In 1896, Arrhenius made the connection between atmospheric CO_2 and global climate!

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

I. *Introduction* : *Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

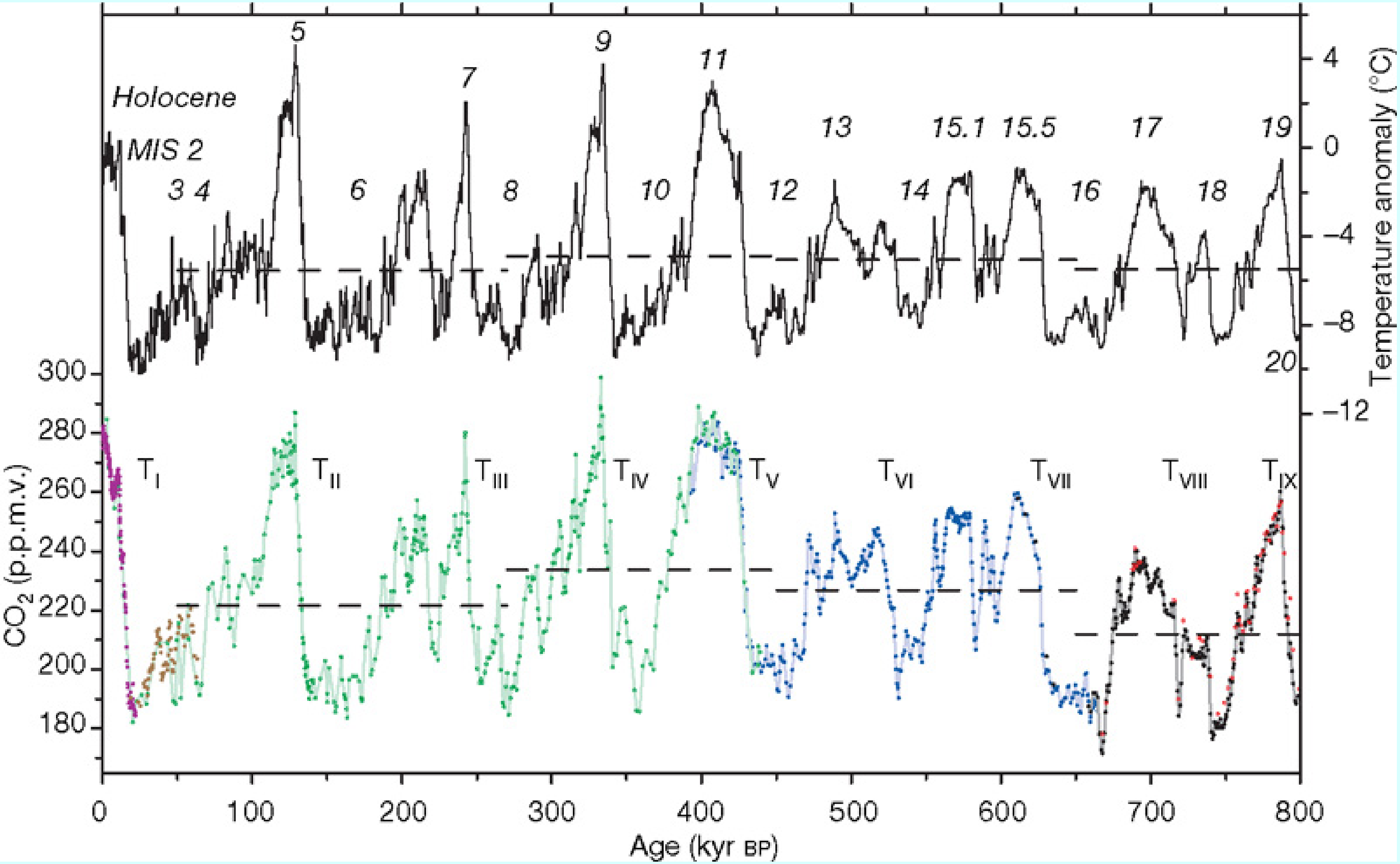
* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.

† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).

‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.

§ *Comptes rendus*, t. vii. p. 41 (1838).

Greenhouse Gases & Global Climate Change



Dieter Lüthi, Martine Le Floch, Bernhard Bereiter, Thomas Blunier, Jean-Marc Barnola, Urs Siegenthaler, Dominique Raynaud, Jean Jouzel, Hubertus Fischer, Kenji Kawamura & Thomas F. Stocker
Nature **453**, 379-382(15 May 2008)
doi:10.1038/nature06949PICA ice core , Antarctica

CO2 Past ▾ CO2 Now ▾ CO2 Future ▾ Show CO2 ▾

CO2.earth
Numbers for living on Earth

Home | Stories ▾ | Vital Signs ▾ | Stabilize CO2 ▾ | Here ▾

Daily CO_2

Feb. 23, 2022 = 420.31 ppm

Feb. 23, 2021 = 416.33 ppm

January CO_2

Jan. 2022 = 417.99 ppm

Jan. 2021 = 415.15 ppm

2021 Global Temperature

+1.12°C relative to 1880-1920

6th warmest year since 1880

Earth's CO2 Home Page

Atmospheric CO_2

January 2022

417.99

parts per million (ppm)

Mauna Loa Observatory, Hawaii (Scripps)

Preliminary data released February 4, 2022

Languages

Select Language

Search

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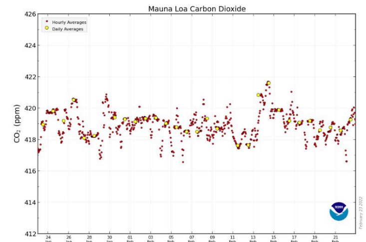
Twitter

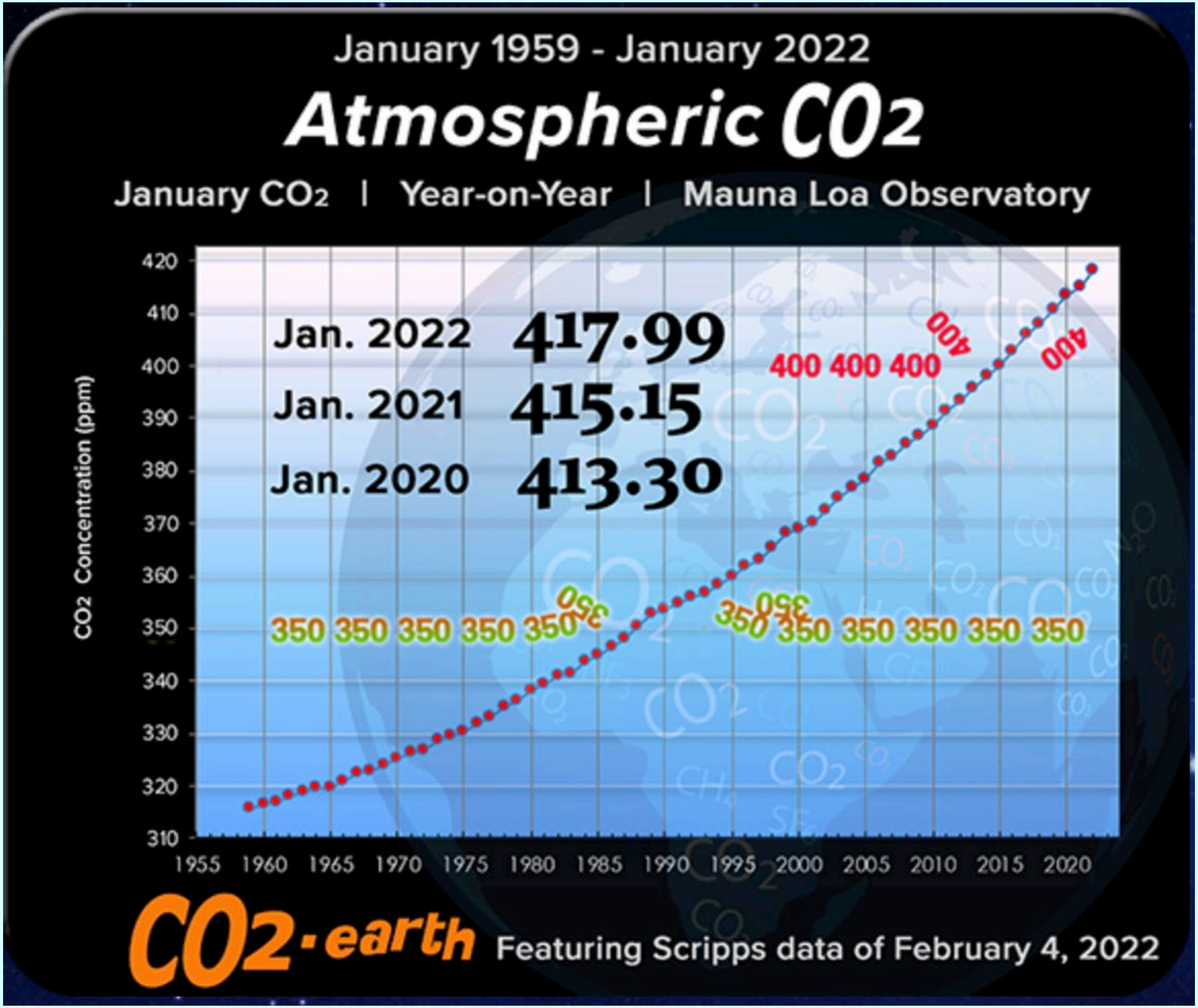
Tweets by @CO2_earth

CO2_Earth
@CO2_earth

419.26 ppm #CO2 in the atmosphere February 22, 2022 Up from 416.40 ppm a year ago Mauna Loa Observatory @NOAA data & graphic: esrl.noaa.gov/gmd/ccgg/trend… CO2.Earth tracking: co2.earth/daily-co2 🙏 View & share often 🙏



Embed | View on Twitter



January 1959 - January 2022
Atmospheric CO2
January CO2 | Year-on-Year | Mauna Loa Observatory
Jan. 2022 417.99
Jan. 2021 415.15
Jan. 2020 413.30
400 400 400
400
400
350 350 350 350 350
350
350
350
350 350 350 350 350
CO2 Concentration (ppm)
420
410
400
390
380
370
360
350
340
330
320
310
1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020
CO2·earth
Featuring Scripps data of February 4, 2022

Time Scales for Exchange

Atm.-surface ocean ~ 10 yr

Atm. - deep ocean ~1000 yr

Atm./Ocean - sediments ~ 10^5 to 10^7 yr.

60X more CO_2 in ocean than in atmosphere!

Oceanic processes drive glacial to interglacial changes in atm. CO_2

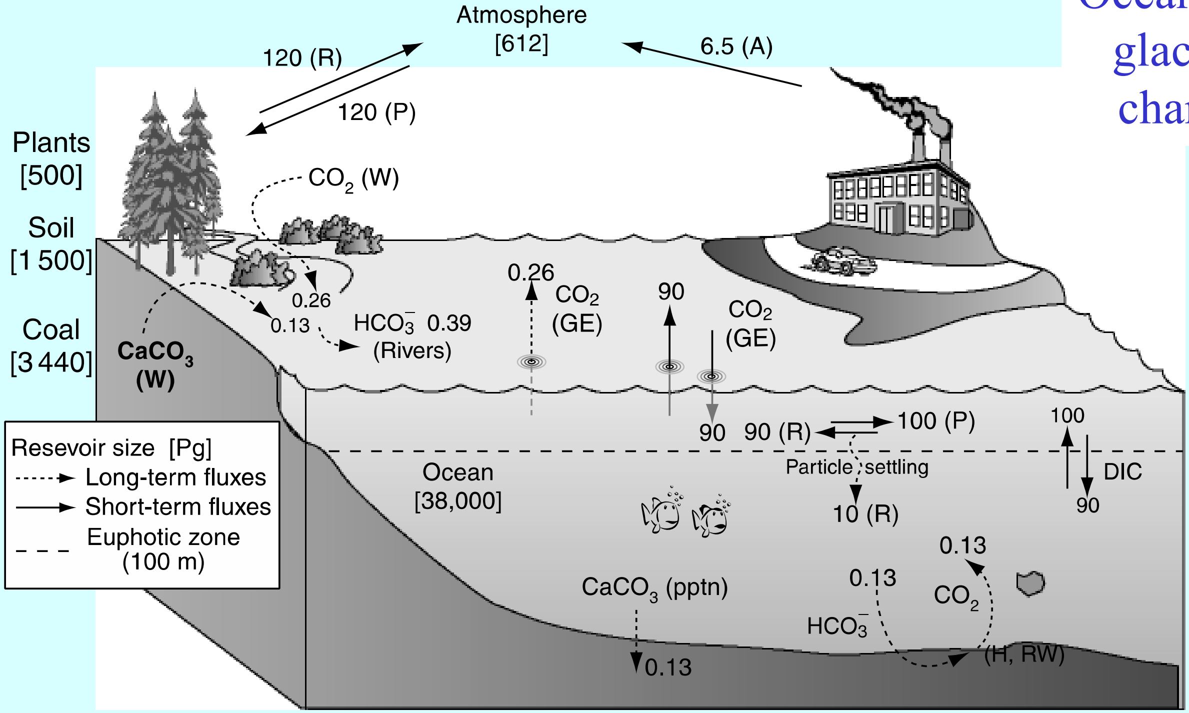


Figure 11.1. The global carbon cycle. Values in brackets are preanthropogenic reservoir sizes in Pg (10^{15} g); values on the arrows are furxes in Pg y^{-1}. Dashed lines represent the long-term carbon cycle determined by weathering. Values are normalized to the flux of DIC from rivers (see Chapter 2). Solid arrows are the shorter-term carbon fluxes associated with photosynthesis and respiration. The wiggly vertical line indicates particulate C and DOC transport from the ocean euphotic zone to deep water. Symbols: W, weathering of carbonates ($CaCO_3 + CO_2 + H_2O \rightarrow 2HCO_3^- + Ca^{2+}$) and silicates (silicate $+ CO_2 + H_2O \rightarrow$ clay $+ HCO_3^- +$ cations); GE, gas exchange; P, gross photosynthesis ($CO_2 + H_2O \rightarrow CH_2O$ (OM) $+ O_2$); R, respiration (CH_2O (OM) $+ O_2 \rightarrow CO_2 + H_2O$); PPT, calcite precipitation (the reverse of carbonate weathering); H, hydrothermal processes; RW, reverse weathering (the reverse of silicate weathering).

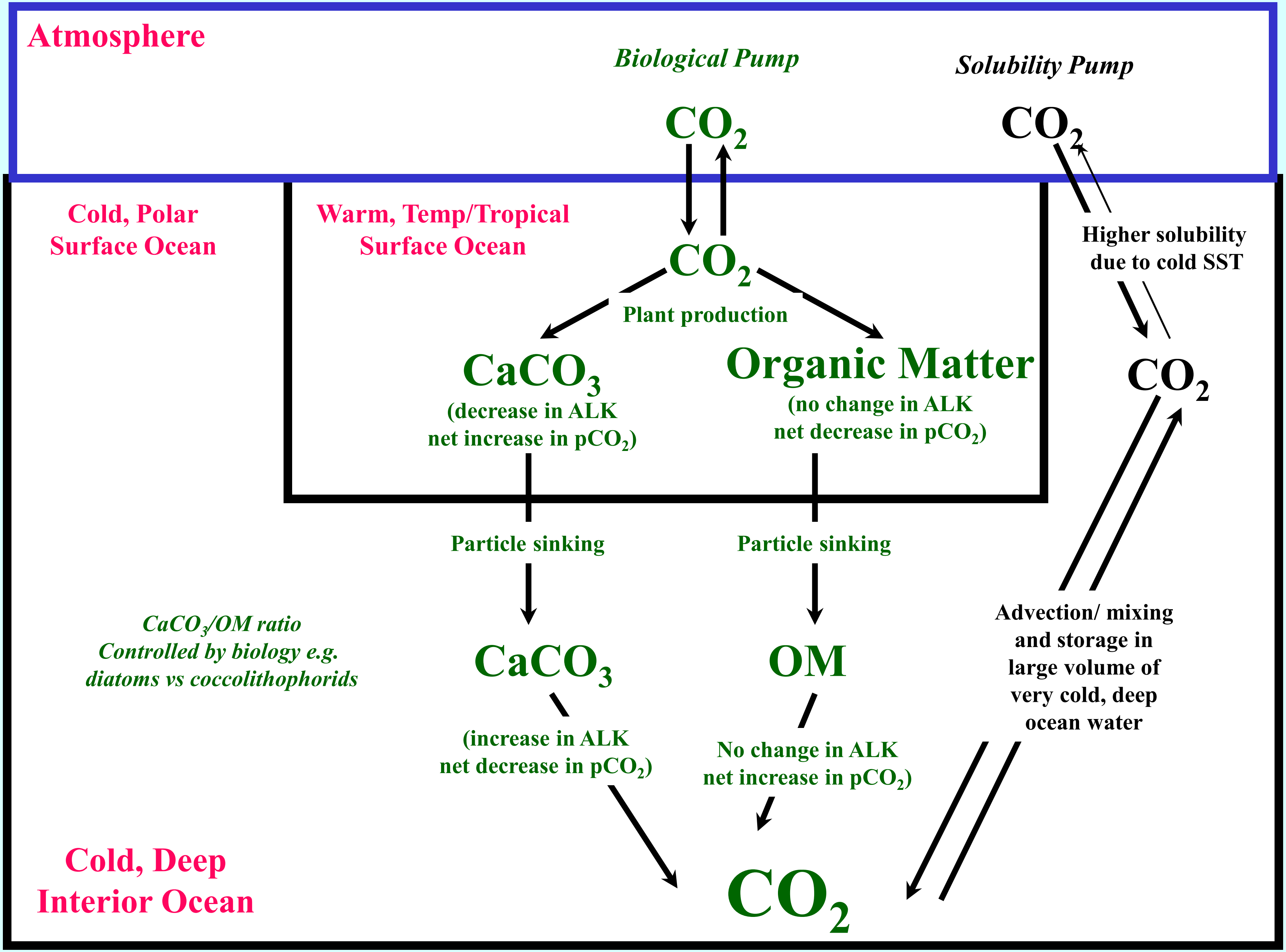
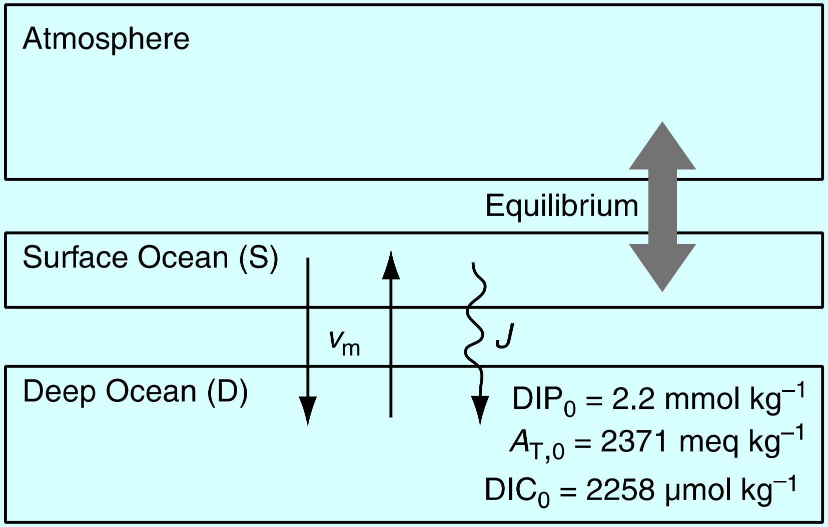

Atmosphere
Biological Pump
Solubility Pump
CO_2
CO_2
Cold, Polar
Surface Ocean
Warm, Temp/Tropical
Surface Ocean
CO_2
Higher solubility
due to cold SST
Plant production
$CaCO_3$
(decrease in ALK
net increase in pCO_2)
Organic Matter
(no change in ALK
net decrease in pCO_2)
CO_2
Particle sinking
Particle sinking
$CaCO_3$/OM ratio
Controlled by biology e.g.
diatoms vs coccolithophorids
$CaCO_3$
OM
Advection/ mixing
and storage in
large volume of
very cold, deep
ocean water
(increase in ALK
net decrease in pCO_2)
No change in ALK
net increase in pCO_2)
Cold, Deep
Interior Ocean
CO_2

Figure 11.2. Sketch of the three-box model of the atmosphere, surface and deep ocean. Equations indicate the circulation dynamics (V_M in m y^{-1}, is the mixing rate between the surface and deep ocean.); stoichiometry of the particulate transport (J in mol m^{-2} y^{-1}); and chemical equilibria of the carbonate system.



Dynamics: $V_D \times \frac{d[C_D]}{dt} = 0 = V_m \times ([C_S] - [C_D]) + J$

Stoichiometry: $\Delta P : \Delta N : \Delta DIC : \Delta A_T : \Delta Ca$

1 : 16 : 136 : 44 : 30

Equilibrium:

$$DIC = [HCO_3^-] + [CO_3^{2-}] + [CO_2]$$

$$A_{C\&B} = [HCO_3^-] + 2 \times [CO_3^{2-}] + [B(OH)_4^-]$$

$$B_T = B(OH)_3 + B(OH_4^-)$$

$$K_{H,CO_2} = \frac{[CO_2]}{f^a_{CO_2}}$$

$$K'_2 = \frac{[CO_3^{2-}][H^+]}{[HCO_3^-]}$$

$$K'_1 = \frac{[HCO_3^-][H^+]}{[CO_2]}$$

$$K'_B = \frac{[B(OH)_4^-][H^+]}{[B(OH)_3]}$$

Table 11.2. *The effect of the solubility and biological pumps on the fugacity of CO_2 in the atmosphere, f_{CO_2}, determined by the simple two-layer ocean model depicted in Fig. 11.2*

The first row is the standard case and the rows under this indicate changes due to temperature, carbon flux, circulation rate and the organic carbon to $CaCO_3$ ratio of the particle flux, OC : $CaCO_3$.

Case	Temp (°C)	$[DIP]_S$ (μmol kg^{-1})	τ_{mix} (y)	$R_{OC:CA}$	DIC_S (μmol kg^{-1})	$A_{T,S}$ (μeq kg^{-1})	f_{CO_2} (atm)
Standard	20	0.5	1000	3.5	2027	2296	375
Temp. effect	15						304
	25						460
Biol. pump							
Carbon flux	20	2.2			2258	2371	1184
		0.0			1959	2274	293
Circulation		0.85	500		2074	2312	446
		0.0	1500		1959	2274	291
OC:$CaCO_3$ (P:OC = 106)		0.5	1000	10:1	2059	2361	337
				1.5:1	1957	2157	485

SOFEX Fe Fertilization Study in Southern Ocean

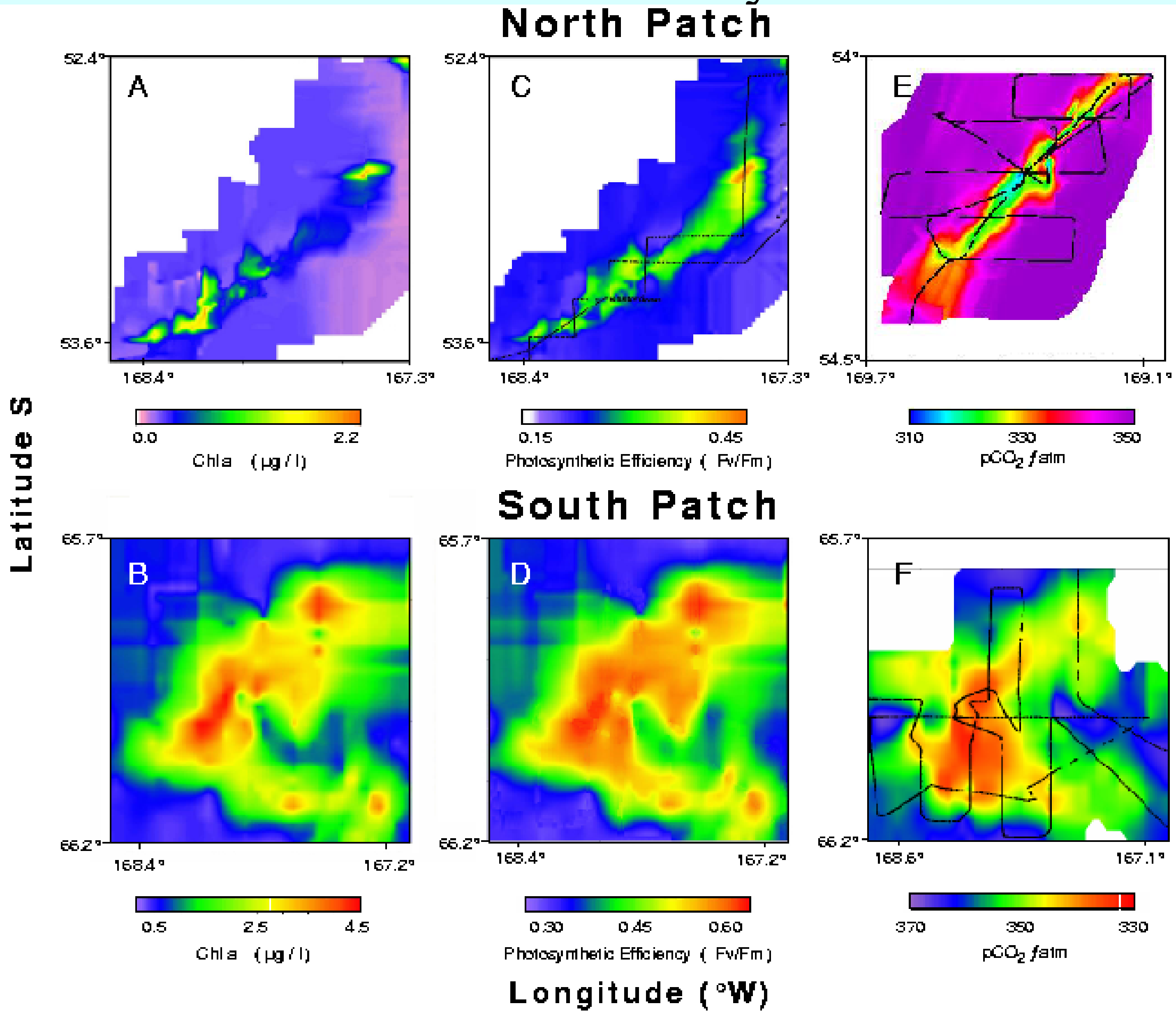
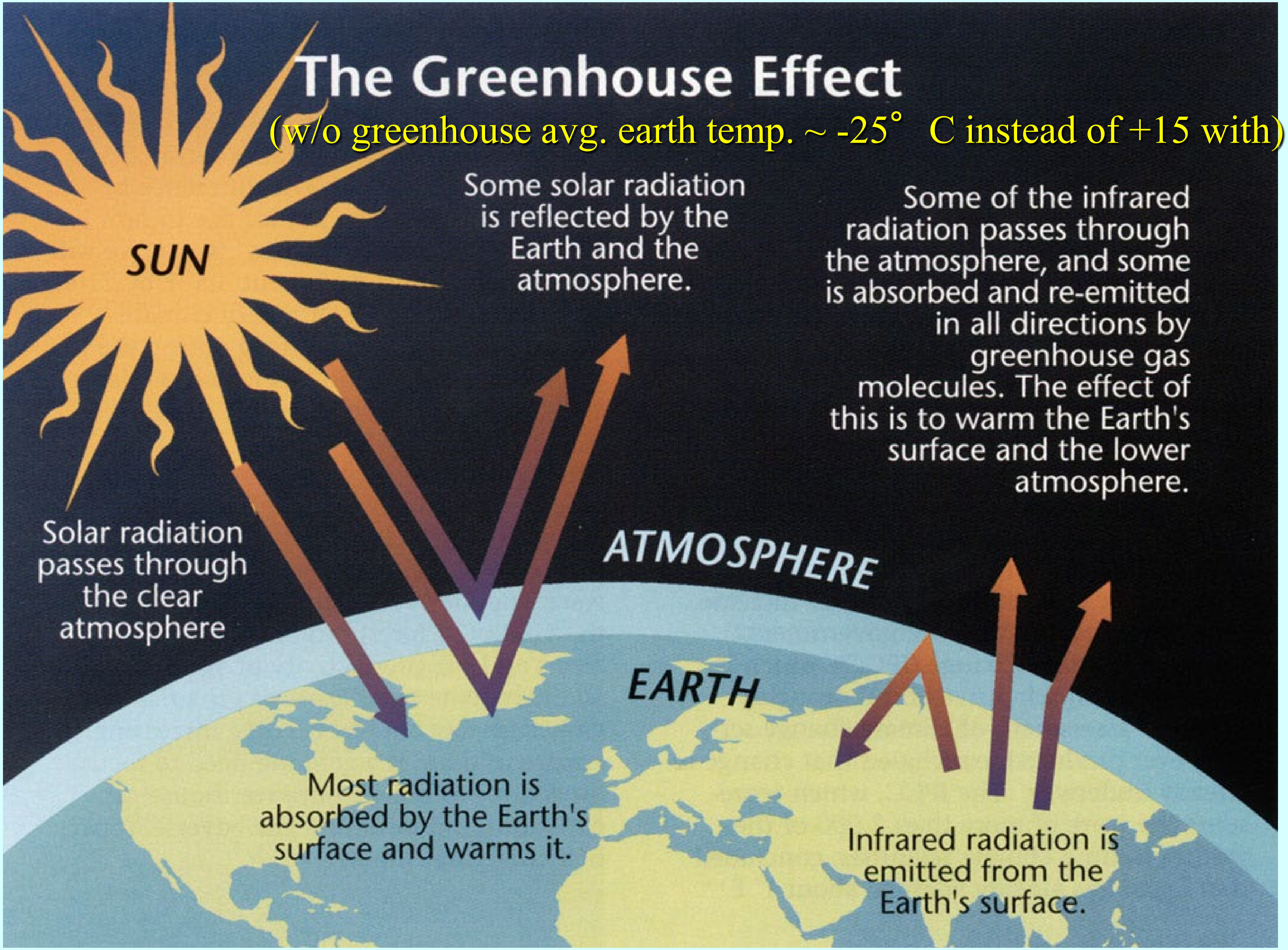
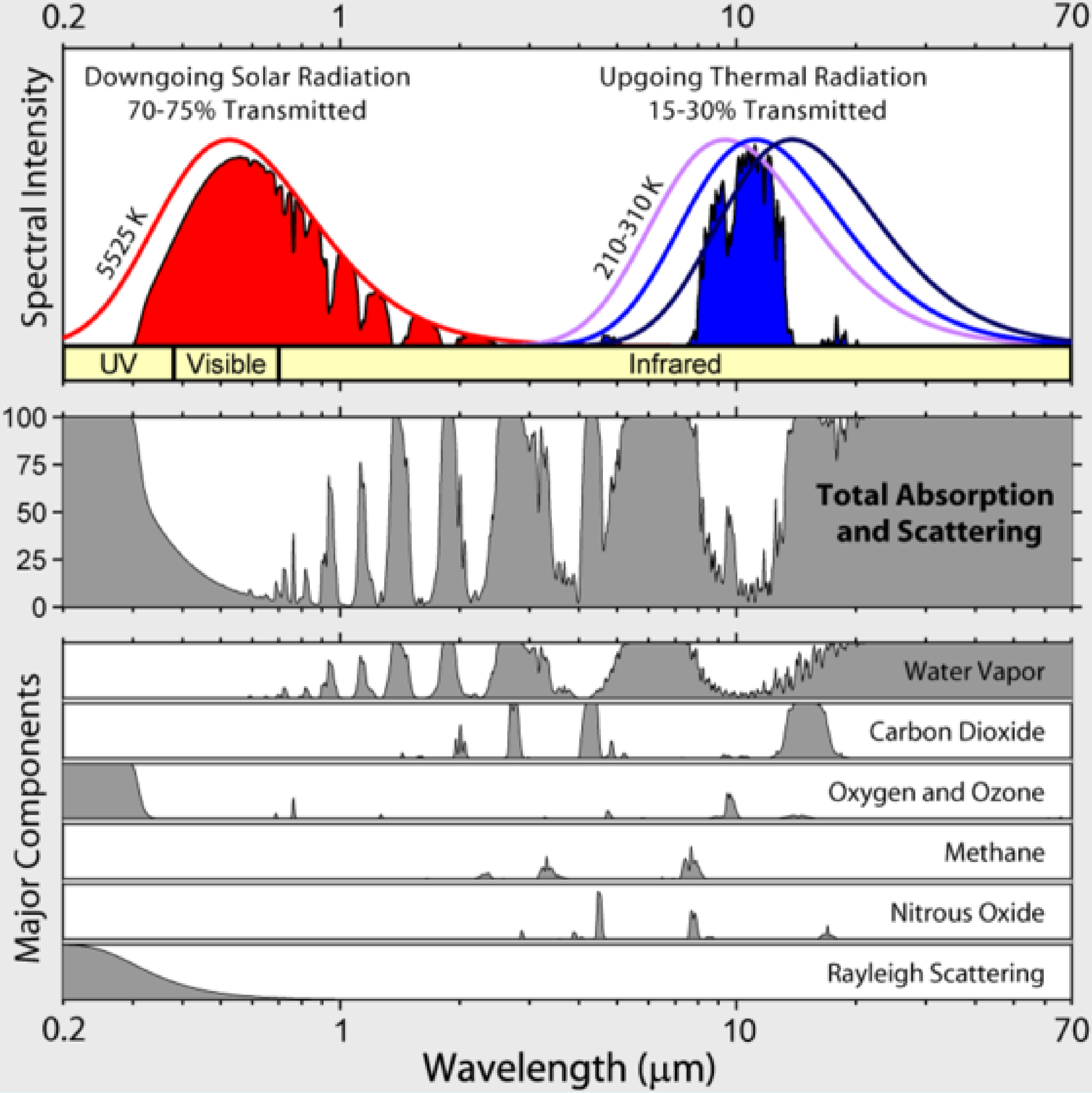


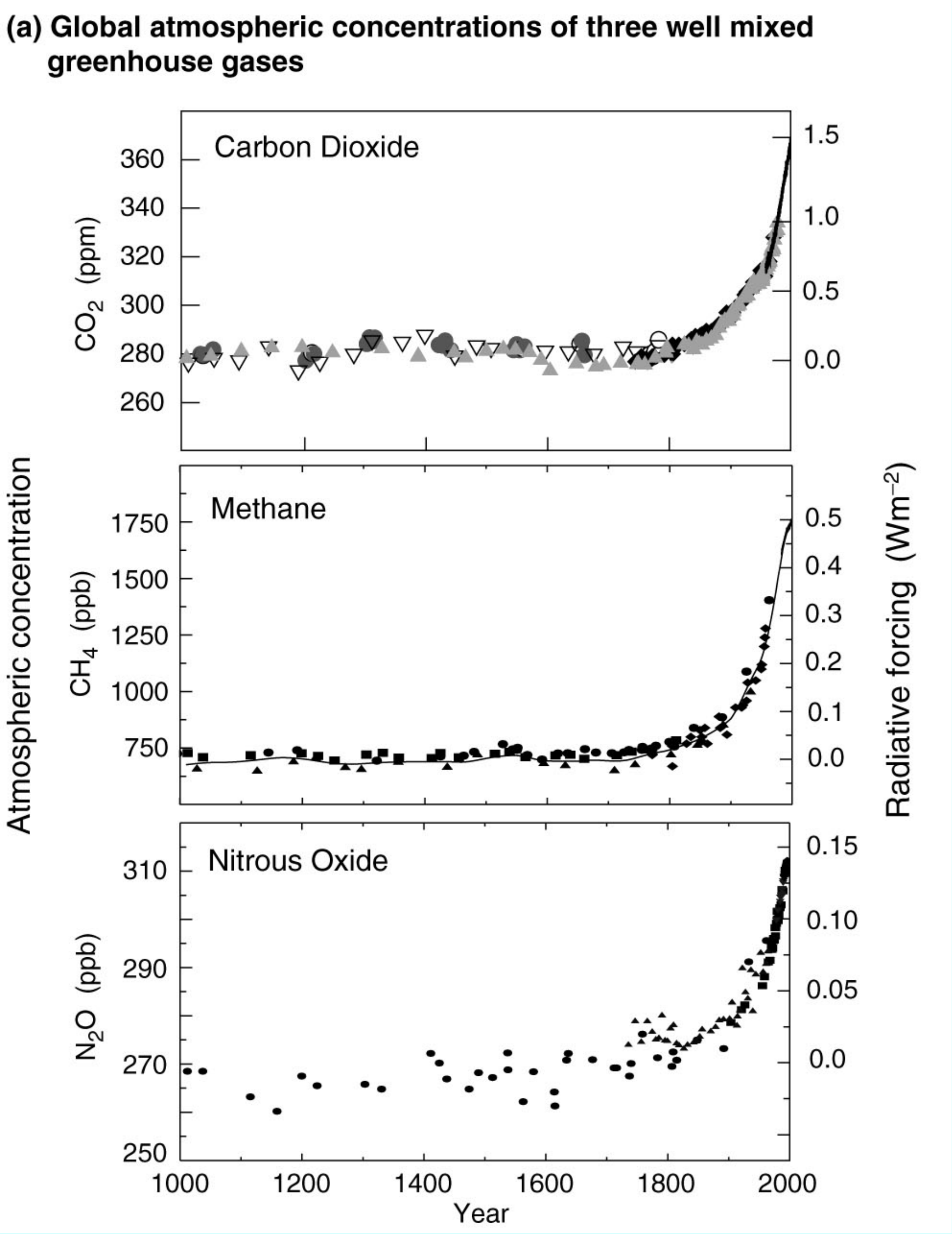
Fig. S3


The Greenhouse Effect
(w/o greenhouse avg. earth temp. ~ -25° C instead of +15 with)
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

Source: OSTP

Radiation Transmitted by the Atmosphere





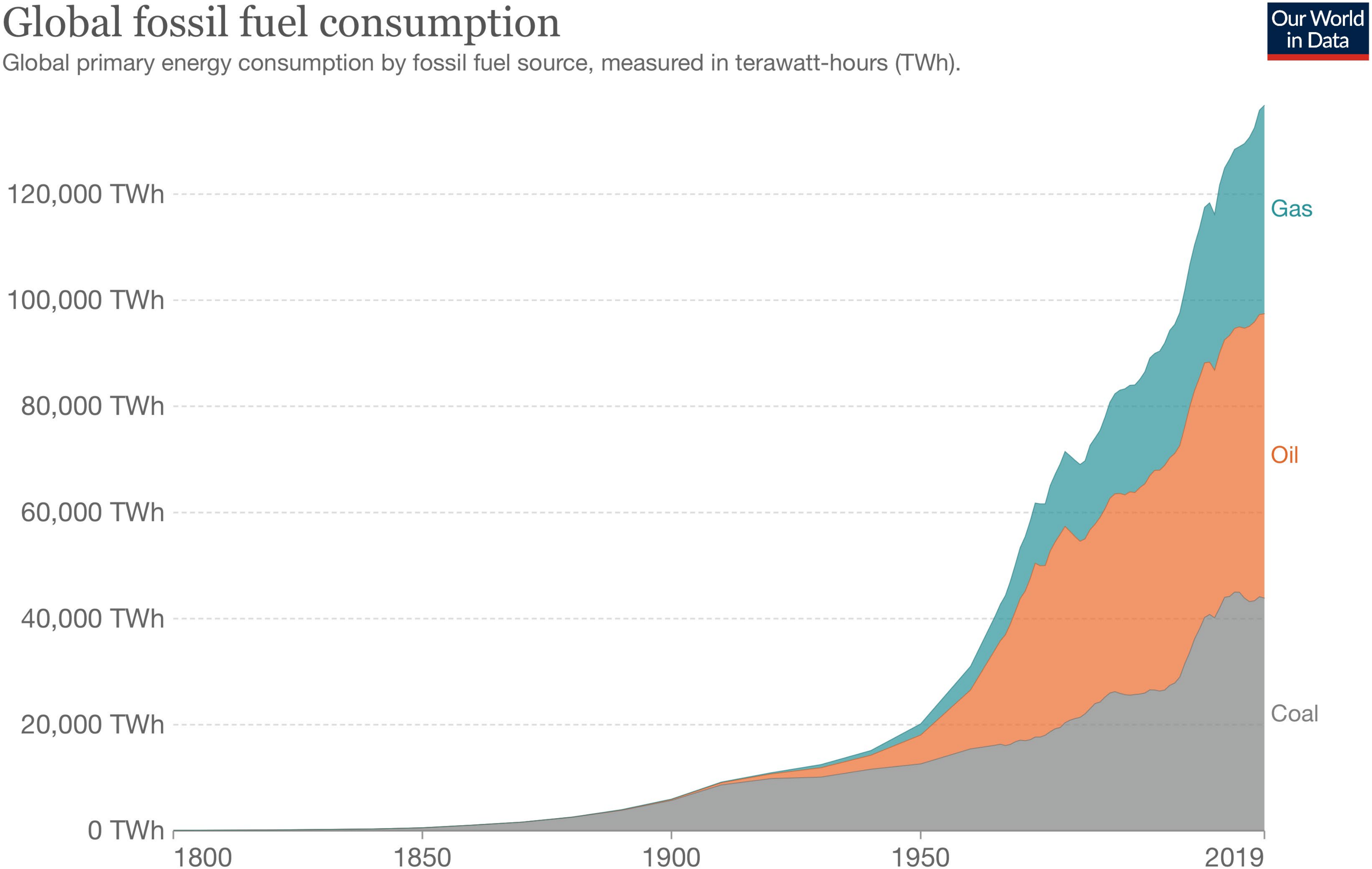
Anthropogenic Influence on Atmospheric Concentration of Greenhouse Gases

Source: IPCC TAR 2001

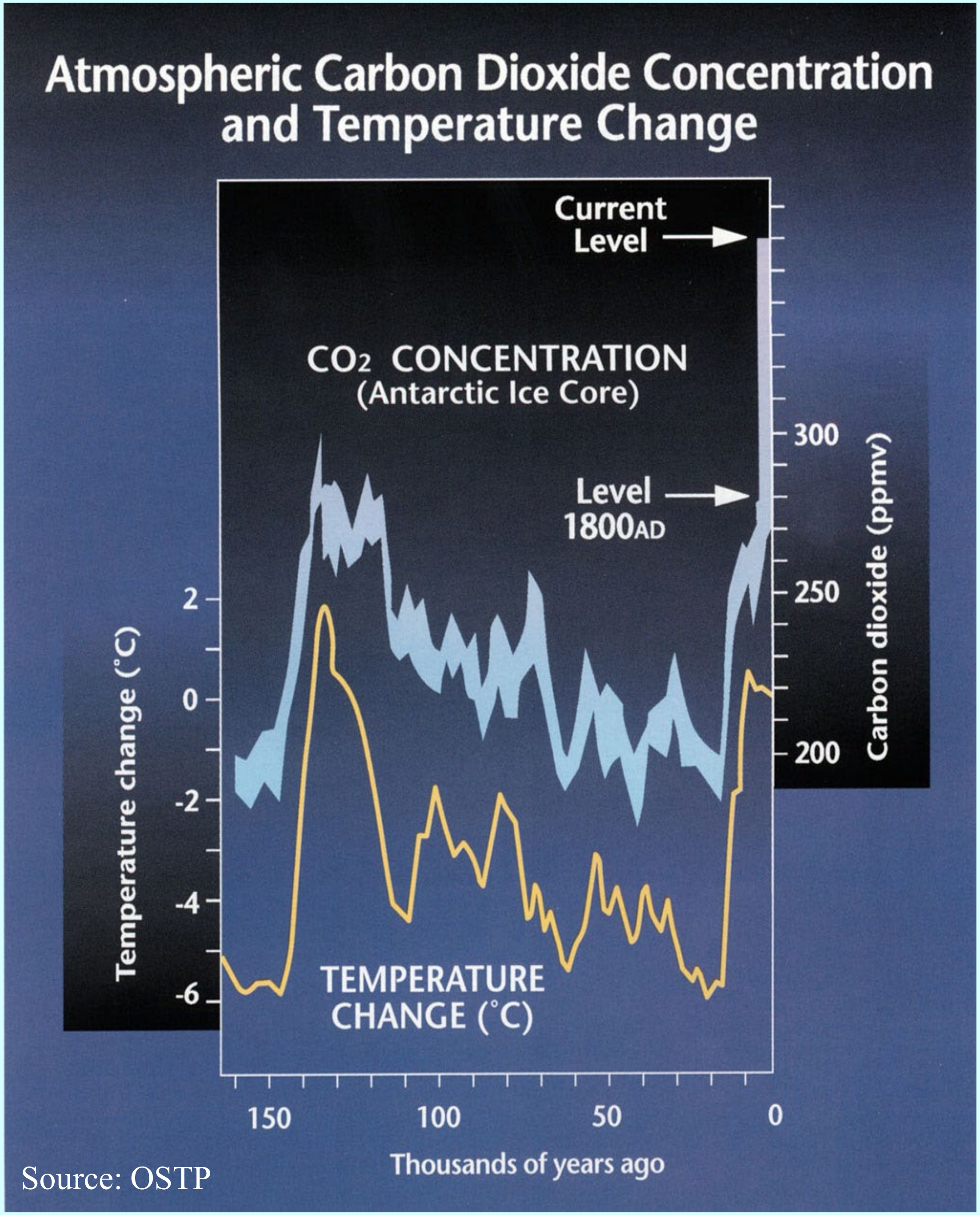
Union of Concerned Scientists

Global fossil fuel consumption

Global primary energy consumption by fossil fuel source, measured in terawatt-hours (TWh).



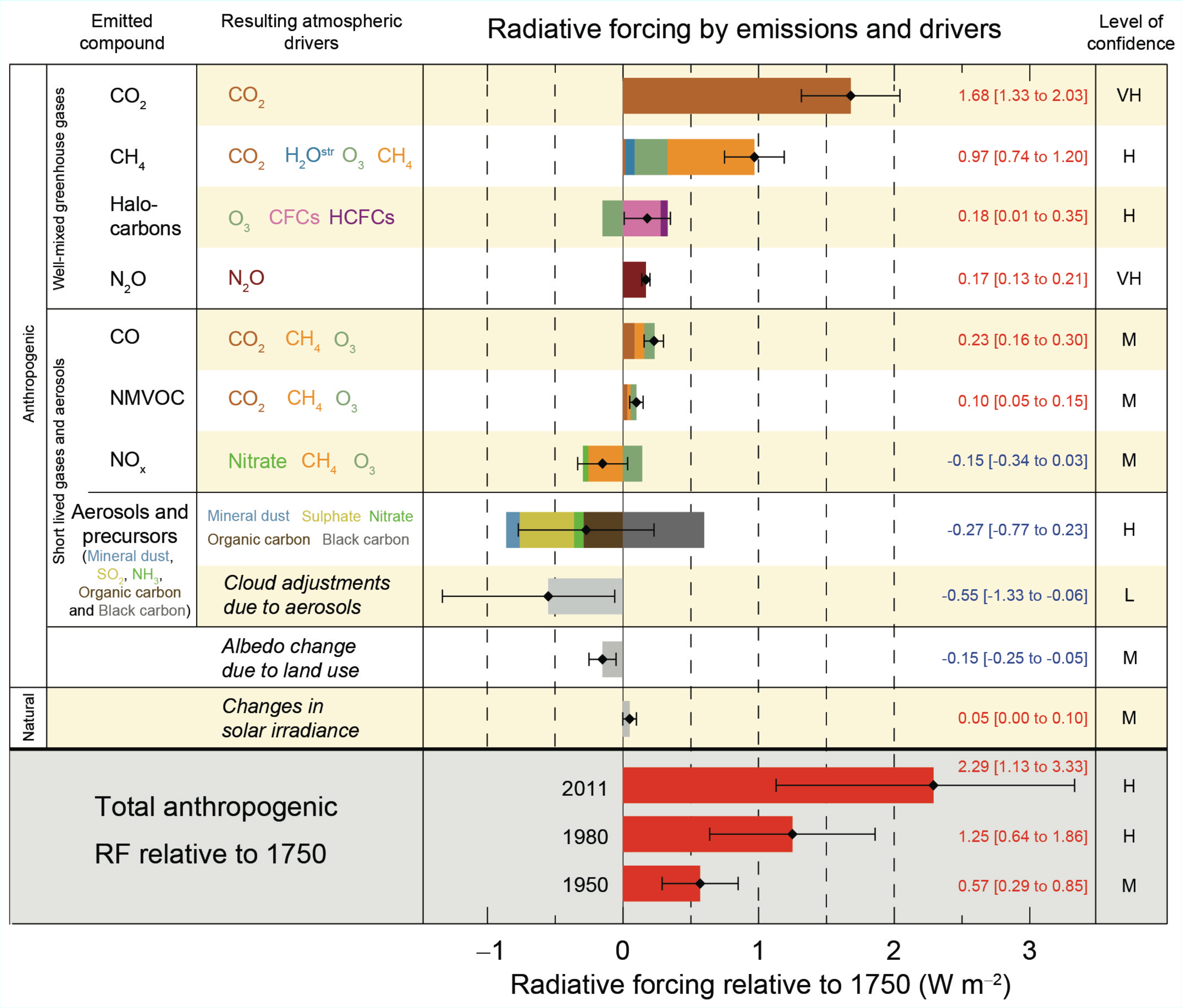
Source: Vaclav Smil (2017). Energy Transitions: Global and National Perspective & BP Statistical Review of World Energy



- Clear correlation between atmospheric CO_2 and temperature over last 160,000 years

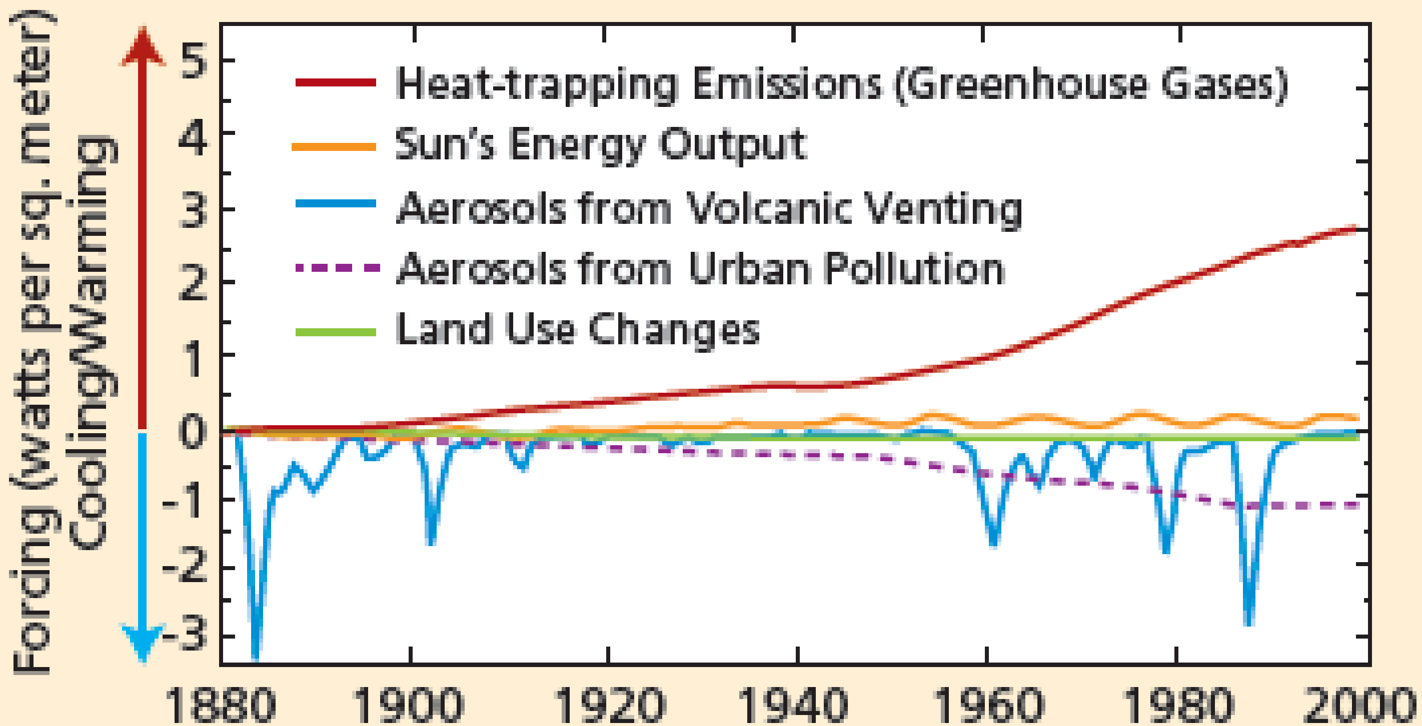
- Current level of CO_2 is *outside* bounds of natural variability

- *Rate* of change of CO_2 is also unprecedented



Emitted compound
Resulting atmospheric drivers
Radiative forcing by emissions and drivers
Level of confidence
Anthropogenic
Well-mixed greenhouse gases
CO2 | CO2 | 1.68 [1.33 to 2.03] | VH
CH4 | CO2 H2Ostr O3 CH4 | 0.97 [0.74 to 1.20] | H
Halo-carbons | O3 CFCs HCFCs | 0.18 [0.01 to 0.35] | H
N2O | N2O | 0.17 [0.13 to 0.21] | VH
Short lived gases and aerosols
CO | CO2 CH4 O3 | 0.23 [0.16 to 0.30] | M
NMVOC | CO2 CH4 O3 | 0.10 [0.05 to 0.15] | M
NOx | Nitrate CH4 O3 | -0.15 [-0.34 to 0.03] | M
Aerosols and precursors (Mineral dust, SO2, NH3, Organic carbon and Black carbon)
Mineral dust Sulphate Nitrate Organic carbon Black carbon | -0.27 [-0.77 to 0.23] | H
Cloud adjustments due to aerosols | -0.55 [-1.33 to -0.06] | L
Albedo change due to land use | -0.15 [-0.25 to -0.05] | M
Natural
Changes in solar irradiance | 0.05 [0.00 to 0.10] | M
Total anthropogenic RF relative to 1750
2011 | 2.29 [1.13 to 3.33] | H
1980 | 1.25 [0.64 to 1.86] | H
1950 | 0.57 [0.29 to 0.85] | M
–1 0 1 2 3
Radiative forcing relative to 1750 (W m-2)

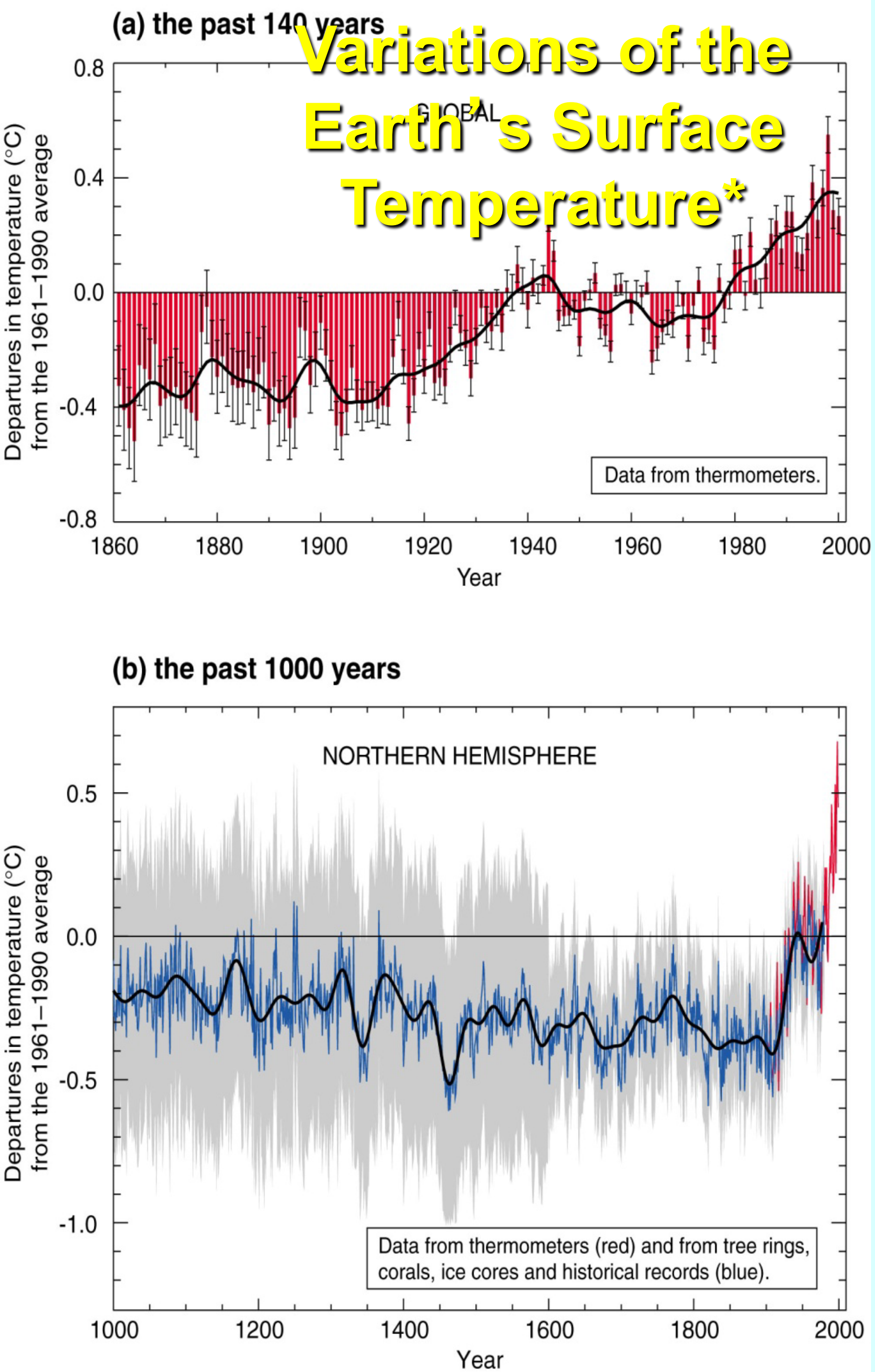
Global Climate Drivers



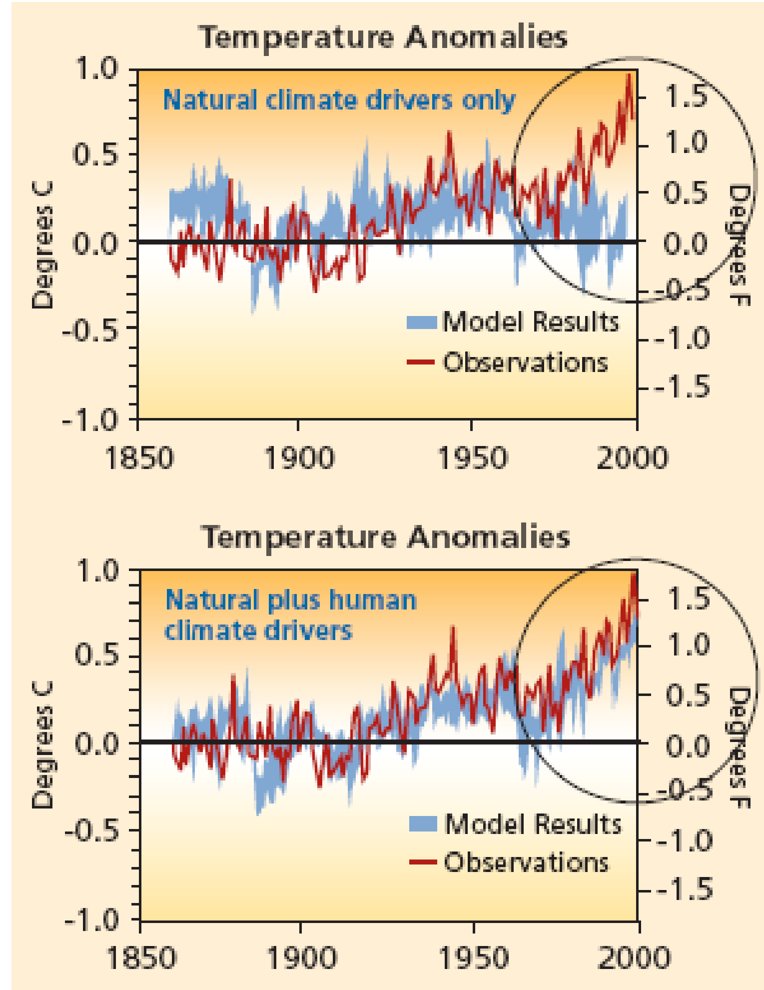
Heat-trapping emissions (greenhouse gases) far outweigh the effects of other drivers acting on Earth's climate.

Source: Hansen et al. 2005.

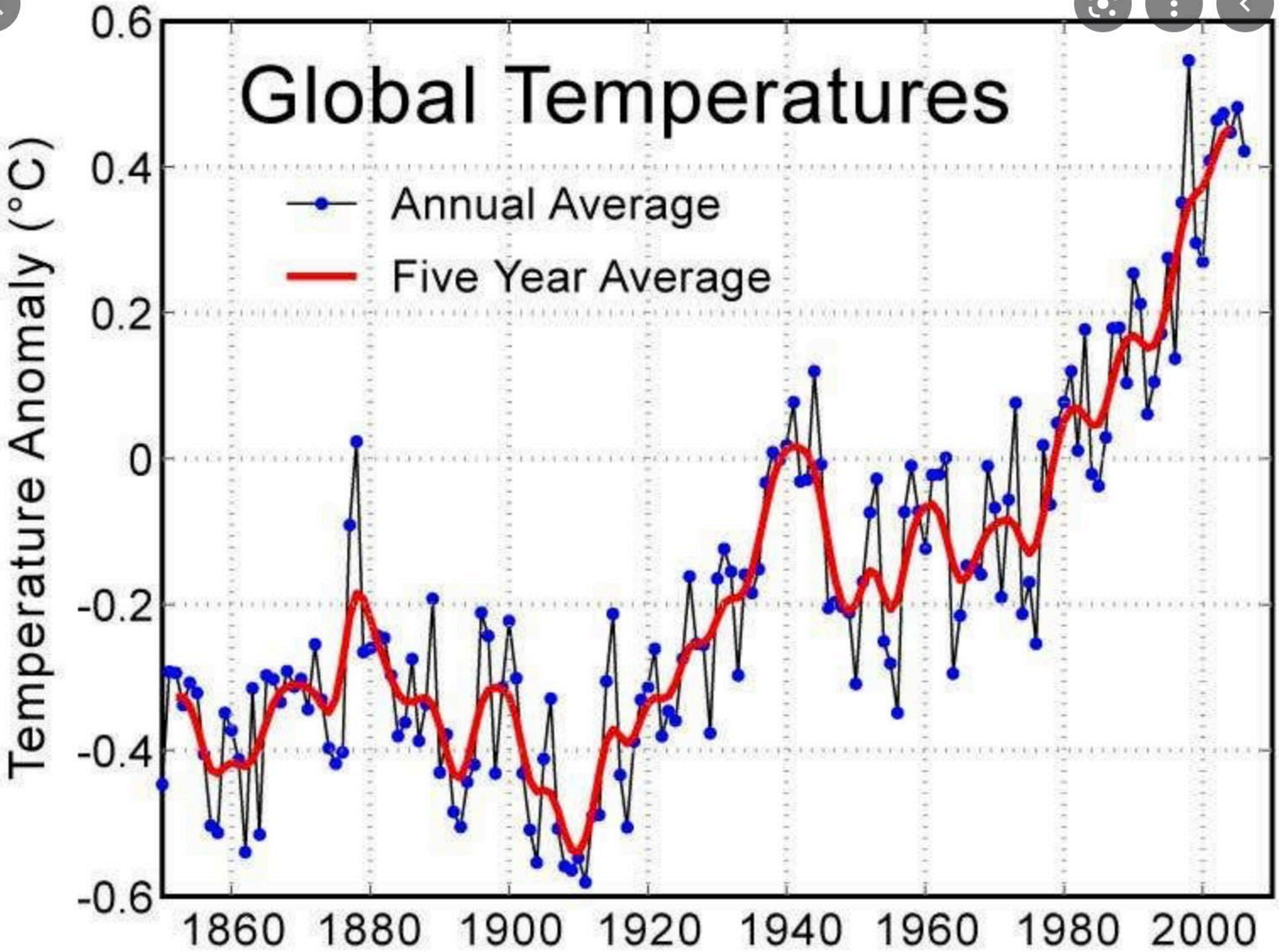
Variations of the Earth's Surface Temperature*

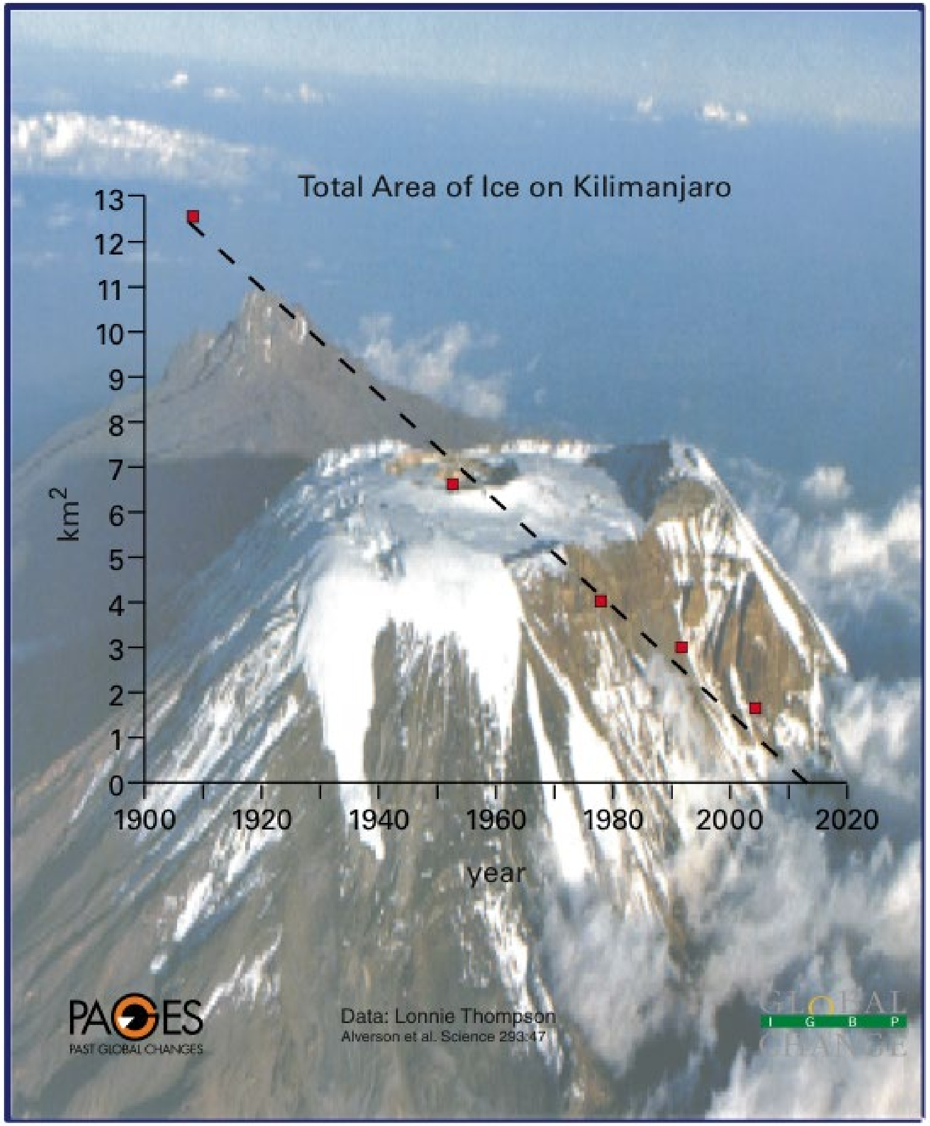


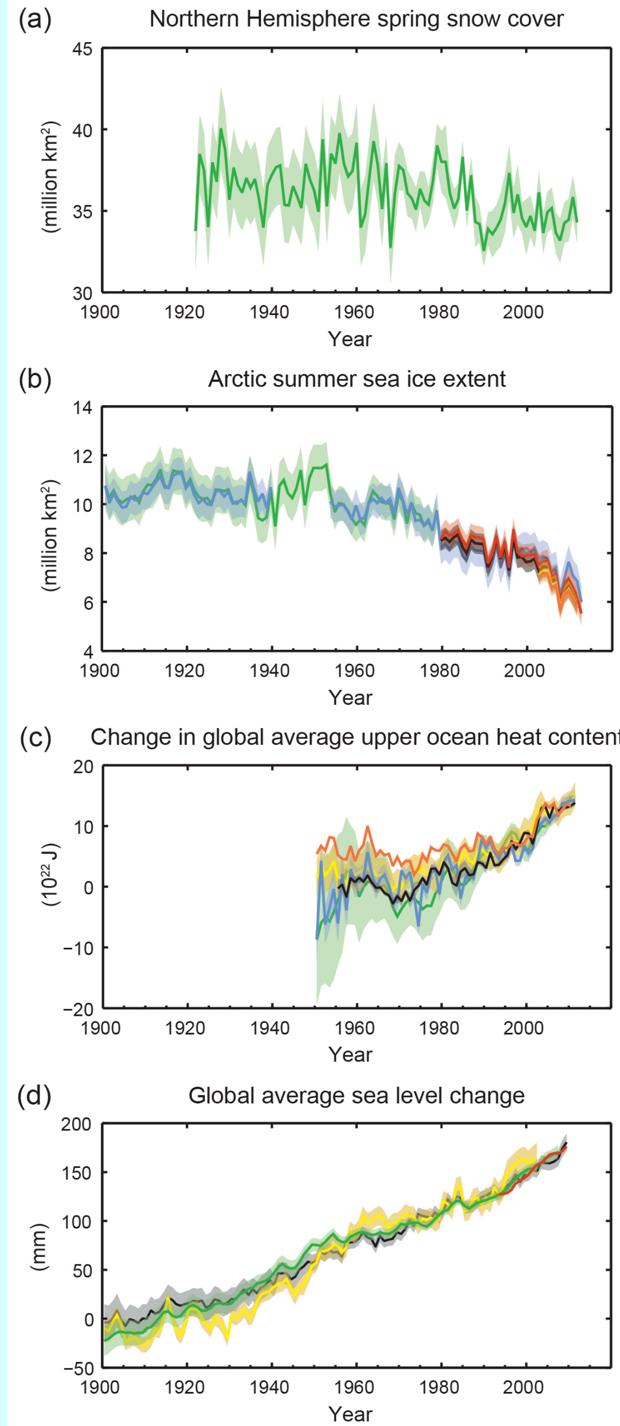
Climate Drivers Compared with Global Surface Temperature

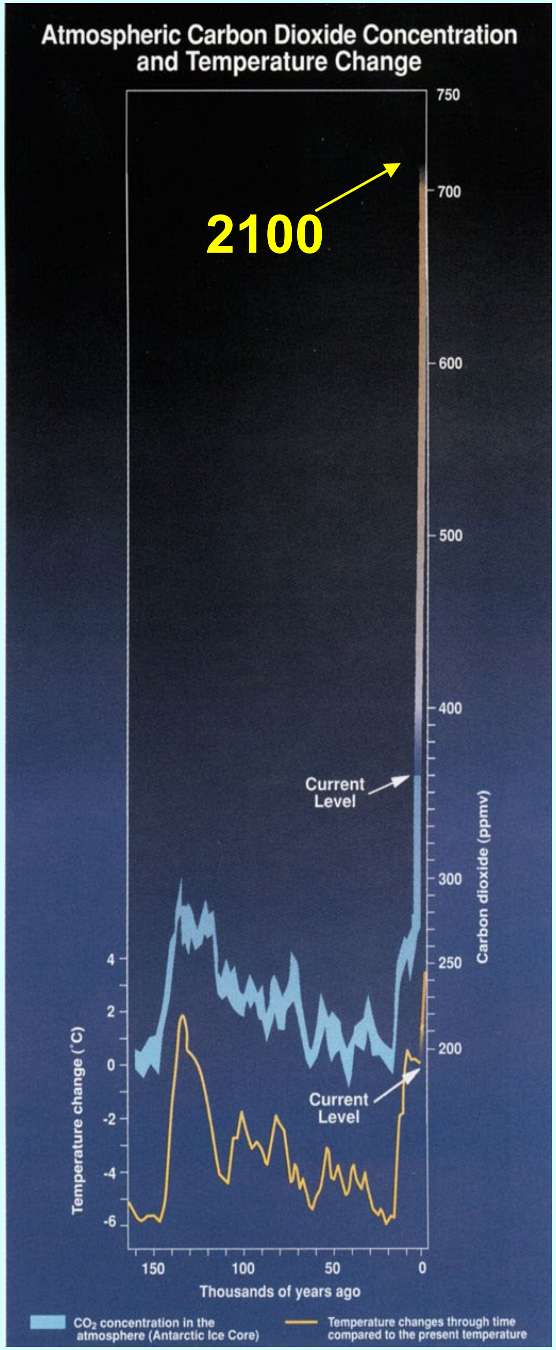


The model output (blue shading) that includes both natural and human-induced drivers (lower graph) gives a better match with the observed temperature response (red line). Source: IPCC TAR 2001.


Global Temperatures
Annual Average
Five Year Average
Temperature Anomaly (°C)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1860
1880
1900
1920
1940
1960
1980
2000


Total Area of Ice on Kilimanjaro
km²
year
PAGES
PAST GLOBAL CHANGES
Data: Lonnie Thompson
Alverson et al. Science 293:47
I G B P


(a) Northern Hemisphere spring snow cover
(million km²)
Year
(b) Arctic summer sea ice extent
(million km²)
Year
(c) Change in global average upper ocean heat content
(10²² J)
Year
(d) Global average sea level change
(mm)
Year

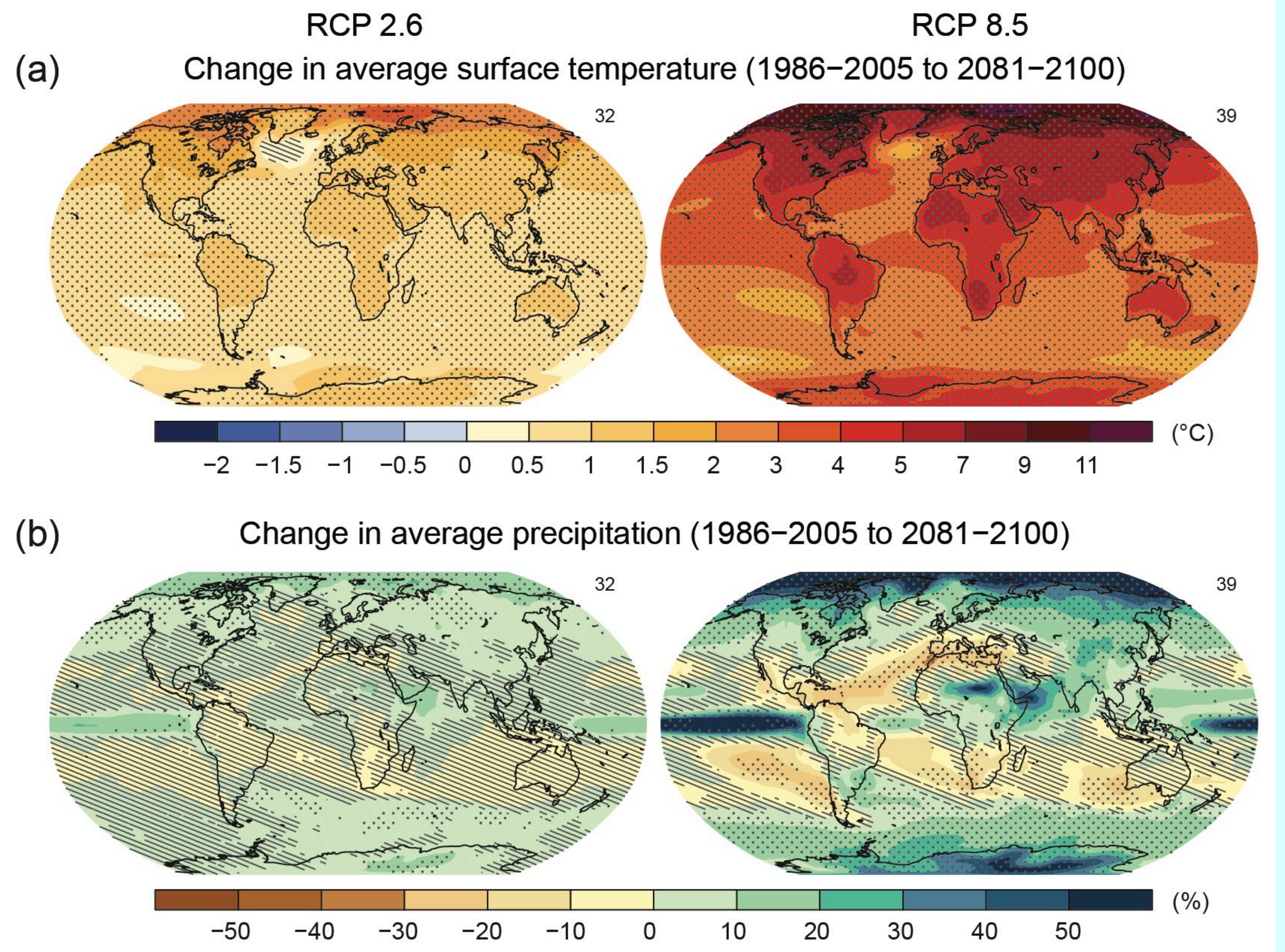


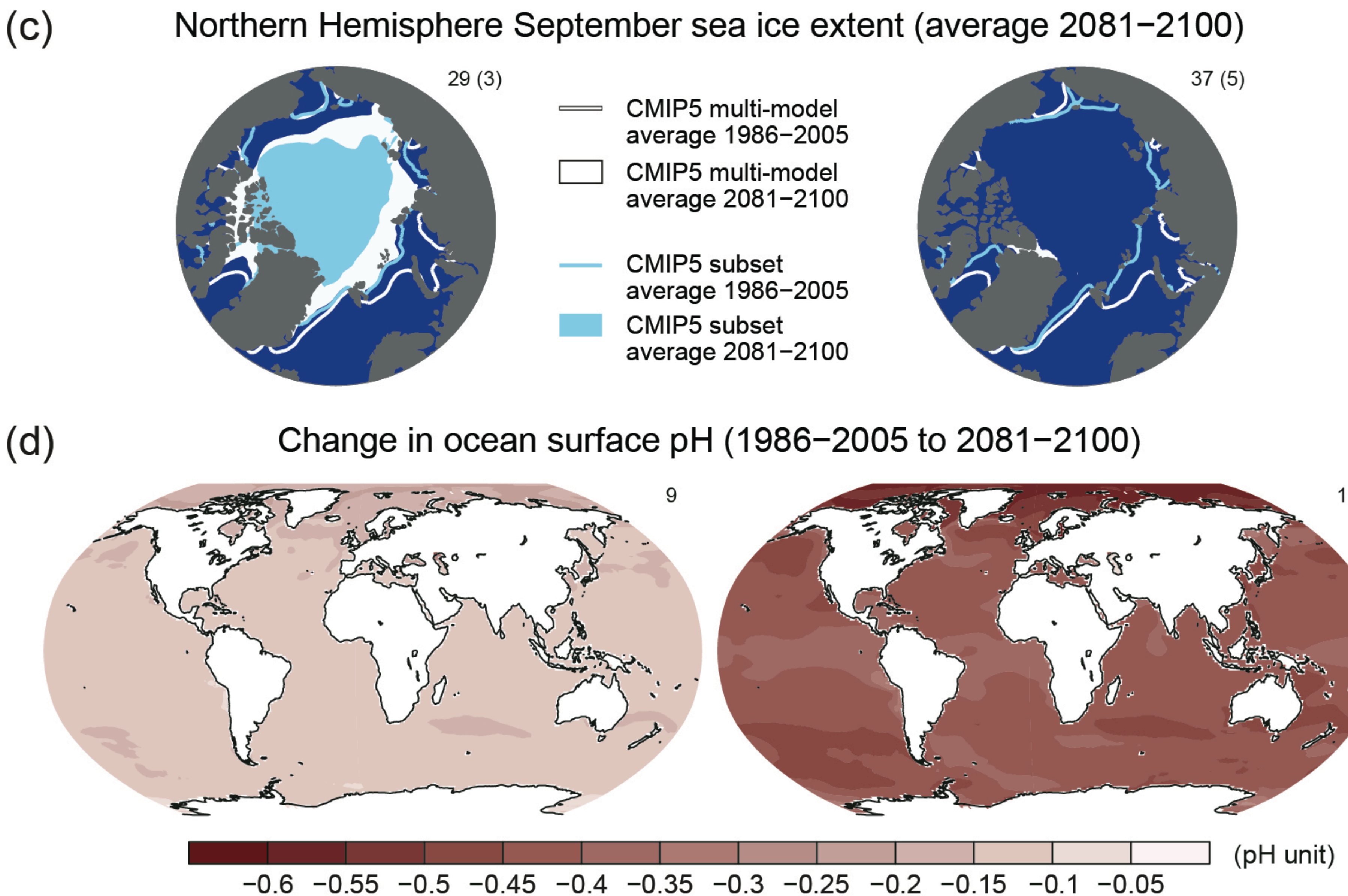
If business as usual:

- CO_2 concentrations will likely be more than 700 ppm by 2100

- Global average temperatures projected to increase between 2.5 - 10.4° F

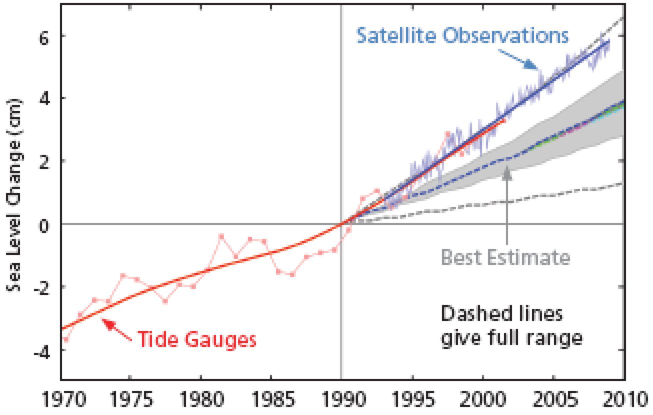
Source: OSTP


RCP 2.6
RCP 8.5
(a)
Change in average surface temperature (1986−2005 to 2081−2100)
32
39
(°C)
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2 3 4 5 7 9 11
(b)
Change in average precipitation (1986−2005 to 2081−2100)
32
39
(%)
−50 −40 −30 −20 −10 0 10 20 30 40 50


(c)
Northern Hemisphere September sea ice extent (average 2081−2100)
29 (3)
37 (5)
CMIP5 multi-model average 1986−2005
CMIP5 multi-model average 2081−2100
CMIP5 subset average 1986−2005
CMIP5 subset average 2081−2100
(d)
Change in ocean surface pH (1986−2005 to 2081−2100)
9
10
−0.6 −0.55 −0.5 −0.45 −0.4 −0.35 −0.3 −0.25 −0.2 −0.15 −0.1 −0.05
(pH unit)

10 m sea level rise

FIGURE 2 **Sea Level Rise in Line with Highest Projection**



Changes in sea level since 1973, compared with IPCC scenarios (dashed lines and gray ranges), based on tide gauges (red) and satellites (blue). From Rahmstorf et al. (2007) updated by Rahmstorf (personal communication).

FIGURE 3 **Sea Level Rise by End of This Century**

New analysis provides estimates for sea level rise by the end of this century between a plausible level and a physically possible though less likely level. Source (IPCC 2007 and Pfeffer et al. 2008).[4,5]

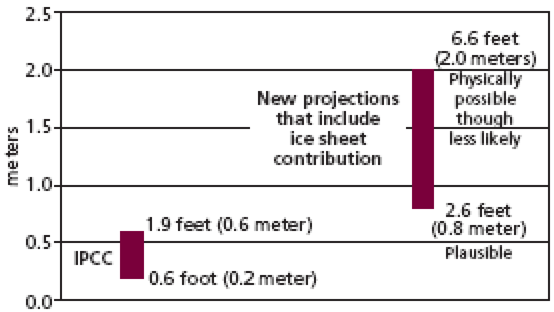
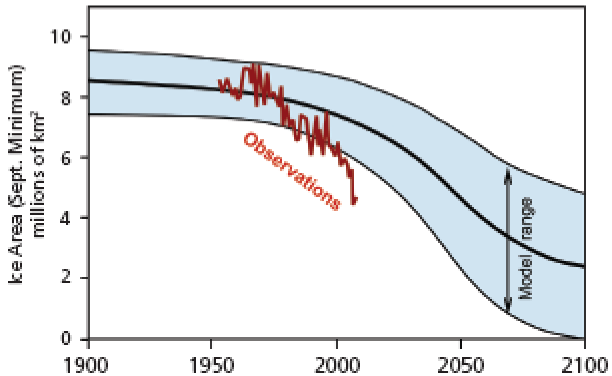
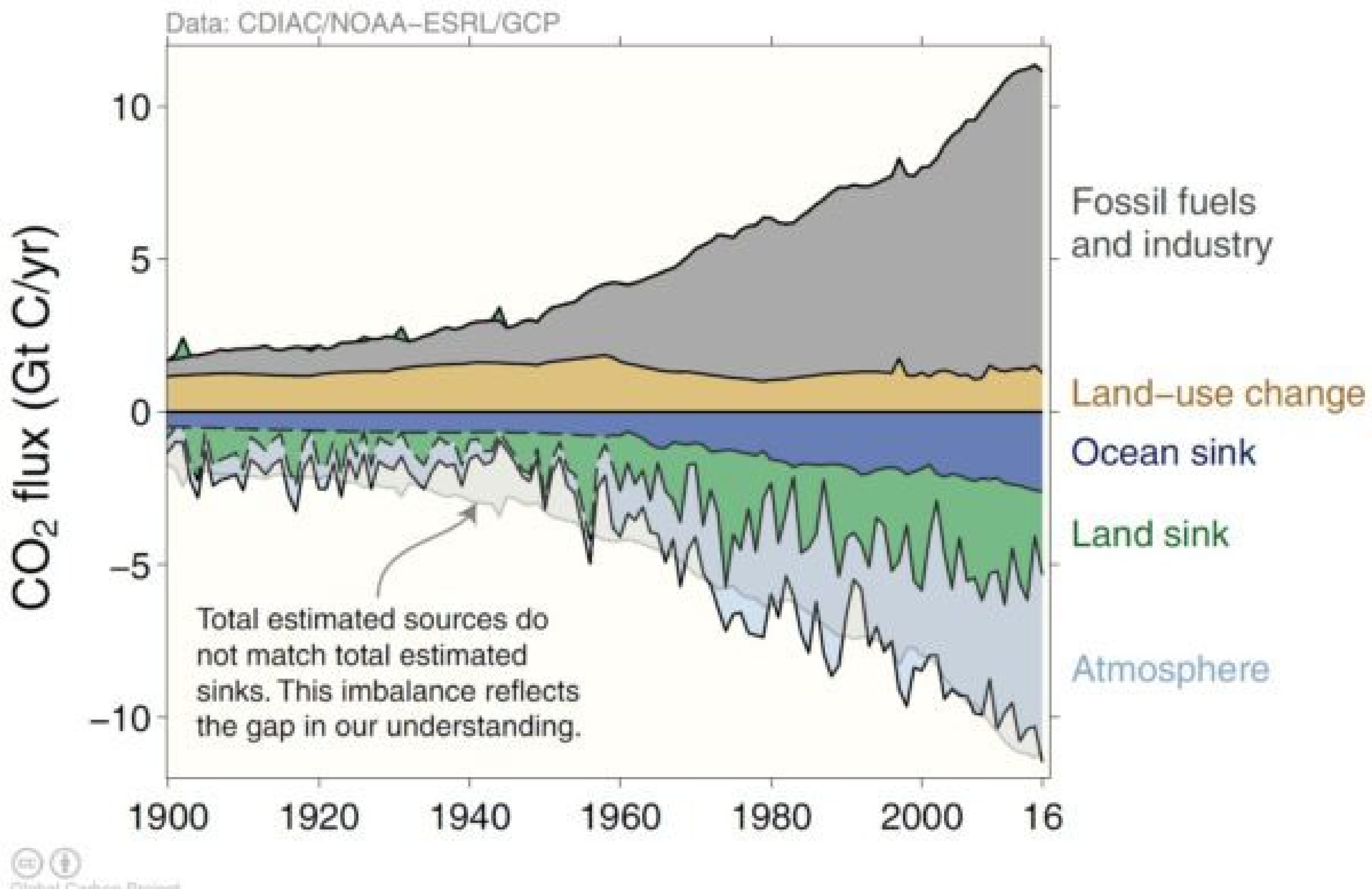


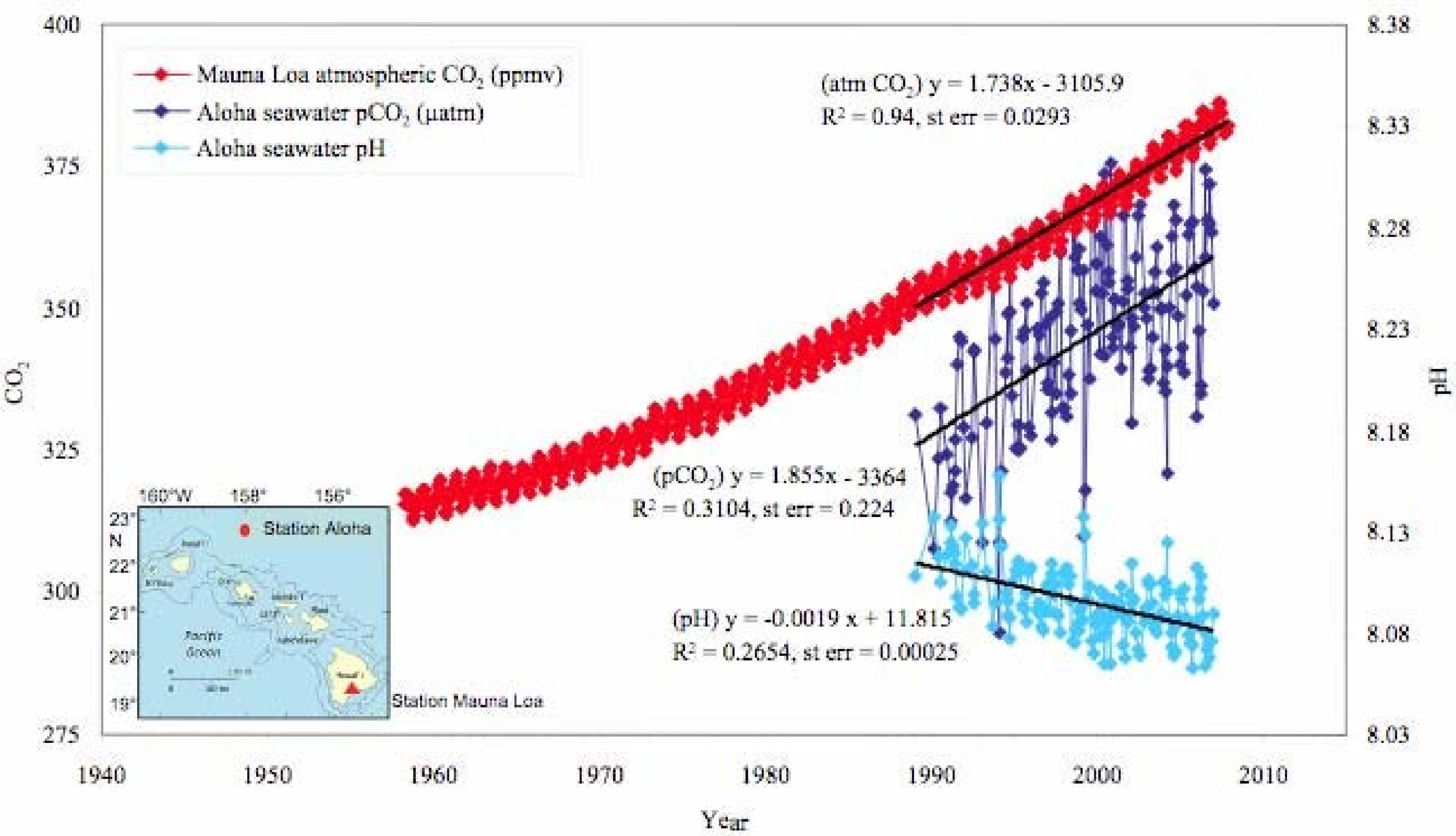
FIGURE 4 **Shrinking Summer Arctic Sea Ice Area**



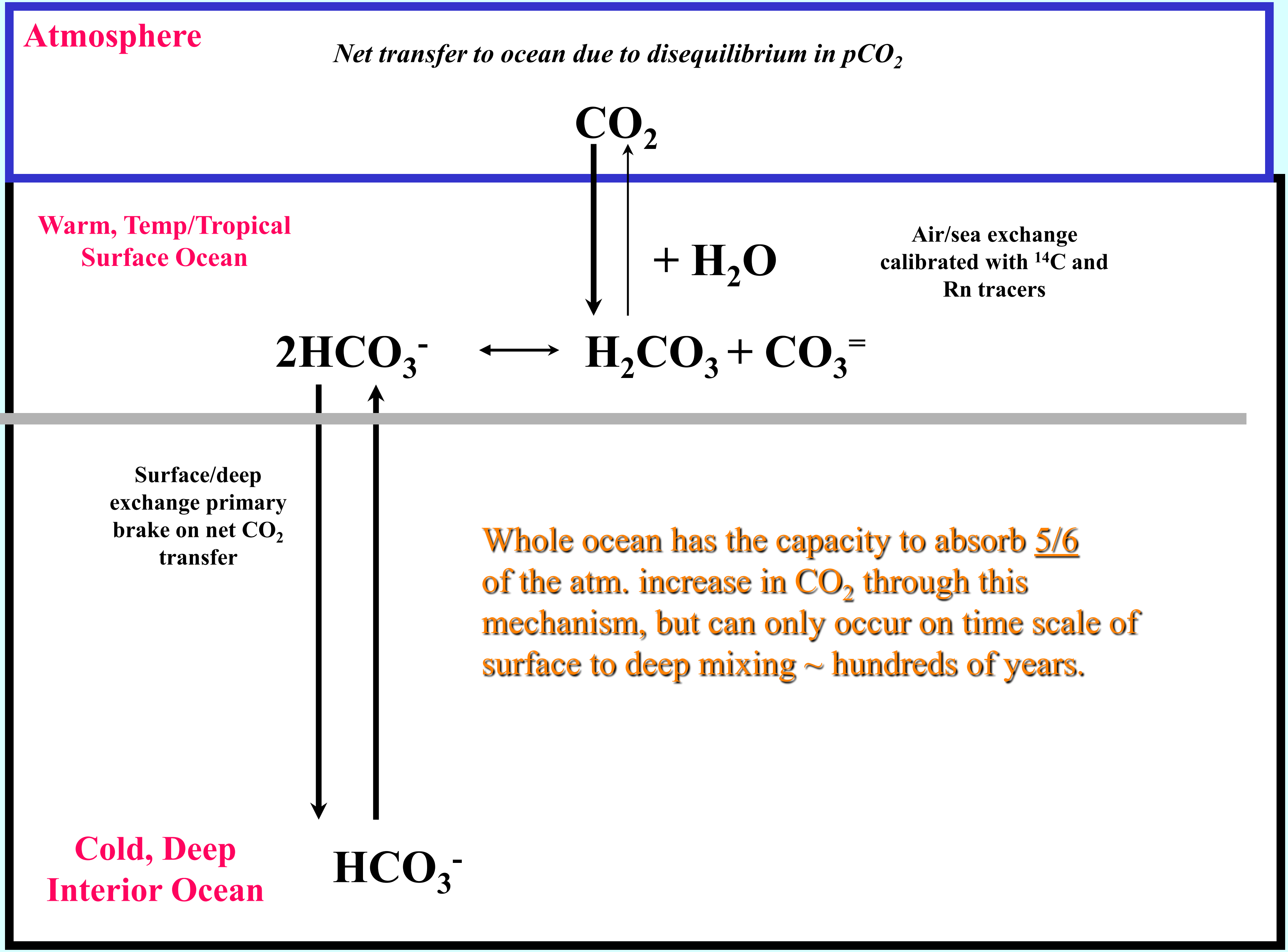
Arctic models of September sea ice area underestimate the rate of observed sea ice retreat. Based on Stroeve et al. 2007.

Source: Dirk Notz from Hamburg adapted figure from *http://www.nsidc.org/news/images/20070430Figure1.png*.

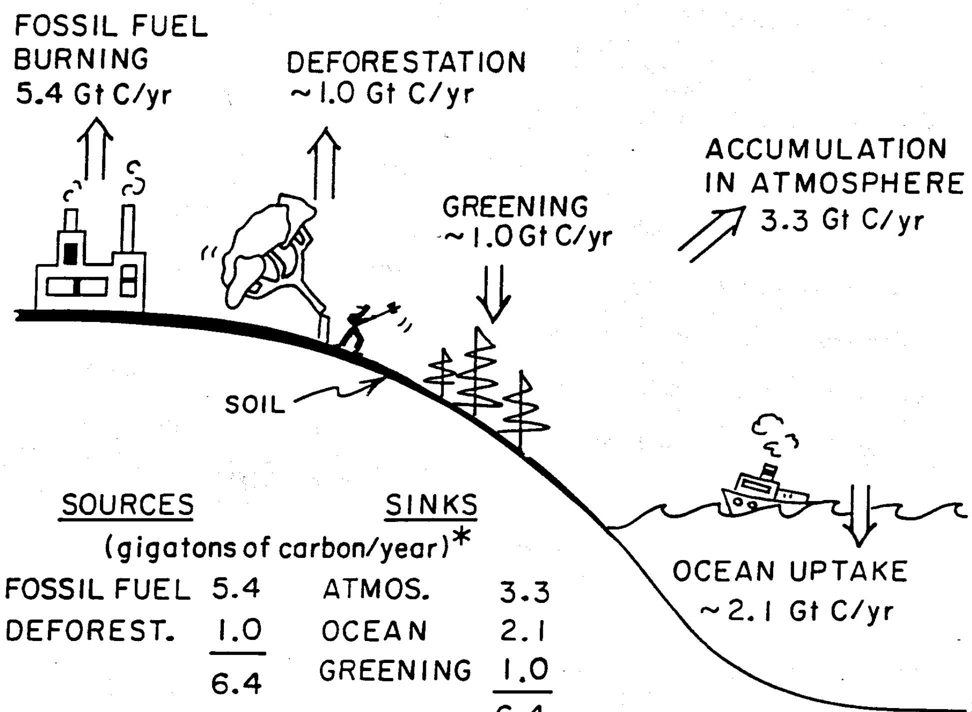

Data: CDIAC/NOAA–ESRL/GCP
CO_2 flux (Gt C/yr)
10
5
0
−5
−10
1900
1920
1940
1960
1980
2000
16
Fossil fuels and industry
Land–use change
Ocean sink
Land sink
Atmosphere
Total estimated sources do not match total estimated sinks. This imbalance reflects the gap in our understanding.
Global Carbon Project



400
375
350
325
300
275
8.38
8.33
8.28
8.23
8.18
8.13
8.08
8.03
CO2
pH
Mauna Loa atmospheric CO2 (ppmv)
Aloha seawater pCO2 (µatm)
Aloha seawater pH
(atm CO2) y = 1.738x - 3105.9
R2 = 0.94, st err = 0.0293
(pCO2) y = 1.855x - 3364
R2 = 0.3104, st err = 0.224
(pH) y = -0.0019 x + 11.815
R2 = 0.2654, st err = 0.00025
160°W
158°
156°
23°
N
22°
21°
20°
19°
Station Aloha
Pacific Ocean
Station Mauna Loa
1940
1950
1960
1970
1980
1990
2000
2010
Year


Atmosphere
Net transfer to ocean due to disequilibrium in pCO_2
CO_2
$+ H_2O$
Air/sea exchange calibrated with ^{14}C and Rn tracers
Warm, Temp/Tropical Surface Ocean
$2HCO_3^- \longleftrightarrow H_2CO_3 + CO_3^=$
Surface/deep exchange primary brake on net CO_2 transfer
Whole ocean has the capacity to absorb 5/6 of the atm. increase in CO_2 through this mechanism, but can only occur on time scale of surface to deep mixing ~ hundreds of years.
Cold, Deep Interior Ocean
HCO_3^-

APROXIMATE
EARTH CARBON BUDGET
FOR THE 1980s;
THE ANTHROPOGENIC PERTURBATION



SOURCES / SINKS
(gigatons of carbon/year)*

SOURCES		SINKS	
FOSSIL FUEL	5.4	ATMOS.	3.3
DEFOREST.	1.0	OCEAN	2.1
		GREENING	1.0
	6.4		6.4

FRAC. TO ATMOS. $\frac{3.3}{6.4} = .52$

FRAC. TO SEA $\frac{2.1}{6.4} = .33$

FRAC. TO CONT. $\frac{1.0}{6.4} = .15$

1.00

*1 Gt = 1×10^{15} grams
= 1×10^{9} tons

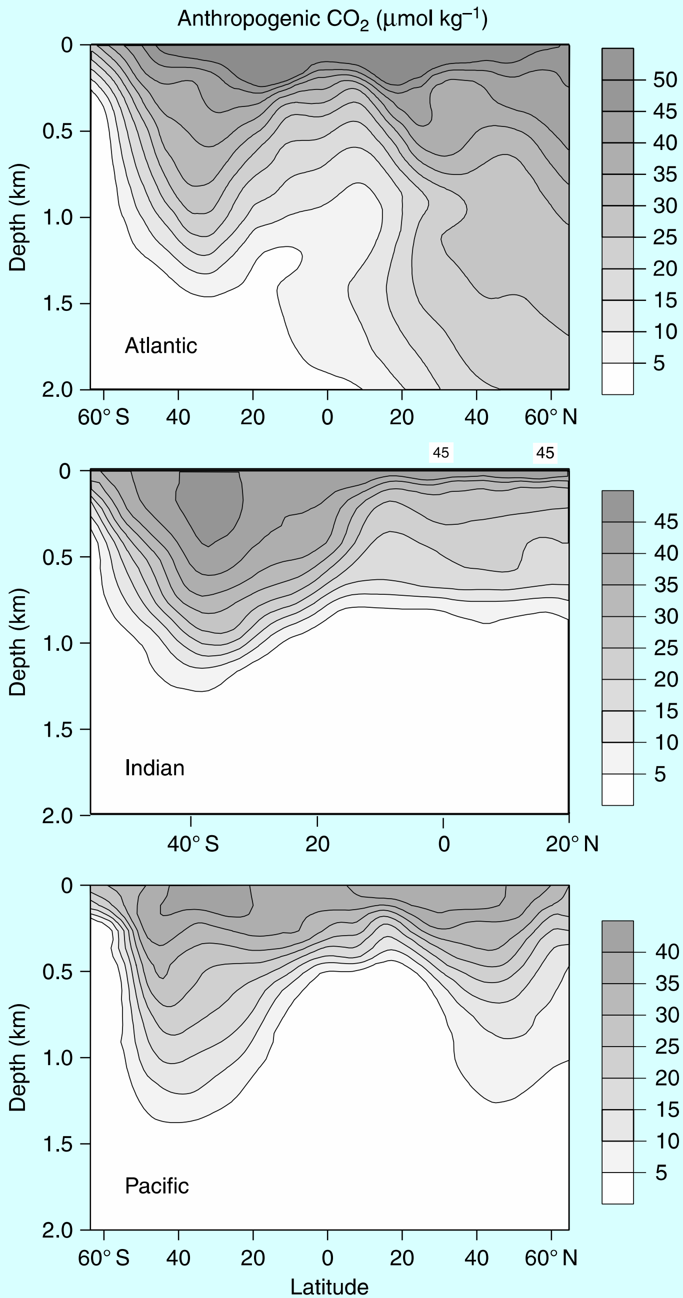


Figure 11.7. A cross section of the anthropogenic CO_2 in the ocean as determined by the C* method. Robert Key, personal communication; Key *et al.* (2004).