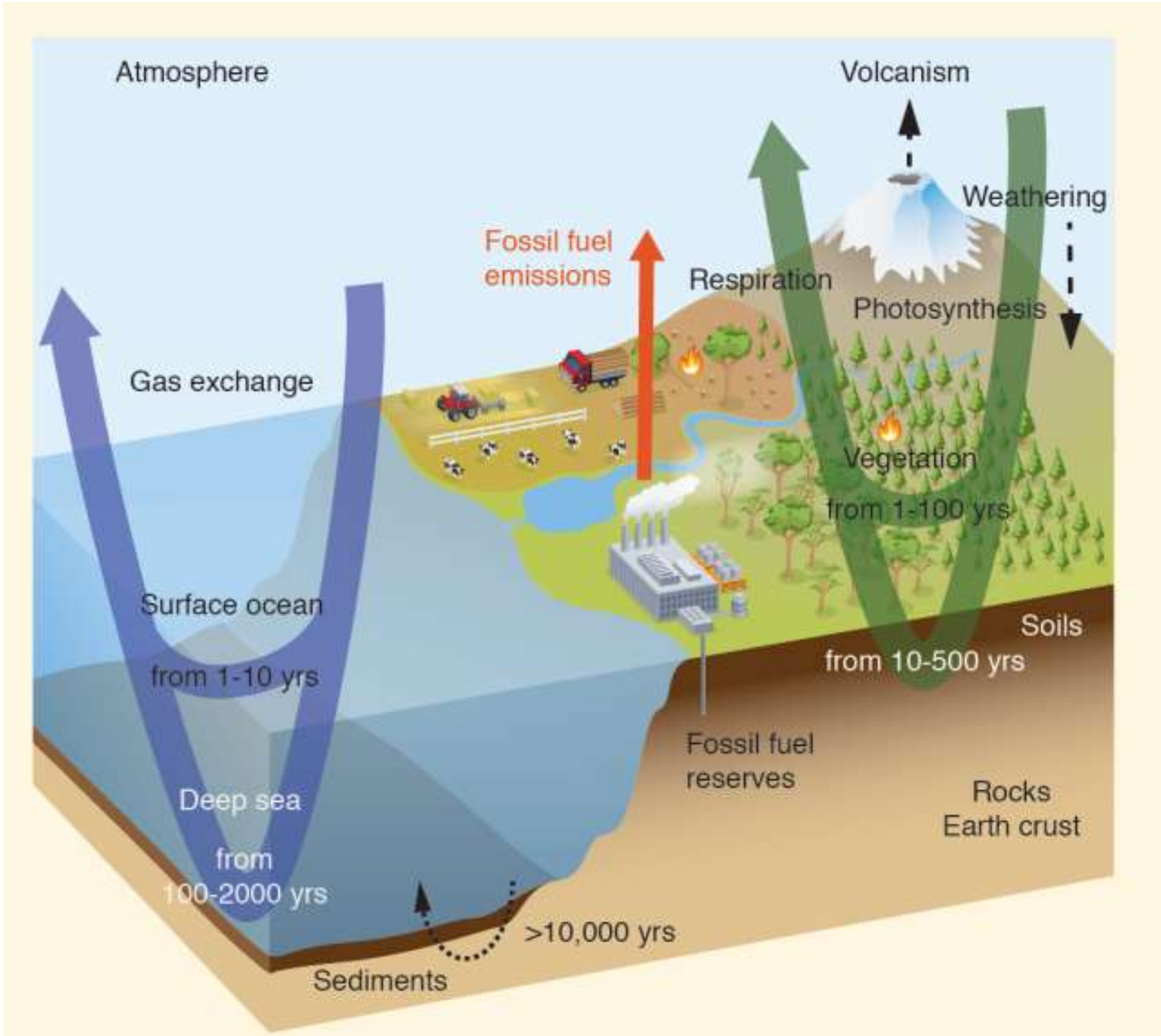
Stocks: Pg C

--pre-industrial (pre 1750)

--industrial period (1750-2011)

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

Global Carbon Cycle - turn over times scales



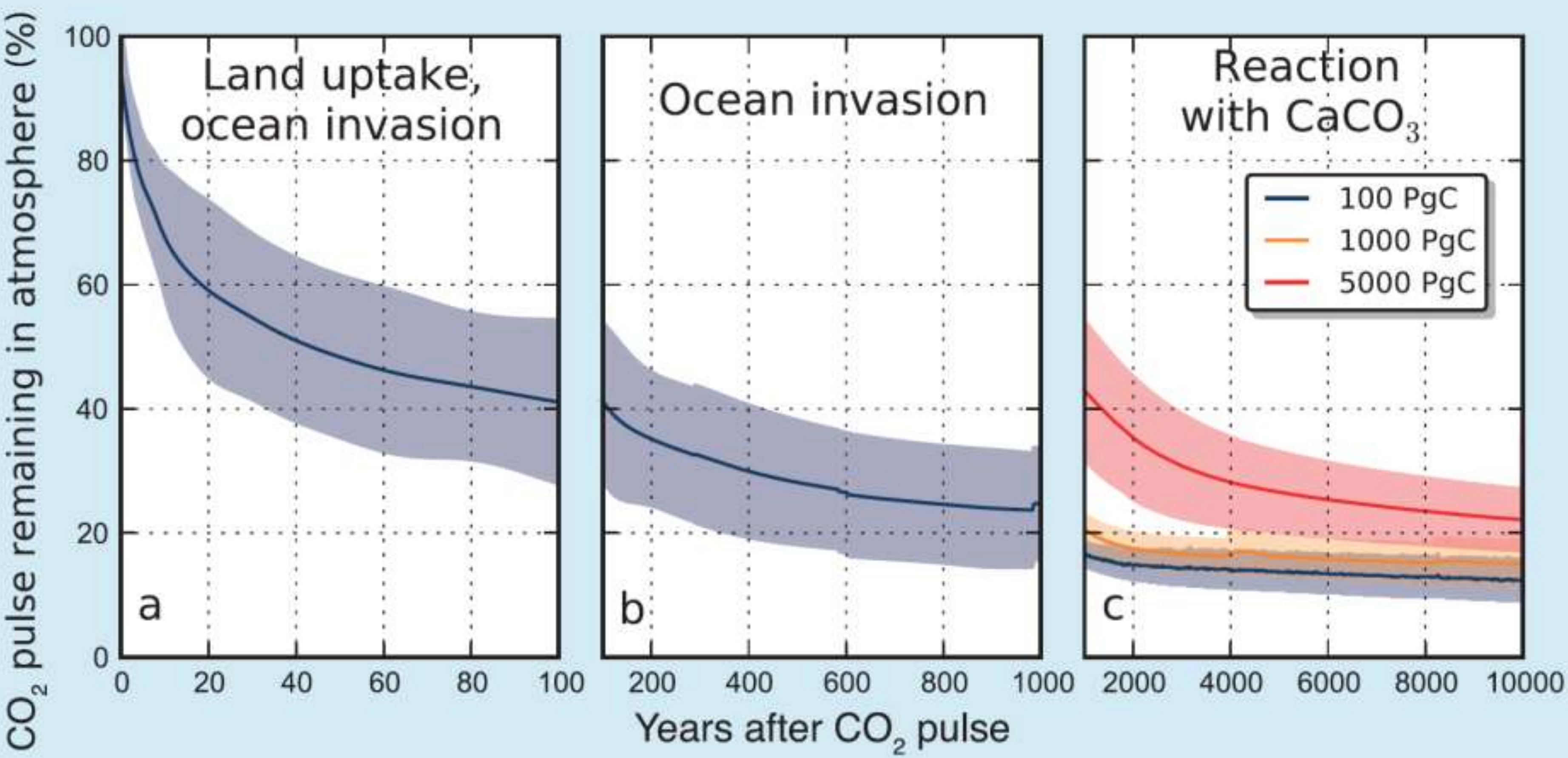
Box 6.1 | Multiple Residence Times for an Excess of Carbon Dioxide Emitted in the Atmosphere

Box 6.1, Table 1 | The main natural processes that remove CO_2 consecutive to a large emission pulse to the atmosphere, their atmospheric CO_2 adjustment time scales, and main (bio)chemical reactions involved.

Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	$1–10^2$	$6CO_2 + 6H_2O + \text{photons} \rightarrow C_6H_{12}O_6 + 6O_2$ $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$
Ocean invasion: Seawater buffer	$10–10^3$	$CO_2 + CO_3^{2-} + H_2O \rightleftharpoons 2HCO_3^-$
Reaction with calcium carbonate	$10^3–10^4$	$CO_2 + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$
Silicate weathering	$10^4–10^6$	$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

$C_6H_{12}O_6$: Sugar
$CaCO_3$:Calcium carbonate
Dissolved carbon dioxide: $CO_{2(aq)}$
Bicarbonate HCO_3^-
Carbonate ion: CO_3^{2-}
Calcium inosilicate mineral (limestone): $CaSiO_3$
Silicon dioxide (quartz): SiO_2

Box 6.1 | Multiple Residence Times for an Excess of Carbon Dioxide Emitted in the Atmosphere



Concept of a single, characteristic atmospheric lifetime is not applicable to CO_2 (→Chapter 8).

Atmospheric CO_2 adjustment to anthropogenic carbon emissions

Phase 1:

-**Within decades**, about 1/3 to 1/2 half of anthropogenic CO2 goes into land and ocean, while the rest stays in the atmosphere.

-**Within centuries**, most of the anthropogenic CO2 will be in the form of additional dissolved inorganic carbon in the ocean, decreasing ocean pH.

-**Within 1 kyr**, the remaining atmospheric fraction of the CO2 emissions is between 15 and 40%, depending on the amount of carbon released. (>Carbonate buffer capacity of ocean decreases with higher CO2 >larger cumulative emissions >higher remaining atmospheric fraction.)

Phase 2:

-Within **several 1 kyr**, ocean pH will be restored by reaction of ocean dissolved CO2 and calcium carbonate (CaCO3) of sea floor sediments, partly replenishing the buffer capacity of the ocean and further drawing down atmospheric CO2 as a new balance is re-established between CaCO3 sedimentation in the ocean and terrestrial weathering.
- Atmospheric CO2 fraction down to 10 to 25% after about 10 kyr.

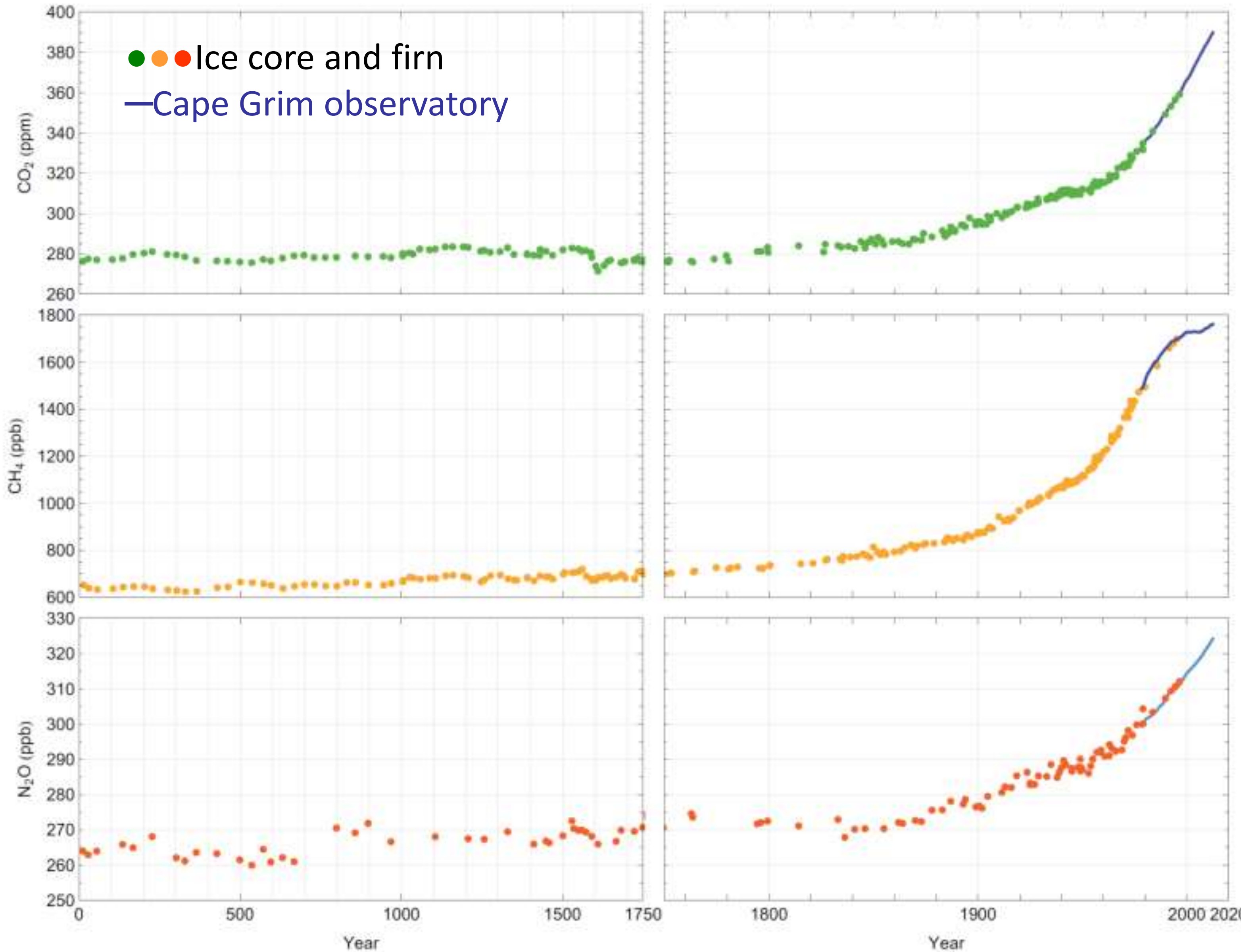
Phase 3:

-Within **several 100 kyr**, rest of emitted CO2 will be removed from atmosphere by silicate weathering (very slow process of CO2 reaction with calcium silicate (CaSiO3) and other minerals of igneous rocks).

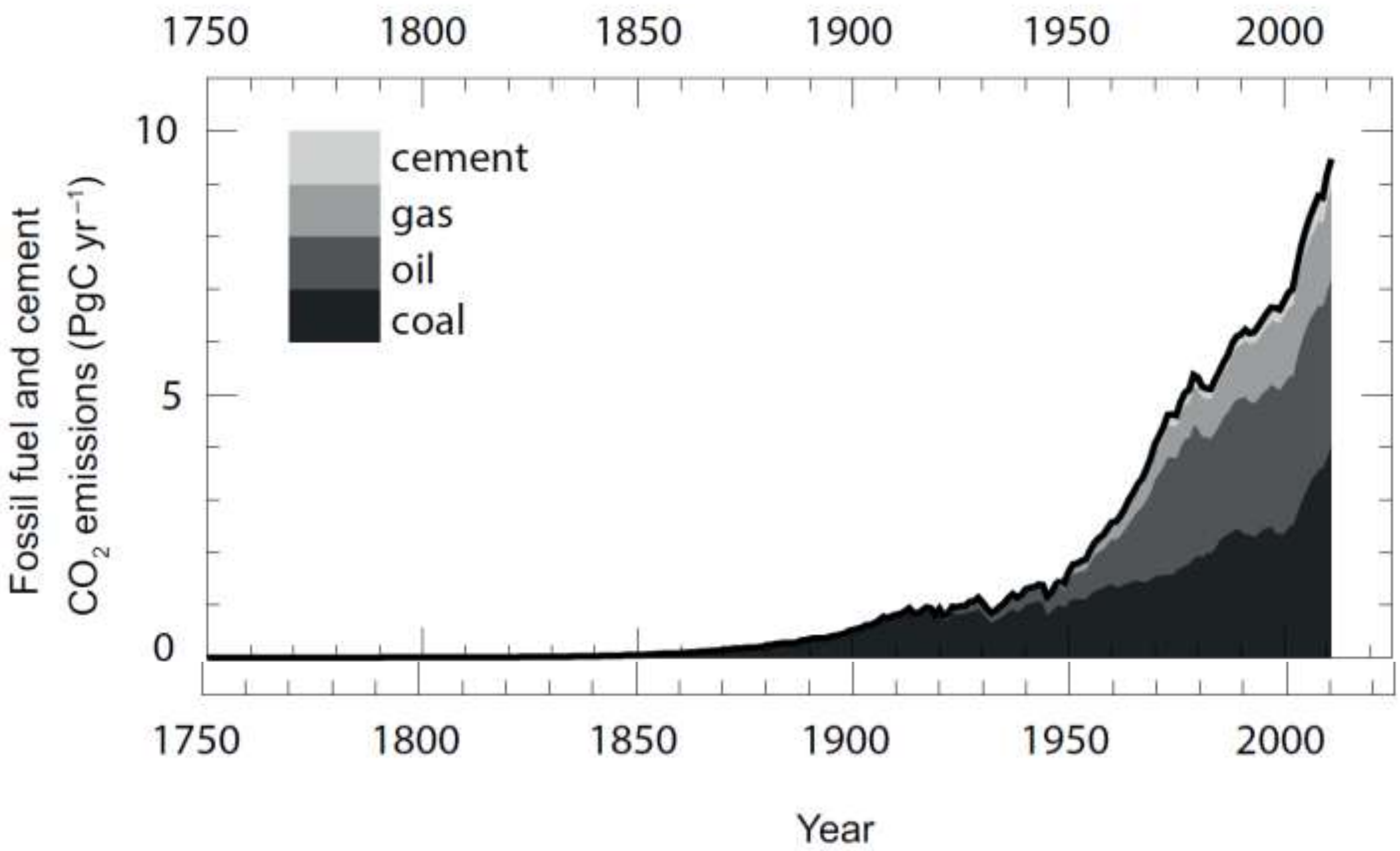
The Carbon Cycle in the IPCC FAR

- Evolution of biogeochemical cycles since industrial era *(Section 6.3)*

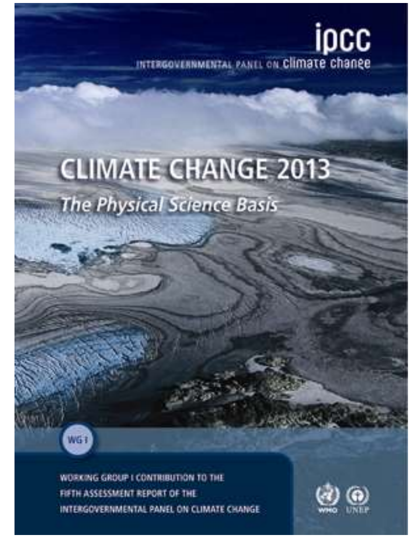
Atmospheric CO_2, CH_4, N_2O pre-industrial era



Anthropogenic CO_2 emissions



IPCC Chapter 6: **Carbon and other biogeochemical cycles**



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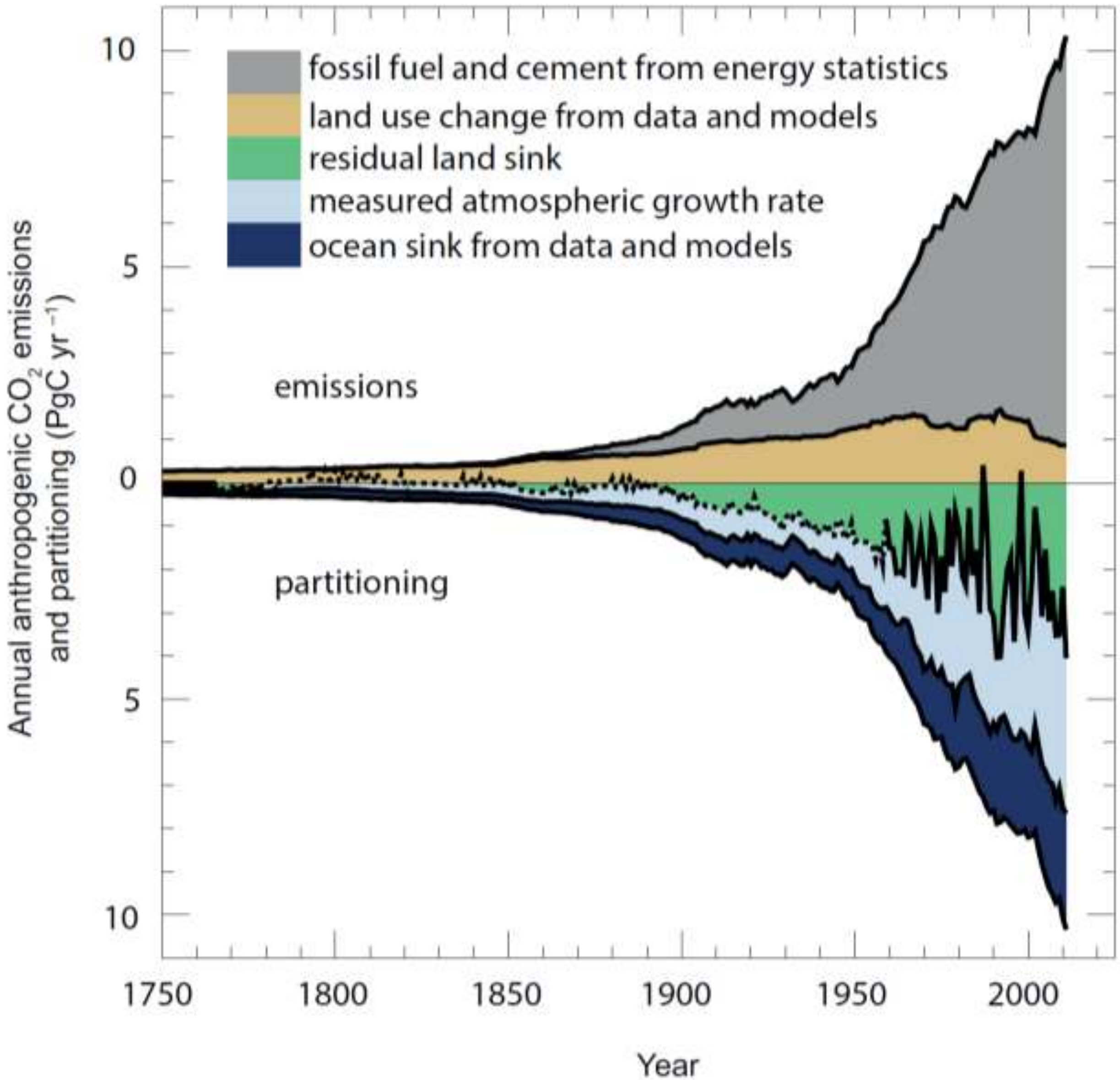
Anthropogenic CO_2 emissions and partitioning



Global anthropogenic CO_2 budget – time evolution

Table 6.1 | Global anthropogenic CO_2 budget, accumulated since the Industrial Revolution (onset in 1750) and averaged over the 1980s, 1990s, 2000s, as well as the last 10 years until 2011. By convention, a negative ocean or land to atmosphere CO_2 flux is equivalent to a gain of carbon by these reservoirs. The table does not include natural exchanges (e.g., rivers, weathering) between reservoirs. The uncertainty range of 90% confidence interval presented here differs from how uncertainties were reported in AR4 (68%).

	1750–2011 Cumulative PgC	1980–1989 PgC yr^{-1}	1990–1999 PgC yr^{-1}	2000–2009 PgC yr^{-1}	2002–2011 PgC yr^{-1}
Atmospheric increase[a]	240 ± 10[f]	3.4 ± 0.2	3.1 ± 0.2	4.0 ± 0.2	4.3 ± 0.2
Fossil fuel combustion and cement production[b]	375 ± 30[f]	5.5 ± 0.4	6.4 ± 0.5	7.8 ± 0.6	8.3 ± 0.7
Ocean-to-atmosphere flux[c]	–155 ± 30[f]	–2.0 ± 0.7	–2.2 ± 0.7	–2.3 ± 0.7	–2.4 ± 0.7
Land-to-atmosphere flux *Partitioned as follows*	30 ± 45[f]	–0.1 ± 0.8	–1.1 ± 0.9	–1.5 ± 0.9	–1.6 ± 1.0
Net land use change[d]	180 ± 80[f,g]	1.4 ± 0.8	1.5 ± 0.8	1.1 ± 0.8	0.9 ± 0.8
Residual land sink[e]	–160 ± 90[f]	–1.5 ± 1.1	–2.6 ± 1.2	–2.6 ± 1.2	–2.5 ± 1.3

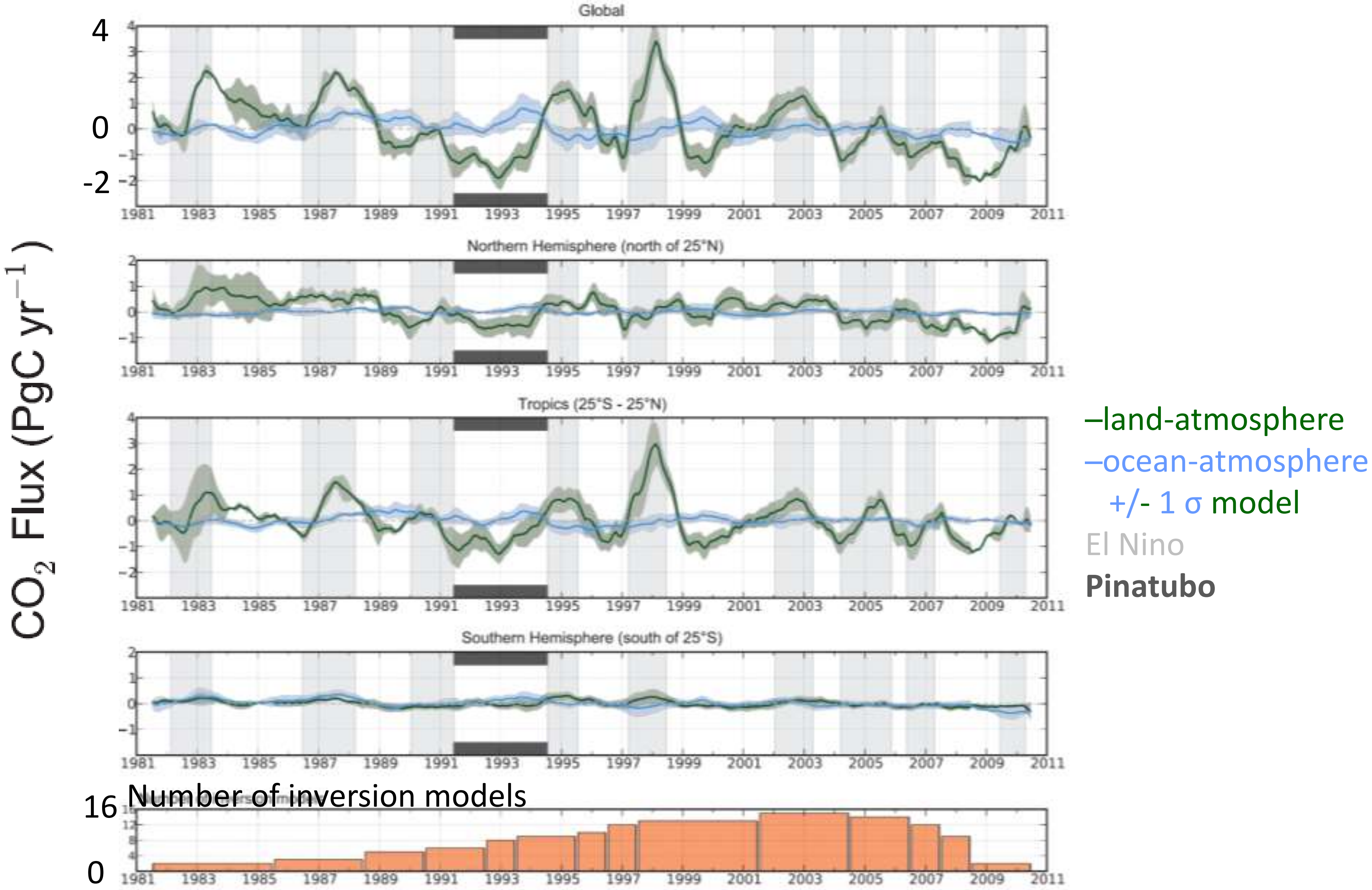
- Varying atmospheric CO2 sources growth; mainly increasing since the last three decades.
- Ocean CO2 sink is also slightly increasing.

Carbon Dioxide from Fossil Fuel Combustion

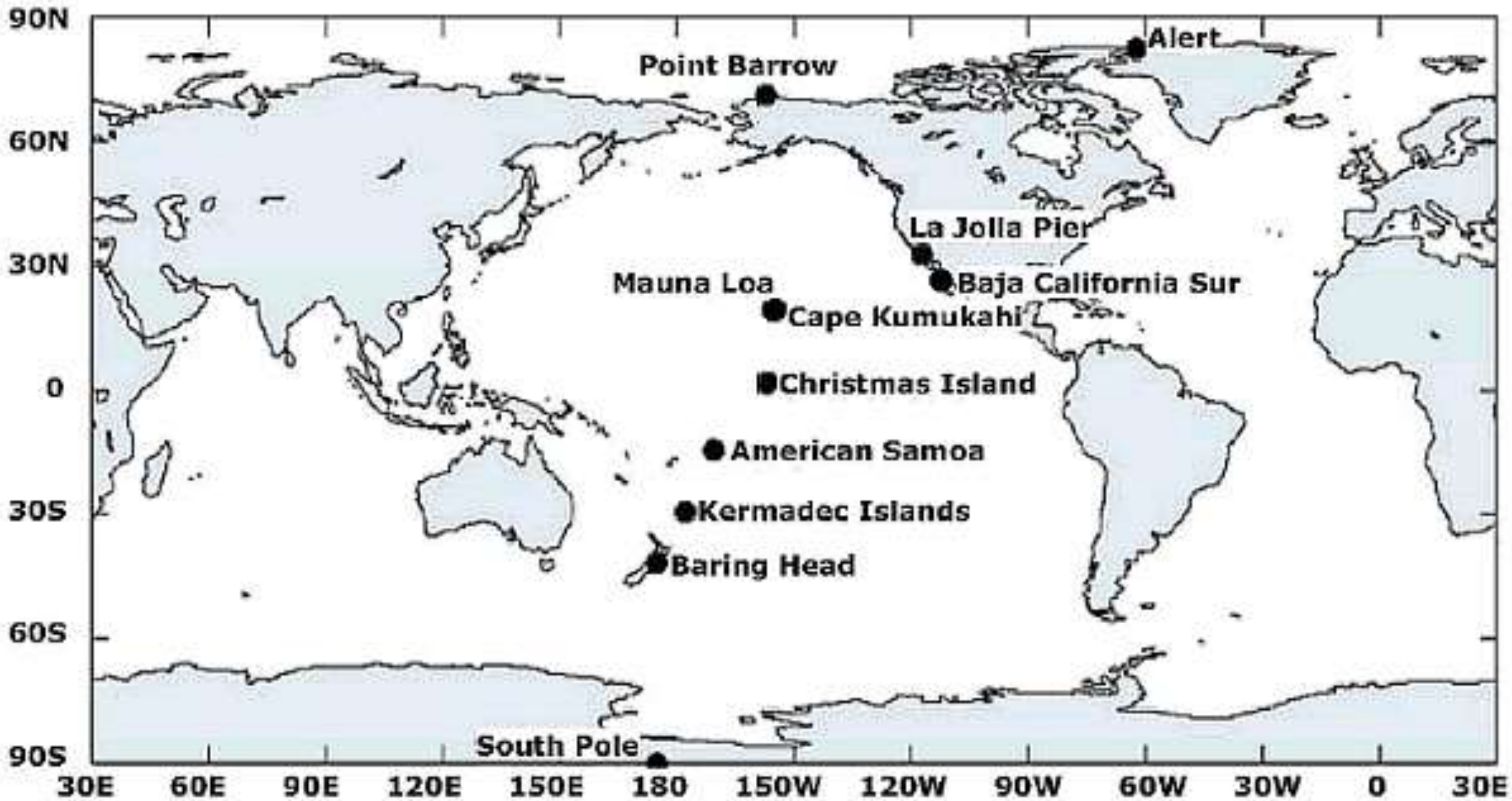
This video shows the accumulation of carbon dioxide (CO_2) in the atmosphere from the burning of coal, oil, and natural gas (fossil fuels) over a two-year time period (2011-2012). The video begins with a map of the world with no fossil fuel CO_2. As time progresses the viewer watches the global accumulation of CO_2 emissions from all fossil fuel sources. Large emitters such as Eastern Asia, Western Europe, and the North East of North America stand out. By the end of 2012, the entire Northern Hemisphere is red, illustrating a total accumulation of about 9 to 10 ppm of CO_2.

www.esrl.noaa.gov/gmd/ccgg/trends/ff.html

CO_2 flux anomalies – inversion modeling

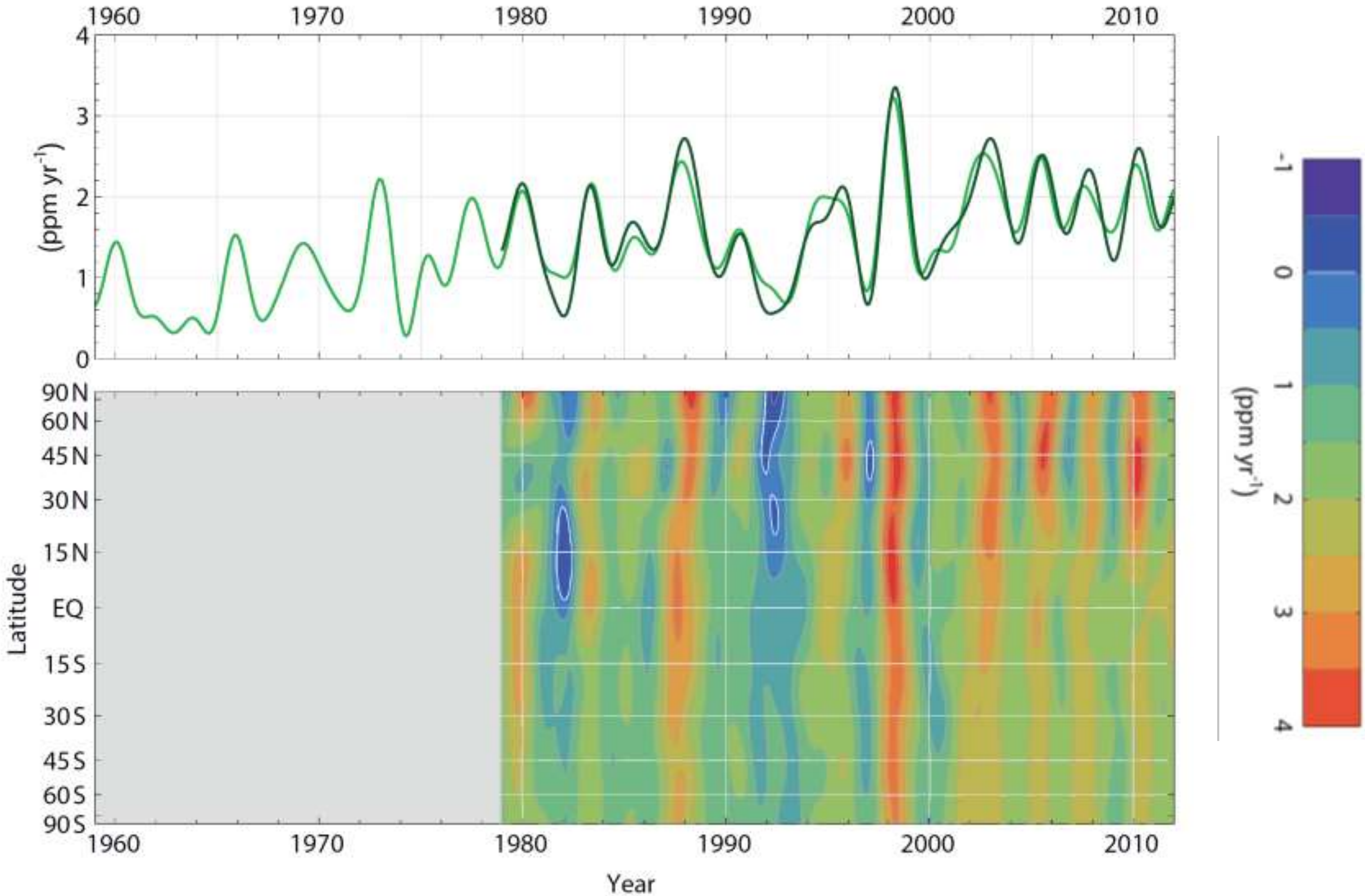


Atmospheric CO_2 Records from monitoring sites of the Scripps Institution of Oceanography (SIO)



Atmospheric CO_2 growth rate [ppm/yr]

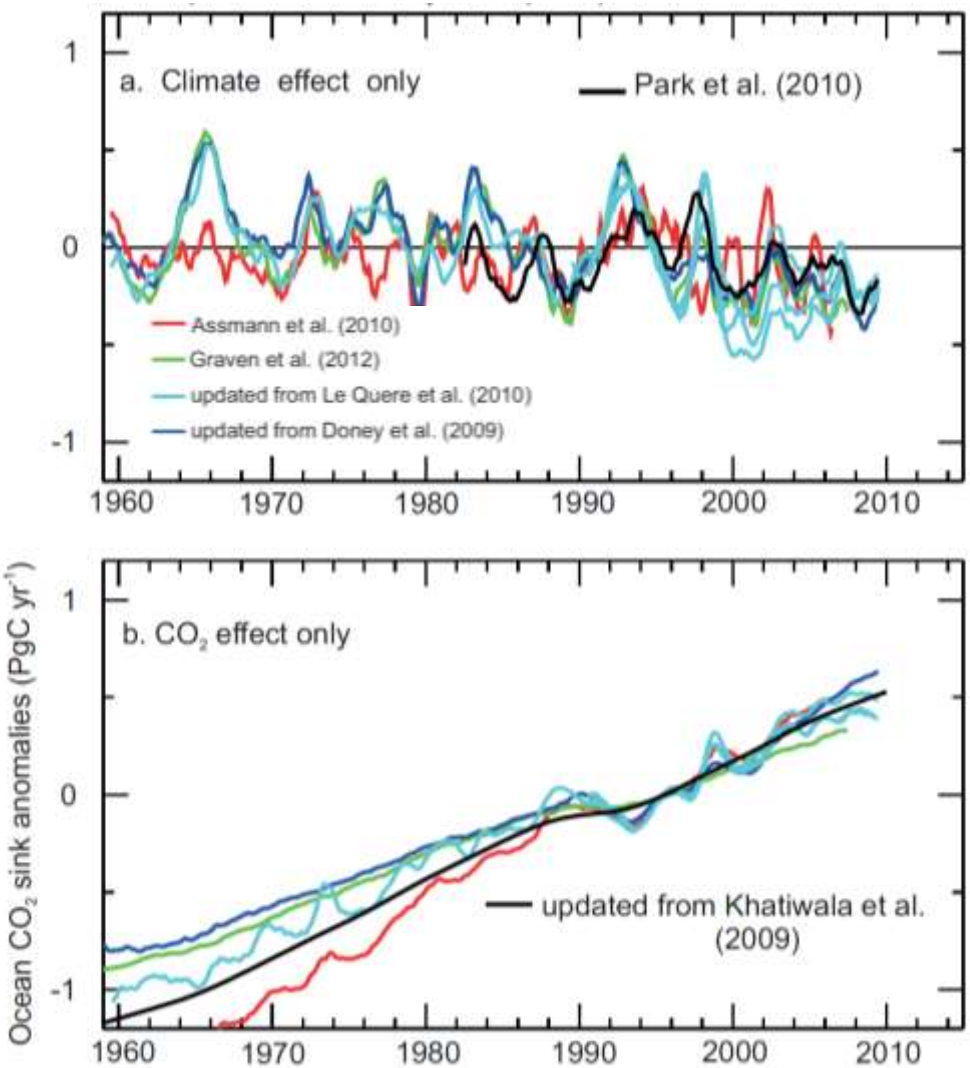
- SIO and NOAO GMD marine observations

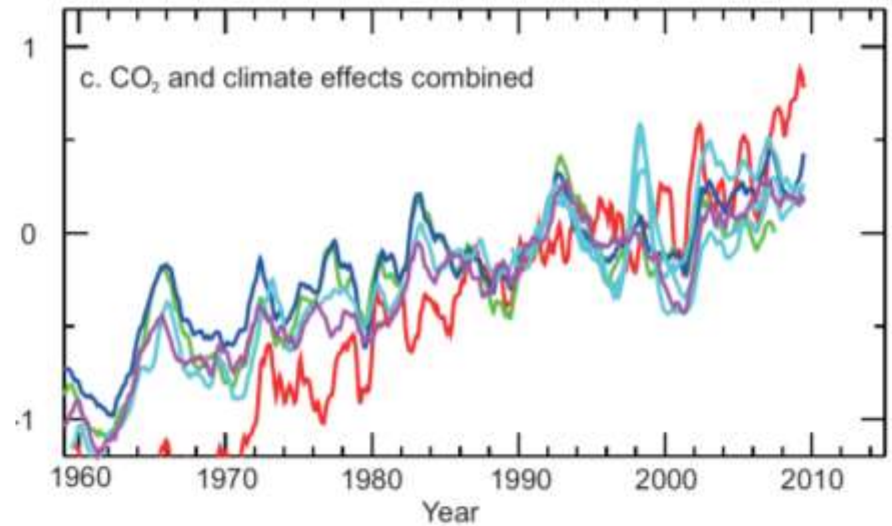


NOAA GMD: National Oceanic & Atmospheric Administration Global Monitoring Division

Ocean CO_2 flux variations - temporal

Anomalous CO_2 ocean-to-atmosphere fluxes wrt 1990-2000 avgs





---- Ocean models

-- Indirect methods based on observations

-Low interannual variability.

-Ocean takes up more CO_2 during El Nino due to the suppression of CO_2 ota fluxes over the East Pacific upwelling.

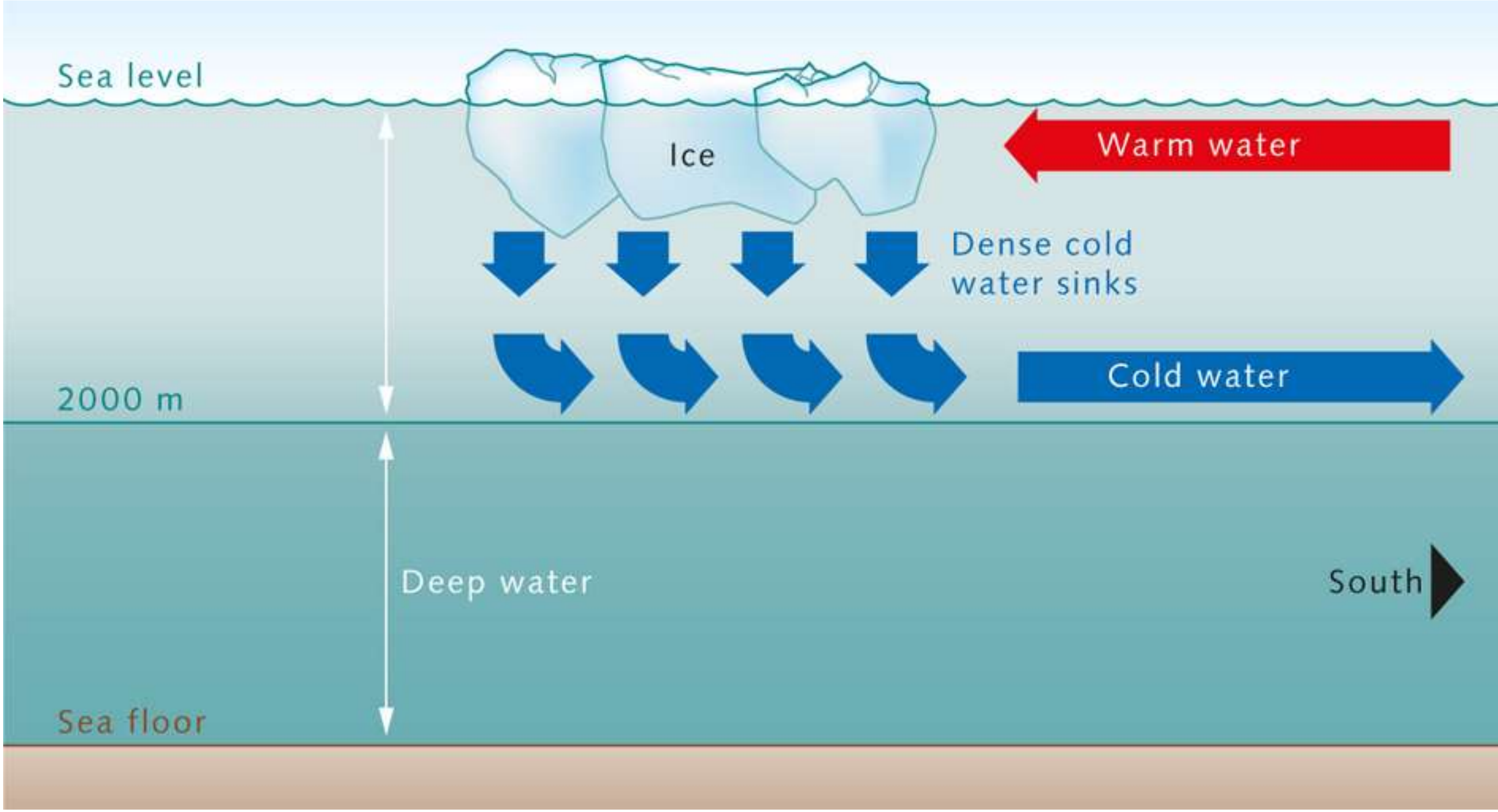
Ocean inorganic carbon storage – regional changes

Section	Time	Storage Rate (mol C m^{-2} yr^{-1})	Data Source
Global average (used in Table 6.1)	2007–2008	0.5 ± 0.2	Khatiwala et al. (2009)
Pacific Ocean			
Section along 30°S	1992–2003	1.0 ± 0.4	Murata et al. (2007)
N of 50°S, 120°W to 180°W	1974–1996	0.9 ± 0.3	Peng et al. (2003)
154°W, 20°N to 50°S	1991–2006	0.6 ± 0.1	Sabine et al. (2008)
140°E to 170°W, 45°S to 65°S	1968–1991/1996	0.4 ± 0.2	Matear and McNeil (2003)
149° W, 4°S to 10°N	1993–2005	0.3 ± 0.1	Murata et al. (2009)
149° W, 24°N to 30°N	1993–2005	0.6 ± 0.2	Murata et al. (2009)
Northeast Pacific	1973–1991	1.3 ± 0.5	Peng et al. (2003)
~160°E, ~45°N	1997–2008	0.4 ± 0.1	Wakita et al. (2010)
North of 20°N	1994–2004/2005	0.4 ± 0.2	Sabine et al. (2008)
150°W, 20°S to 20°N	1991/1992–2006	0.3 ± 0.1	Sabine et al. (2008)
Indian Ocean			
2 [illegible]	[illegible]	[illegible]	[illegible]
1 [illegible]	[illegible]	[illegible]	[illegible]
S [illegible]	[illegible]	[illegible]	[illegible]
Atlantic Ocean			
Section along 30°S	1992/1993–2003	0.6 ± 0.1	Murata et al. (2010)
~30°W, 56°S to 15°S	1989–2005	0.8	Wanninkhof et al. (2010)
20°W, 64°N to 15°N	1993–2003	0.6	Wanninkhof et al. (2010)
~25°W, 15°N to 15°S	1993–2003	0.2	Wanninkhof et al. (2010)
40°N to 65°N	1981–1997/1999	2.2 ± 0.7	Friis et al. (2005)
20°N to 40°N	1981–2004	1.2 ± 0.3	Tanhua et al. (2007)
Nordic Seas	1981–2002/2003	0.9 ± 0.2	Olsen et al. (2006)
Sub-decadal variations			
Irminger Sea	1981–1991	0.6 ± 0.4	Pérez et al. (2008)
Irminger Sea	1991–1996	2.3 ± 0.6	Pérez et al. (2008)
Irminger Sea	1997–2006	0.8 ± 0.2	Pérez et al. (2008)

Anthropogenic Carbon uptake is observed to be larger over the high latitude oceans because of the more vigorous convection there.

Table 6.5 | Regional rates of change in inorganic carbon storage from shipboard repeated hydrographic cross sections.

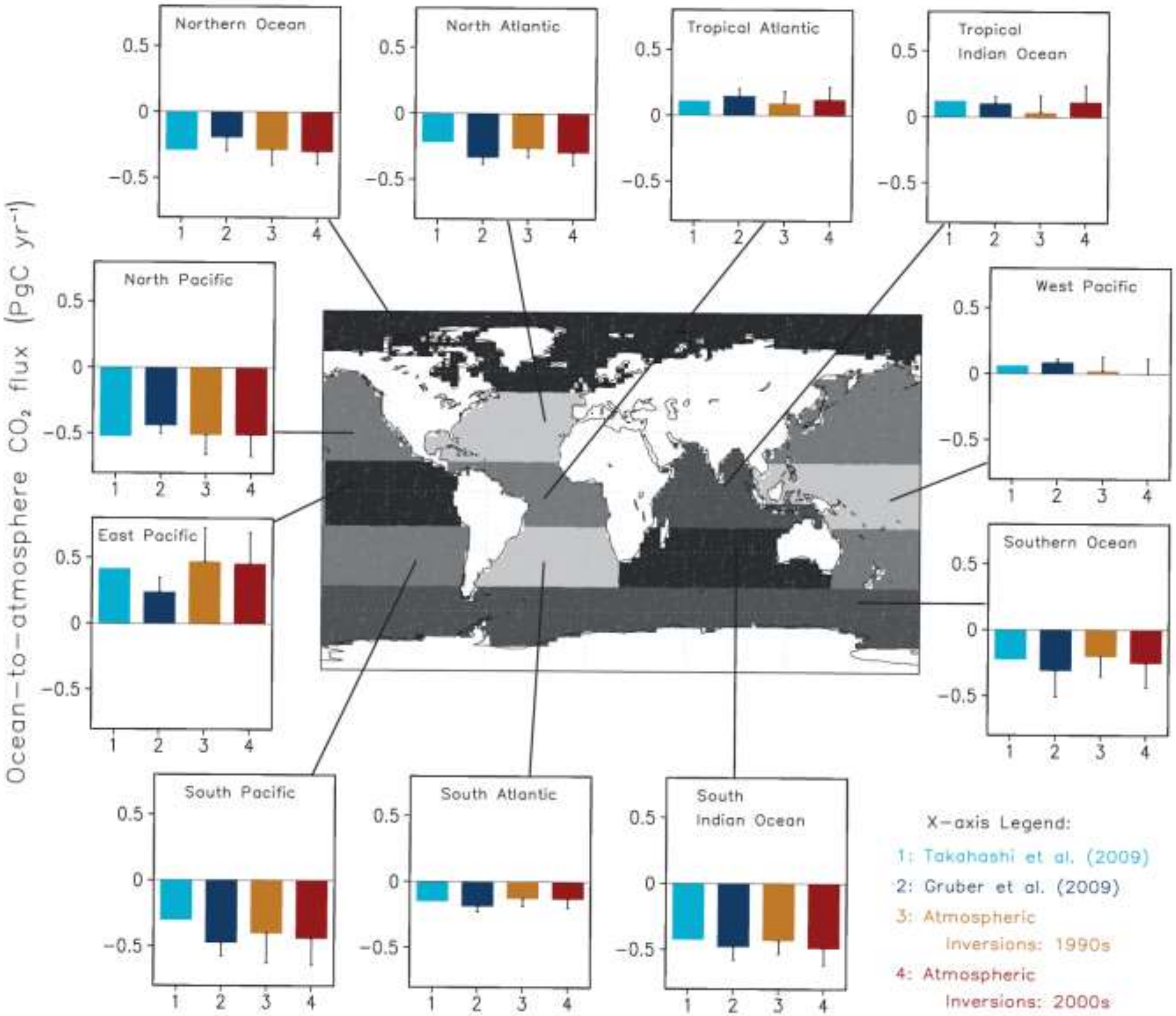
Ocean convection



worldoceanreview.com

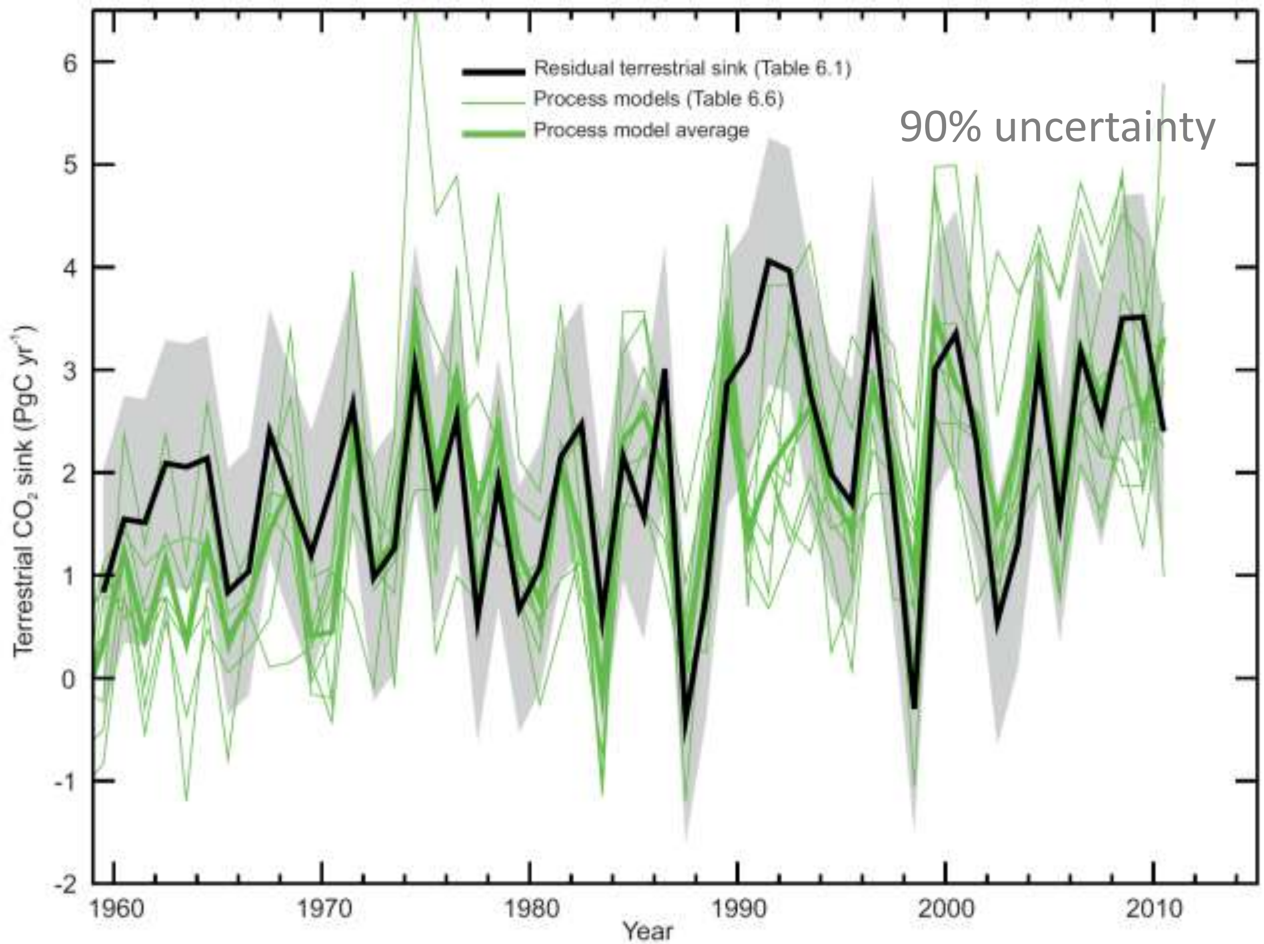
Decadal oceanic CO_2 fluxes

2000s-1990s



Terrestrial CO_2 sink – temporal

models wo land use change



- Large interannual variability; large uncertainties.
- Tropical land ecosystems dominate global CO_2 variability.
- During El Nino/La Nina enhanced land CO_2 source/sink.
- ENSO-Volcanic Index time series explains 75% of the observed variability.

Box 6.3 | The Carbon Dioxide Fertilisation Effect

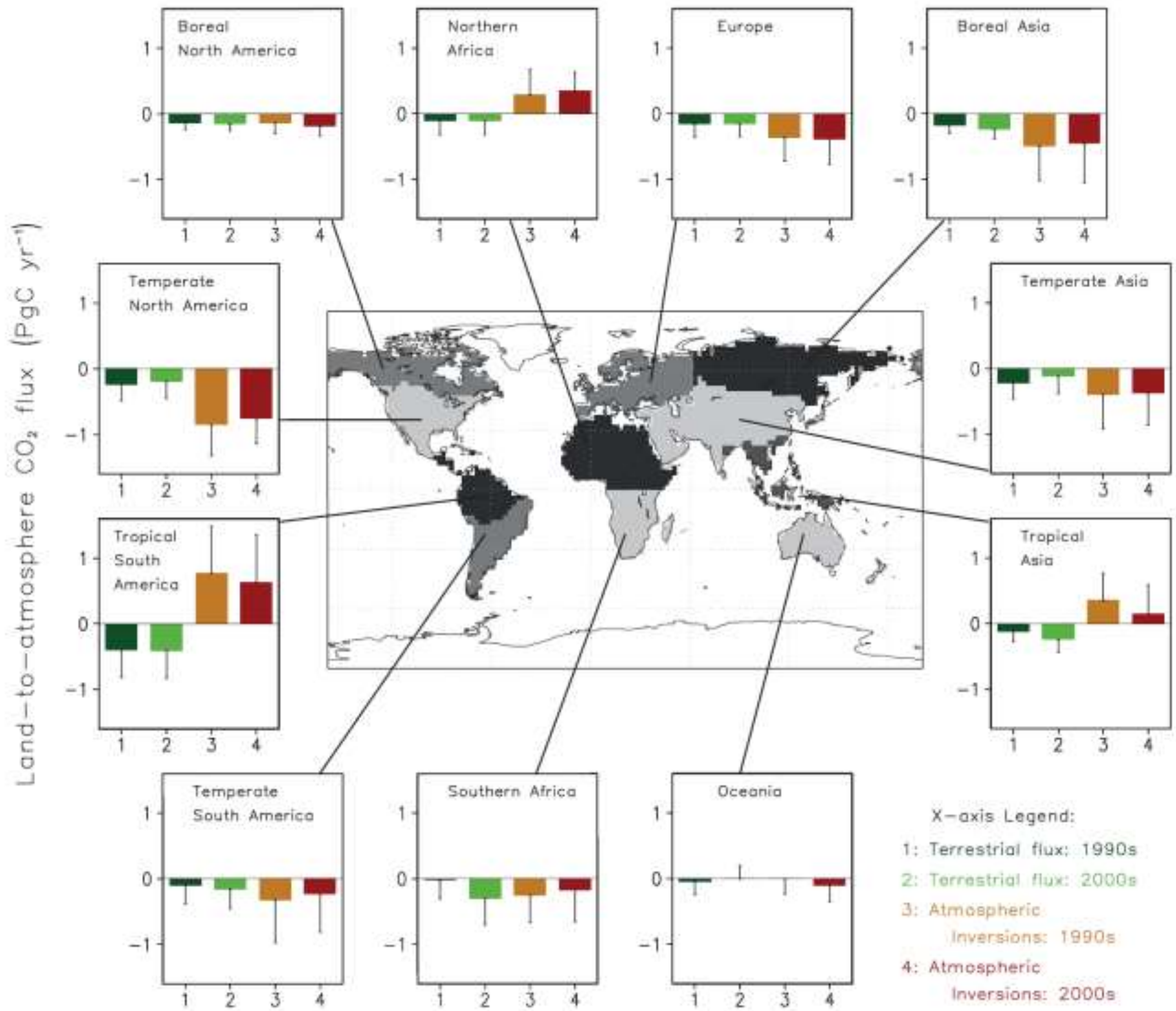
Elevated atmospheric CO_2 concentrations lead to higher leaf photosynthesis and reduced canopy transpiration, which in turn lead to increased plant water use efficiency and reduced fluxes of surface latent heat. The increase in leaf photosynthesis with rising CO_2, the so-called CO_2 fertilisation effect, plays a dominant role in terrestrial biogeochemical models to explain the global land carbon sink (Sitch et al., 2008), yet it is one of most unconstrained process in those models.

Field experiments provide a direct evidence of increased photosynthesis rates and water use efficiency (plant carbon gains per unit of water loss from transpiration) in plants growing under elevated CO_2. These physiological changes translate into a broad range of higher plant carbon accumulation in more than two-thirds of the experiments and with increased net primary productivity (NPP) of about 20 to 25% at double CO_2 from pre-industrial concentrations (Ainsworth and Long, 2004; Luo et al., 2004, 2006; Nowak et al., 2004; Norby et al., 2005;Canadell et al., 2007a; Denman et al., 2007; Ainsworth et al., 2012; Wang et al., 2012a). Since the AR4, new evidence is available from long-term Free-air CO_2 Enrichment (FACE) experiments in temperate ecosystems showing the capacity of ecosystems exposed to elevated CO_2 to sustain higher rates of carbon accumulation over multiple years (Liberloo et al., 2009; McCarthy et al., 2010; Aranjuelo et al., 2011; Dawes et al., 2011; Lee et al., 2011; Zak et al., 2011). However, FACE experiments also show the diminishing or lack of CO_2 fertilisation effect in some ecosystems and for some plant species (Dukes et al., 2005; Adair et al., 2009; Bader et al., 2009; Norby et al., 2010; Newingham et al., 2013). This lack of response occurs despite increased water use efficiency, also confirmed with tree ring evidence (Gedalof and Berg, 2010; Peñuelas et al., 2011).

Nutrient limitation is hypothesized as primary cause for reduced or lack of CO_2 fertilisation effect observed on NPP in some experiments (Luo et al., 2004; Dukes et al., 2005; Finzi et al., 2007; Norby et al., 2010). Nitrogen and phosphorus are *very likely* to play the most important role in this limitation of the CO_2 fertilisation effect on NPP, with nitrogen limitation prevalent in temperate and boreal ecosystems, and phosphorus limitation in the tropics (Luo et al., 2004; Vitousek et al., 2010; Wang et al., 2010a; Goll et al., 2012). Micronutrients interact in diverse ways with other nutrients in constraining NPP such as molybdenum and phosphorus in the tropics (Wurzburger et al., 2012). Thus, with *high confidence*, the CO_2 fertilisation effect will lead to enhanced NPP, but significant uncertainties remain on the magnitude of this effect, given the lack of experiments outside of temperate climates.

Decadal terrestrial CO_2 fluxes - regional

2000s-1990s



Regional CO_2 budgets

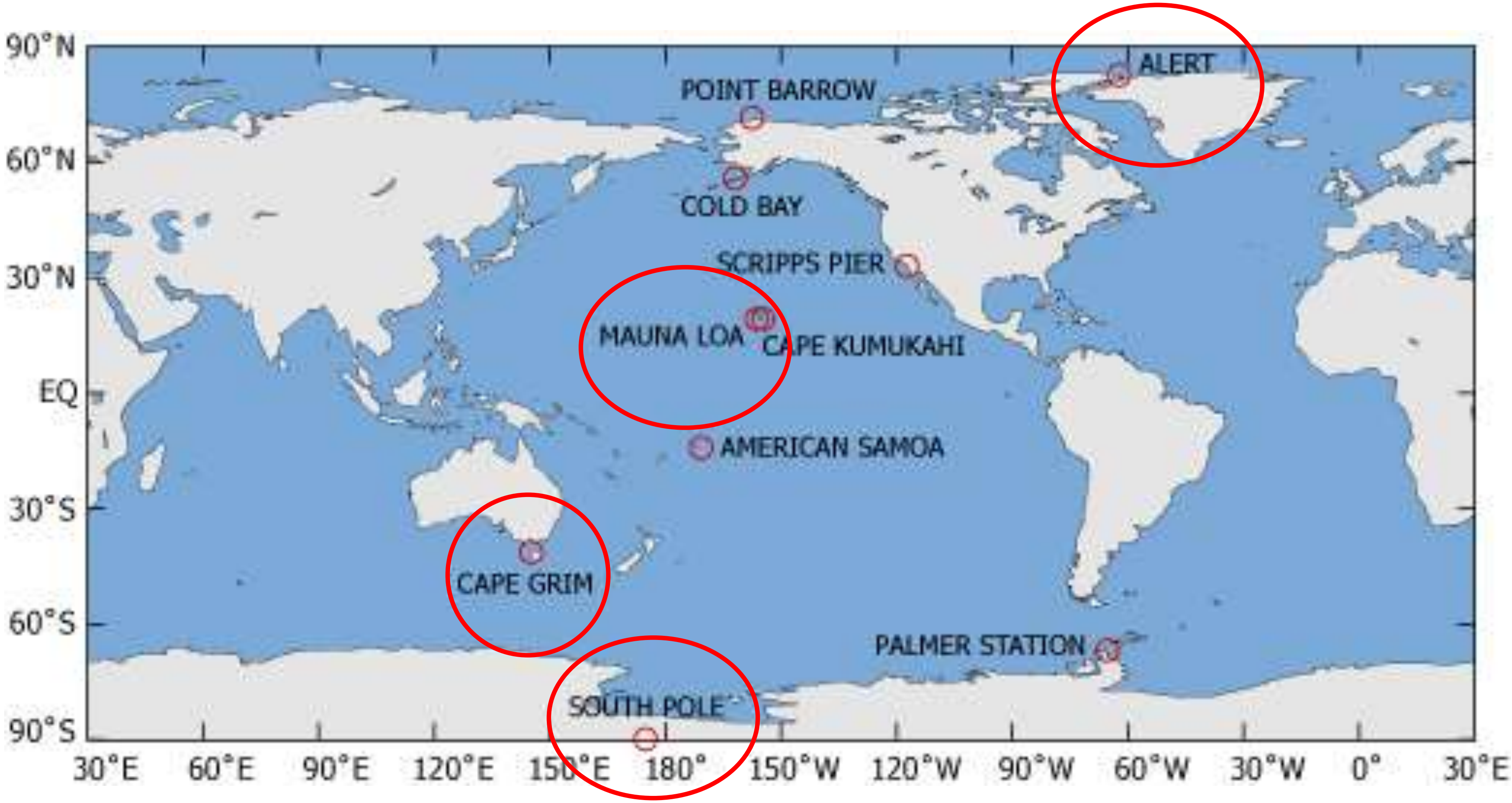
Table 6.6 | Regional CO_2 budgets using top-down estimates (atmospheric inversions) and bottom-up estimates (inventory data, biogeochemical modelling, eddy-covariance), excluding fossil fuel emissions. A positive sign indicates a flux from the atmosphere to the land (i.e., a land sink).

Region	CO_2 Sink ($PgC\ yr^{-1}$)	Uncertainty[a]	Period	Reference
Artic Tundra	0.1	±0.3[b]	2000–2006	McGuire et al. (2012)
Australia	0.04	±0.03	1990–2009	Haverd et al. (2013)
East Asia	0.25	±0.1	1990–2009	Piao et al. (2012)
Europe	0.9	±0.2	2001–2005	Luyssaert et al. (2012)
North America	0.6	±0.02	2000–2005	King et al. (2012)
Russian Federation	0.6	–0.3 to –1.3	1990–2007	Dolman et al. (2012)
South Asia	0.15	±0.24	2000–2009	Patra et al. (2013)
South America	–0.3	±0.3	2000–2005	Gloor et al. (2012)

Notes:

[a] One standard deviation from mean unless indicated otherwise.

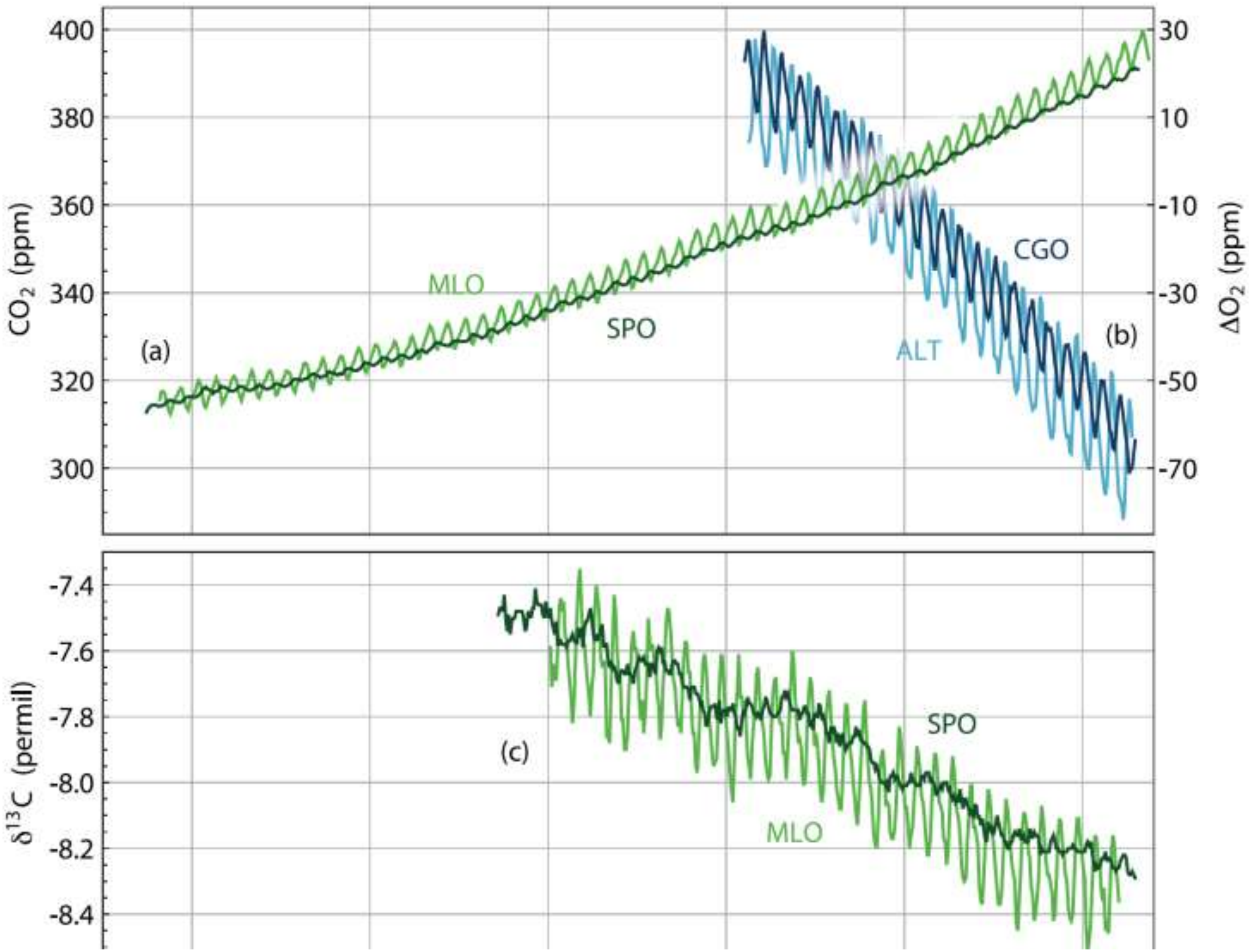
[b] Based on range provided.



MLO: Mauna Loa Observatory SPO: South Pole Observatory
ALT: Alert NH CGO: Cape Grim Observatory

crippso2.ucsd.edu

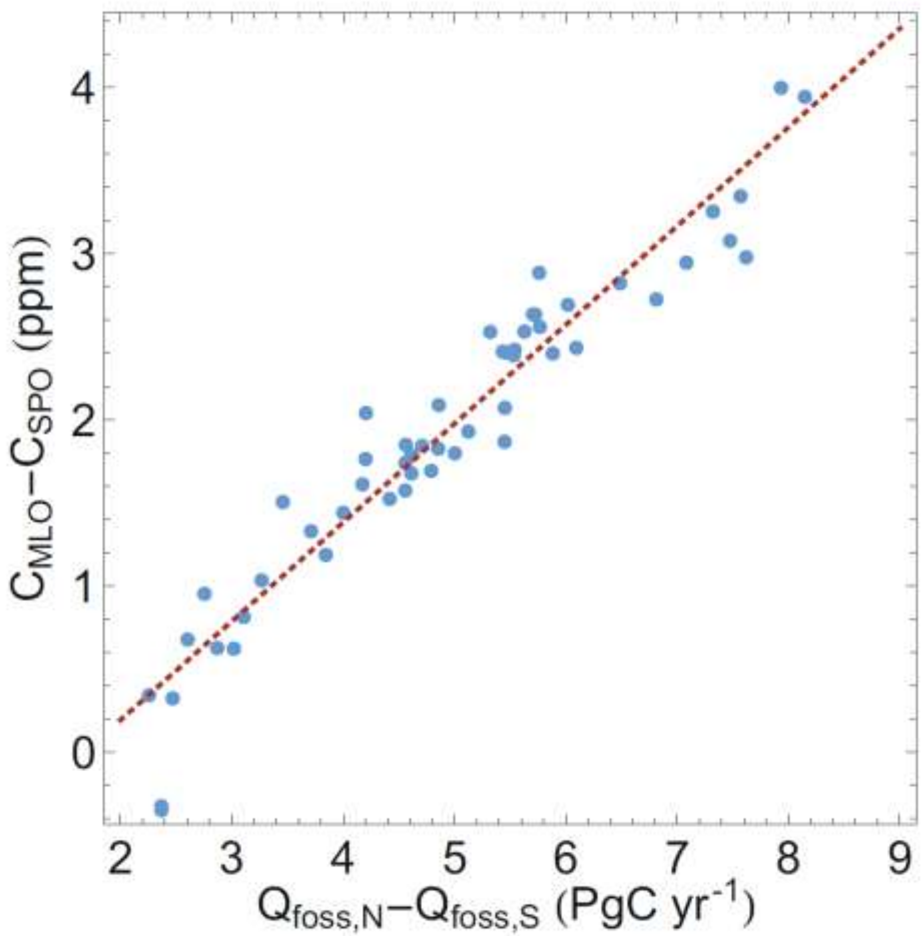
Atmospheric concentrations of CO_2, O_2, $^{13}C/^{12}C$ stable isotope ratio in CO_2



CO_2 from fossil fuels and from land biosphere has a lower 13C/12C stable isotope ratio than the CO_2 in the atmosphere.

>decreasing trend in atmospheric 13C/12C ratio of atmospheric CO_2 concentration.

Atmospheric CO_2 concentrations [ppm] versus fossil fuel combustion emissions [PgC/yr]: NH-SH differences



Fossil fuel CO_2 emissions take place mainly in industrialised countries (NH).
>Atmospheric CO_2 concentrations are higher in the NH than for the SH.
>Atmosphere CO_2 concentration diff follows linearly fossil fuel combustion emissions gradient.

Summary

"With a **very high confidence**, the increase in **CO2 emissions** from **fossil fuel burning** and those arising from **land use change** are the **dominant cause** of the observed **increase in atmospheric CO2** concentration. Several lines of evidence support this conclusion:

- The **observed decrease** in **atmospheric O2** content over past two decades and the **lower O2 content in** the **northern compared to** the **SH** are **consistent with** the **burning** of **fossil fuels**.
- **CO2** from **fossil fuels** and from the **land biosphere** has a **lower 13C/12C stable isotope ratio** than the CO2 in the atmosphere. This induces a **decreasing** temporal **trend** in the **atmospheric 13C/12C ratio** of **atmospheric CO2 concentration** as well as, on annual average, slightly lower 13C/12C values in the NH (Figure 6.3). These signals are measured.
- Most of the fossil fuel CO2 emissions take place in the industrialised countries north of the equator. Consistent with this, on annual average, **atmospheric CO2 measurement stations** in the **NH** record **increasingly higher CO2 concentrations than stations in the SH**, as witnessed by the observations from Mauna Loa, Hawaii, and the South Pole."

GLOBAL CARBON PROJECT

Carbon Budget 2014 – Executive Summary

www.globalcarbonproject.org/carbonbudget/index.htm

GLOBAL CARBON PROJECT

All the data is shown in billion tonnes CO_2 ($GtCO_2$)

1 Gigatonne (Gt) = 1 billion tonnes = 1×10^{15}g = 1 Petagram (Pg)

1 kg carbon (C) = 3.664 kg carbon dioxide (CO_2)

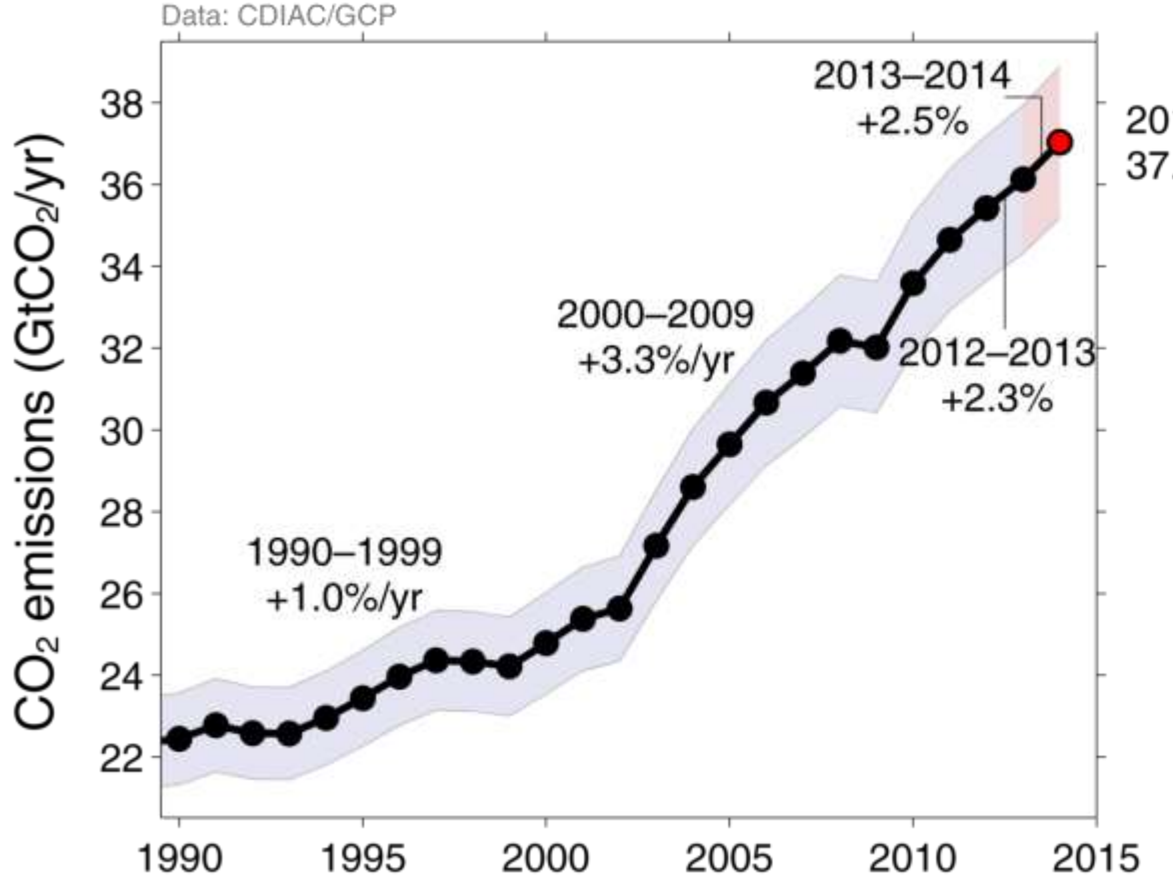
1 GtC = 3.664 billion tonnes CO_2 = 3.664 $GtCO_2$

Disclaimer

Fossil Fuel and Cement Emissions

Global fossil fuel and cement emissions: 36.1 ± 1.8 GtCO_2 in 2013, 61% over 1990

● Projection for 2014 : 37.0 ± 1.9 GtCO_2, 65% over 1990



Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

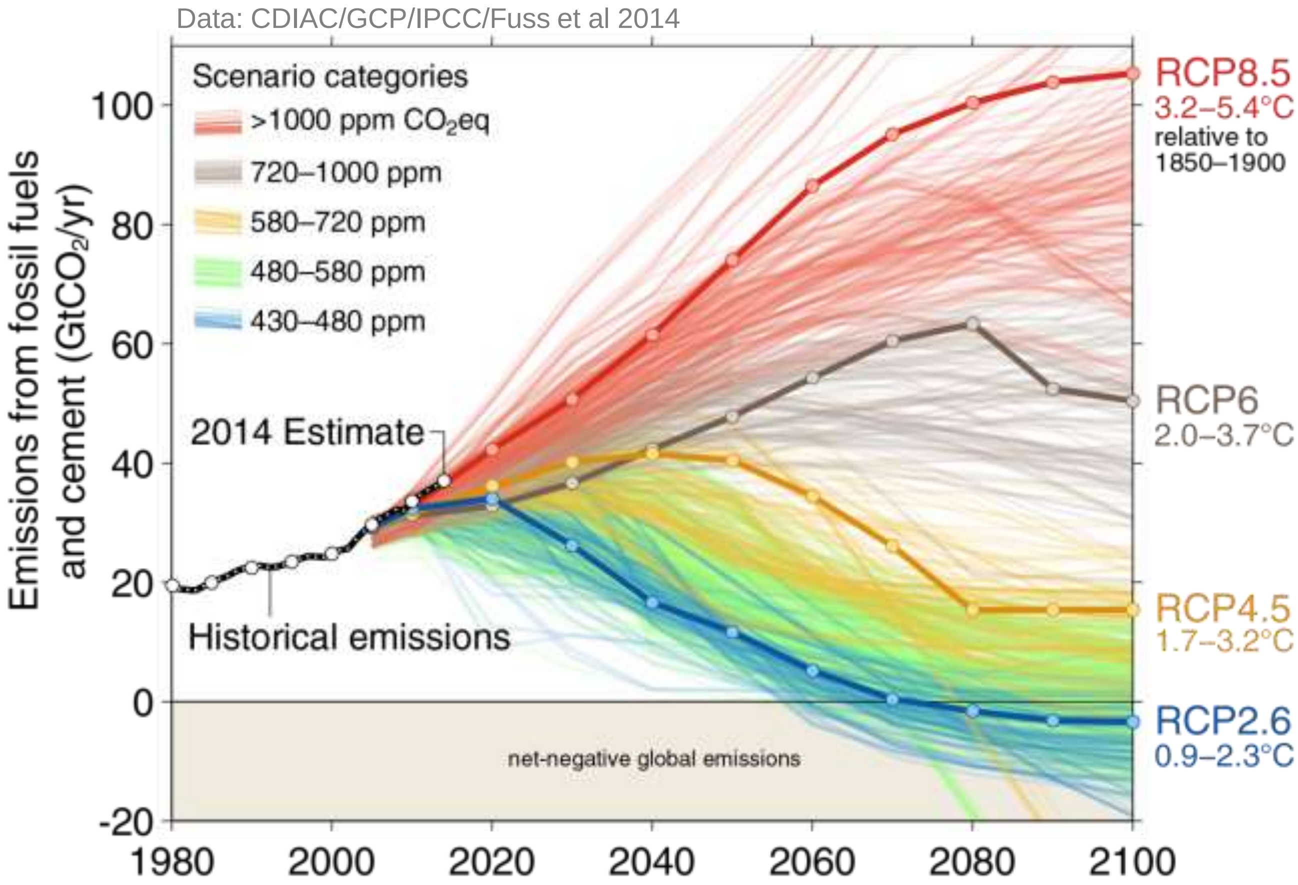
Estimates for 2011, 2012, and 2013 are preliminary

Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Observed Emissions and Emissions Scenarios

Emissions are on track for 3.2–5.4ºC "likely" increase in temperature above pre-industrial

Large and sustained mitigation is required to keep below 2ºC

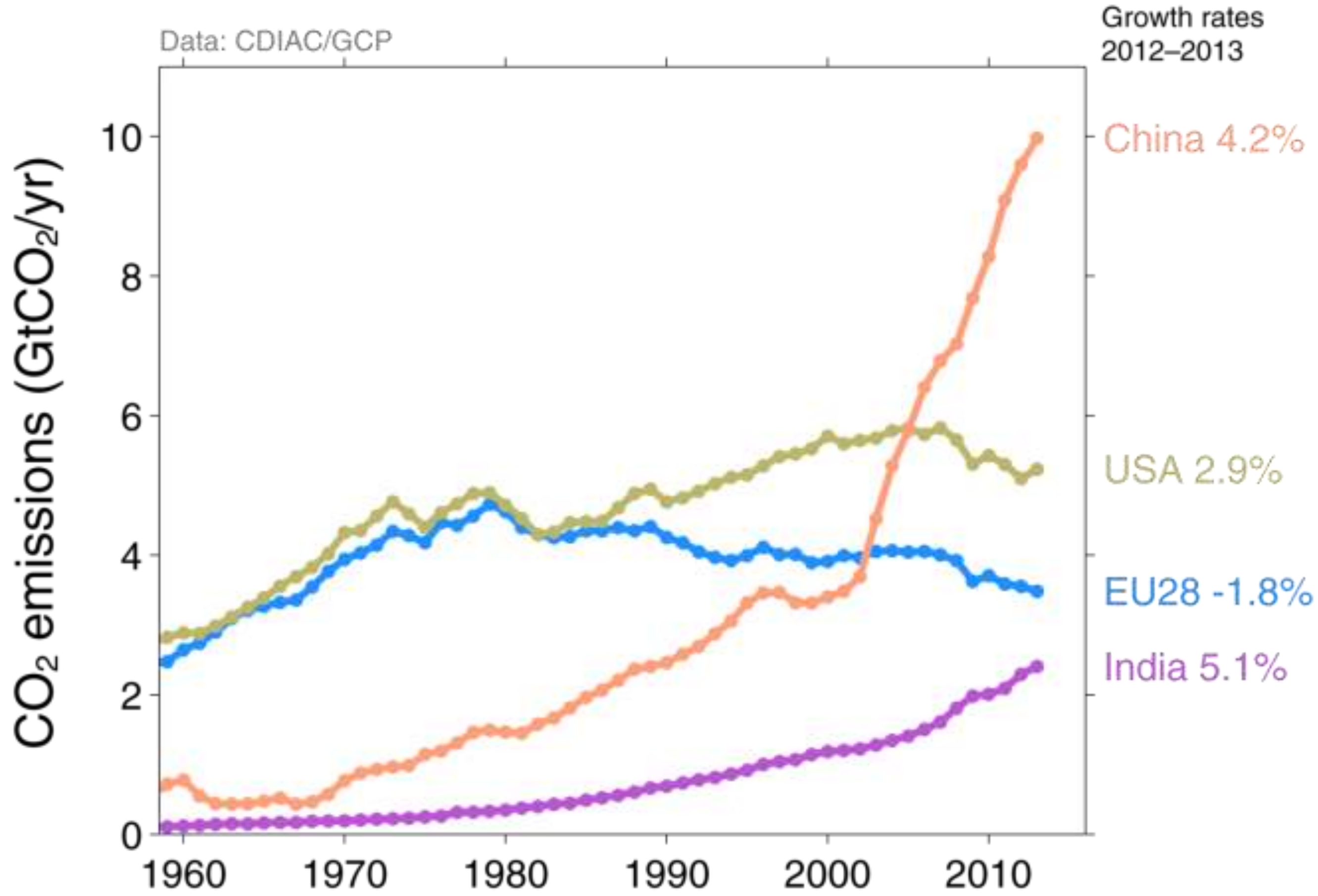


Over 1000 scenarios from the IPCC Fifth Assessment Report are shown

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

Top Fossil Fuel Emitters (Absolute)

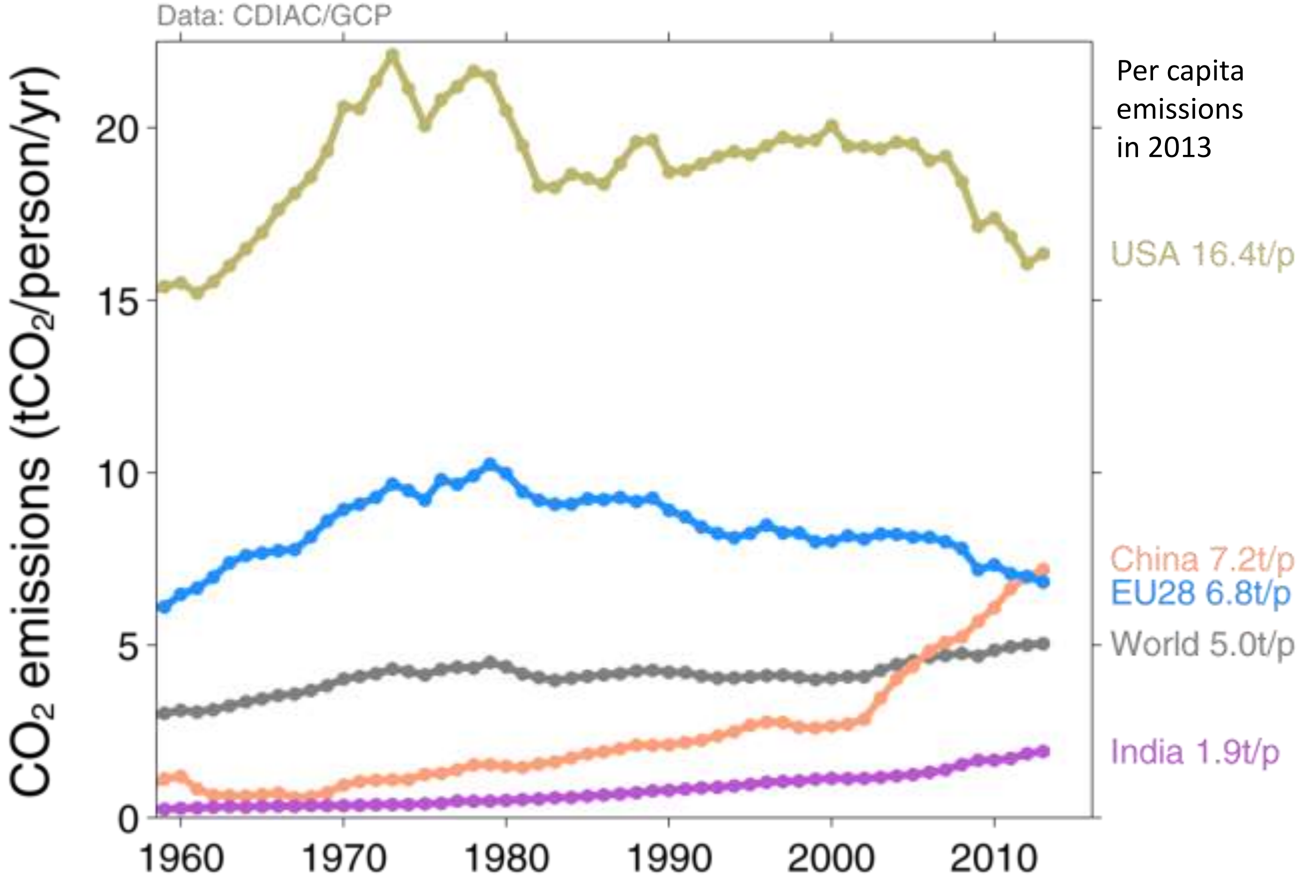
The top four emitters in 2013 covered 58% of global emissions
China (28%), United States (14%), EU28 (10%), India (7%)



Bunkers fuel used for international transport is 3% of global emissions
Statistical differences between the global estimates and sum of national totals is 3% of global emissions
Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Top Fossil Fuel Emitters (Per Capita)

China's per capita emissions have passed the EU28 and are 45% above the global average



Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Closing the Carbon Budget

Fate of Anthropogenic CO_2 Emissions (2004-2013 average)

32.4±1.6 $GtCO_2$/yr 91%

3.3±1.8 $GtCO_2$/yr 9%

+

15.8±0.4 $GtCO_2$/yr
44%

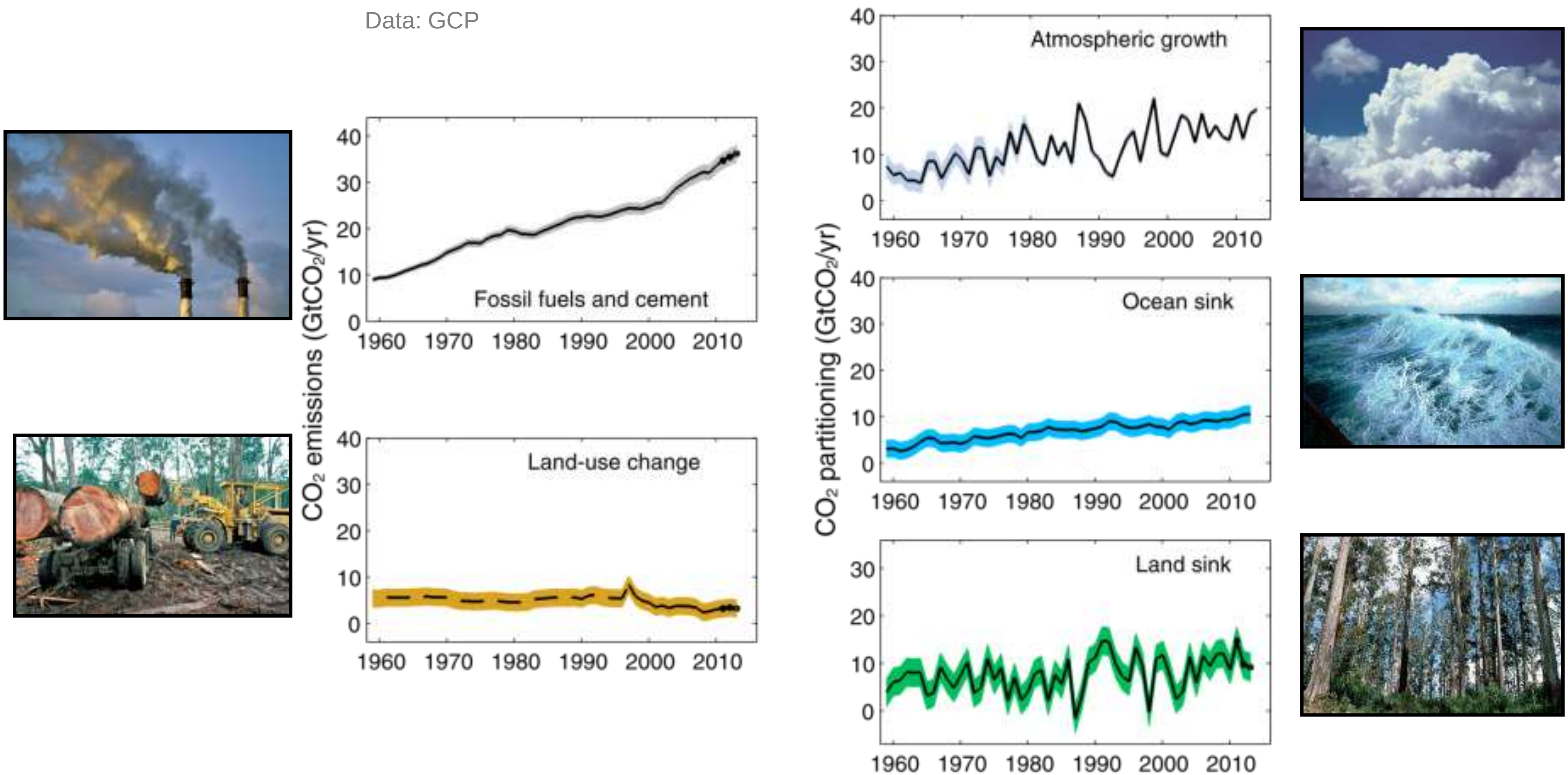
10.6±2.9 $GtCO_2$/yr
29%
Calculated as the residual of all other flux components

26%
9.4±1.8 $GtCO_2$/yr

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

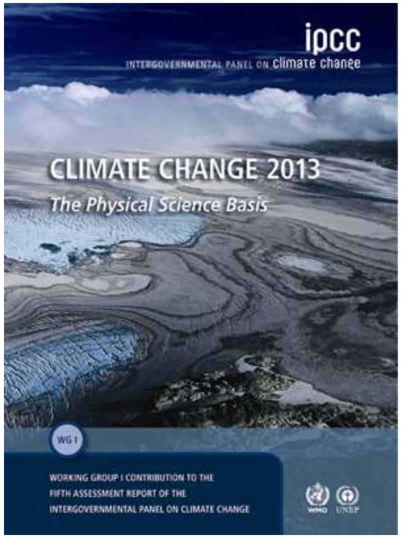
Changes in the Budget over Time

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



Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

IPCC Chapter 6: **Carbon and other biogeochemical cycles**



- Background
- Introduction: Global Carbon Cycle *(Section 6.1)*
- Evolution of biogeochemical cycles since industrial era *(Section 6.3)*
- Global Carbon Budget in 2014
- Projections of future carbon cycles *(Section 6.4)*
- Variations in Carbon cycle before the fossil fuel era *(Section 6.2)*
- Executive Summary (Ch. 6)

Ciais, P., Cet al., 2013: Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

The Carbon Cycle in the IPCC FAR

Projections of future carbon cycles

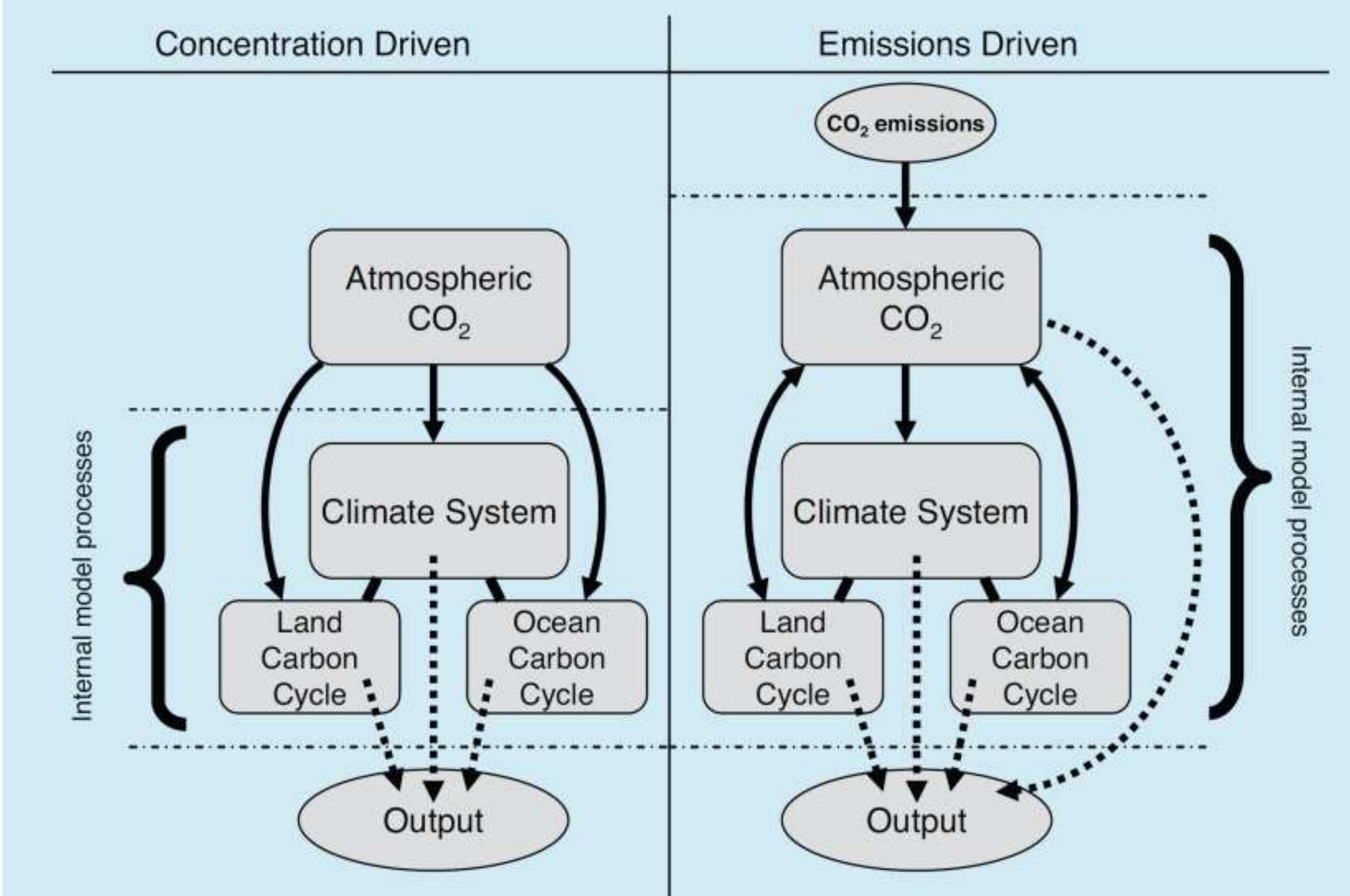
(Section 6.4)

Box 6.4 | Climate–Carbon Cycle Models and Experimental Design

What are coupled climate–carbon cycle models and why do we need them?

- **Physical climate models** with additional components of land and ocean biogeochemistry, respond to climate change conditions to influence in return the atmospheric CO_2 concentration.
- **Forcing** input: observed anthropogenic CO_2 and other GHG emissions, aerosols, solar and volcanic time series, (orbital forcing).
- **Earth System Models (ESMs)**: 'climate–carbon cycle models', predictive link between fossil fuel CO_2 emissions, CO_2 concentrations and climate >CMIP5!
- **Earth System Models of Intermediate Complexity (EMICs)**: similar experiments, reduced resolution or complexity, run much more quickly, used for longer experiments or large ensembles.
- **CMIP5 ESM** models: **concentration driven** or **emissions driven**.

Box 6.4 | Climate–Carbon Cycle Models and Experimental Design



$$E = \frac{dCO_2}{dt}_{prescribed} + (land\_carbon\_uptake + ocean\_carbon\_uptake)$$

$$\frac{dCO_2}{dt}_{simulated} = E - (land\_carbon\_uptake + ocean\_carbon\_uptake)$$

E: «compatible fossil fuel» emissions

E: «anthropgenic» emissions

Feedback analysis simulations

	CO_2 input to radiation scheme	CO_2 input to carbon-cycle scheme	Reason
Fully coupled			Simulates the fully coupled system
'Biogeochemically' coupled 'esmFixClim'			Isolates the carbon-cycle response to CO_2 (β) for land and oceans
Radiatively coupled 'esmFdbk'			Isolates carbon-cycle response to climate change (γ) for land and for oceans

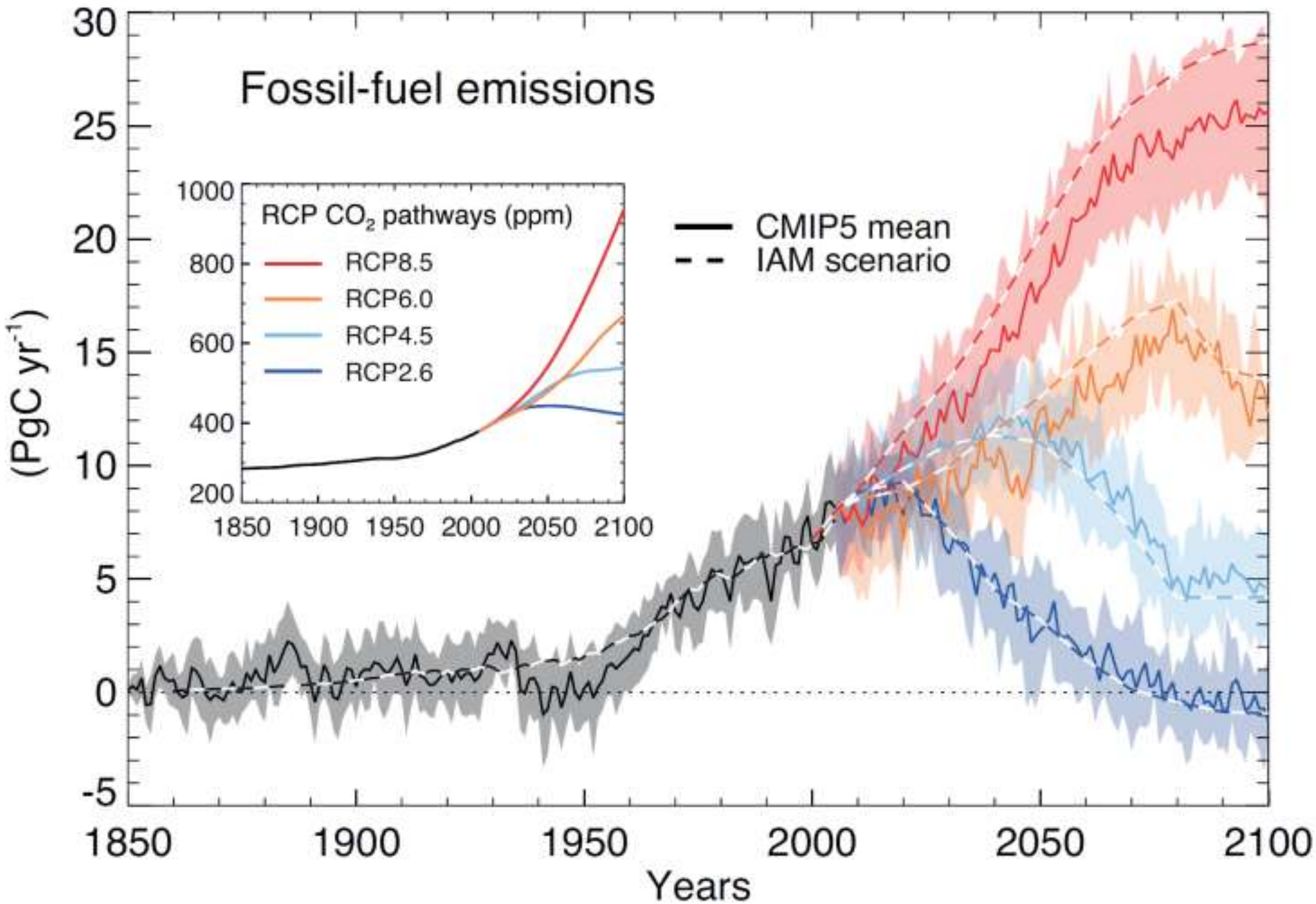
>The Coupled Carbon Cycle Climate Model Intercomparison Project (**C4MIP**)

CMIP5 carbon cycle models

Table 6.11 | CMIP5 model descriptions in terms of carbon cycle attributes and processes.

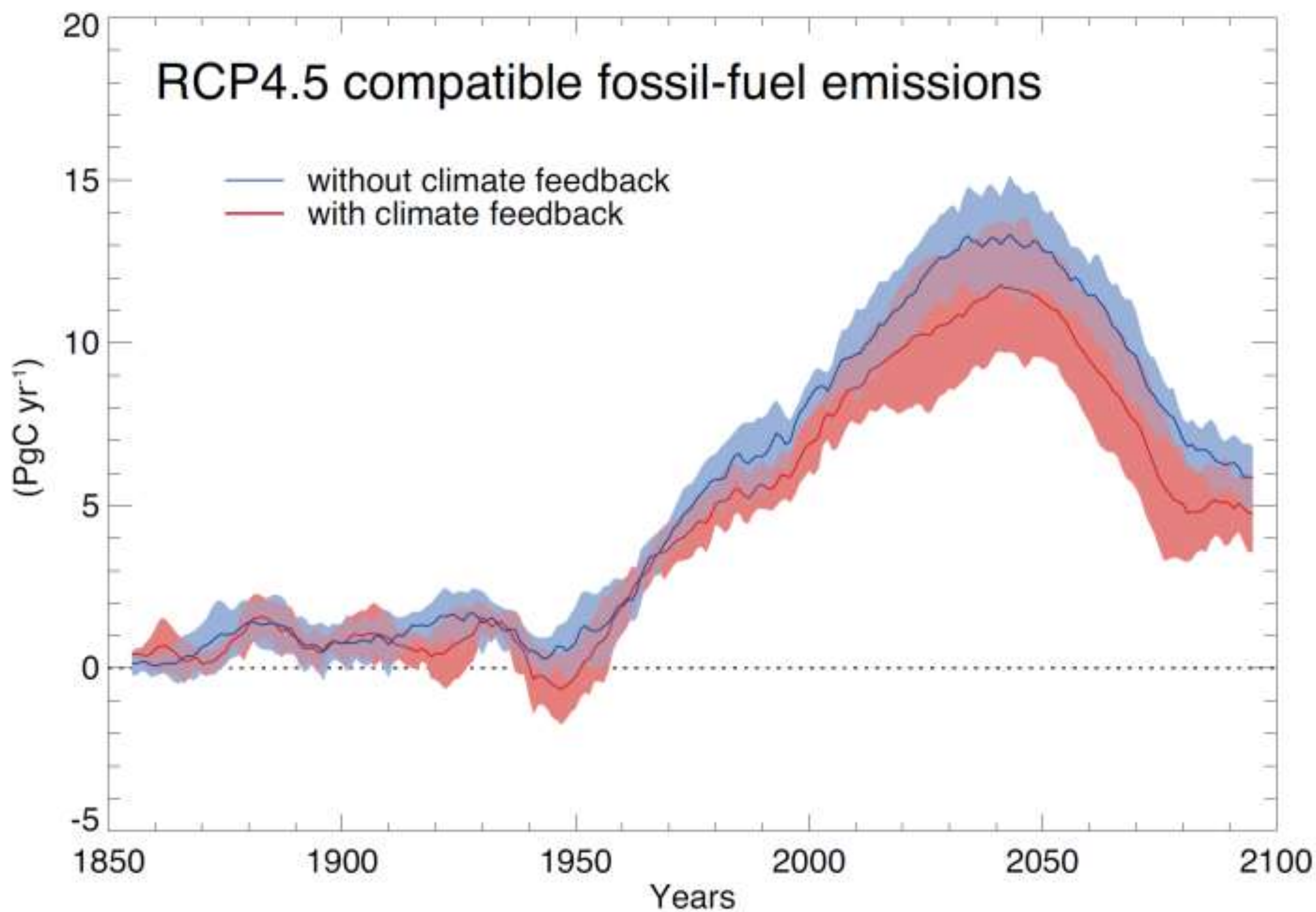
Model	Modelling Centre	Atmos Resolution	Ocean Resolution	Land-Carbon						Ocean Carbon			Reference
				Model Name	Dynamic Vegetation Cover?	No. of PFTs	Incl. LUC?	Nitrogen-Cycle	Fire	Model Name	No. of Plankton Types	Micronutrients?	
BCC-CSM1.1	BCC	≈2.8°, L26	0.3–1°, L40	BCC_AVIM1.0	N	15		N	N	OCMIP2	n/a	n/a	Wu et al. (2013)
CanESM2	CCCma	T63, L35	1.41° × 0.94°, L40	CTEM	N	9	Y	N	N	CMOC	1	N	Arora et al. (2011)
CESM1-BGC	NSF-DOE-NCAR	FV 0.9 × 1.25	1°	CLM4	N	15	Y	Y	Y	BEC	4	Y	Long et al. (2013)
GFDL-ESM2G	NOAA GFDL	2 × 2.5°, L24	1°, tri-polar, 1/3° at equator, L63.	LM3	Y	5	Y	N	Y	TOPAZ2	6	y	Dunne et al. (2012); Dunne et al. (2013)
GFDL-ESM2M	NOAA GFDL	2 × 2.5°, L24	1°, tri-polar, 1/3° at equator, L50.	LM3	Y	5	Y	N	Y	TOPAZ2	6	y	Dunne et al. (2012); Dunne et al. (2013)
HadGEM2-ES	MOHC	N96 (~ 1.6°), L38	1°, 1/3° at equator, L40	JULES	Y	5	Y	N	N	Diat-HadOCC	3	Y	Collins et al. (2011); Jones et al. (2011)
INMCM4	INM												
IPSL-CM5A-LR	IPSL	3.75 × 1.9 , L39	Zonal 2°, Meridional 2°–0.5° L31	ORCHIDEE	N	13	Y	N	Y	PISCES	2	Y	Dufresne et al. (2013)
MIROC-ESM	MIROC	T42, L80	Zonal: 1.4°, Meridional: 0.5–1.7°, Vertical: L43+BBL1	SEIB-DGVM	Y	13	Y	N	N	NPZD (Oschlies, 2001)	2 (Phyto-plankton and Zoolo-plankton)	N	Watanabe et al. (2011)
MPI-ESM-LR	MPI-M	T63 (~ 1.9°), L47	ca.1.5°, L47	JSBACH	Y	12 (8 natural)	Y	N	Y	HAMOCC	2	Y	Raddatz et al. (2007), Brovkin et al. (2009), Maier-Reimer et al. (2005)
NorESM-ME	NCC	1.9 × 2.5°, L26	1°, L53	CLM4	N	16	Y	Y	Y	HAMOCC	2	N	Iversen et al. (2013)

Concentration driven ESM CMIP5 models: compatible fossil fuel emissions



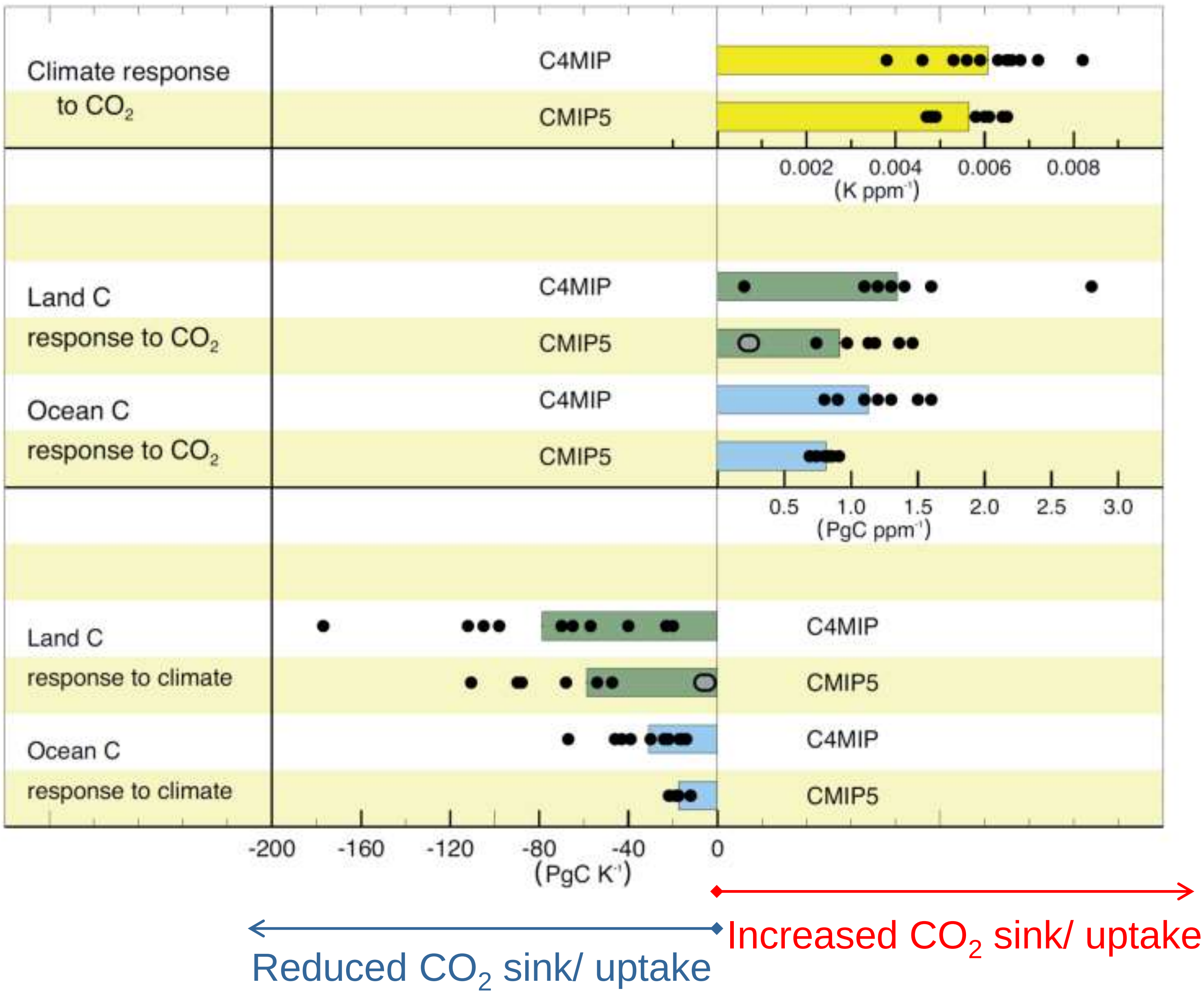
Integrated Assessment Models (IAM) used to create the RCP scenarios

CC Climate Feedback

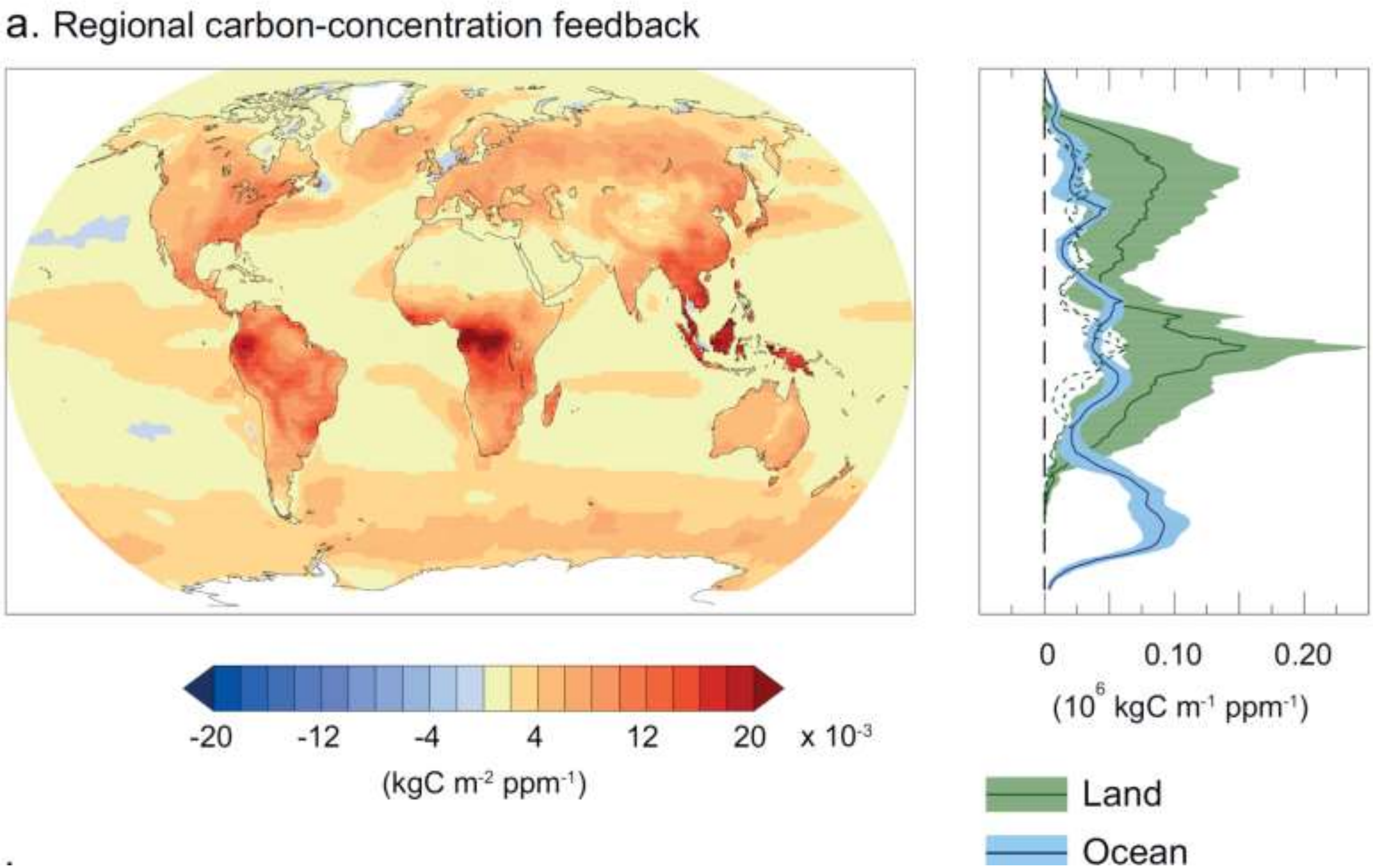


Using decoupled RCP4.5 simulations five CMIP5 ESMs agree that the **climate impact on carbon uptake by both land and oceans will reduce** the compatible fossil fuel **CO_2 emissions** for that scenario **by** between **6% and 29% between 2006 and 2100** respectively (157 ± 76 PgC (1 standard deviation) less carbon).

Carbon Cycle Feedback Metrics

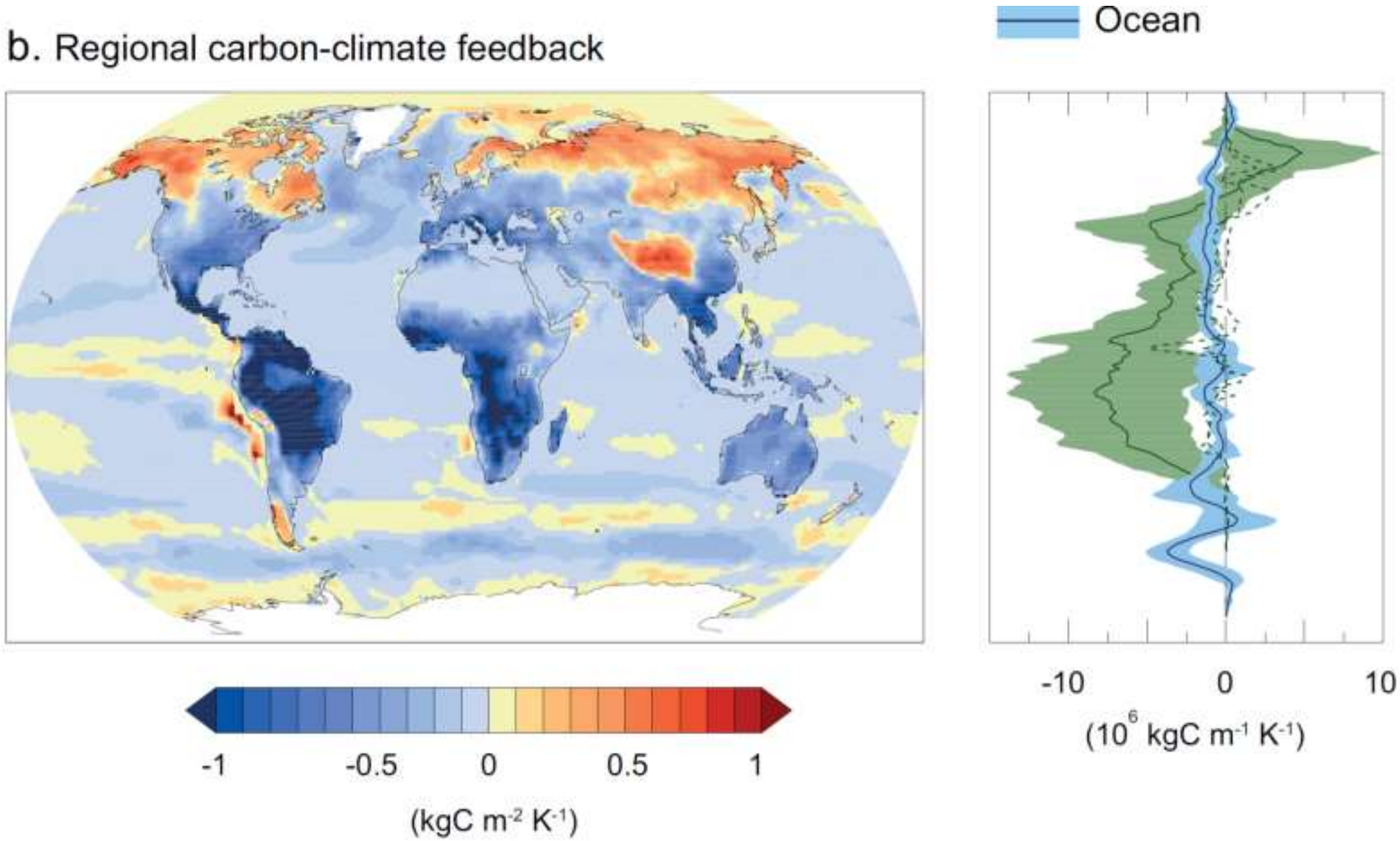


CMIP5 *concentration-driven* 1%/ yr CO_2 simulations



- **Increased CO_2** is projected by the CMIP5 models to **increase oceanic CO_2 sinks** almost everywhere (**positive β**) (**high confidence**) with the exception of some limited areas.
- The regions with the **strongest increase of oceanic CO_2 sinks** in response to higher atmospheric CO_2 are the **North Atlantic** and the **Southern Oceans** (>Chapter 3).

CMIP5 *concentration-driven* 1%/ yr CO_2 simulations



- **Climate warming** is projected by the CMIP5 models to **reduce oceanic carbon uptake** in most oceanic regions (negative γ) (medium confidence).
- The North Atlantic Ocean and the mid-latitude Southern Ocean have the largest negative γ_o values.

Why?

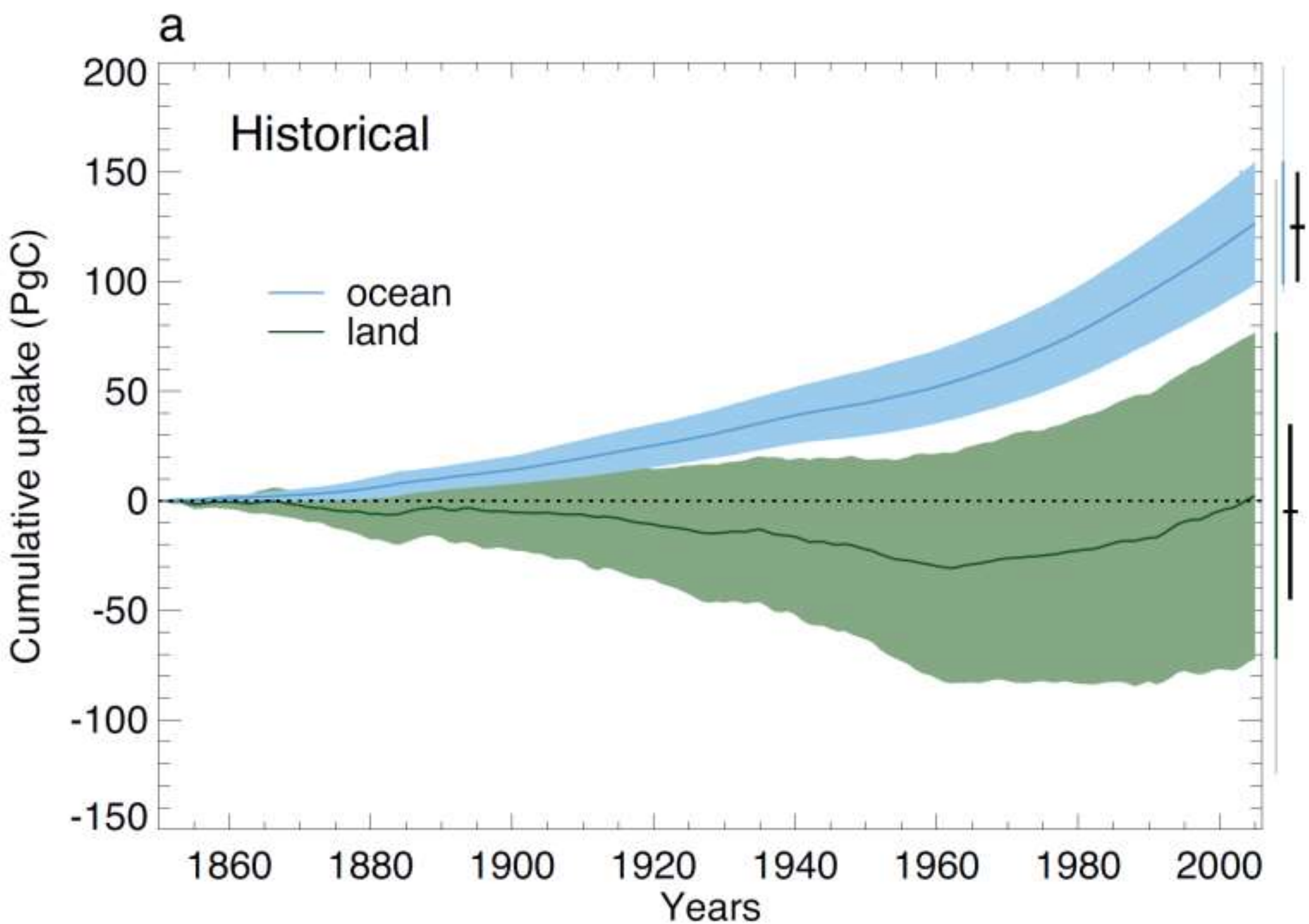
Climate warming is projected by the CMIP5 models to **reduce oceanic carbon uptake** in most oceanic regions (negative γ) (medium confidence).

- This sensitivity of ocean CO_2 sinks to climate, γ_o, is mostly negative (i.e., a reduced regional ocean CO_2 sink in response to climate change) but with regions of positive values in the Arctic, the Antarctic and in the equatorial Pacific (i.e., climate change increases ocean CO_2 sink in these regions).

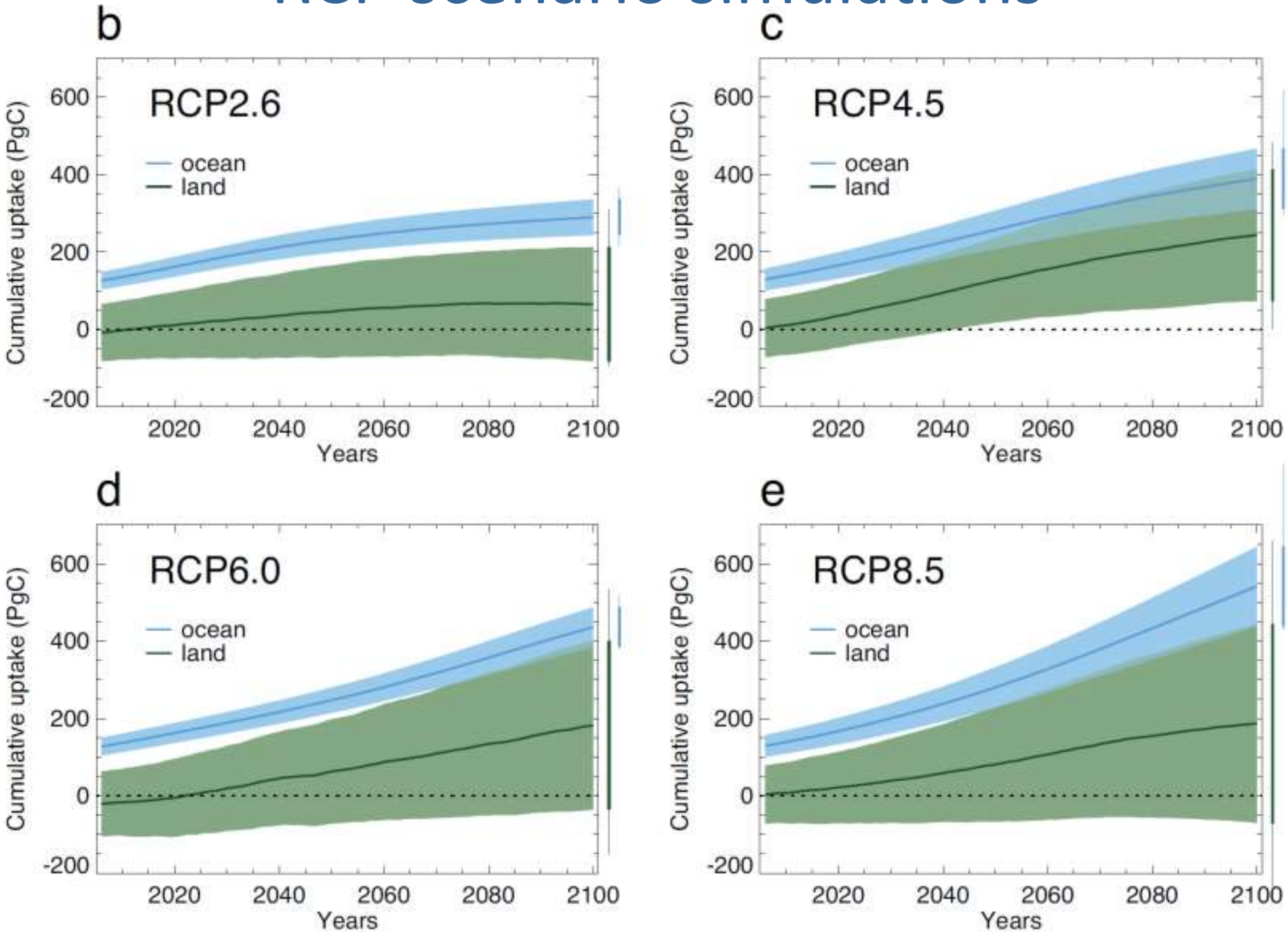
- **Reduced CO_2 uptake** in response to climate change in the sub-polar Southern Ocean and the tropical regions has been attributed to warming induced decreased CO_2 solubility, reduced CO_2 uptake in the mid latitudes to decreased CO_2 solubility and decreased water mass formation which reduces the absorption of anthropogenic CO_2 in intermediate and deep waters (Roy et al., 2011).

- **Increased uptake** in the Arctic Ocean and the polar South-ern Ocean is partly associated with a reduction in the fractional sea ice coverage (Roy et al., 2011).

Cumulative land and ocean uptake: historical period 1850-2005 simulations



Cumulative land and ocean uptake: RCP scenario simulations

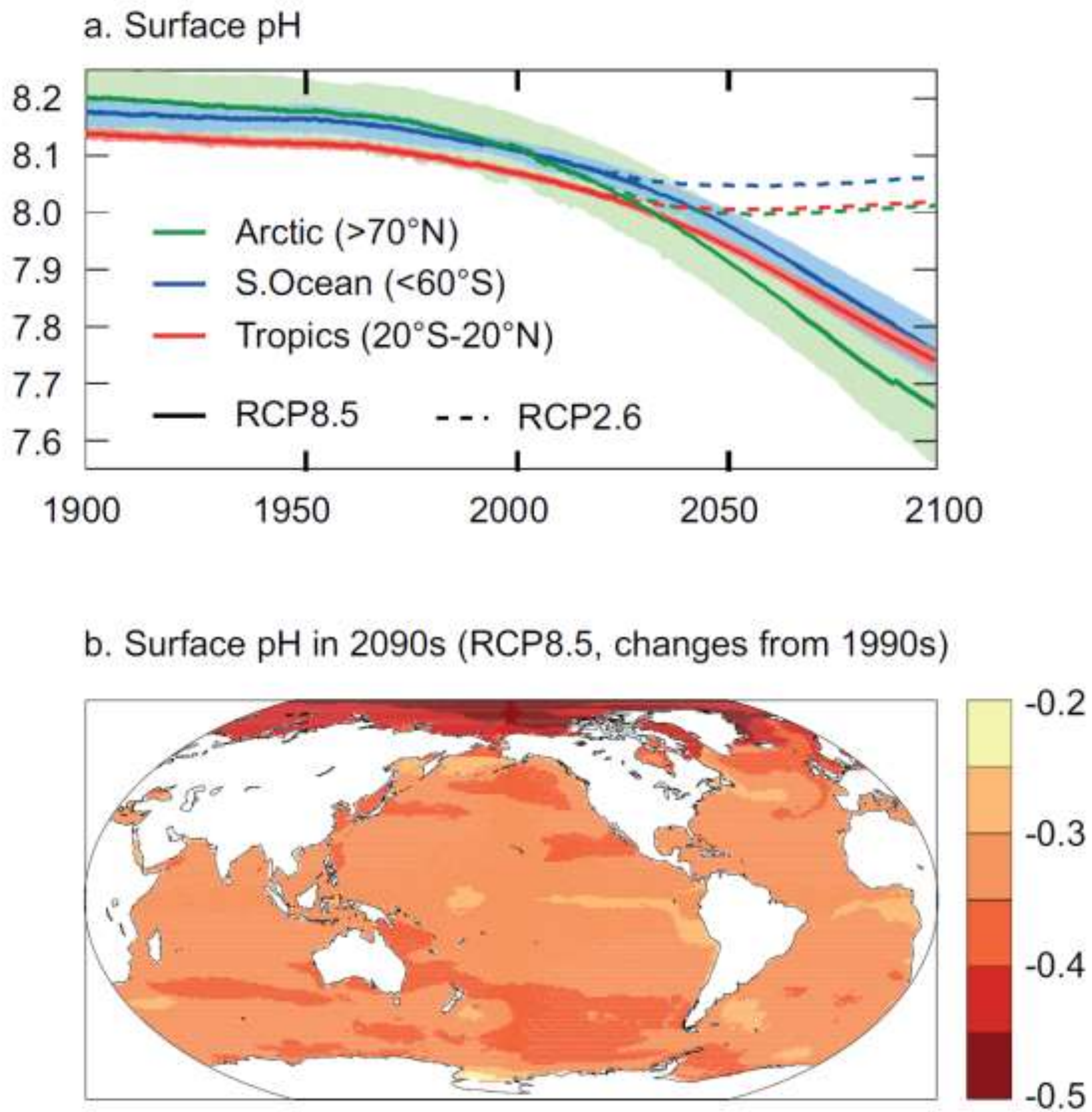


CC Future Projections - Summary

"There is **high confidence** that **increased atmospheric CO_2** will lead to **increased land** and **ocean carbon uptake** but by an uncertain amount.

- Models agree on the sign of land and ocean response to rising CO_2 but show only medium and low agreement for the magnitude of ocean and land carbon uptake respectively.
- Future climate change will decrease land and ocean carbon uptake compared to the case with constant climate (medium confidence).
- With very high confidence, for all four RCP scenarios, all models project continued ocean uptake throughout the 21st century, with higher uptake corresponding to higher concentration pathways.
- For RCP4.5, all the models also project an increase in land carbon uptake, but for RCP2.6, RCP6.0 and RCP8.5 a minority of models (4 out of 11 for RCP2.6, 1 out of 8 for RCP6.0 and 4 out of 15 for RCP8.5; Jones et al., 2013) project a decrease in land carbon storage at 2100 relative to 2005.
- Model spread in land carbon projections is much greater than model spread in ocean carbon projections, at least in part due to different treatment of land use change. "

Ocean acidification?



Future Projections - Summary

- **With very high confidence, ocean carbon uptake of anthropogenic CO_2 emissions will continue under all four Representative Concentration Pathways (RCPs) through to 2100, with higher uptake corresponding to higher concentration pathways.** … there is low confidence on the magnitude of modelled future land carbon changes.

- **There is high confidence that climate change will partially offset increases in global land and ocean carbon sinks caused by rising atmospheric CO_2.** …There is a high agreement between models that tropical ecosystems will store less carbon in a warmer climate. There is medium agreement between models that at high latitudes warming will increase land carbon storage… There is high agreement between CMIP5 ESMs that ocean warming and circulation changes will reduce the rate of carbon uptake in the Southern Ocean and North Atlantic, but that carbon uptake will nevertheless persist in those regions.

Future Projections

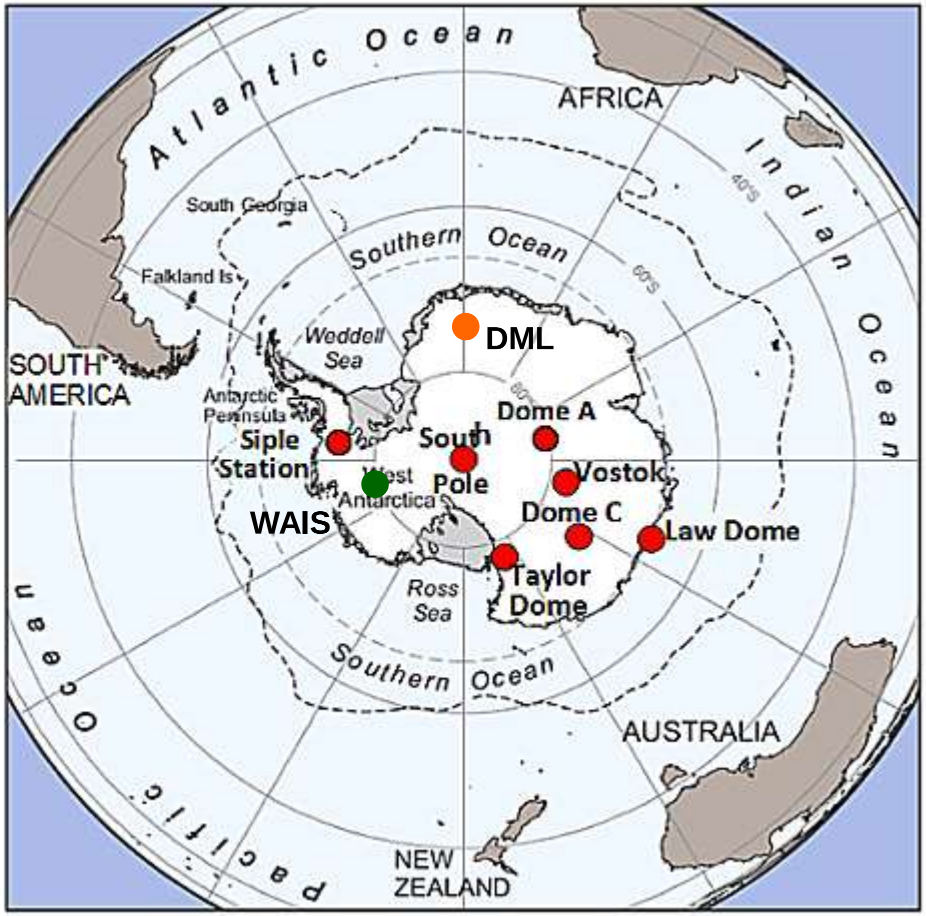
- **Taking climate and carbon cycle feedbacks into account, we can quantify the fossil fuel emissions compatible with the RCPs.**
- **It is virtually certain that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades.** Ocean acidification in the surface ocean will follow atmospheric CO_2 while it will also increase in the deep ocean as CO_2 continues to penetrate the abyss. The CMIP5 models consistently project worldwide increased ocean acidification to 2100 under all RCPs.
- **The removal of human-emitted CO_2 from the atmosphere by natural processes will take a few hundred thousand years (high confidence).** Depending on the RCP scenario considered, about 15 to 40% of emitted CO_2 will remain in the atmosphere longer than 1,000 years. This very long time required by sinks to remove anthropogenic CO2 makes climate change caused by elevated CO_2 irreversible on human time scale.

The Carbon Cycle in the IPCC FAR

- Variations in Carbon cycle before the fossil fuel era *(Section 6.2)*

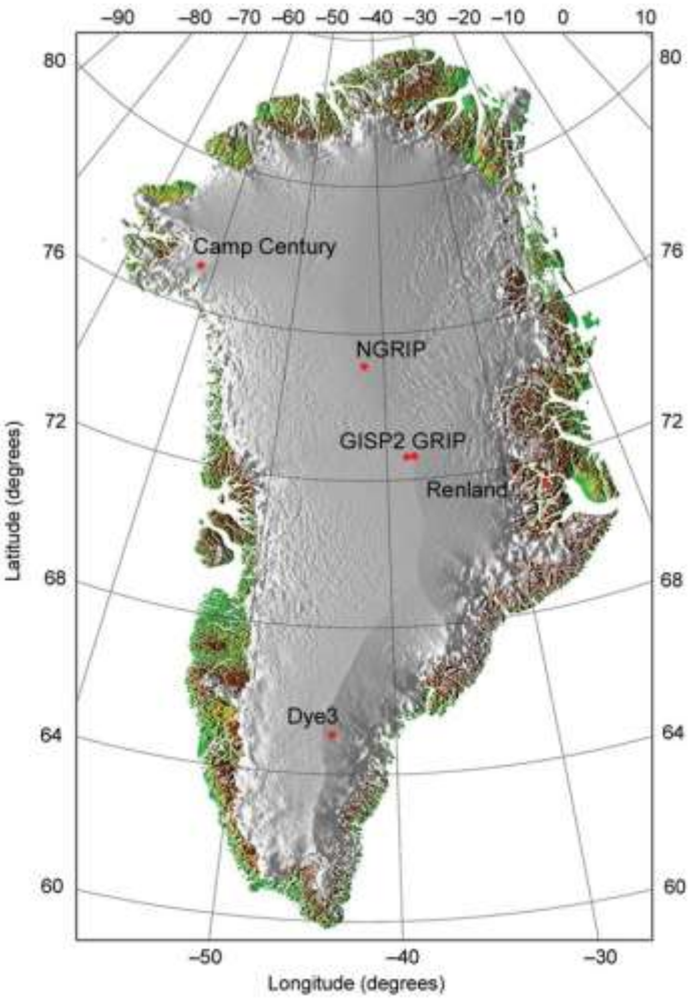
Ice core records

Antarctica



cdiac.ornl.gov/trends/co2/modern_co2.html

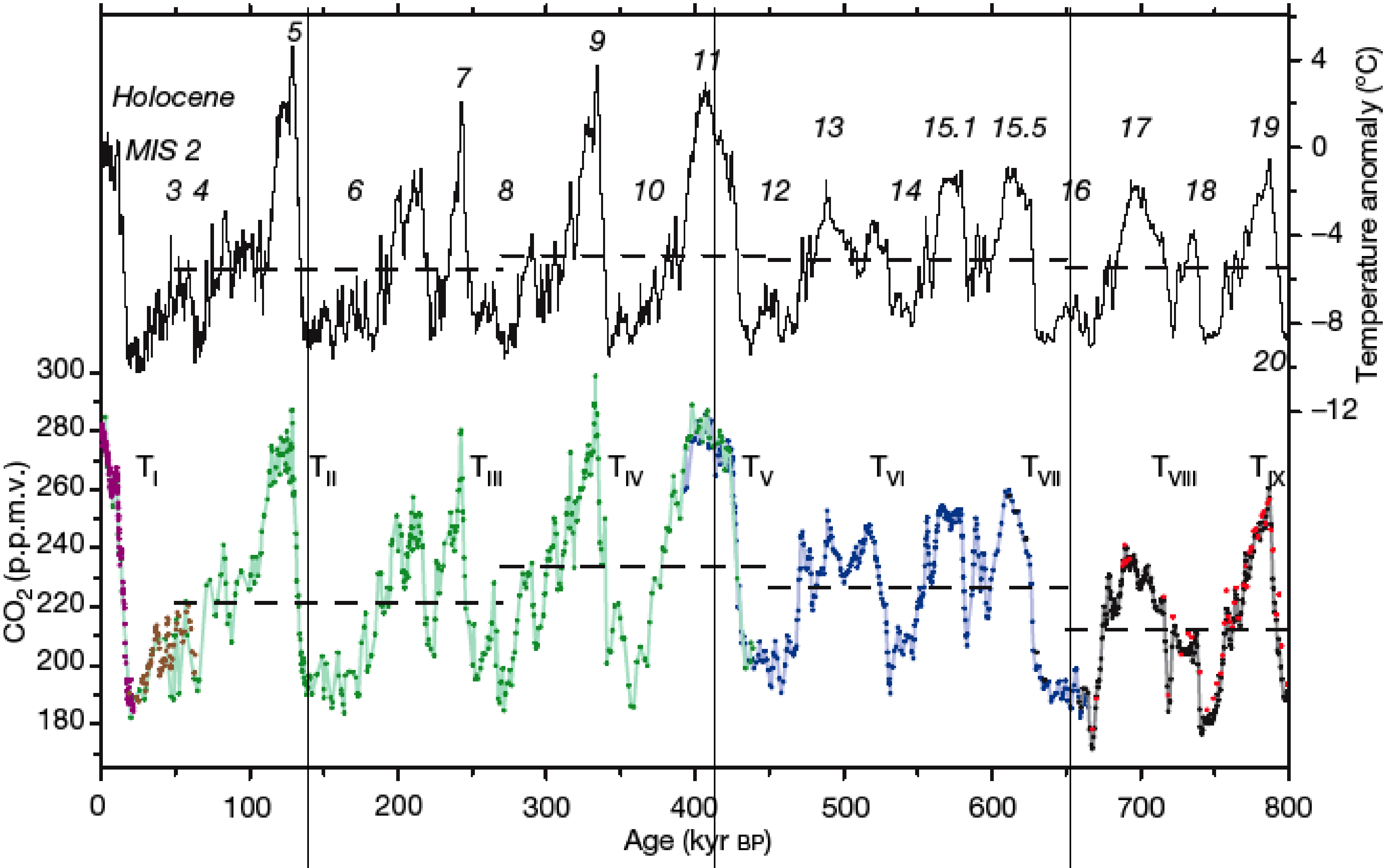
Greenland Ice Core Project (GRIP)



Andersen et al. (2004, Nature)

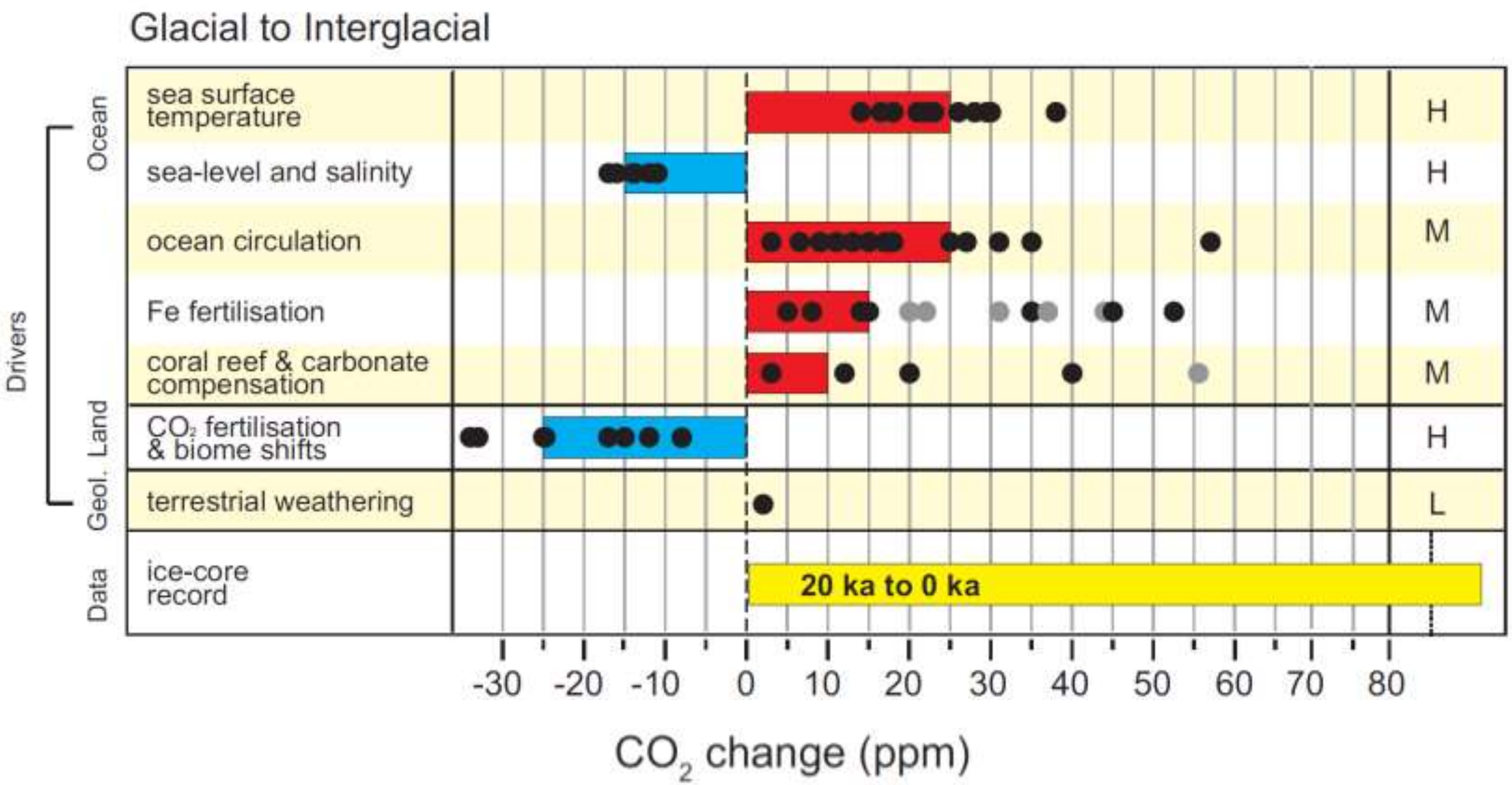
800 ka of CO_2 and Temperature

(DOME C ice core)



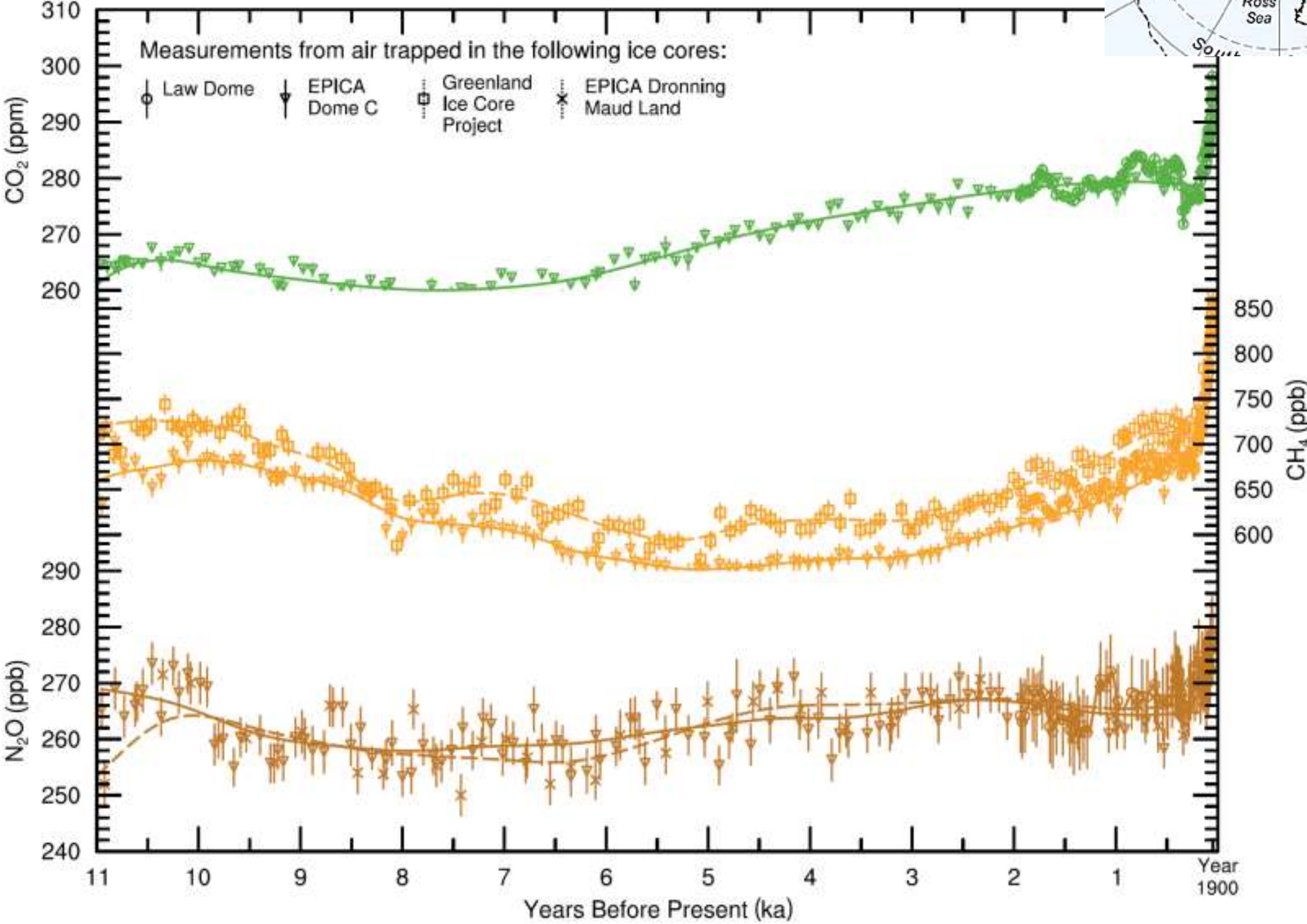
Barnola et al., 1987 Petit et al., 1999 Siegenthaler et al., 2005 Lüthi et al., 2008

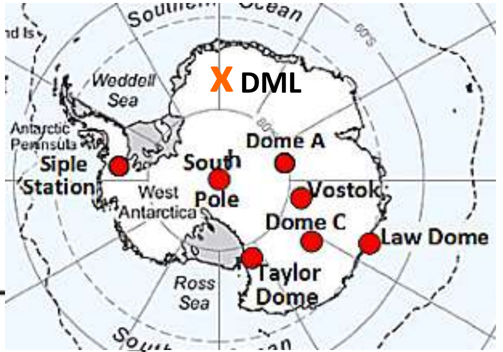
CO_2 concentration changes from Last Glacial Maximum (20 ka) to late Holocene (0ka)



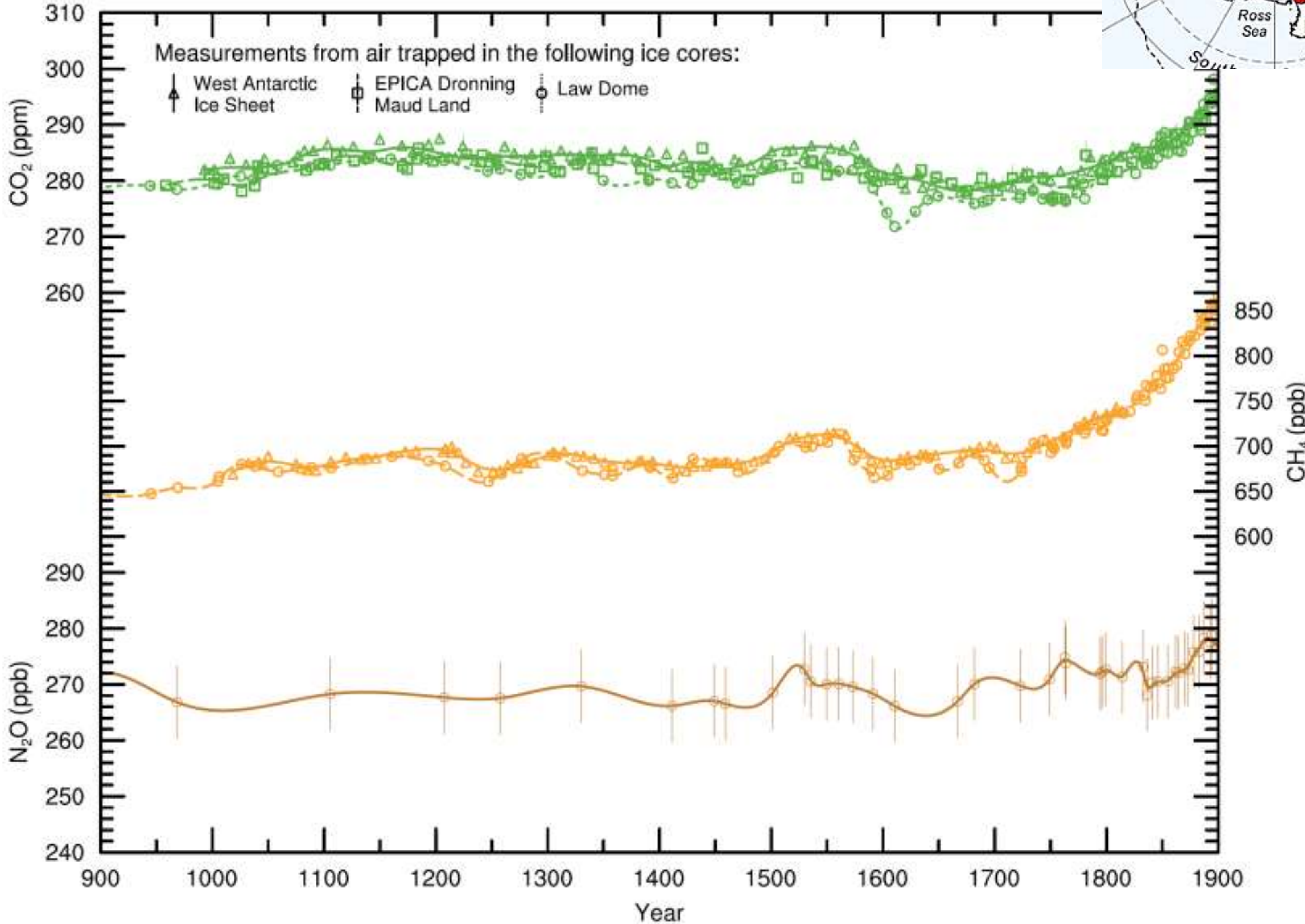
Variations in atmospheric CO_2 from glacial to interglacial periods were caused by decreased ocean carbon storage (500 to 1200 PgC), partly compensated by increased land carbon storage (300 to 1000 PgC).

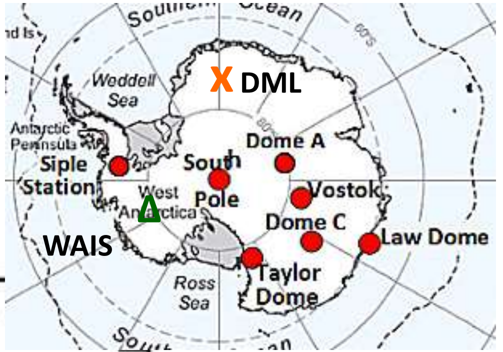
Atmospheric CO_2, CH_4, N_2O during the Holocene



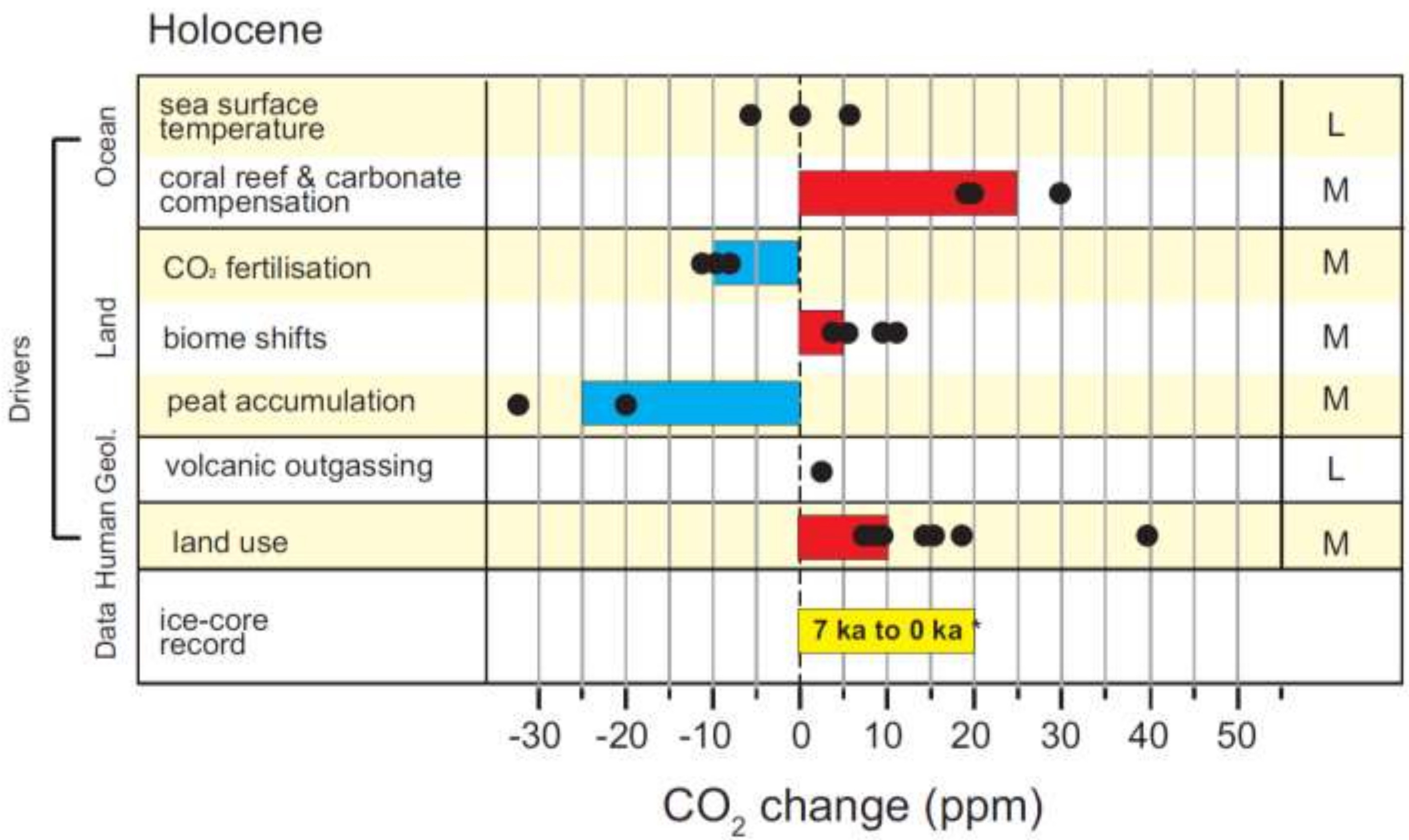


Atmospheric CO_2, CH_4, N_2O for the last 1ka





CO_2 concentration changes during the Holocene (7ka to 0ka)



Past Carbon Cycle Changes - Summary

- **During the last 7000 years prior to 1750, atmospheric CO_2 from ice cores shows only very slow changes (increase) from 260 ppm to 280 ppm, in contrast to the human-caused increase of CO_2 since pre-industrial times.**

- **The contribution of CO_2 emissions from early anthropogenic land use is unlikely sufficient to explain the CO_2 increase prior to 1750.**

- **Further back in time, during the past 800,000 years prior to 1750, atmospheric CO_2 varied from 180 ppm during glacial (cold) up to 300 ppm during interglacial (warm) periods.** This is well established from multiple ice core measurements.