The Global Carbon Cycle

Introduction

Temporal scales of the global carbon cycle

- **The current (short-term) cycle**
  - **production**
  - **respiration/decomposition**
- **The long-term cycle**
  - **rock weathering**
  - **carbonates in ocean**
  - **burials**

Atmospheric methane

Atmospheric carbon monoxide

Global carbon reservoirs

Global C pools	Gt C (Pg C)	Percent of total	Excluding rocks	Turnover time (y)	
Lithosphere	**75011150**	**99.94**			
limestone	60000000	79.94		>> 1 Ma	
kerogen	15000000	19.99		>> 1 Ma	
methane clathrates	11000	0.01		>> 1 Ma	
"active" sediments	150	0.00		0.1-1000	80% coastal, 20% deep sea
Ocean	**39200**	**0.05**	**93.02**		
Organic C	1078	0.00	1.83	varies	
Living	2	0.00	0.00	0.1-1	
Dissolved carbonate	38000	0.05	90.18	2000	
Soils	**1580**	**0.00**	**3.75**		
peat	360	0.00	0.85	>1000	
microbial	15-30	0.00	0.05	<10	
intermediate	250-500	0.00	0.89	<100	
slow	600-800	0.00	1.66	0.1-100 ka	
Atmosphere	**750**	**0.00**	**1.78**	~3-5	
Plants	**610**	**0.00**	**1.45**	50	
Total	**75053290**				
Refs: Hedges, 1992; Eswaran et al., 1993; Siegerthaler & Sarmiento, 1993; Schimel et al., 1994; Schimel et al., 1995					

The current (short-term) global carbon cycle

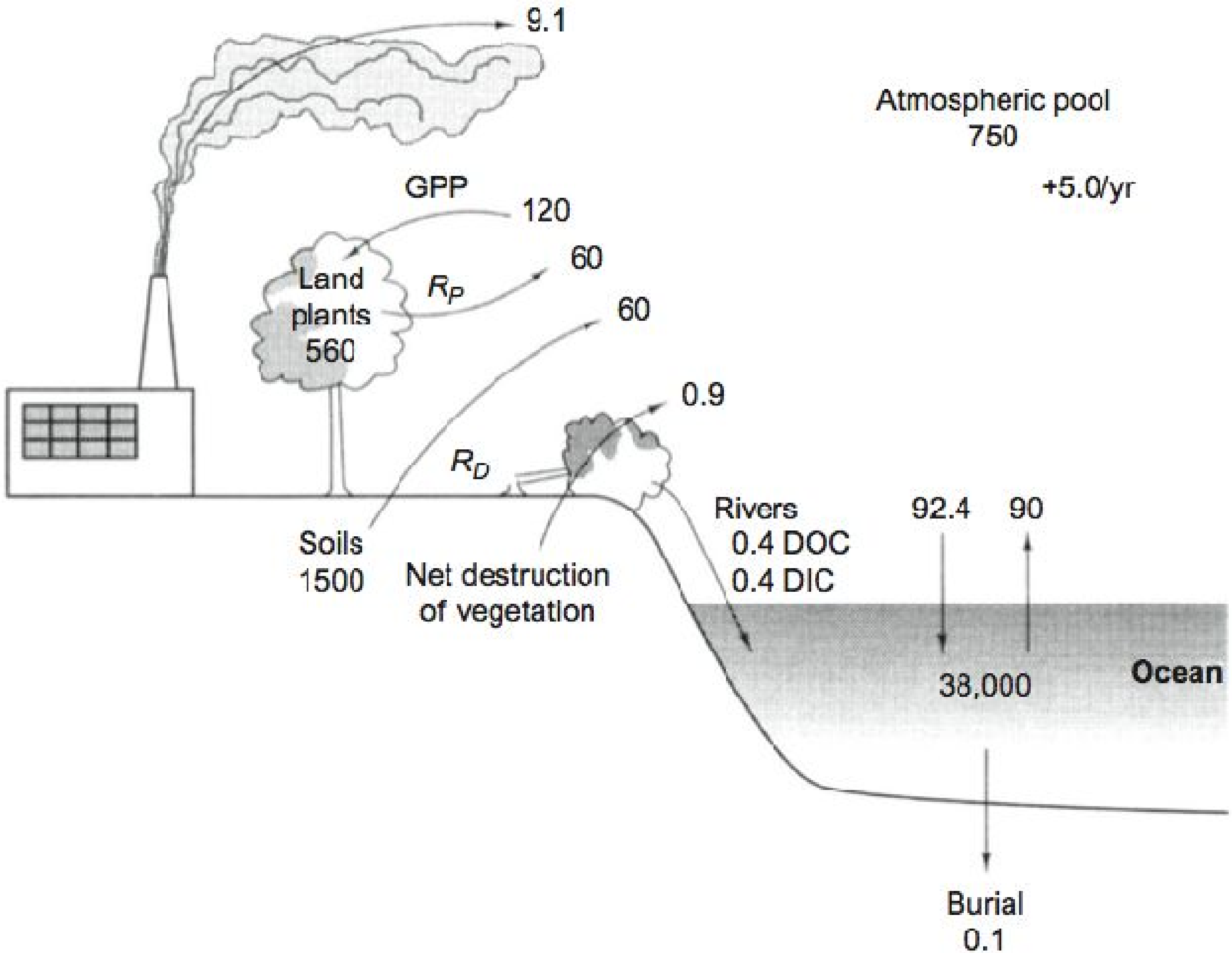
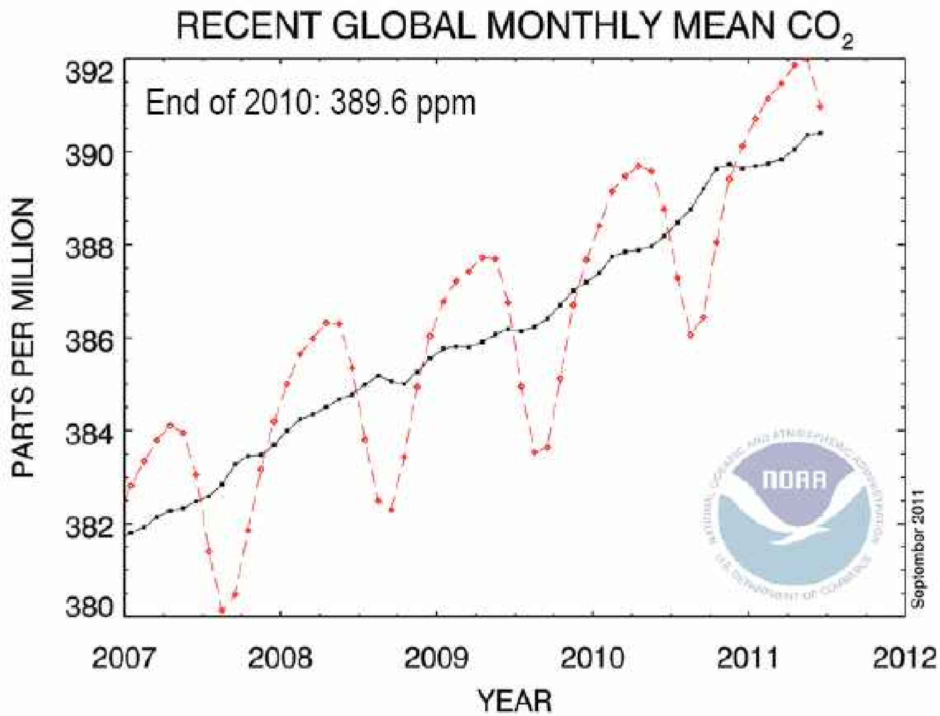


FIGURE 11.1 The global carbon cycle. All pools are expressed in units of 10^{15} g C and all annual fluxes in units of 10^{15} g C/yr, estimated for 2010. Values are taken from the text.

Atmospheric CO_2 Concentration



Annual Growth Rates (decadal means)

1970 – 1979: 1.3 ppm y^{-1}

1980 – 1989: 1.6 ppm y^{1}

1990 – 1999: 1.5 ppm y^{-1}

2000 – 2010: 1.9 ppm y^{-1}

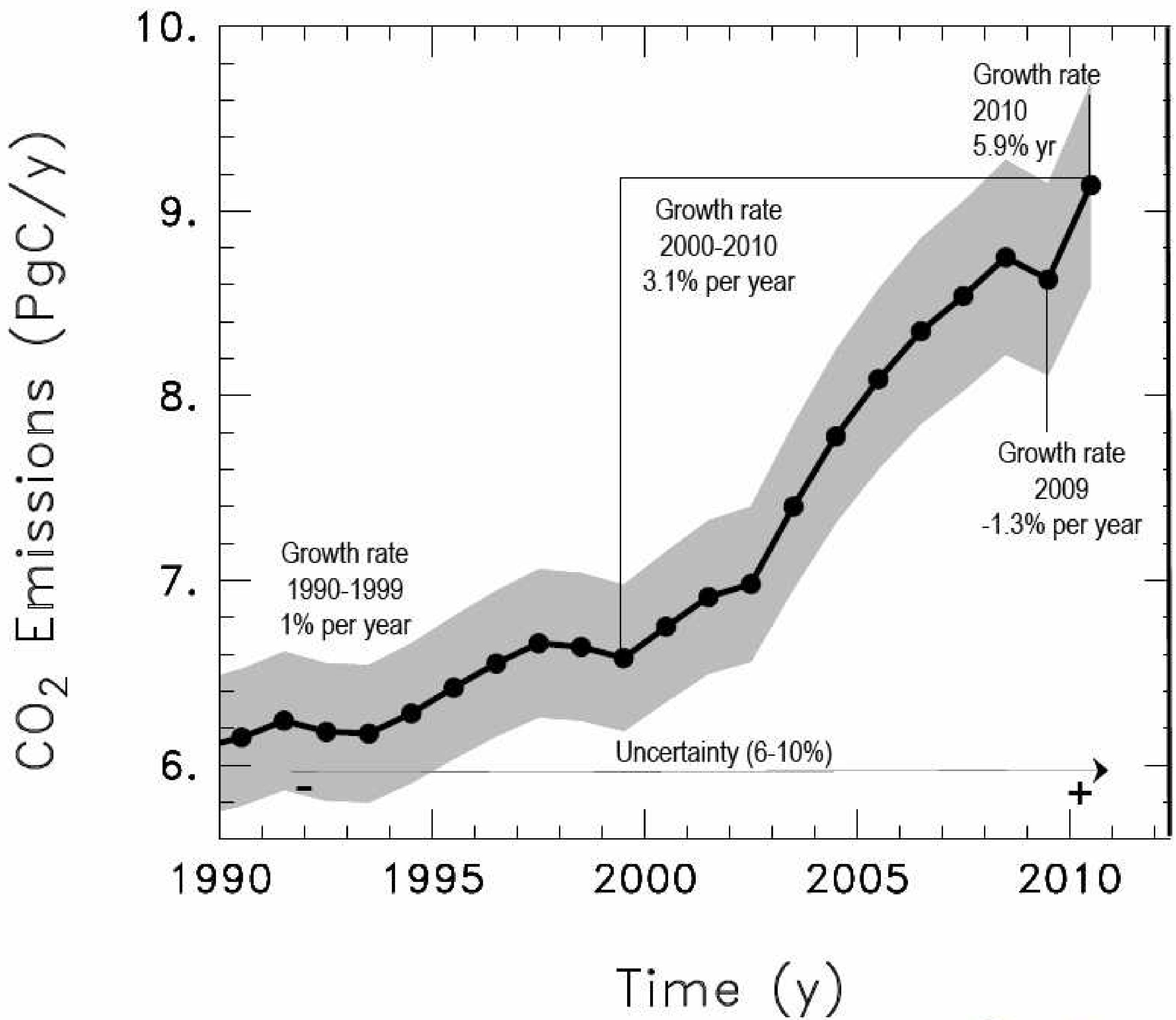
Annual Mea	Growth Rate (ppm y^{-1})
2010	2.36
2009	1.63
2008	1.81
2007	2.11
2006	1.83
2005	2.39
2004	1.58
2003	2.20
2002	2.40
2001	1.89
2000	1.22

Global Carbon Project

Data Source: Thomas Conway, 2011, NOAA/ESRL + Scripts Institution

Earth System Science Partnership · DIVERSITAS · GLOBAL CHANGE · IHDP · WCRP

Fossil Fuel & Cement CO_2 Emissions



Peters et al. 2011, Nature CC; Data: Boden, Marland, Andres-CDIAC 2011; Marland et al. 2009

TABLE 11.1 Global Budget for Anthropogenic CO_2 in Earth's Atmosphere

	Fossil fuel		Biomass destruction[a]	=	Atmospheric increase		Ocean uptake		Terrestrial uptake	References
1990s	6.4	+	1.6	=	3.2	+	2.2	+	2.6	IPCC (2007)
2000–2007			1.1						2.3	Pan et al. (2011)
2010[b]	9.1		0.9		5.0		2.4		2.6	

Note: All data in 10^{15} g C/yr.

[a] *Net biomass destruction in the tropics.*

[b] *Source: www.globalcarbonproject.org/carbonbudget/index.htm.*

Fate of Anthropogenic CO_2 Emissions (2010)

9.1±0.5 PgC y^{-1}

+

0.9±0.7 PgC y^{-1}

5.0±0.2 PgC y^{-1}

50%

2.6±1.0 PgC y^{-1}

26%

Calculated as the residual of all other flux components

24%

2.4±0.5 PgC y^{-1}

Average of 5 models

Global Carbon Project 2010; Updated from Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS

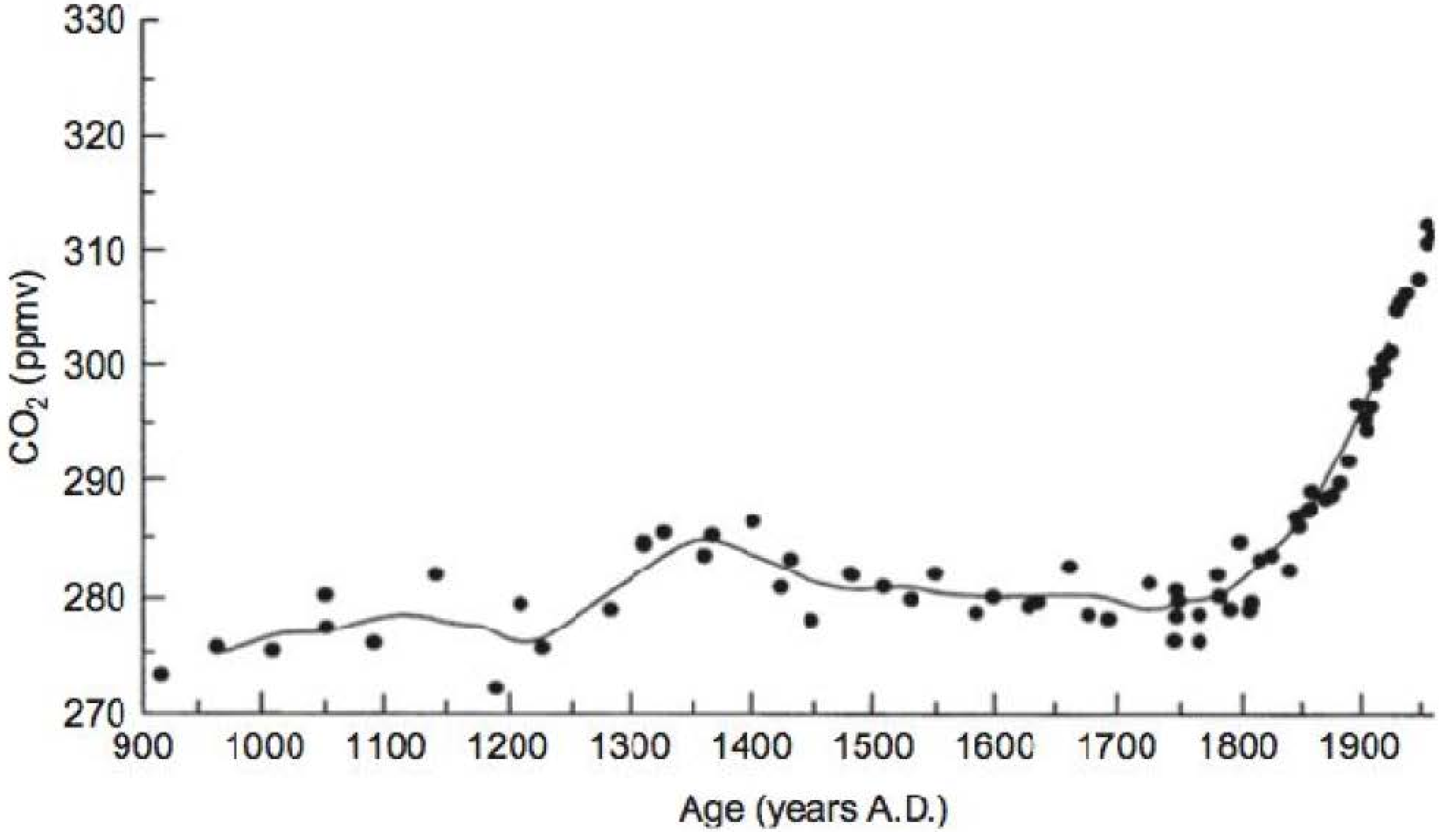
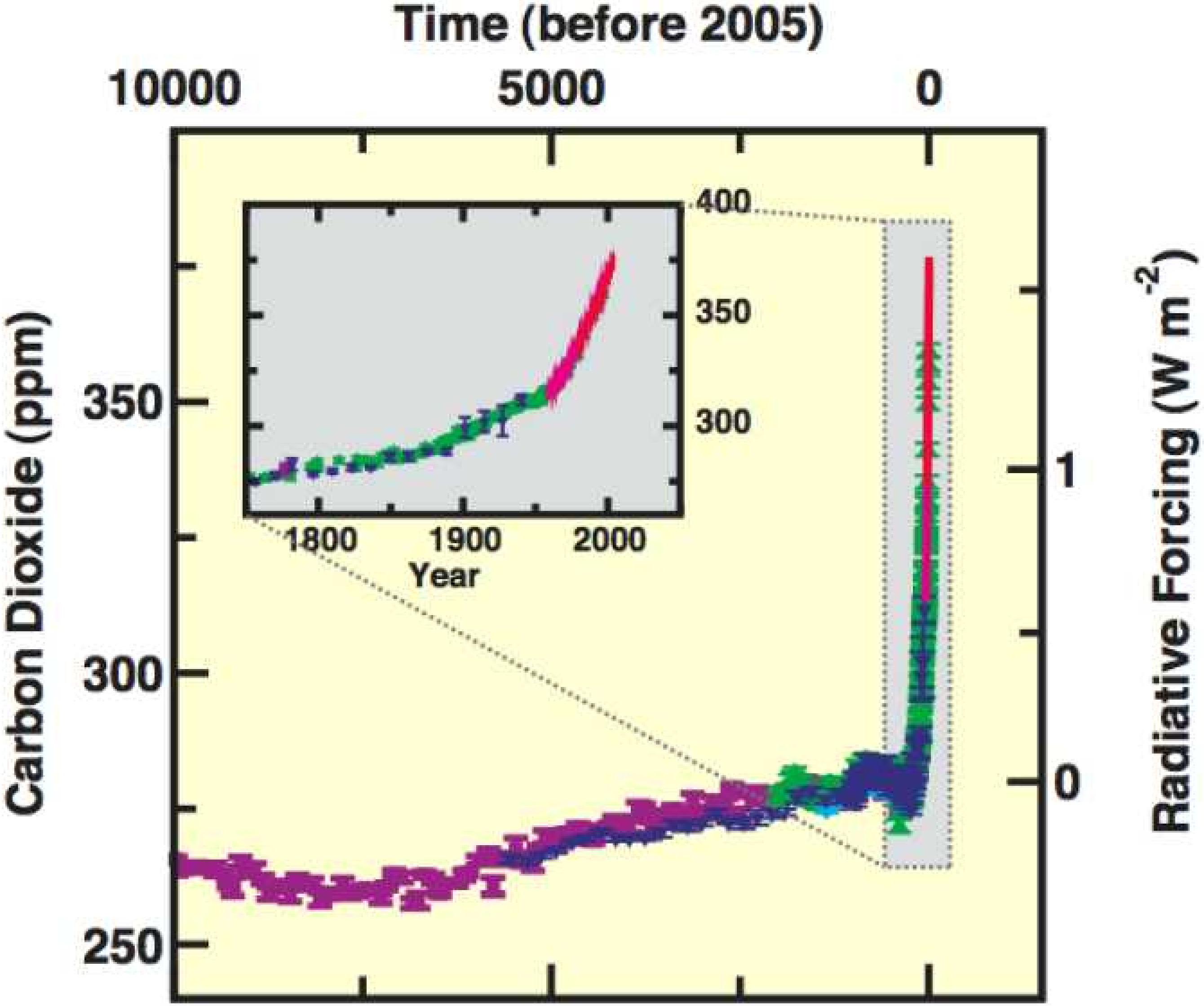
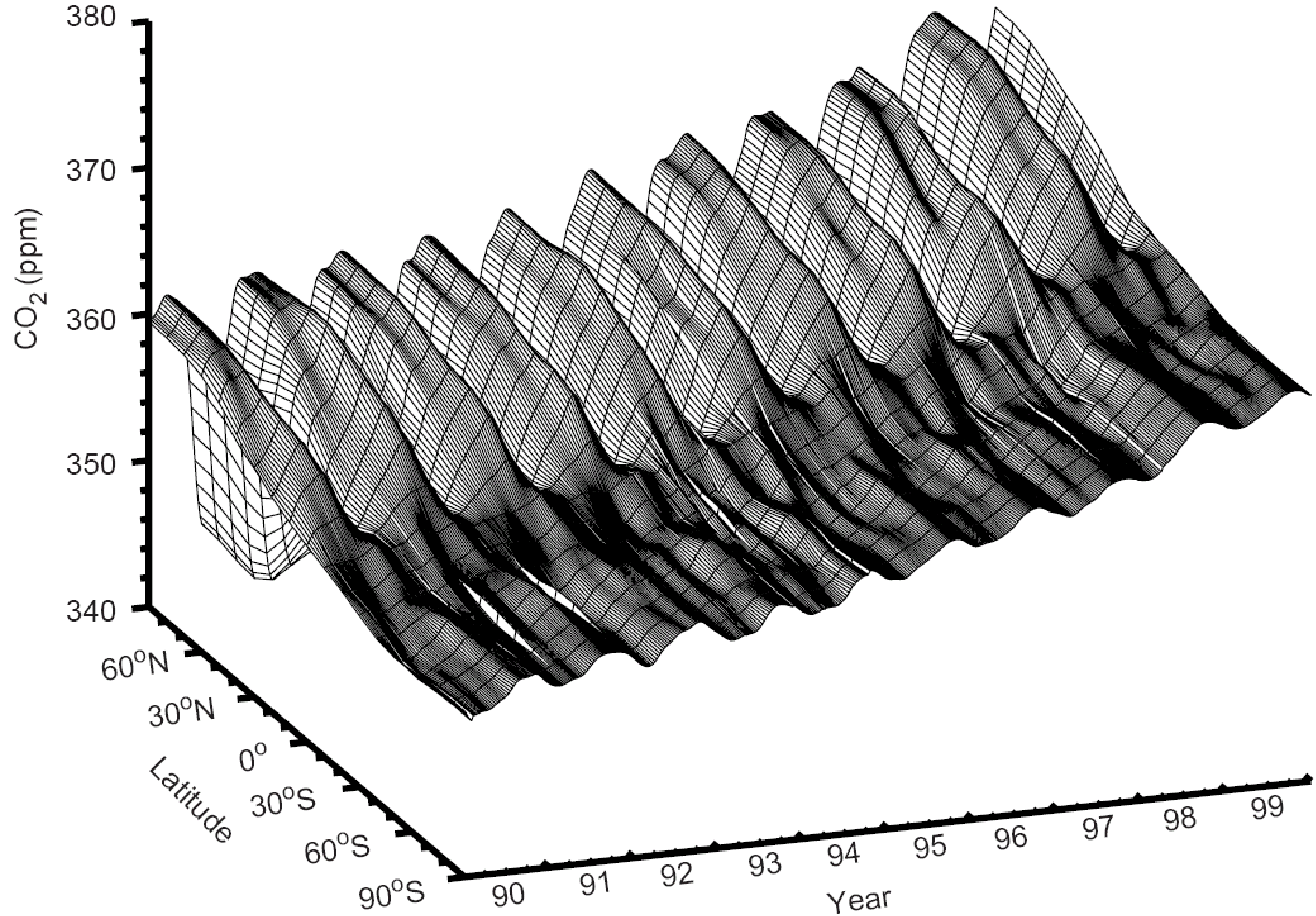


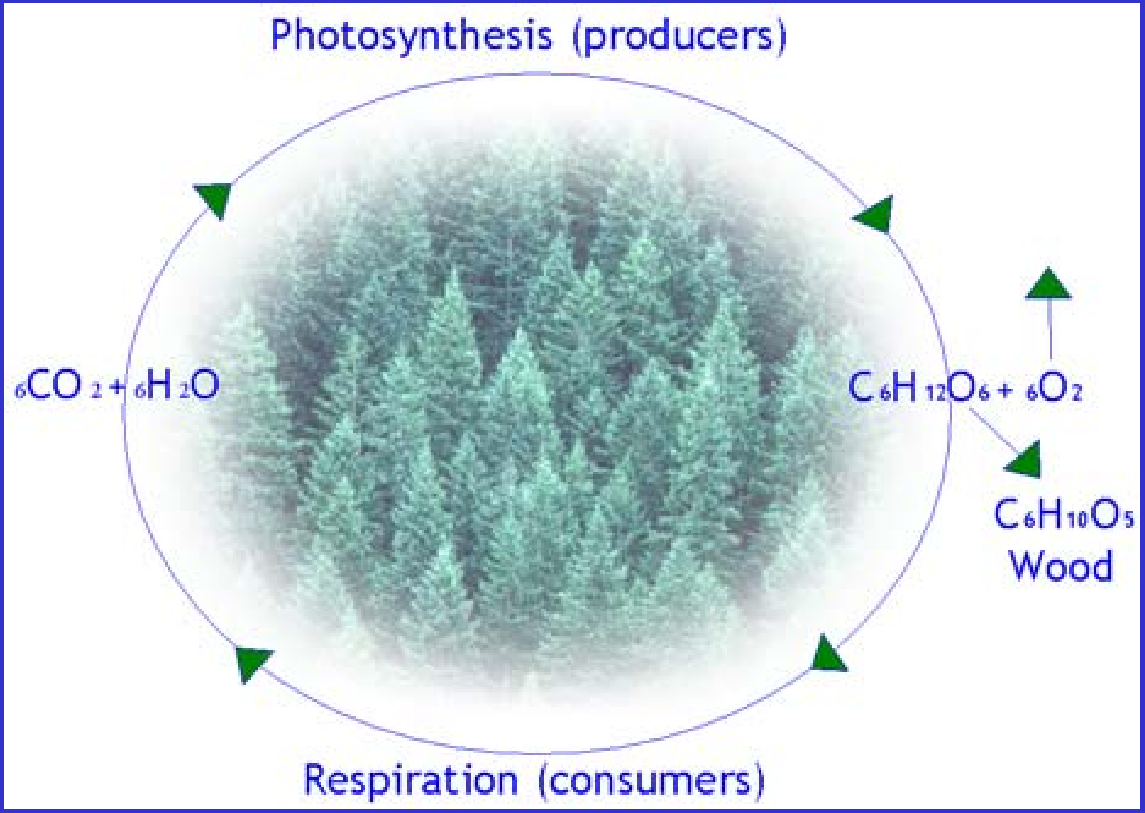
FIGURE 11.5 Concentrations of atmospheric CO_2 estimated from bubbles of gas trapped in ice cores from Antarctica. *Source: From Barnola et al. (1995).*

Changes in Greenhouse Gases from ice-Core and Modern Data



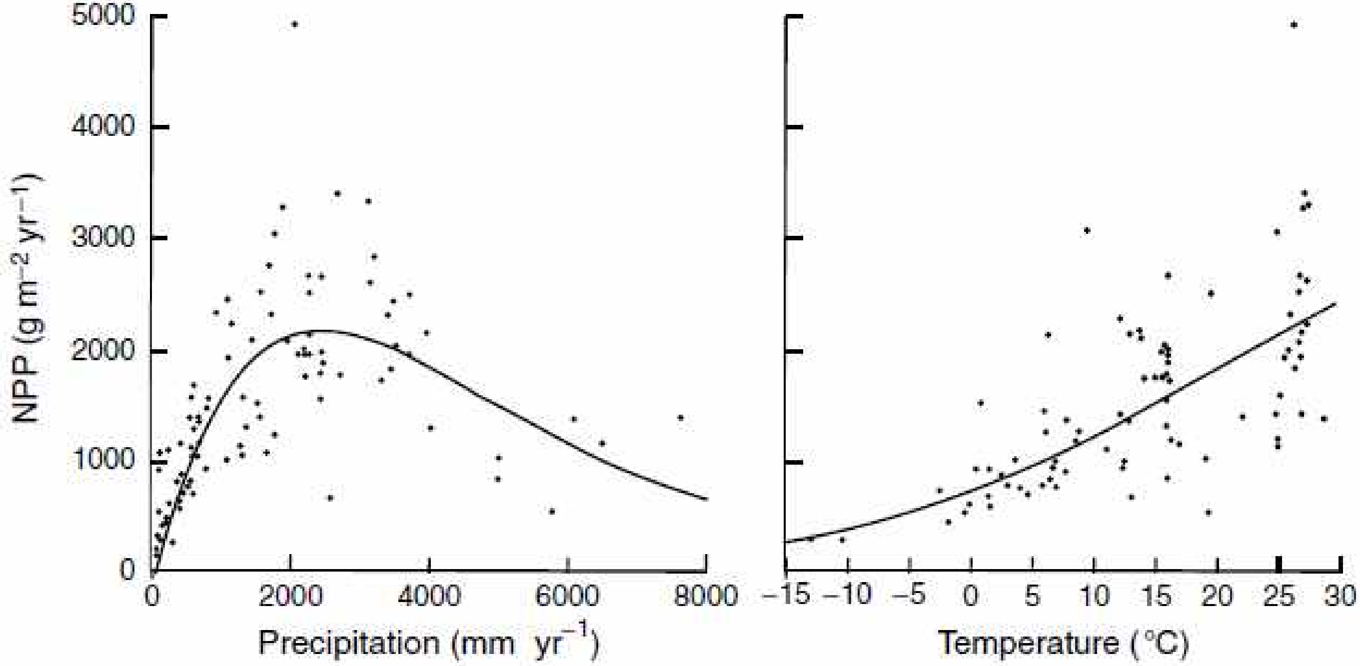


National Oceanic and Atmospheric Administration (NOAA), Climate Monitoring and Diagnostics Laboratory (CMDL), Carbon Cycle-Greenhouse Gases.



Photosynthesis: $CO_2 + H_2O + \text{energy} = (CH_2O) + O_2$

Respiration: $(CH_2O) + O_2 = CO_2 + H_2O + \text{energy}$



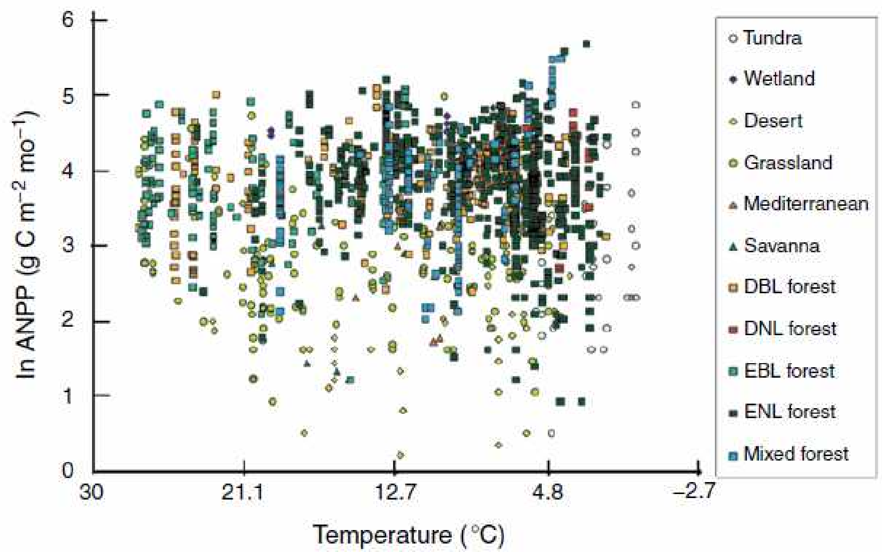


Fig. 6.10 Relationship of aboveground NPP per month of growing season (log scale) to the average growing-season temperature (graphed from high to low) for the world's ecosystems. When adjusted for length of growing season, aboveground NPP (ANPP) shows no relationship to growing-season temperature. Redrawn from Kerkhoff et al. (2005)

Both Figures were taken from Chapin et al. 2011. Principle of Terrestrial Ecosystem Ecology 2nd Edition.

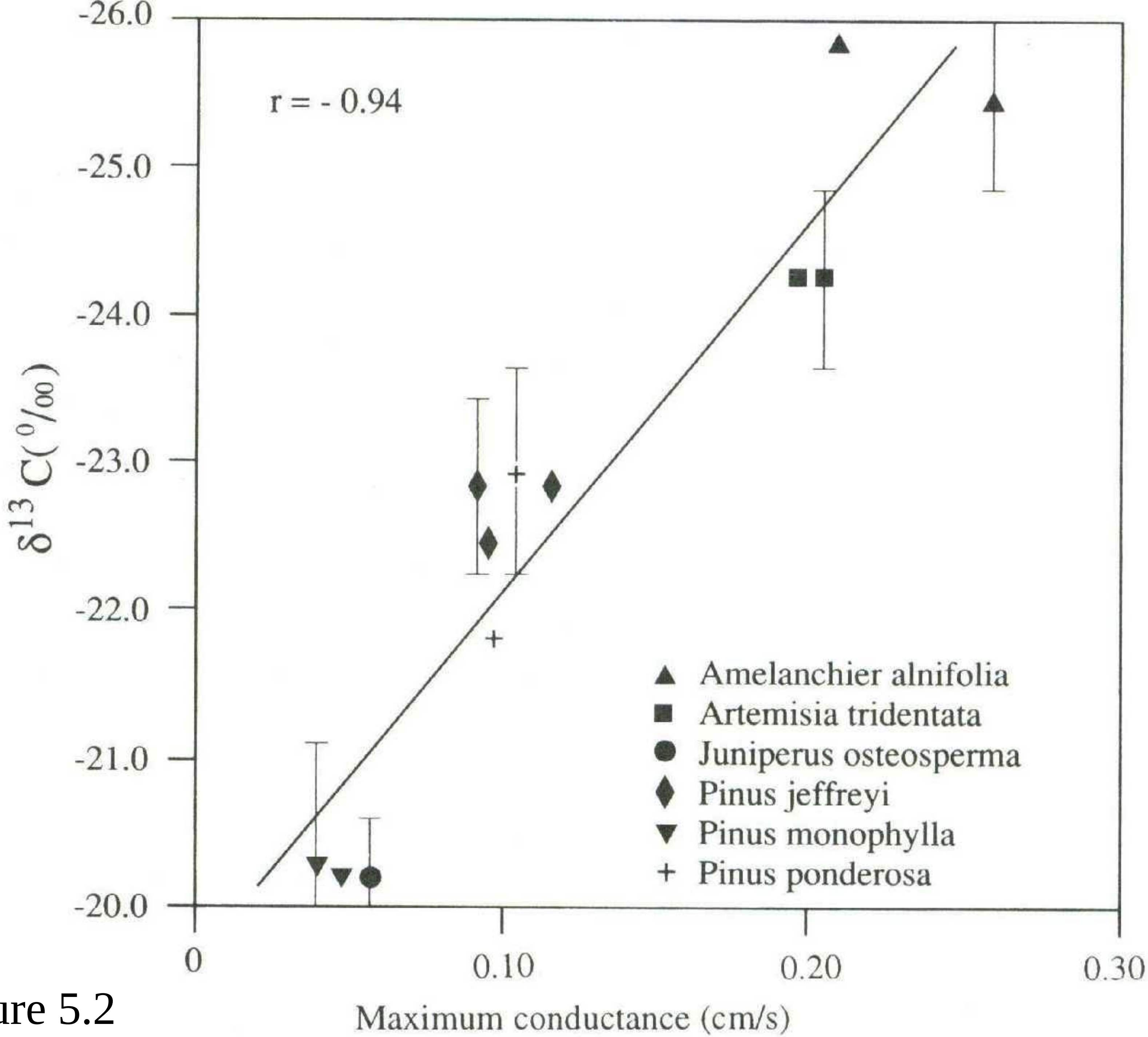

-26.0
-25.0
-24.0
-23.0
-22.0
-21.0
-20.0
r = - 0.94
δ13 C(0/00)
Amelanchier alnifolia
Artemisia tridentata
Juniperus osteosperma
Pinus jeffreyi
Pinus monophylla
Pinus ponderosa
0
0.10
0.20
0.30
Maximum conductance (cm/s)

Figure 5.2

The Delta Notation

$$\delta^{13}C = [(R_{sample} - R_{std}) / R_{std}] X 1000$$

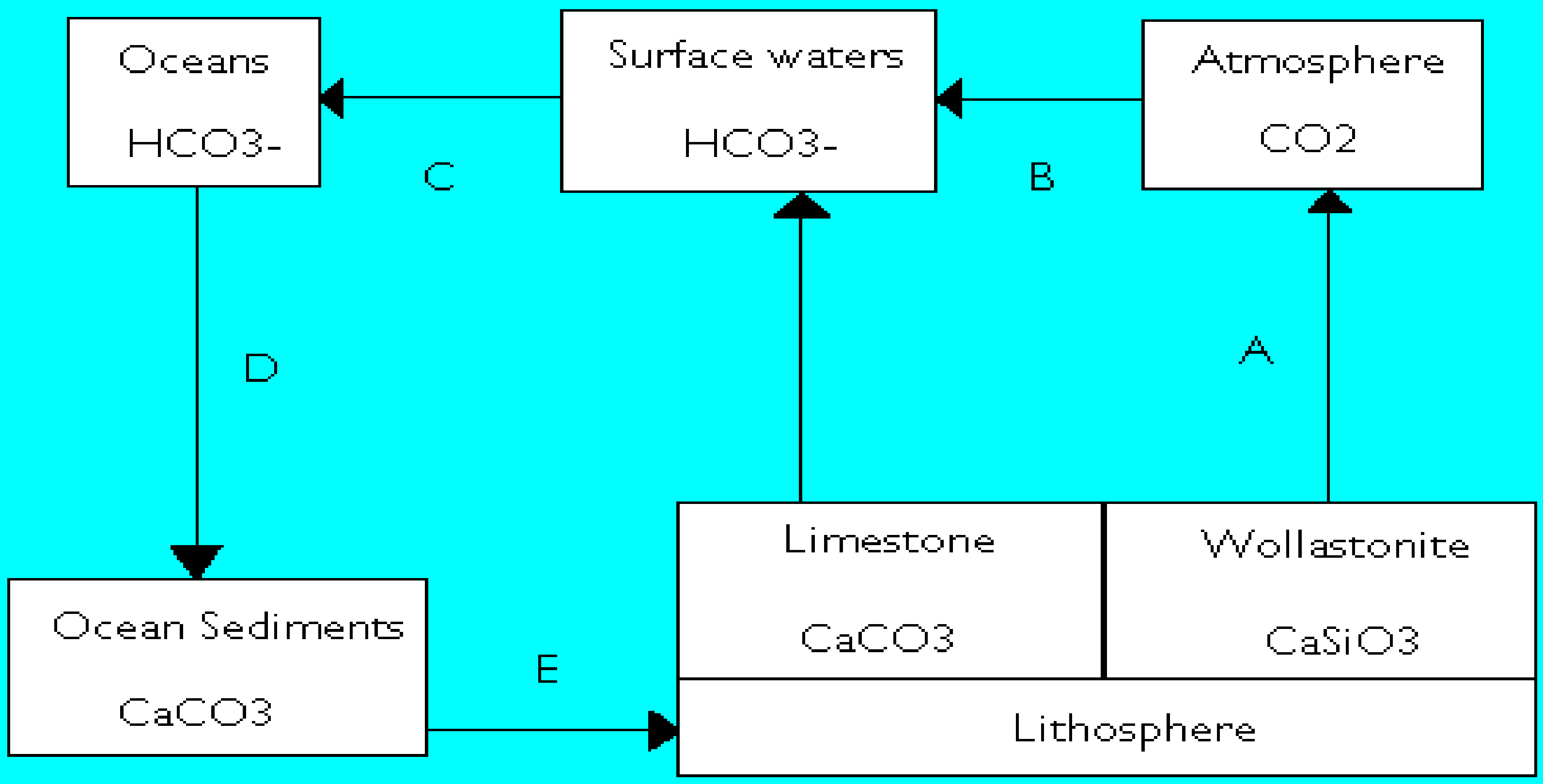
R: $^{13}C/^{12}C$

Photosynthetic Pathways of CO_2 fixation in Higher Plants

Characteristics	C_3	C_4	CAM*
CO_2 acceptor	RuBP	PEP	In light: RuBP In dark: PEP
First product of photosynthesis	C3 acids (PGA)	C4 acids	In light: PGA In dark: malate
C isotope ratio in photosynthate ($\delta^{13}C$)	**-20 to -40%o**	**-10 to -20 %o**	**-10 to -35 %o**
CO_2-compensation level	30-50 ppm	<10 ppm	In light: 0-200 ppm In dark: <5 ppm
Photosynthetic capacity	slight to high	high to very high	In light: slight In dark: medium
Dry matter production	Medium	High	Low

*CAM: Crassulacean Acid Metabolism

The long-term carbon cycle



A. Volcanoes offgas CO_2.

B. Atmospheric CO_2 dissolves in lakes and rivers

C. Carbonic acid reacts with silicate rocks

D. Organisms build shells of carbonate

E. Lithification as limestone or subduction

Volcanoes:

$$CaCO_3 + SiO_2 \longrightarrow CaSiO_3 + CO_2$$

Carbonate equilibrium

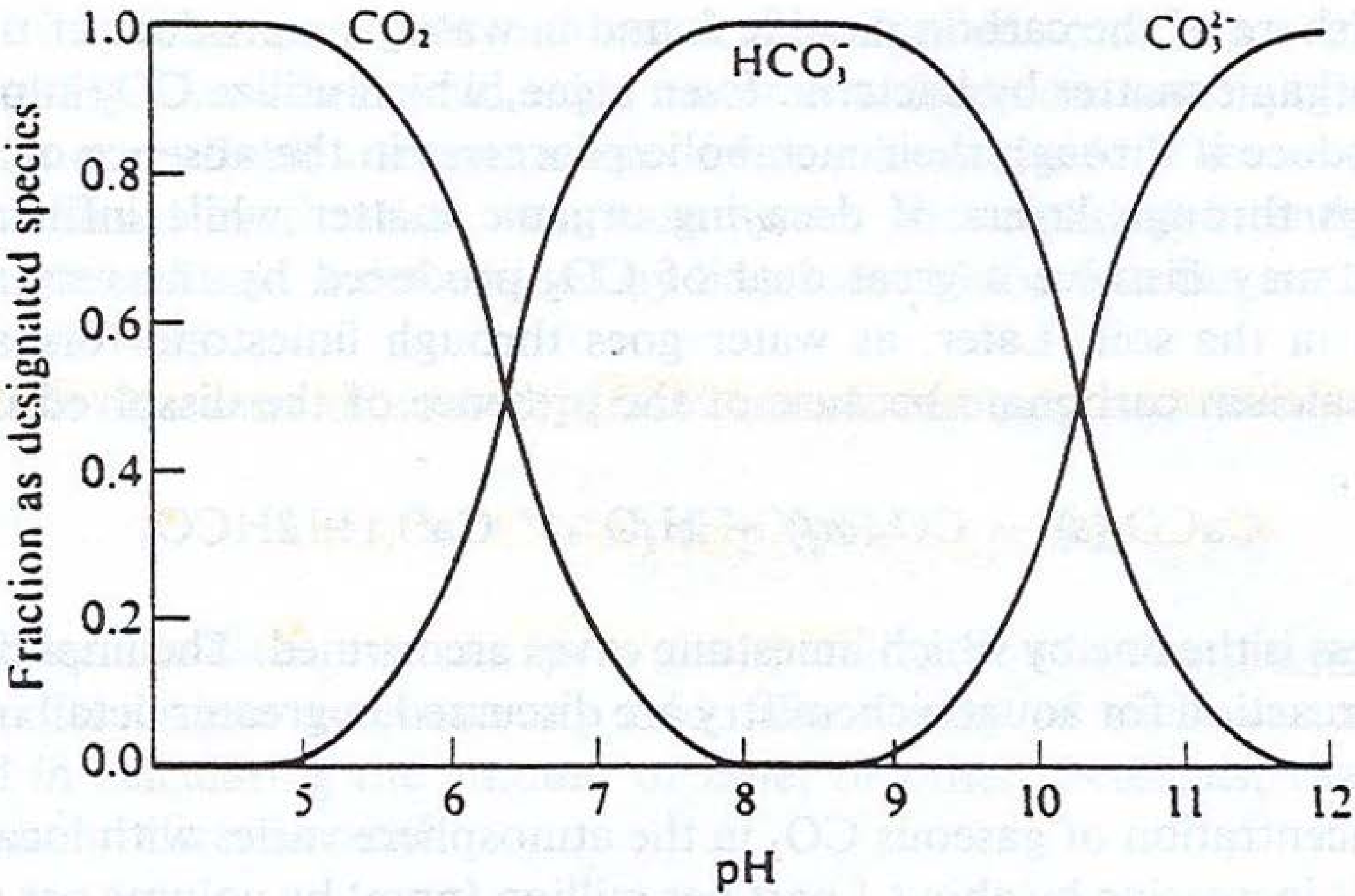
Carbon dioxide and water:

$$H_2O + CO_2 \text{ <--> } H^+ + HCO_3^- \text{ <--> } H^+ + CO_3^{2-}$$

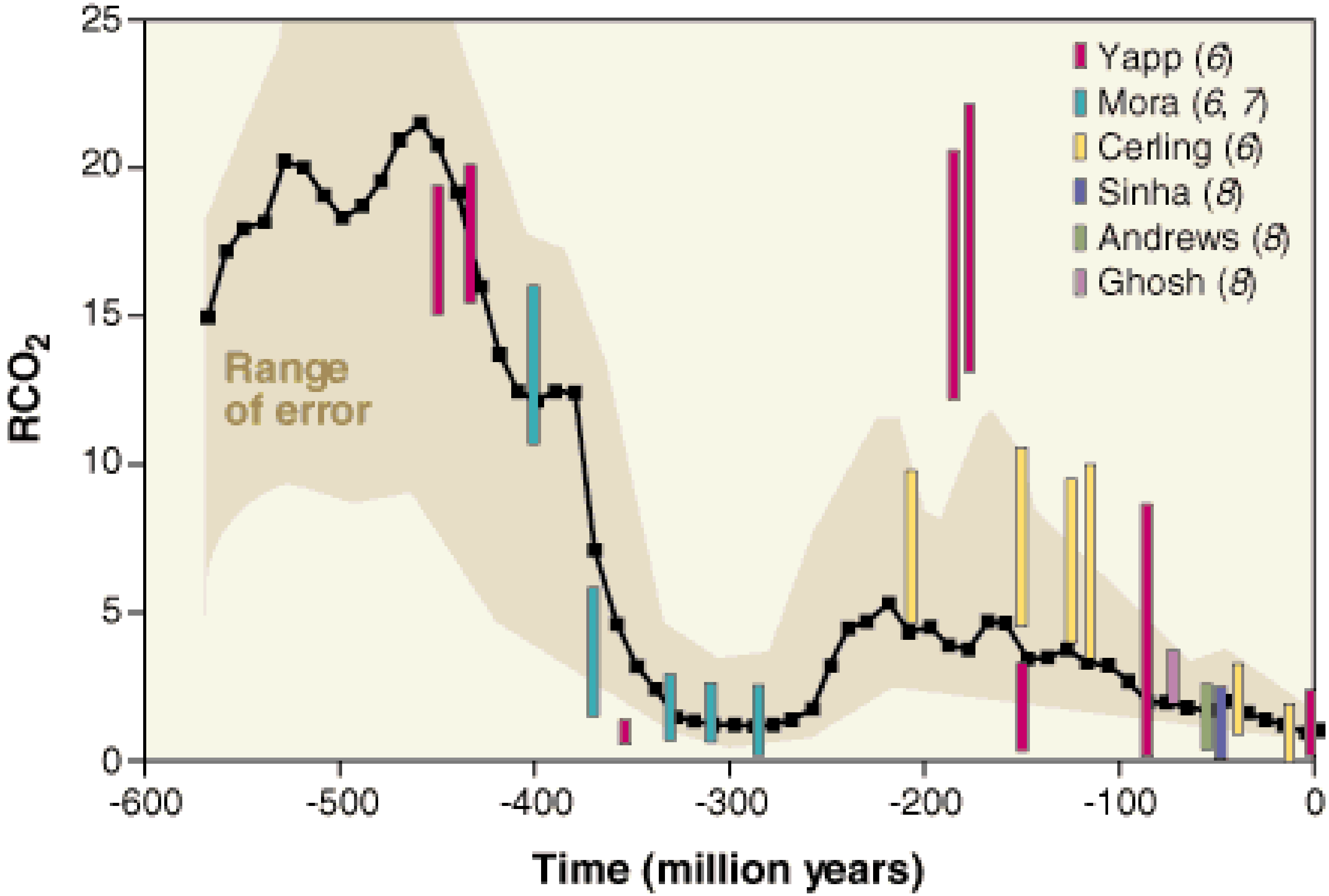
Carbonate rocks and water:

$$CaCO_3 + H_2CO_3 \text{ <--> } Ca_2^+ + 2HCO_3^-$$

Influence of pH on carbonate



Distribution of species diagram for the CO_2–HCO_3^-–CO_3^{2-} system in water.



By Robert A. Berner
SCIENCE, Volume 276, Number 5312 Issue of 25 Apr 1997, p 544.
This slow process may only contribute 0.04 to 0.08 10^{15} g C per year to the atmospheric pool.

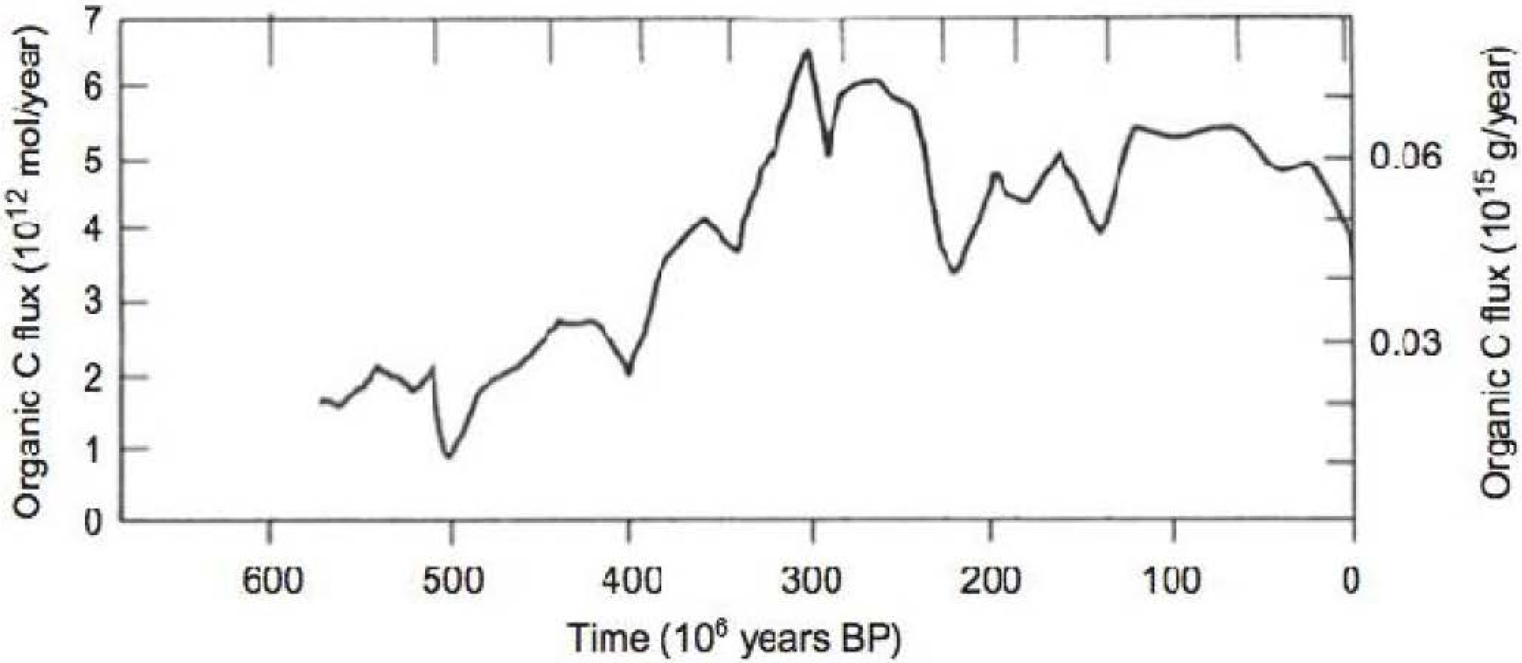


FIGURE 11.4 Burial of organic carbon on Earth during the past 600 million years. *Source: From Olson et al. (1985).*

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Temporal scales of the global carbon cycle

Atmospheric methane

Atmospheric carbon monoxide

Link the carbon cycle with the oxygen cycle

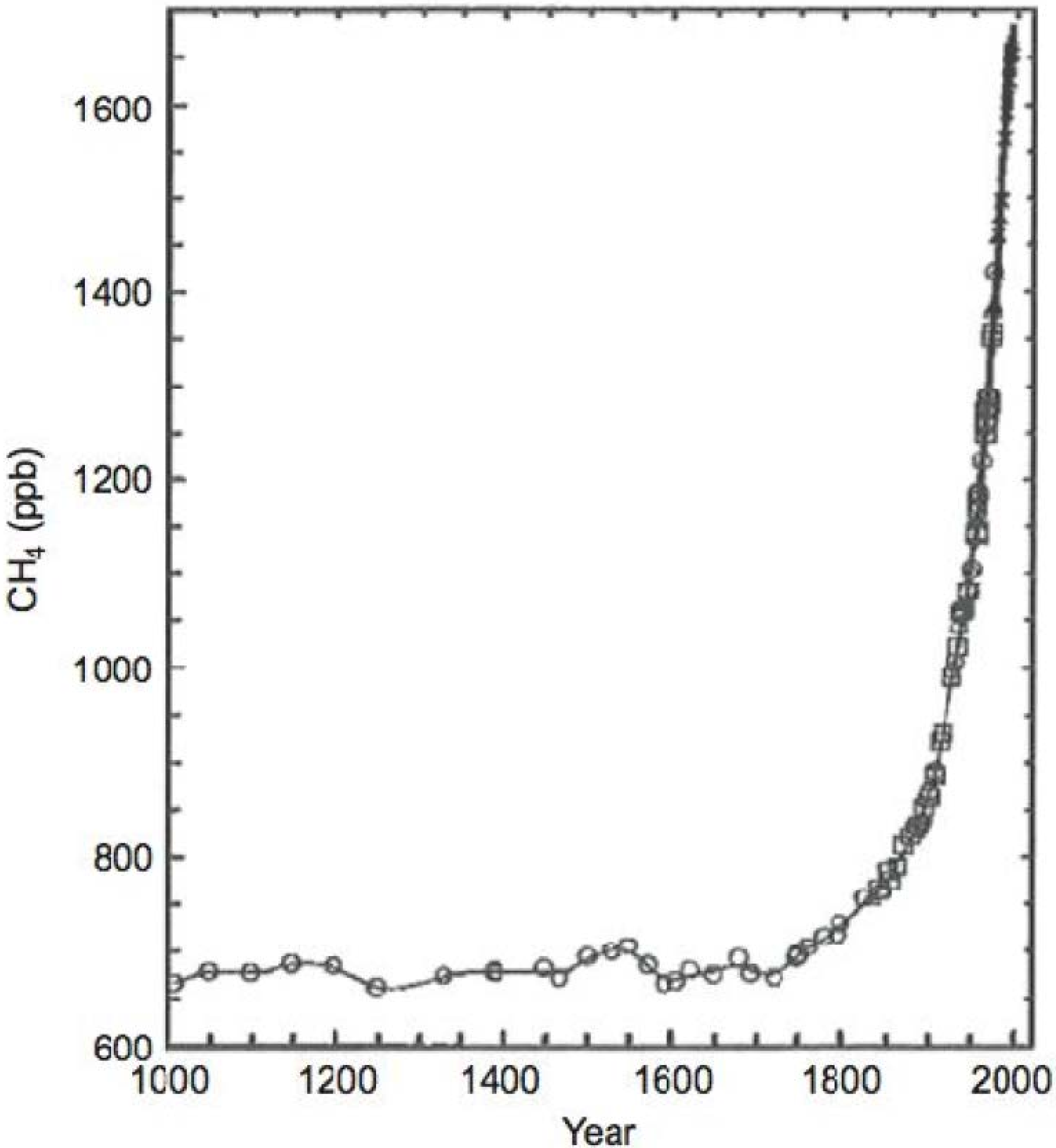


FIGURE 11.6 Concentrations of CH_4 in air extracted from Antarctic ice cores. *Source: From Etheridge et al. (1998). Used with permission of the American Geophysical Union.*

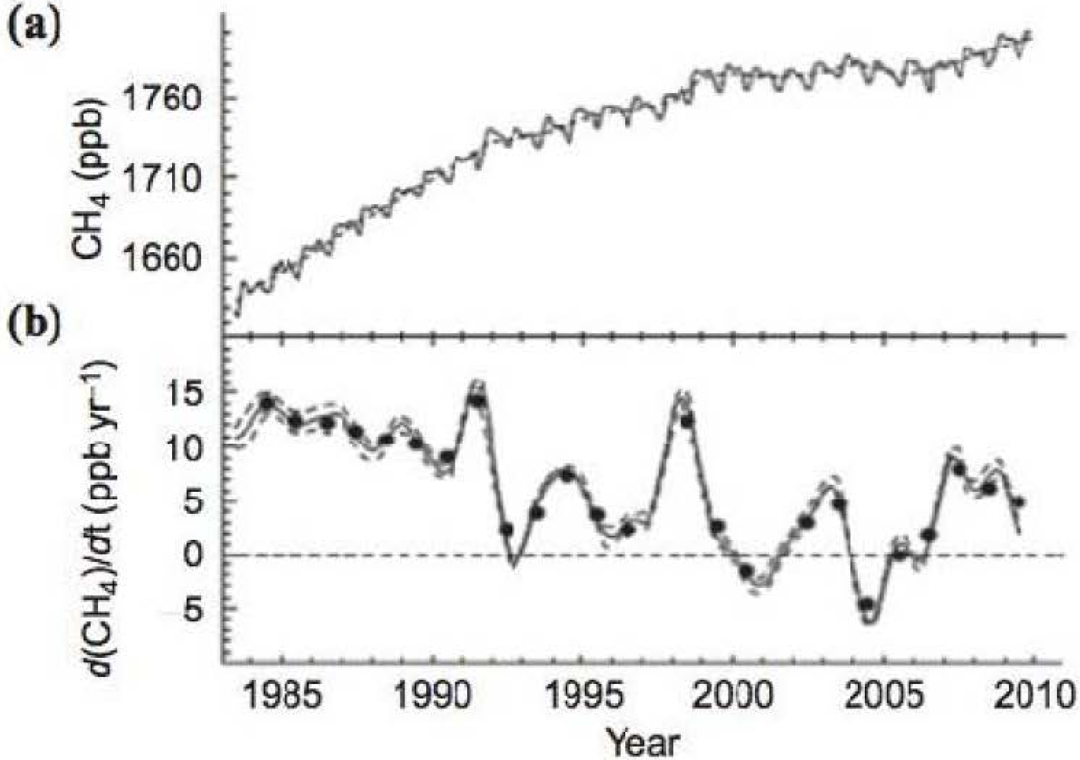


FIGURE 11.8 Concentration of methane (a) and its annual change (b) in Earth's atmosphere during the past three decades. *Source: From Dlugokencky et al. (2011). Used with permission of The Royal Society.*

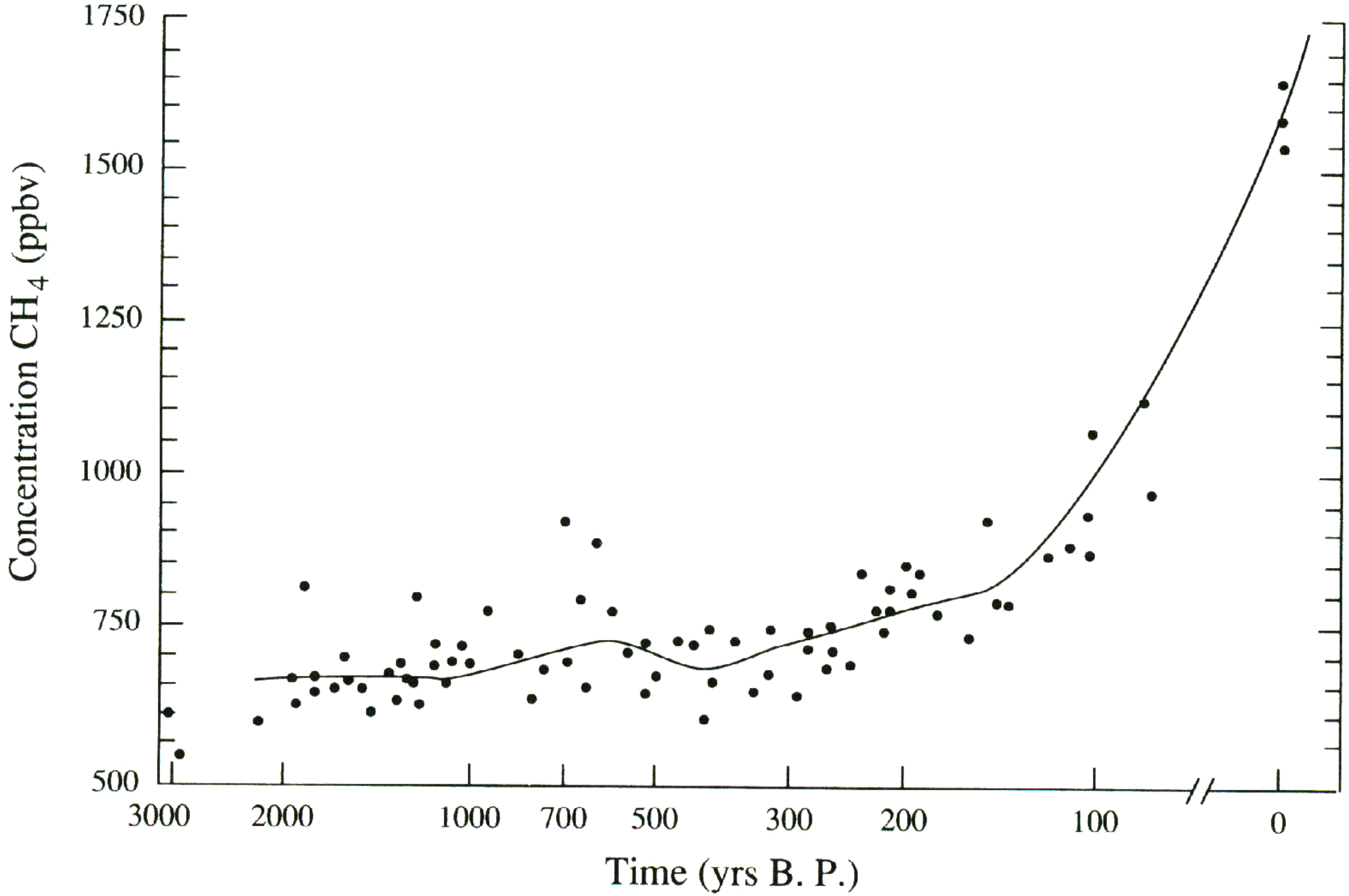


Figure 11.6 Concentration of CH_4 in air extracted from ice cores in Greenland and Antarctica and from contemporary air samples. From Cicerone and Oremland (1988).

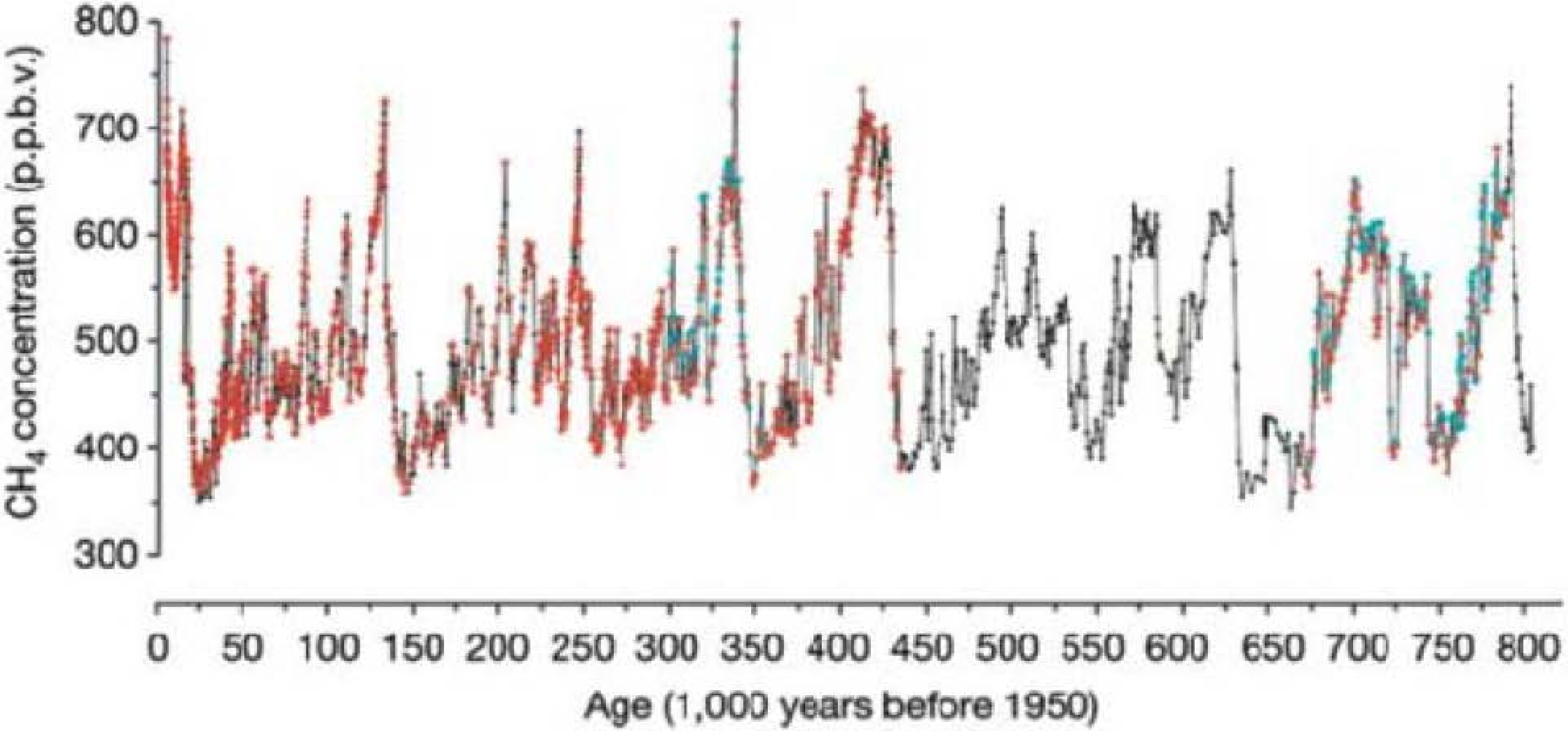


FIGURE 11.7 Concentrations of CH_4 in air that is extracted from ice cores in Antarctica dating to 800,000 years before present. *Source: From Loulergue et al. (2008). Compare to Figure 1.2.*

TABLE 11.2 Estimated Sources and Sinks of Methane in the Atmosphere in 2010

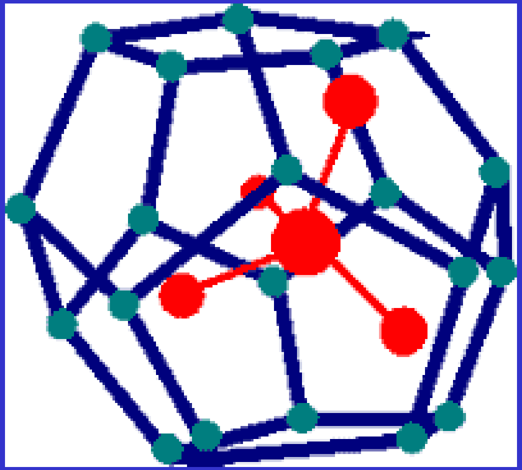
Natural sources	Flux (10^{12} g CH_4/yr)		References
Wetlands	143		Neef et al. 2010
Tropics		46	Bloom et al. 2010
Northern latitude		20	Christensen et al. 1996
Upland vegetation	10 (estimate)		Megonigal and Guenther 2008; Kirschbaum et al. 2006
Termites	19		Sanderson 1996
Oceans	10		Reeburgh 2007
Geological seepage[a]	33		Etiope et al. 2008

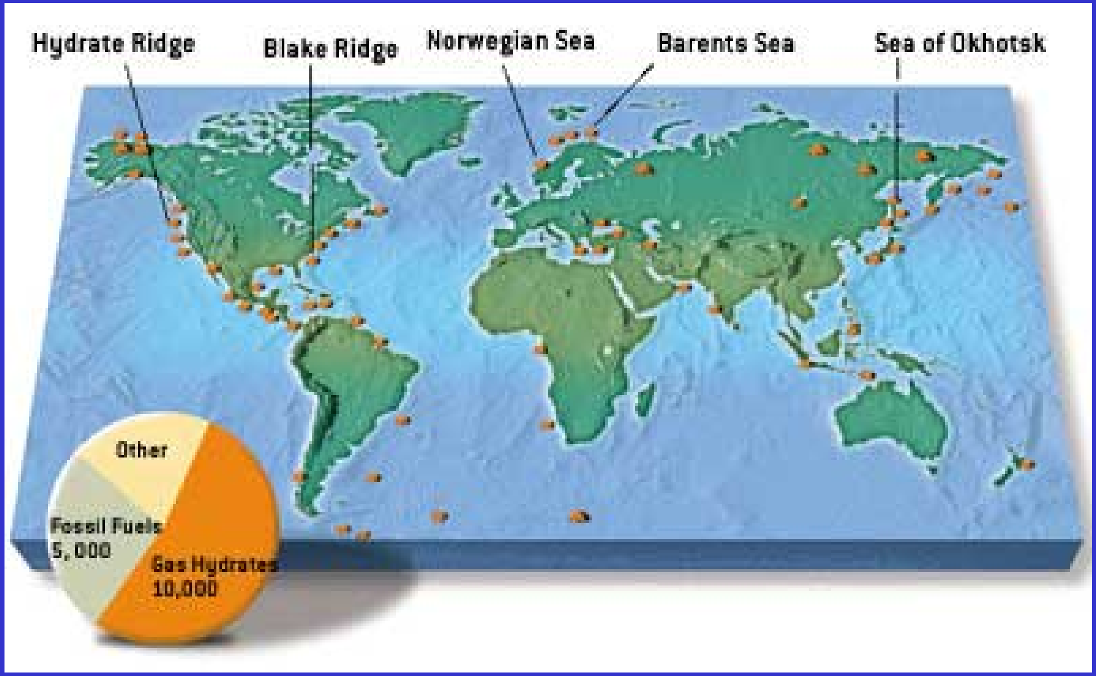
Anthropogenic sources		
Fossil fuel related		
Coal mines	30	Prather et al. 1995
Coal combustion	15	Prather et al. 1995
Oil and gas	72	Neef et al. 2010
Waste and waste management		
Landfills	18	Bogner and Matthews 2003
Animal waste	25	Prather et al. 1995
Sewage treatment	25	Prather et al. 1995
Ruminants	116	Neef et al. 2010
Reservoirs	70	St. Louis et al. 2000
Biomass burning	19	Kaiser et al. 2012
Rice cultivation	40	Sass and Fisher 1997, Bloom et al. 2010
Total sources	**645**	
Sinks		
Reaction with OH radicals	522	Neef et al. 2010
Removal in the stratosphere	34	Neef et al. 2010
Removal by soils	25	Curry 2007 Dutaur and Verchot 2007
Total sinks	**581**	
Atmospheric increase (2007)	23	Dlugokencky et al. 2009

Note: All data in 10^{12} g CH_4/yr from various sources as cited here and in the text.

[a] *Total geological seepage less marine.*

Methane clathrates





The Global Carbon Cycle

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Atmospheric methane

Atmospheric carbon monoxide

Link the carbon cycle with the oxygen cycle

Carbon Monoxide

Atmospheric CO:

- Short lifetime ~ 4 months
- high variability in concentration

Removal from Atmosphere:

- by reaction with hydroxyl radical

$$CO + *OH \rightarrow CO_2 + H$$

- by soil microorganisms
  - Fungi capable of CO metabolism- *penicillium* and *aspergillus*
  - Some bacteria may be involved as well

Production of CO:

- some aquatic and terrestrial organisms produce CO
- major source of CO at high altitudes is probably a photochemical reaction that CO_2 undergoes:

$$CO_2 + \text{light} \rightarrow CO + O$$

TABLE 11.3 Budget for Major Sources and Sinks for CO in the Atmosphere

Sources	**Flux**
Fossil fuel combustion	400
Biofuel combustion	160
Biomass burning	460[a]
Oxidation of methane	820
Oxidation of other volatile carbon compounds	521
Total	**2361**
Sinks	
Uptake by soils (Sanhueza et al. 1998)	115–230
Oxidation by OH reactions (Prather et al. 1995)	1400–2600
Stratospheric destruction	100
Total	**1615–3030**

Note: All units are 10^{12} g CO/yr; from Duncan et al. (2007) unless otherwise noted.

[a] *Kaiser et al. (2012), Jain (2007), and Mieville et al. (2010) give alternative estimates of 351, 372, and 500 × 10^{12} g CO/yr, respectively.*

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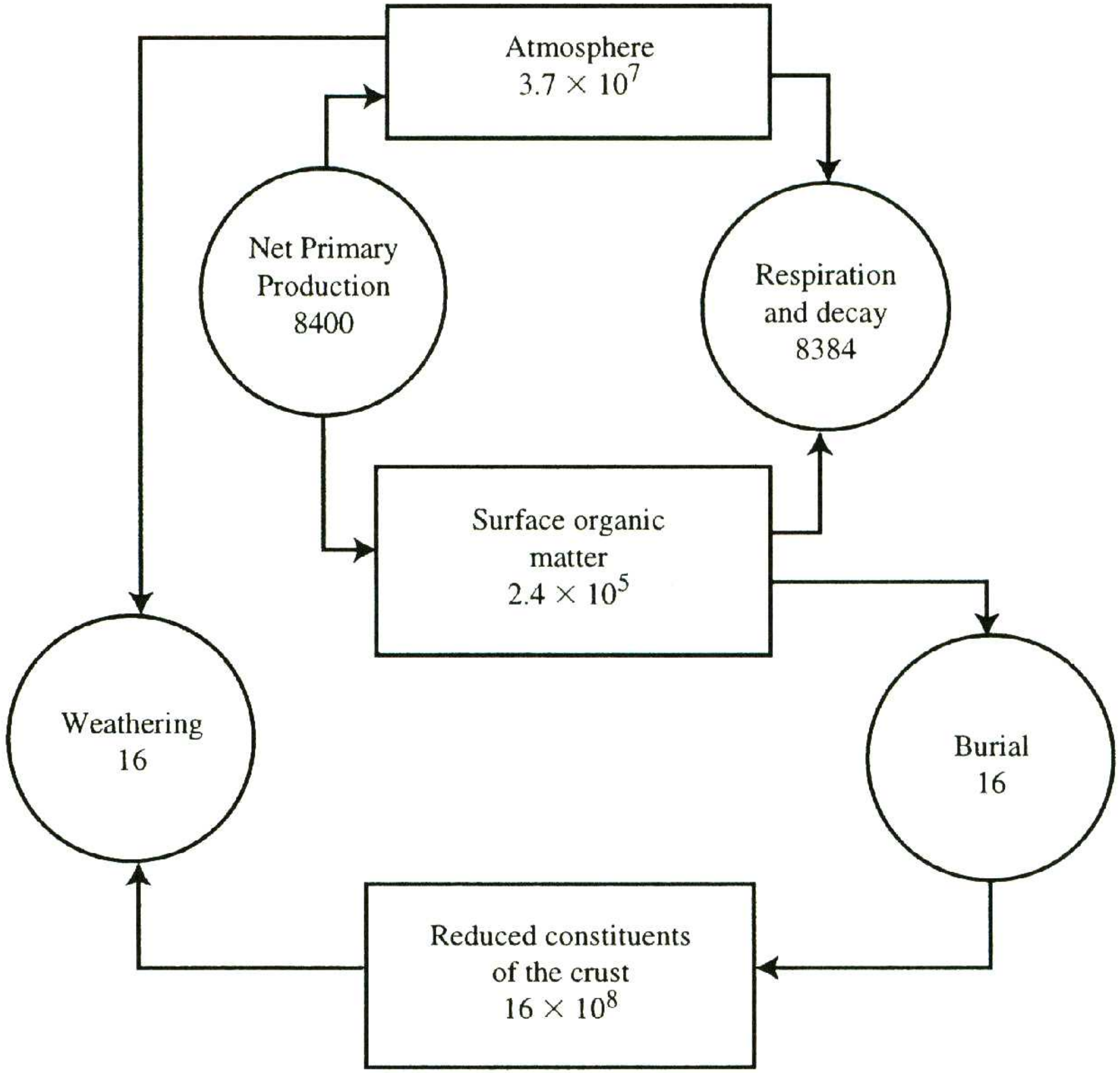


Figure 11.7 A simple model for the global biogeochemical cycle of O_2. Data are expressed in units of 10^{12} moles of O_2 per year or the equivalent amount of reduced compounds. Note that a small misbalance in the ratio of photosynthesis to respiration can result in a net storage of reduced organic materials in the crust and an accumulation of O_2 in the atmosphere. Modified from an original conception by Walker (1980) to reflect values derived in this text.

Schlesinger 1997

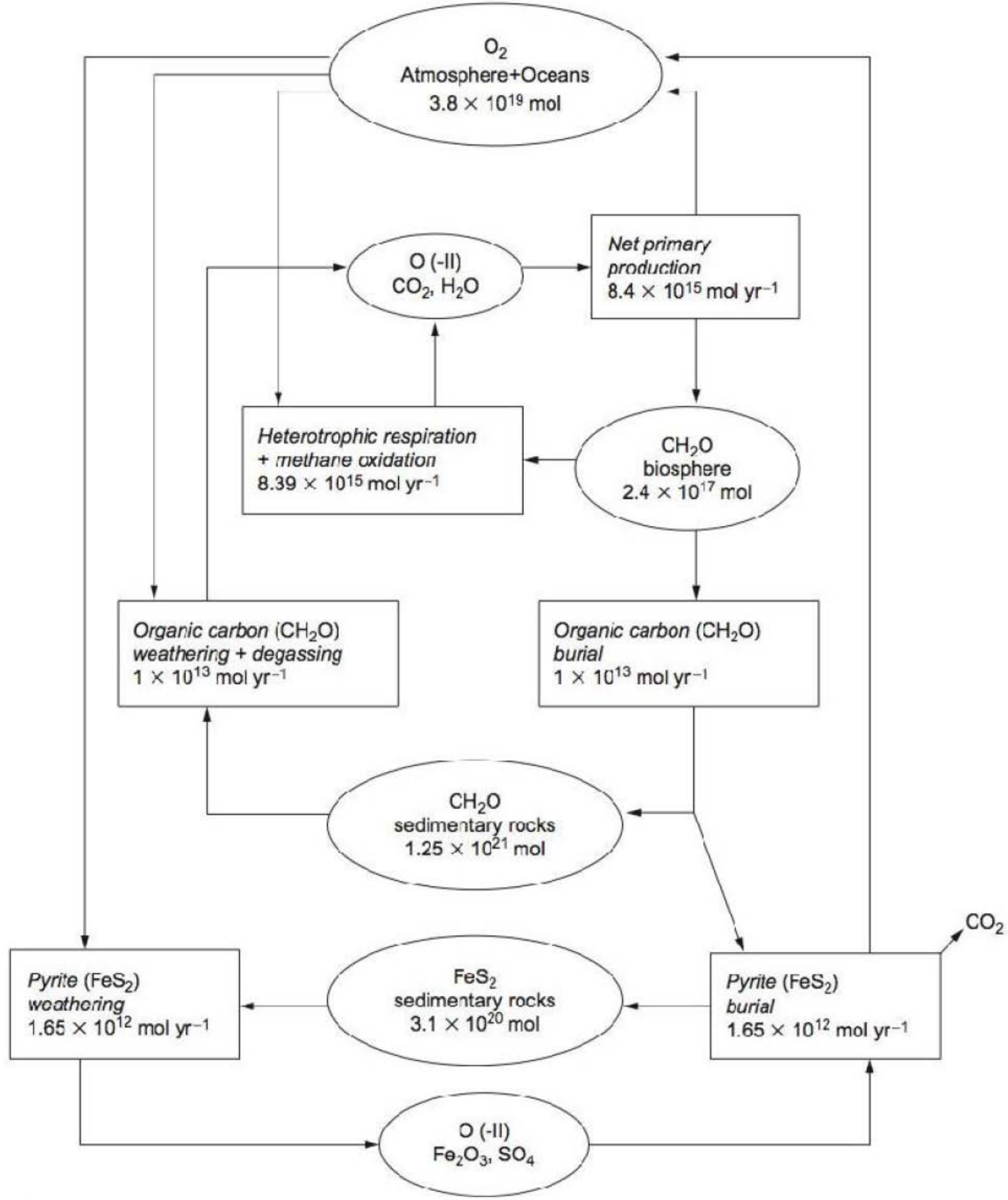


FIGURE 11.9 Linkage of the global carbon and oxygen cycles. Ovals contain estimates of the reservoirs of O_2 or the equivalent amount of reduced molecules that could be oxidized by O_2. Boxes indicate fluxes of O_2 or reduced molecules in moles/year. *Source: Modified from Lenton (2001).*

Battle et al. SCIENCE VOL 287:2467, 31 MARCH 2000

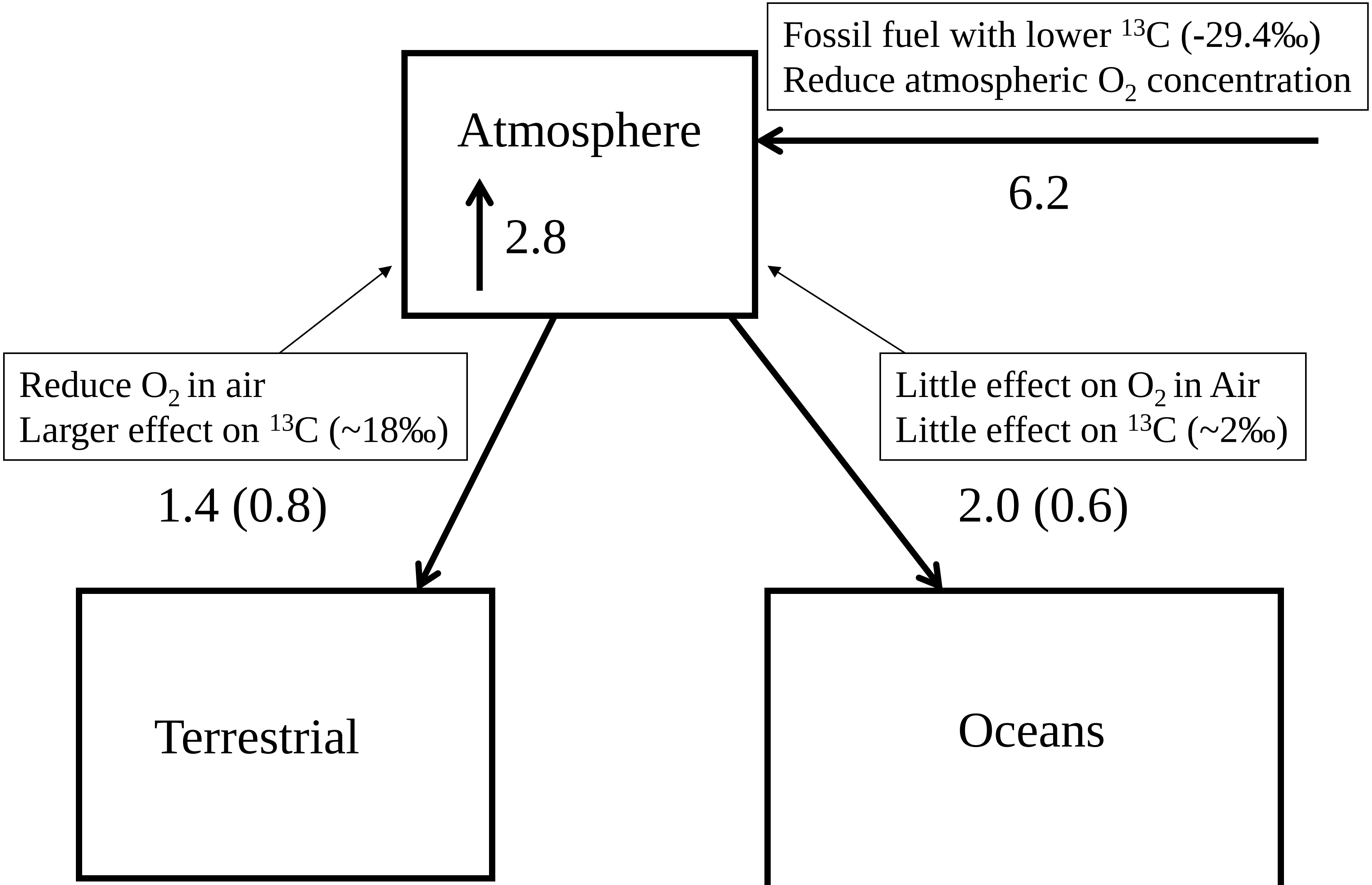
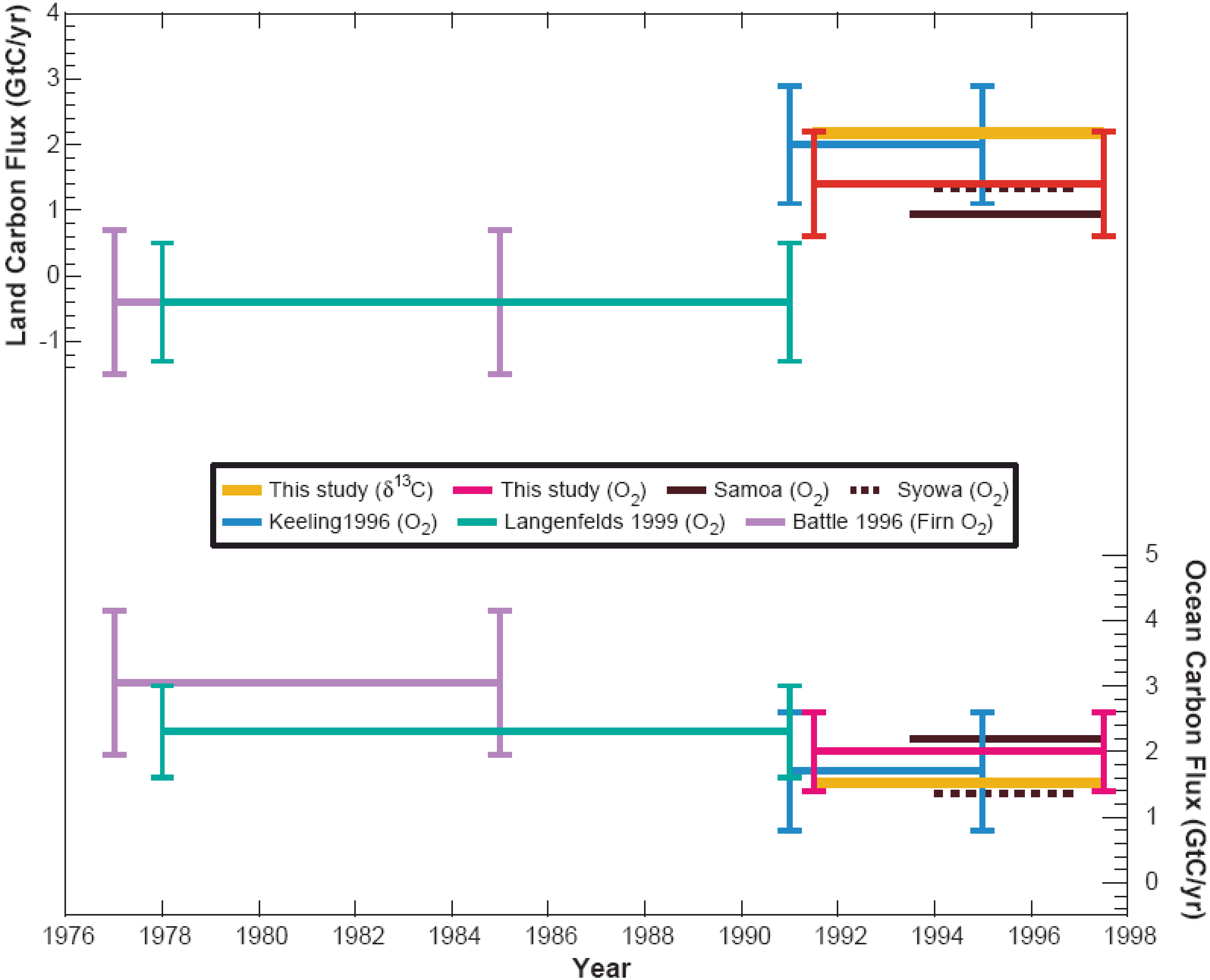
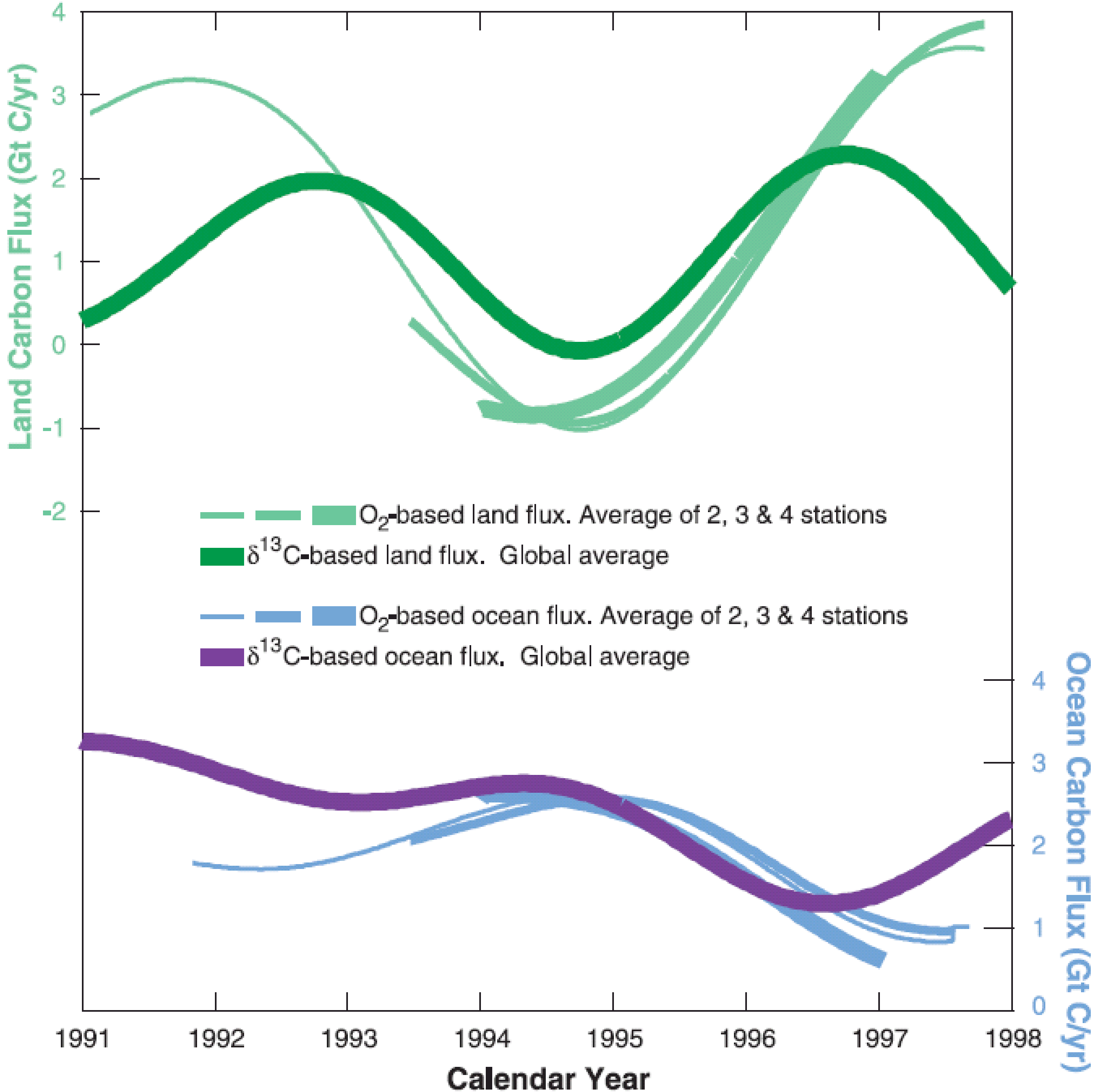


Table 1. Values of the quantities used in this study. Uncertainties in $d(O_2/N_2)/dt$ are due to standard drift and choice of fit (*19*), respectively. The latter is given for an average of data from two sites. The "values" of the measured trends in O_2 and CO_2 are illustrative only, because our results are calculated from related quantities [see (*19*)].

Quantity	Value	Source
f_{fuel}	−6.21 ± 0.37 GtC/year	(*1*)
f_{cement}	−0.184 ± 0.011 GtC/year	(*1*)
Combustion stoichiometry	1.43 ± 0.02	(*16*)
Photosynthetic stoichiometry	1.1 ± 0.06	(*17*)
$d(O_2/N_2)/dt$	−16 ± 0.8 ± 0.35 per meg/year	This study
$d(CO_2)/dt$	1.24 ± 0.05 ppm/year	This study
CO_2 (in 1995)	760 ± 1 GtC	This study
$d/dt\ \delta^{13}_{atm}$	−0.013 ± 0.008 ‰/year	This study
δ^{13}_{fuel} (in 1995)	−29.4 ± 1.8 ‰	(*32*)
δ^{13}_{atm} (in 1995)	−7.86 ± 0.015 ‰	This study
$\epsilon_{air\text{-}land}$	−18 ± 1 ‰	This study
$\epsilon_{air\text{-}sea}$	−2 ± 1 ‰	(*33, 34*)

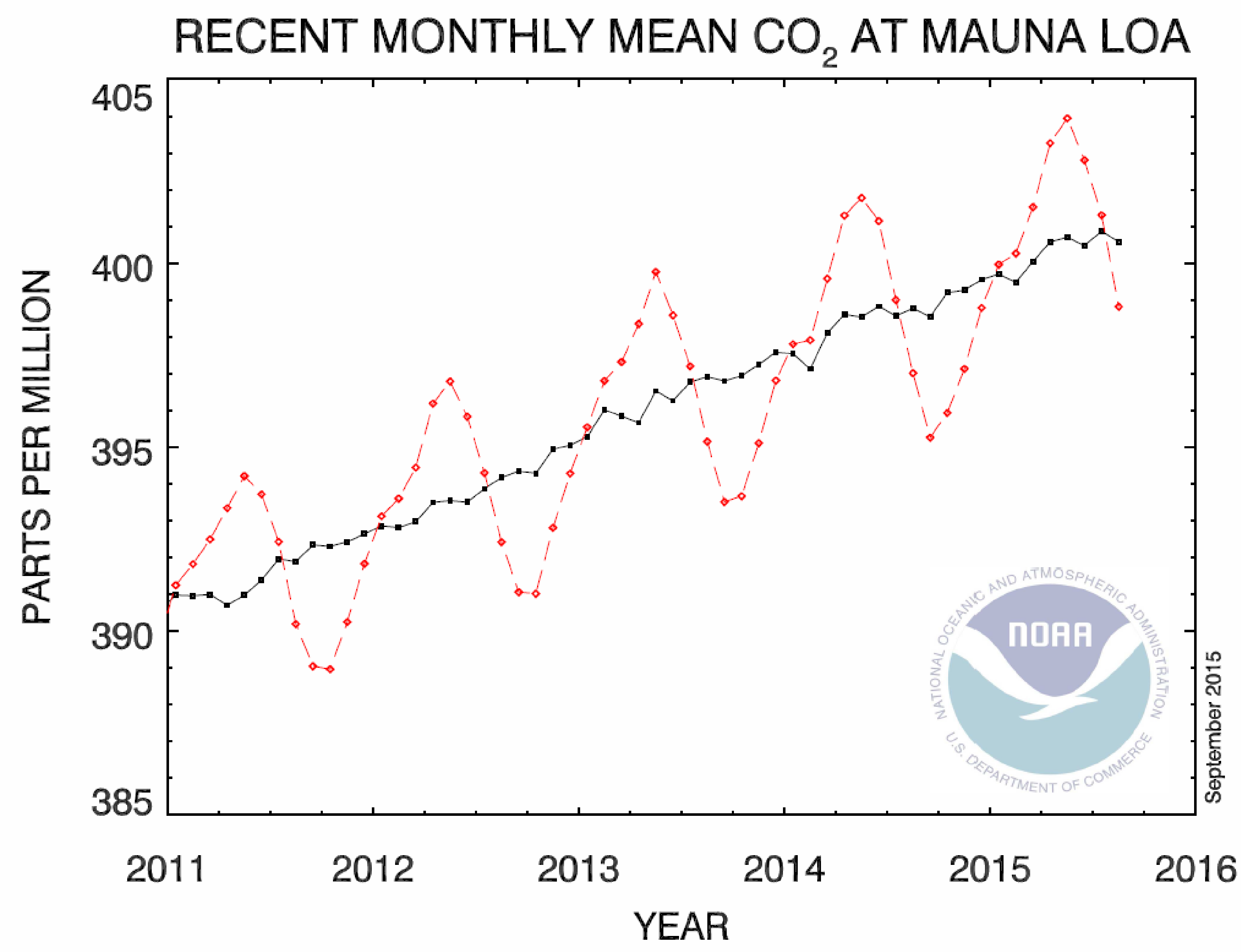


Land Carbon Flux (GtC/yr)
4
3
2
1
0
-1
This study (δ^{13}C)
This study (O2)
Samoa (O2)
Syowa (O2)
Keeling1996 (O2)
Langenfelds 1999 (O2)
Battle 1996 (Firn O2)
Ocean Carbon Flux (GtC/yr)
5
4
3
2
1
0
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
Year



Land Carbon Flux (Gt C/yr)
4
3
2
1
0
-1
-2
O2-based land flux. Average of 2, 3 & 4 stations
δ13C-based land flux. Global average
O2-based ocean flux. Average of 2, 3 & 4 stations
δ13C-based ocean flux. Global average
Ocean Carbon Flux (Gt C/yr)
4
3
2
1
0
1991
1992
1993
1994
1995
1996
1997
1998
Calendar Year

August 2015: 398.82 ppm
August 2014: 397.01 ppm



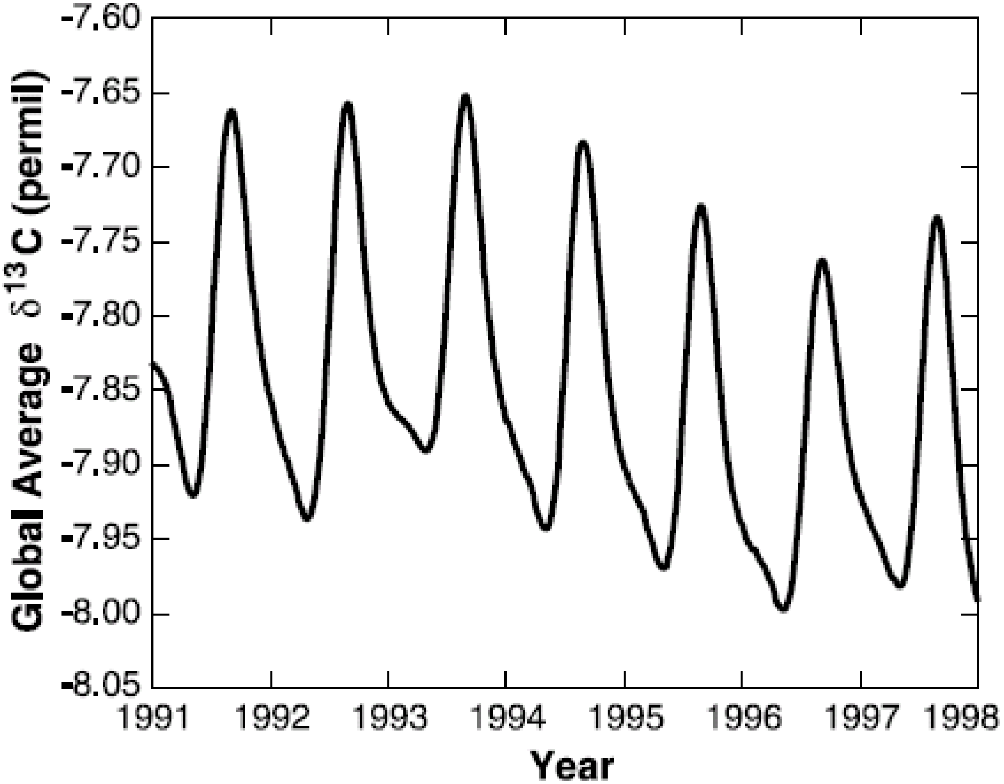


Fig. 2. The global average $\delta^{13}C$ record, measured by the NOAA-CMDL/CU-INSTAAR network with calibration as described in the text.