Tyler Prize Lecture

Charles David Keeling

2005

"We know astonishingly little about every aspect of the environment from its past history, to its present state, to how to conserve and protect it."

From AUTHOR'S MESSAGE in "State of Fear," a novel by Michael Crichton published in 2004.

LIVES IN
THE AGE OF THE "PNEUMO-CHEMISTS"
1750-1800

George Washington	1732-1799
Franz Joseph Haydn	1732-1809
James Boswell	1740-1795

Discoveries of the ‘Pneumo-Chemists’

Publication Data

Joseph Black	1754	"Fixed air" (CO_2)
Henry Cavendish	1766	"inflammable air" (H_2)
Joseph Priestley	1775	"dephlogisticated air" (O_2)
Henry Cavendish	1784	Water consists of two gases (H_2, O_2)
Antoine Lavoisier	1772-1782	Air consists of two elements (O_2, N_2) Definition of ‘oxidation’ Carbon dioxide consists of two elements (C, O_2)

Discoveries of the 'Biochemists'

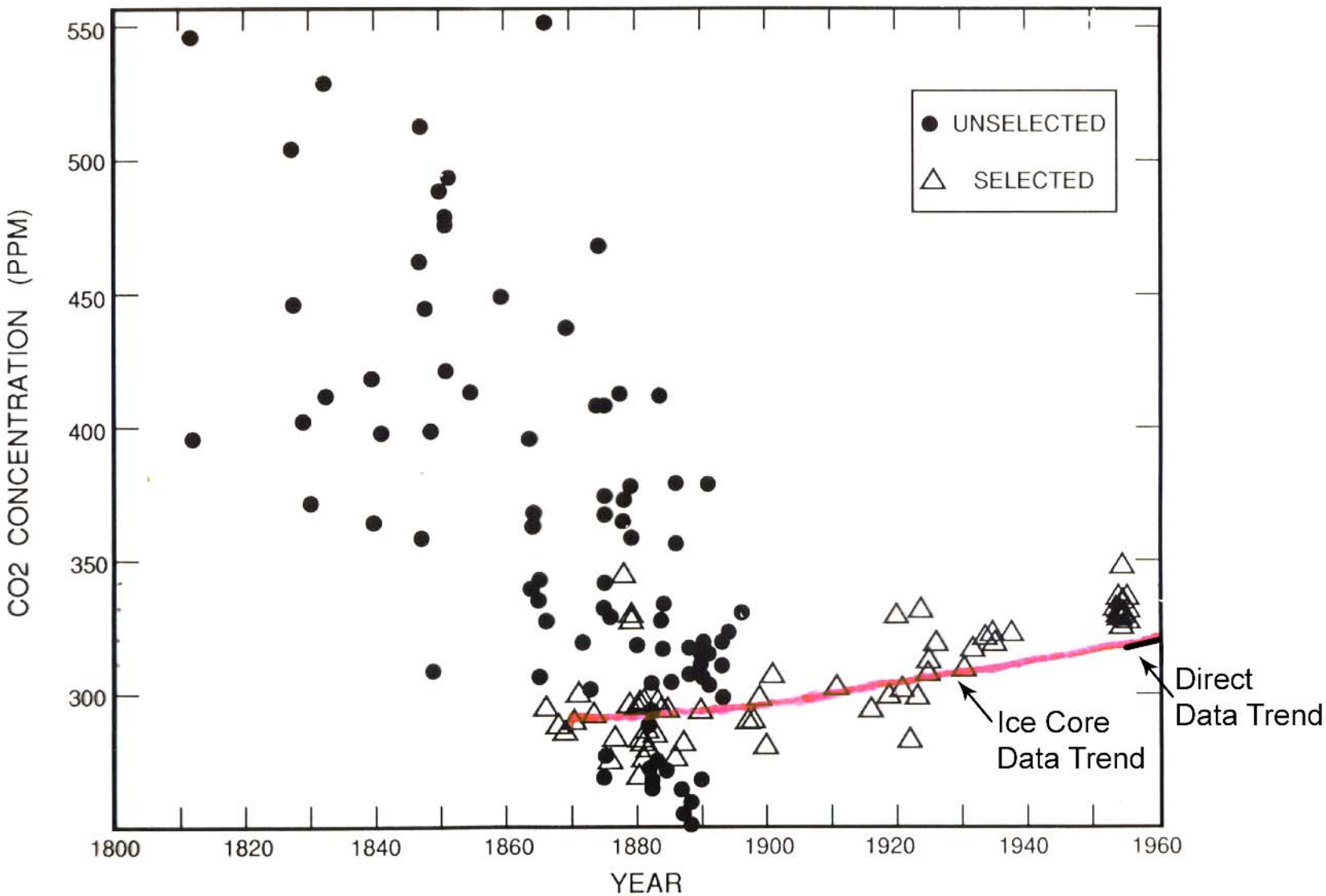
Joseph Priestley	1772	Restoration of "injured air" by plants
Jan Ingen-Housz*	1779	Plants need light to make "vital air" (O_2). They "poison" air in the dark.
	1781	"Green matter" under water formed bubbles of pure "dephlogisticated air"
Jean Senebier	1783	Growing plants require "fixed air" as well as light
Jan Ingen-Housz	1796	Plants acquire "juices" from soil but "carbon" from the air in the form of "carbonic acid". They release "oxygen"
Theodore de Saussure	1804	Air is the only source of carbon for plants. Weight increase in plants also require that they assimilate water

* Hurried publication - experiments conducted the same year

Early Measurements of CO_2 in Air

	Approximate Time	Mean Concentrations Found
Alexander von Humboldt	1797	circa 1% (10000 ppmv)
John Dalton	1802	683 ppmv
Theodore de Saussure	1815	596 ppmv
	1827	506 ppmv
	1828	447 ppmv
	1829	403 ppmv
	1830	373 ppmv
Jean Baptiste Boussingault	1818-40	365 ppmv
Jules Reiset	1870	290 ppmv

Data Analysis of C.S. Calendar



Buch (1948)

CO_2 Concentration in Different Types of Air

High Arctic:	150 - 230 ppmv
Modified Arctic:	283 - 316 ppmv
Maritime Polar:	309 - 345 ppmv
Tropical:	319 - 349 ppmv

ppmv: parts of CO_2 per million parts of dry air by volume

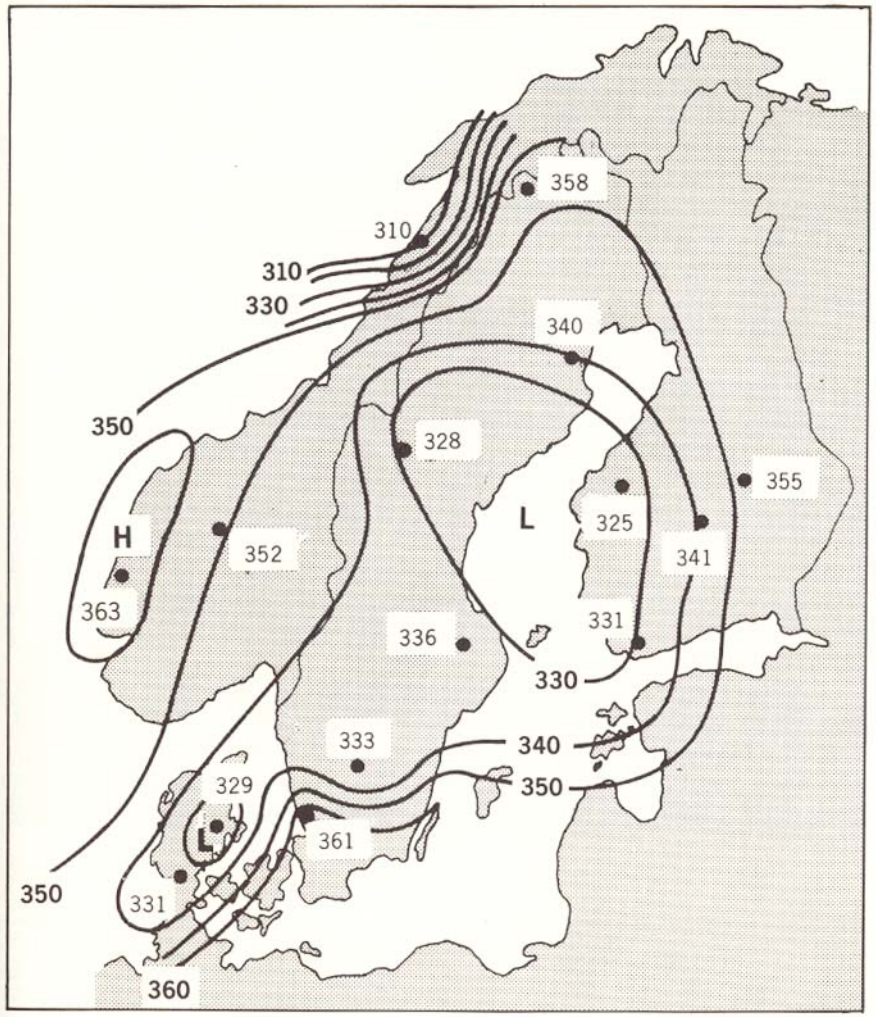


Figure 1. Concentrations of atmospheric CO_2 over Scandinavia (ppm) on February 20, 1955. The approximate pattern is shown by contour lines in a manner similar to Bischof's (1960, Fig. 6). Concentrations were determined by absorption of CO_2 in barium hydroxide solution.

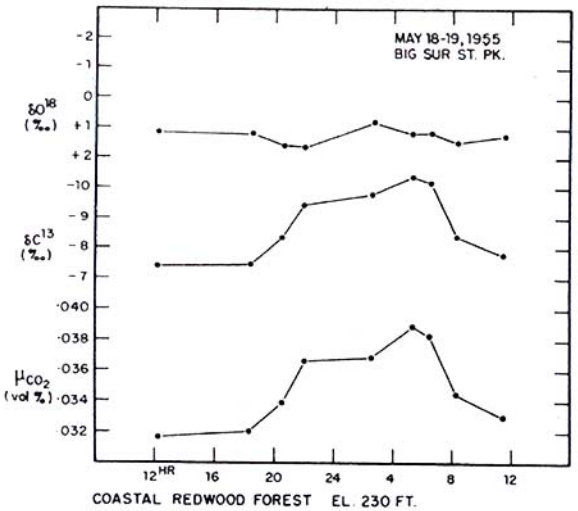


Fig. 1. Diurnal variation in the concentration and isotope ratios of atmospheric carbon dioxide in a coastal redwood forest of California.

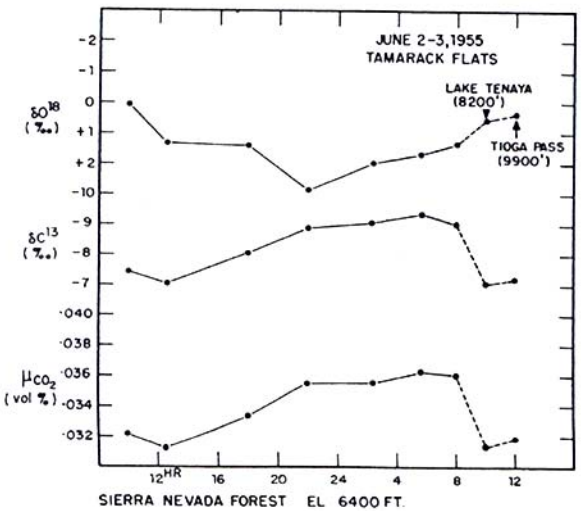


Fig. 2. Diurnal variation in the concentration and isotope ratios of atmospheric carbon dioxide in a forest of the Sierra Nevada.

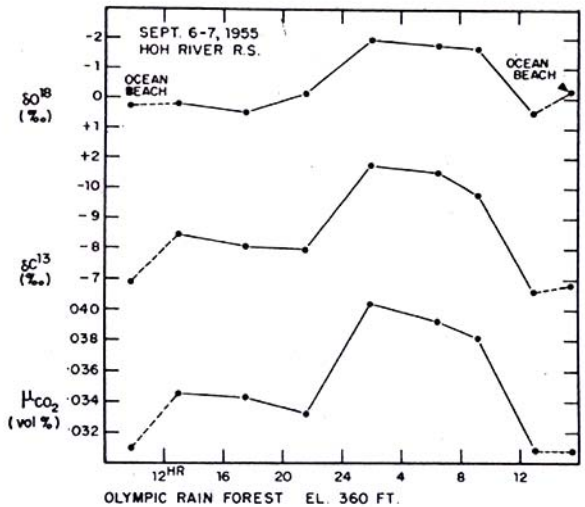


Fig. 5. Diurnal variation in the concentration and isotope ratios of atmospheric carbon dioxide in a rain forest of the Olympic Peninsula of Washington.

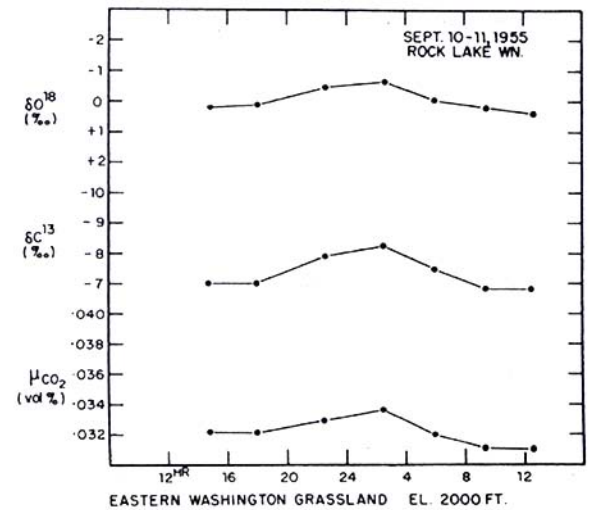


Fig. 6. Diurnal variation in the concentration and isotope ratios of atmospheric carbon dioxide in grassland of eastern Washington.

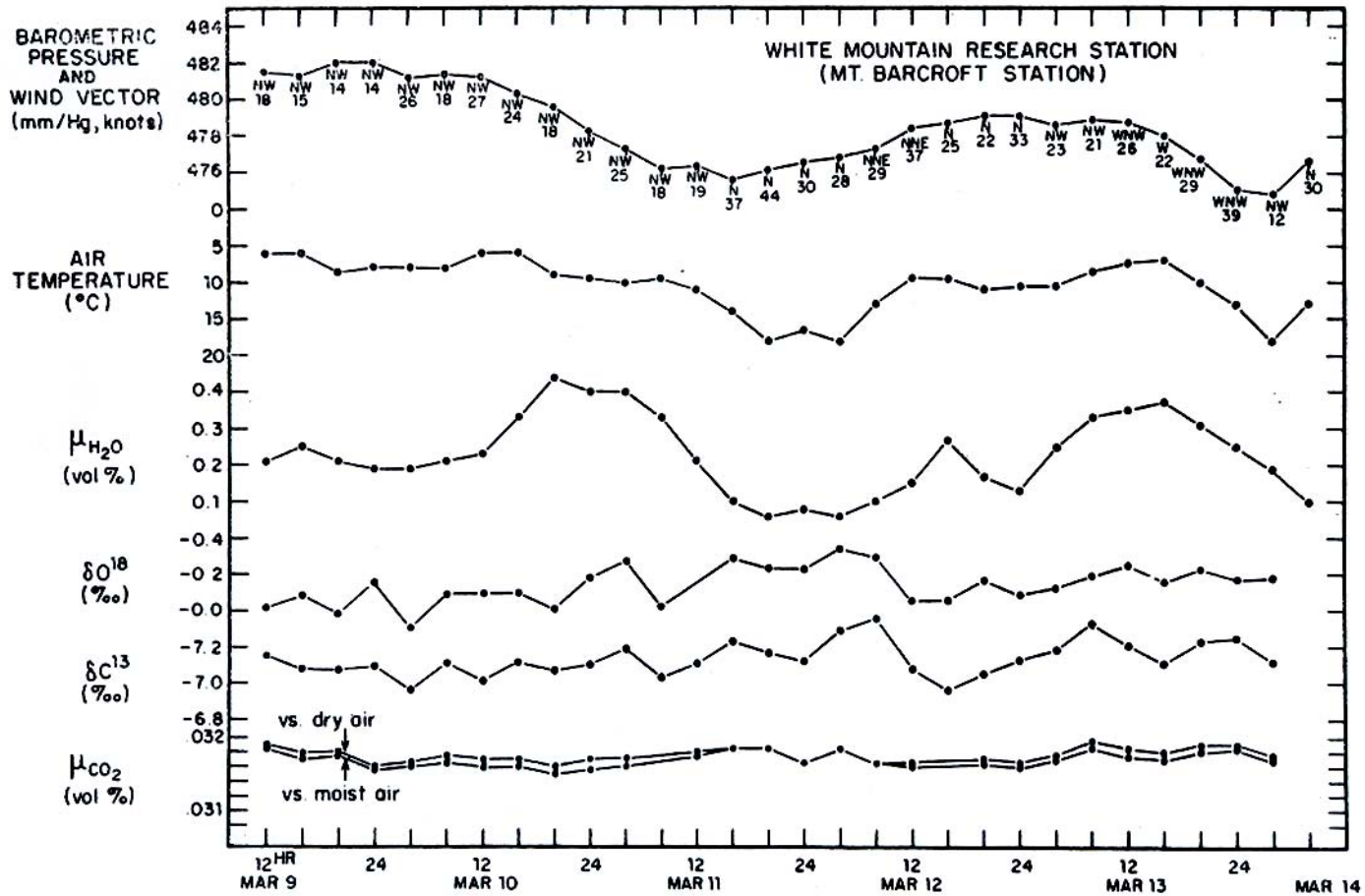
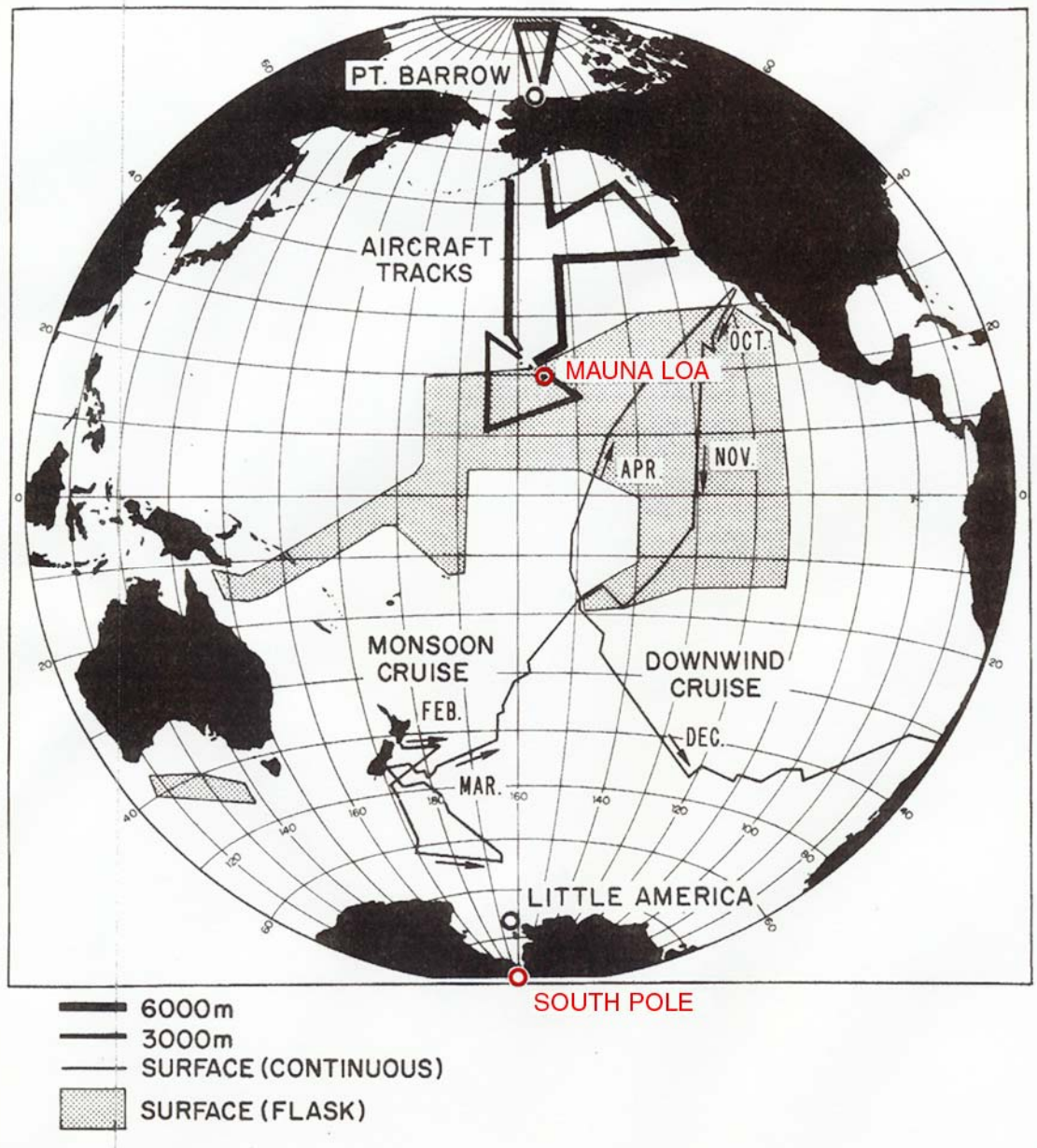
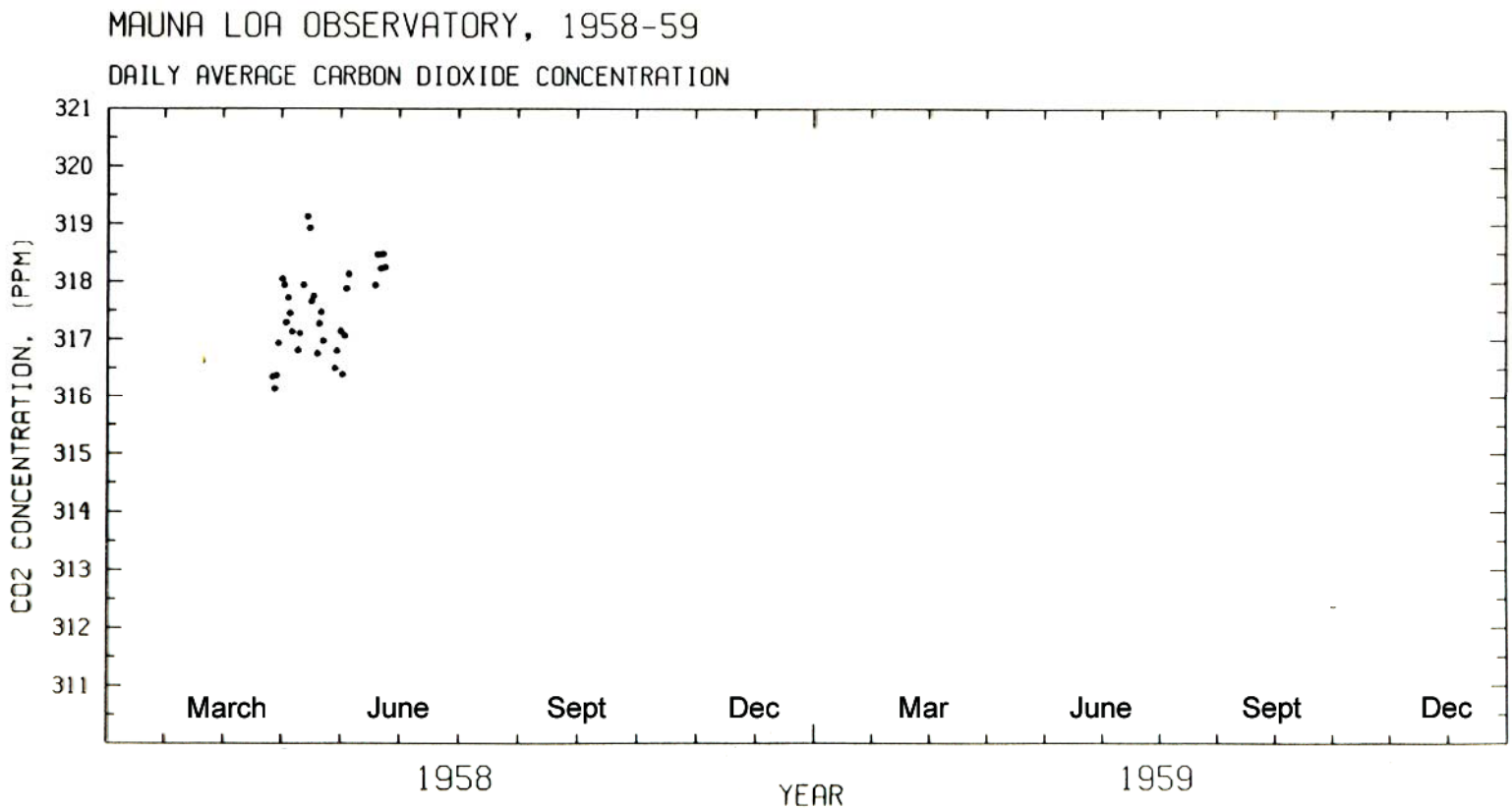
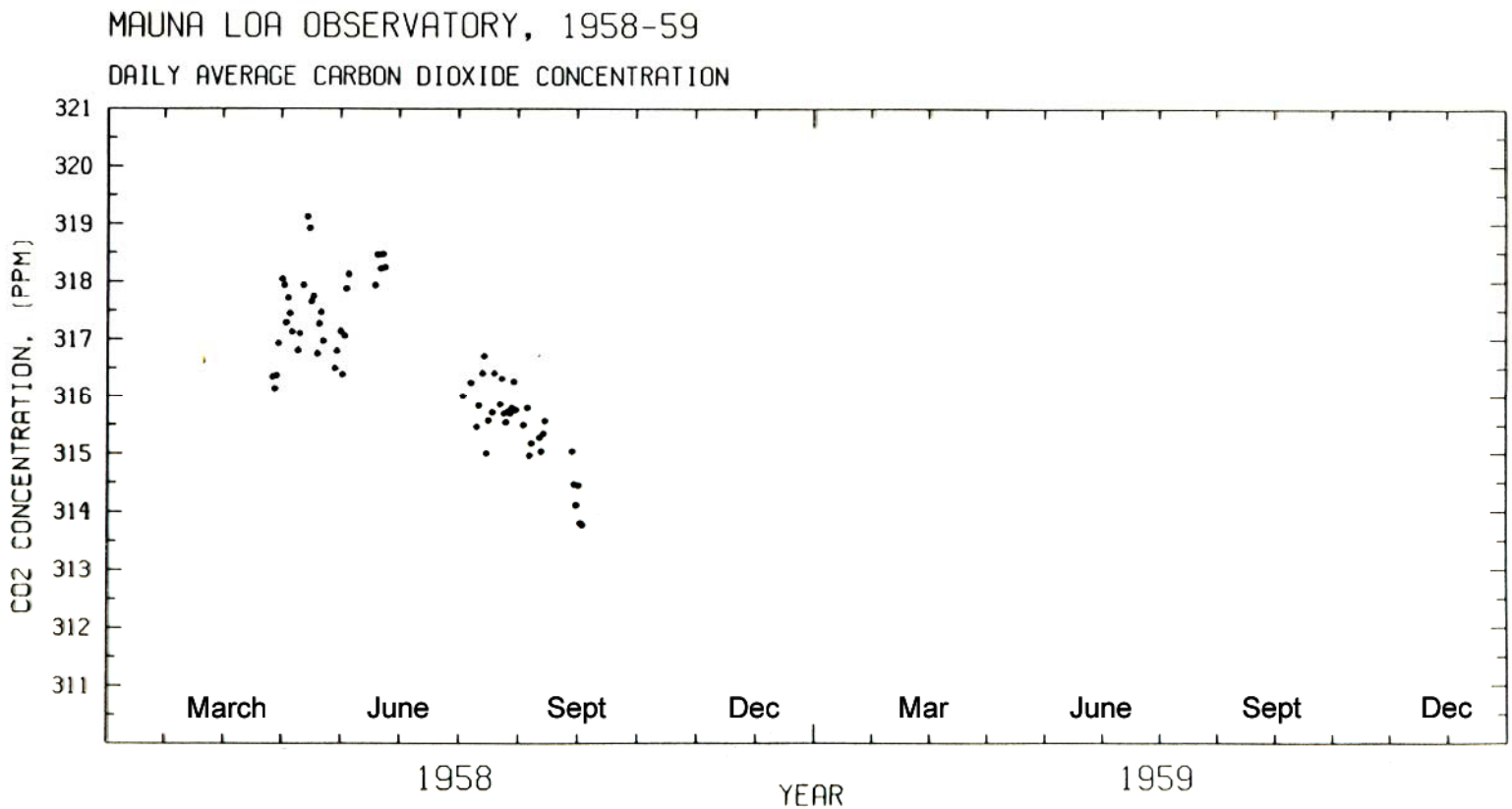
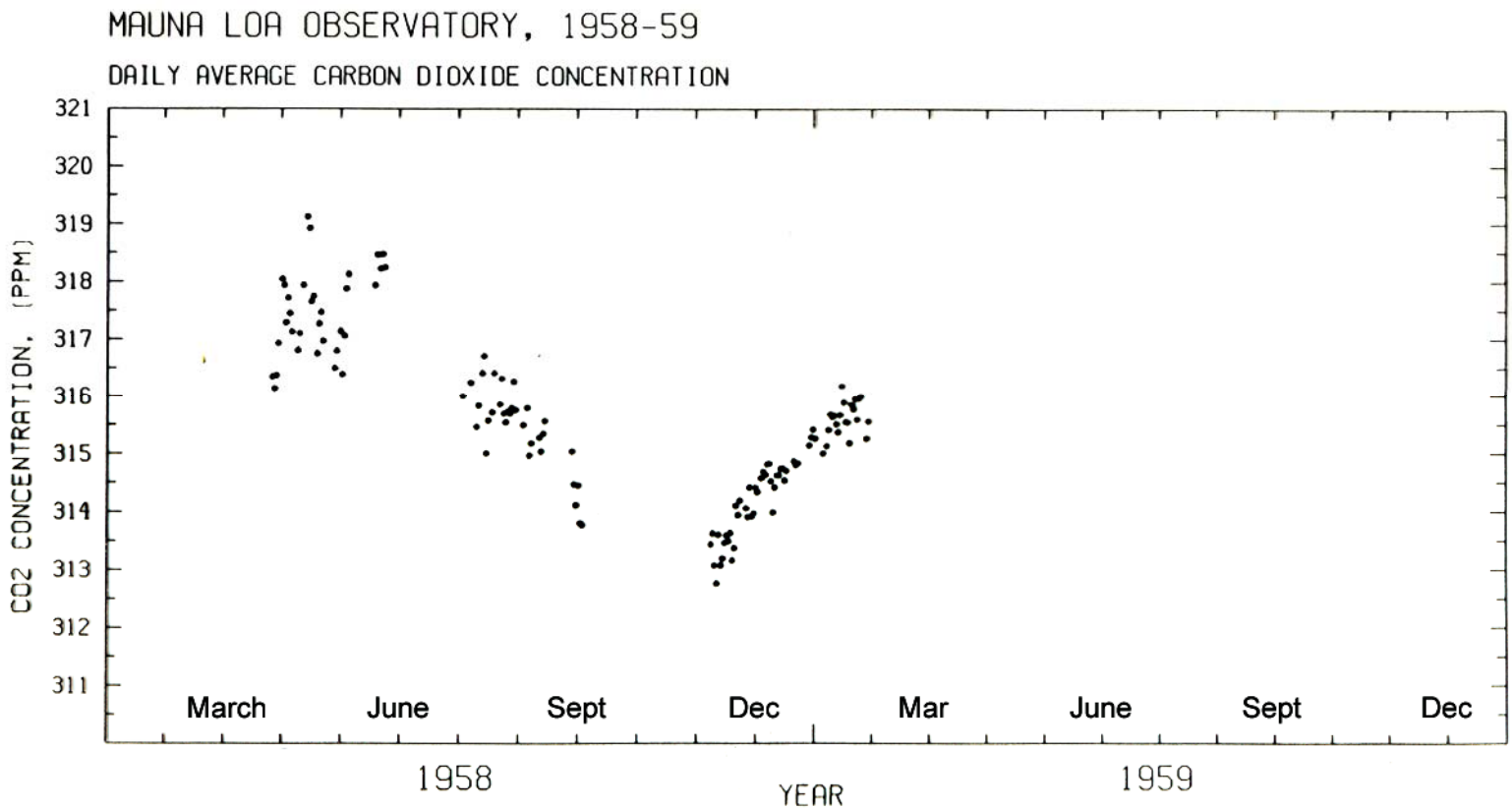


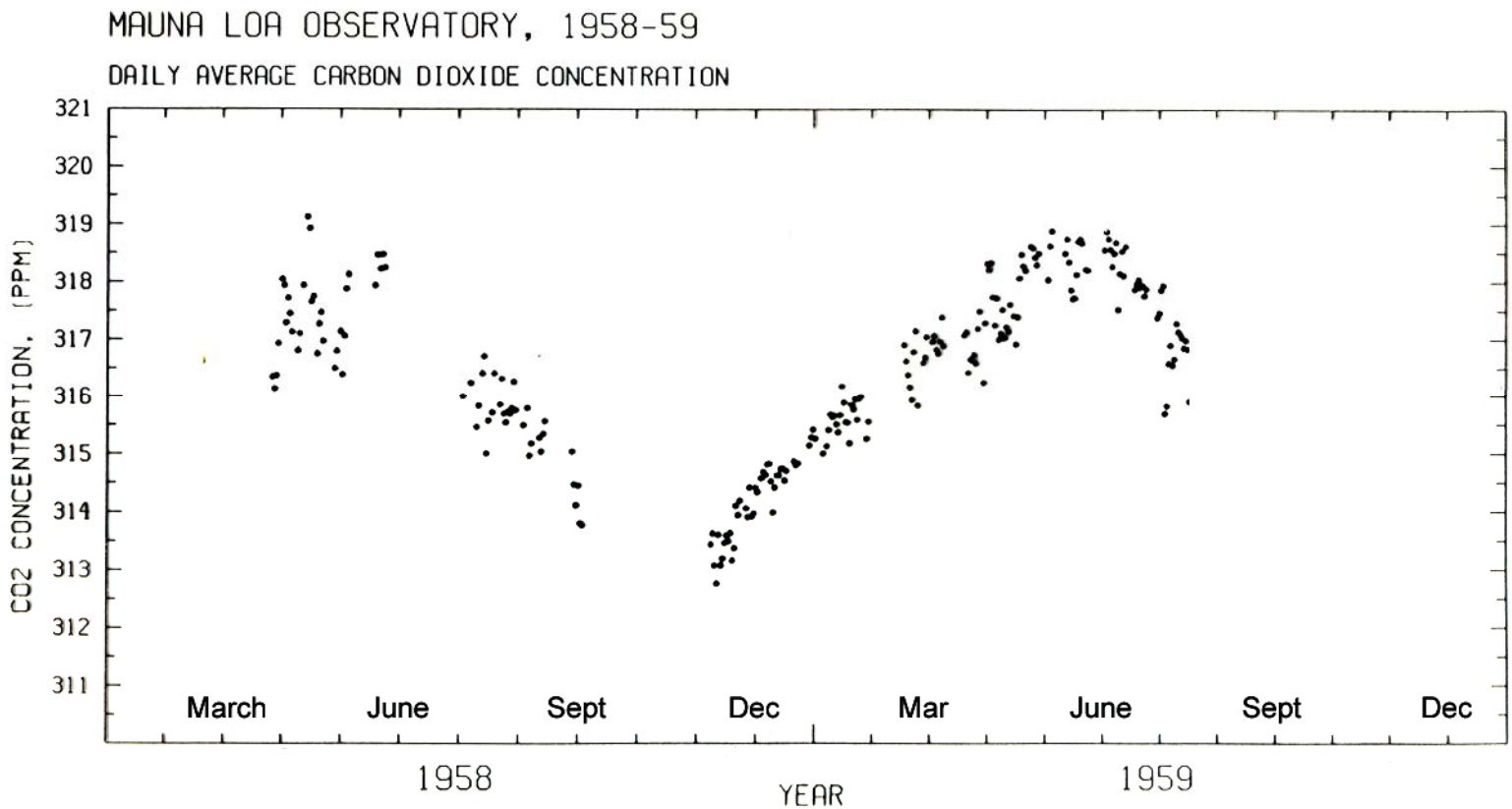
Fig. 2. Variation in the concentration and isotope ratios of atmospheric carbon dioxide, and in barometric pressure, wind vector, air temperature and water vapour concentration, over barren ground near White Mountain Research Station in the Inyo Mountains of California.

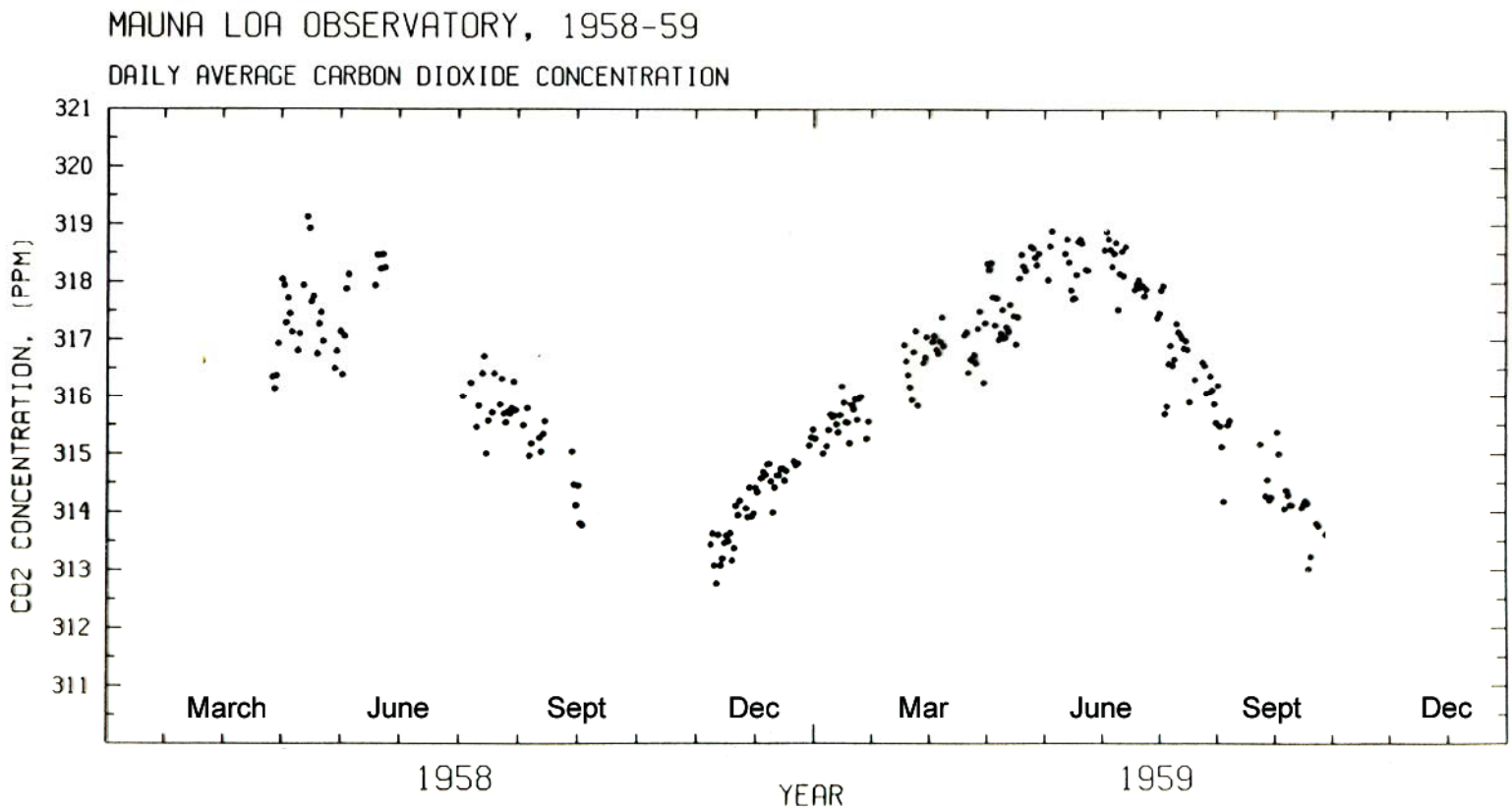

PT. BARROW
AIRCRAFT TRACKS
MAUNA LOA
OCT.
APR.
NOV.
MONSOON CRUISE
FEB.
MAR.
DOWNWIND CRUISE
DEC.
LITTLE AMERICA
SOUTH POLE
6000m
3000m
SURFACE (CONTINUOUS)
SURFACE (FLASK)


MAUNA LOA OBSERVATORY, 1958-59
DAILY AVERAGE CARBON DIOXIDE CONCENTRATION
CO2 CONCENTRATION, (PPM)
321
320
319
318
317
316
315
314
313
312
311
March
June
Sept
Dec
Mar
June
Sept
Dec
1958
YEAR
1959


MAUNA LOA OBSERVATORY, 1958-59
DAILY AVERAGE CARBON DIOXIDE CONCENTRATION
CO2 CONCENTRATION, (PPM)
321
320
319
318
317
316
315
314
313
312
311
March
June
Sept
Dec
Mar
June
Sept
Dec
1958
YEAR
1959


MAUNA LOA OBSERVATORY, 1958-59
DAILY AVERAGE CARBON DIOXIDE CONCENTRATION
CO2 CONCENTRATION, (PPM)
321
320
319
318
317
316
315
314
313
312
311
March
June
Sept
Dec
Mar
June
Sept
Dec
1958
YEAR
1959


MAUNA LOA OBSERVATORY, 1958-59
DAILY AVERAGE CARBON DIOXIDE CONCENTRATION
CO2 CONCENTRATION, (PPM)
321
320
319
318
317
316
315
314
313
312
311
March
June
Sept
Dec
Mar
June
Sept
Dec
1958
1959
YEAR


MAUNA LOA OBSERVATORY, 1958-59
DAILY AVERAGE CARBON DIOXIDE CONCENTRATION
CO2 CONCENTRATION, (PPM)
321
320
319
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317
316
315
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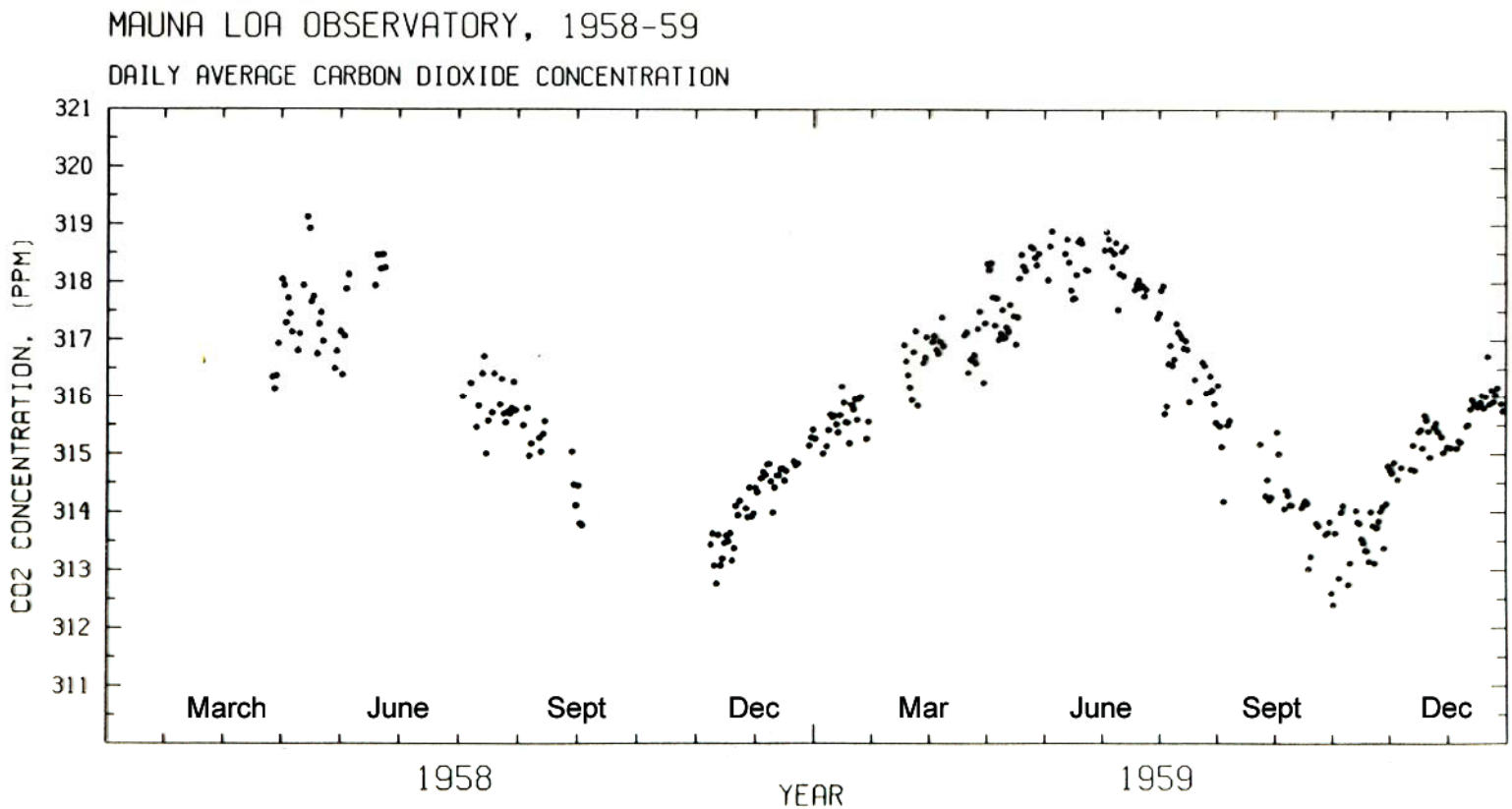
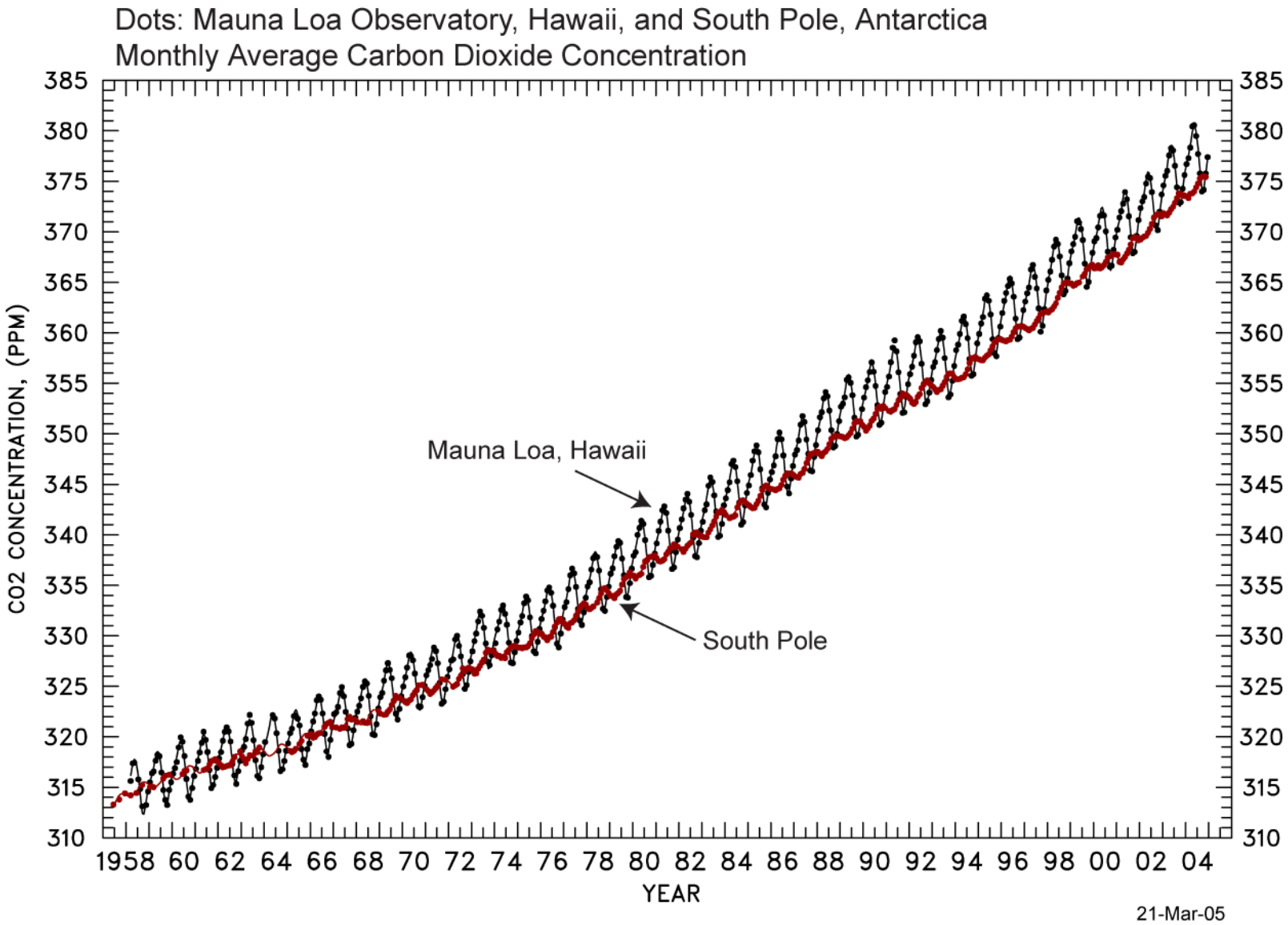
313
312
311
March
June
Sept
Dec
Mar
June
Sept
Dec
1958
1959
YEAR


MAUNA LOA OBSERVATORY, 1958-59
DAILY AVERAGE CARBON DIOXIDE CONCENTRATION
CO2 CONCENTRATION, (PPM)
321
320
319
318
317
316
315
314
313
312
311
March
June
Sept
Dec
Mar
June
Sept
Dec
1958
YEAR
1959

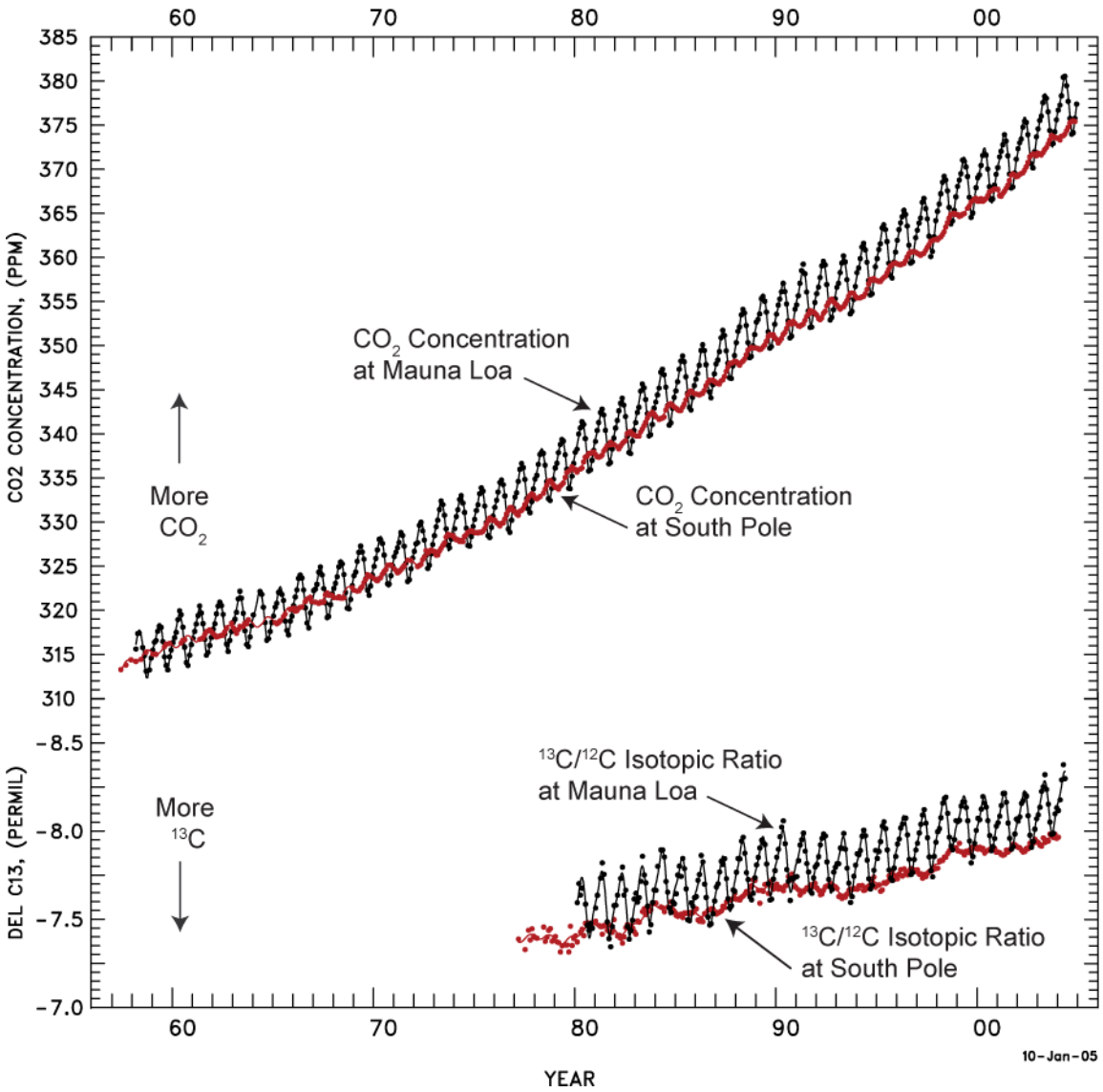
CO_2 Concentration in Different Regions in 1962

Arctic:	313 - 325 ppmv
Pacific Ocean near 20˚N:	315 - 321 ppmv
Equatorial Pacific:	317 - 321 ppmv
South Pole:	317 - 319 ppmv

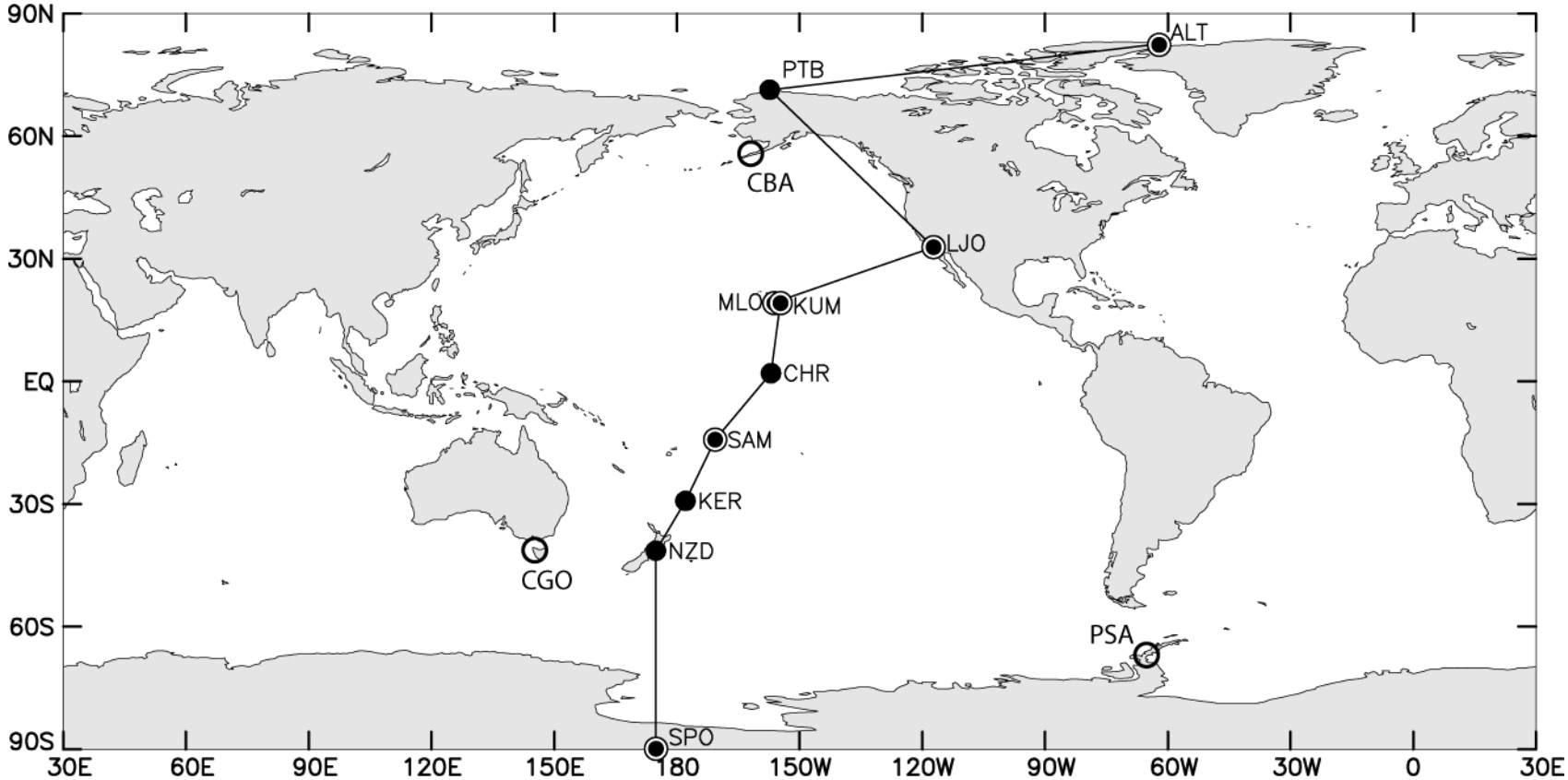
Measurements by the Scripps Institution of Oceanography


Dots: Mauna Loa Observatory, Hawaii, and South Pole, Antarctica
Monthly Average Carbon Dioxide Concentration
CO2 CONCENTRATION, (PPM)
385
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
Mauna Loa, Hawaii
South Pole
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
21-Mar-05

Mauna Loa Observatory, Hawaii, and South Pole, Antarctica

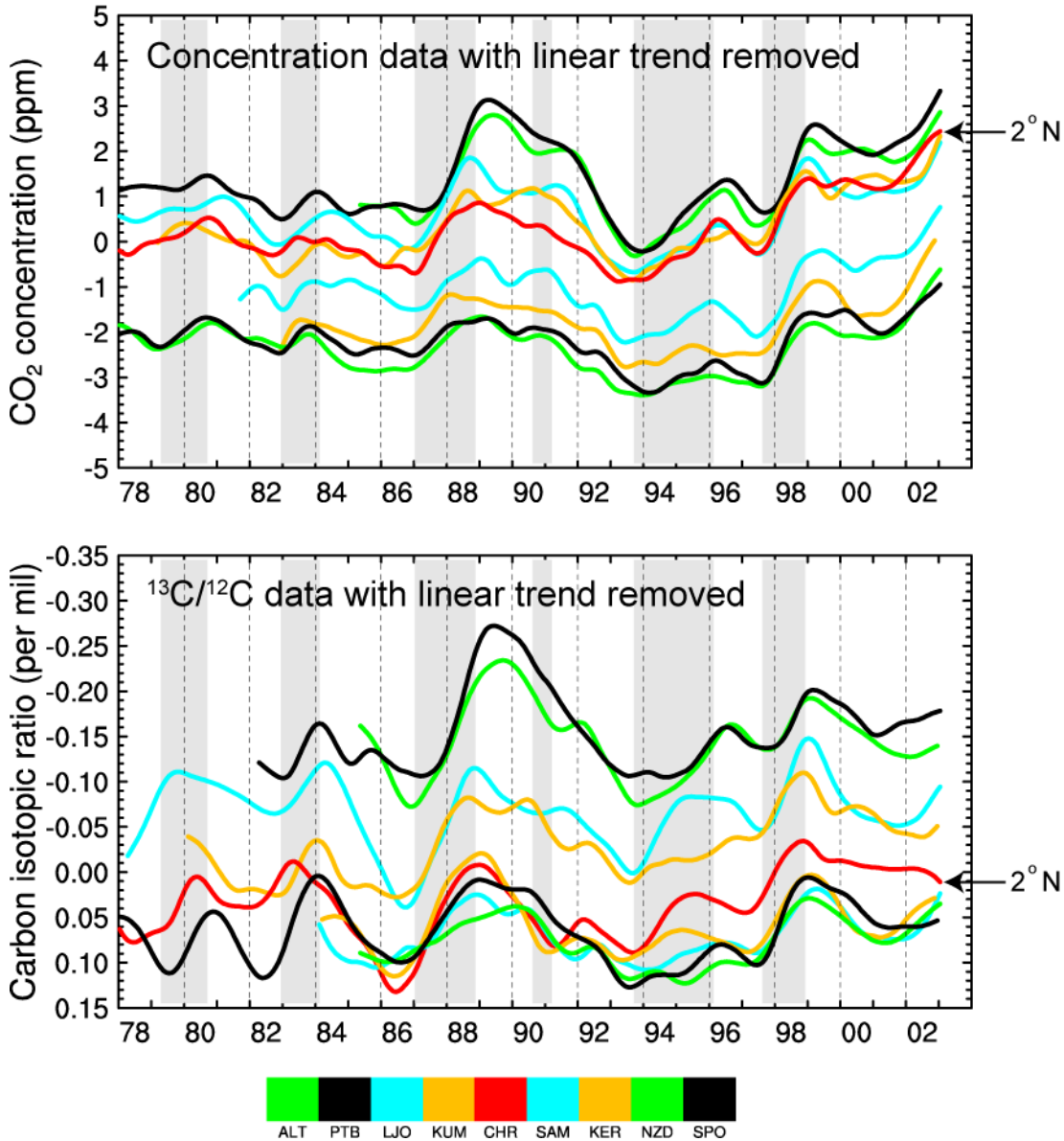


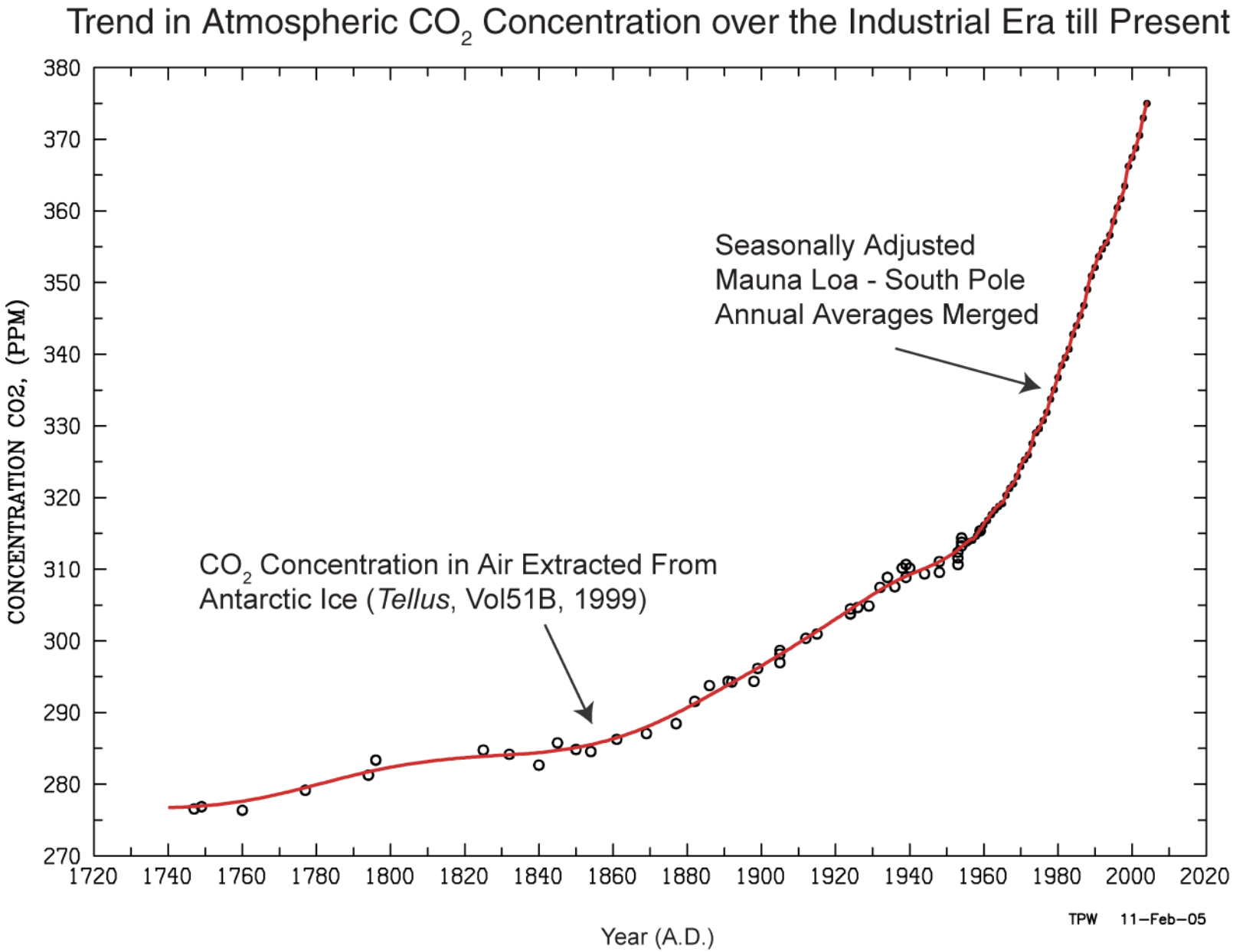
Atmospheric Sampling Stations

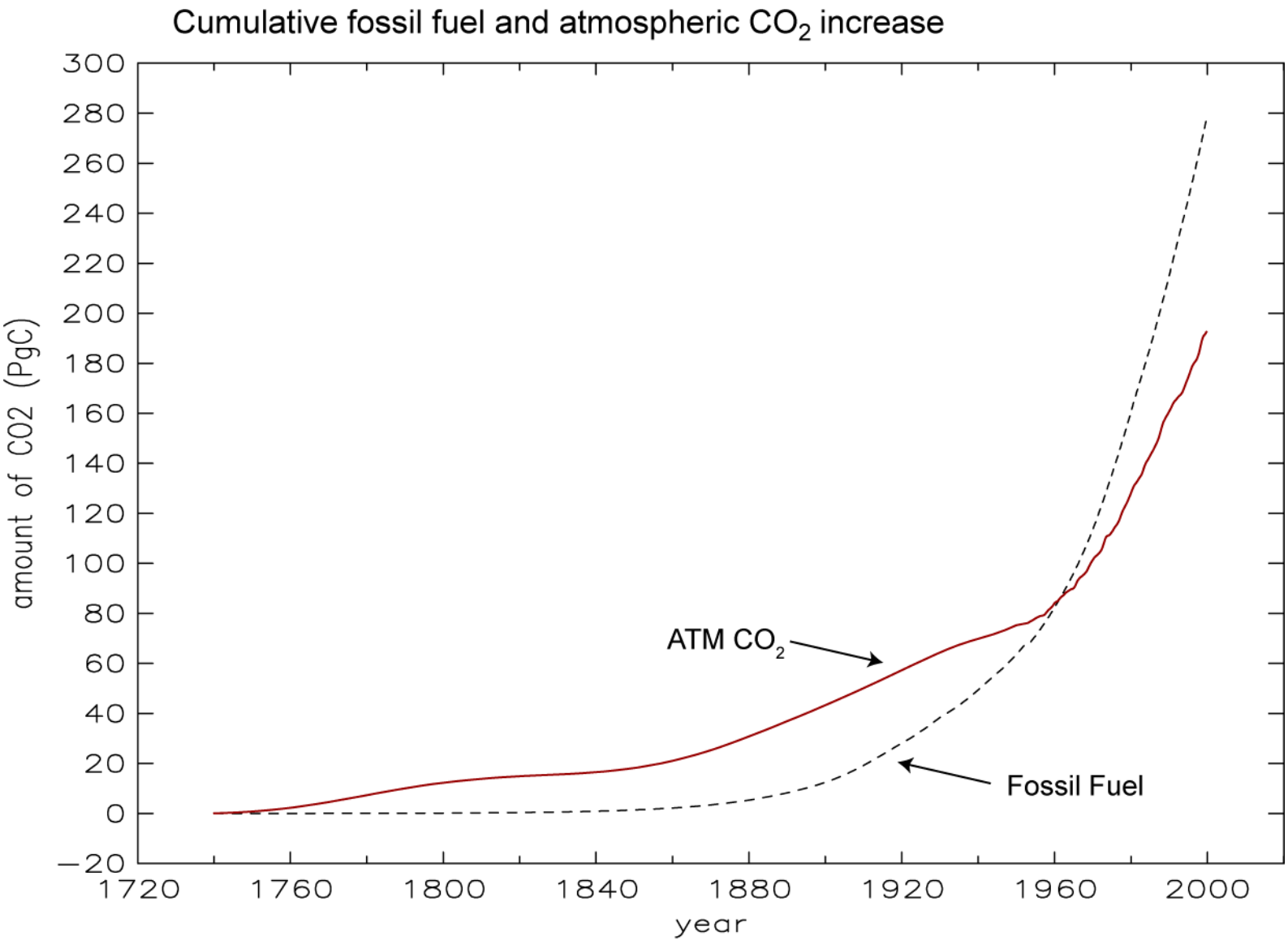


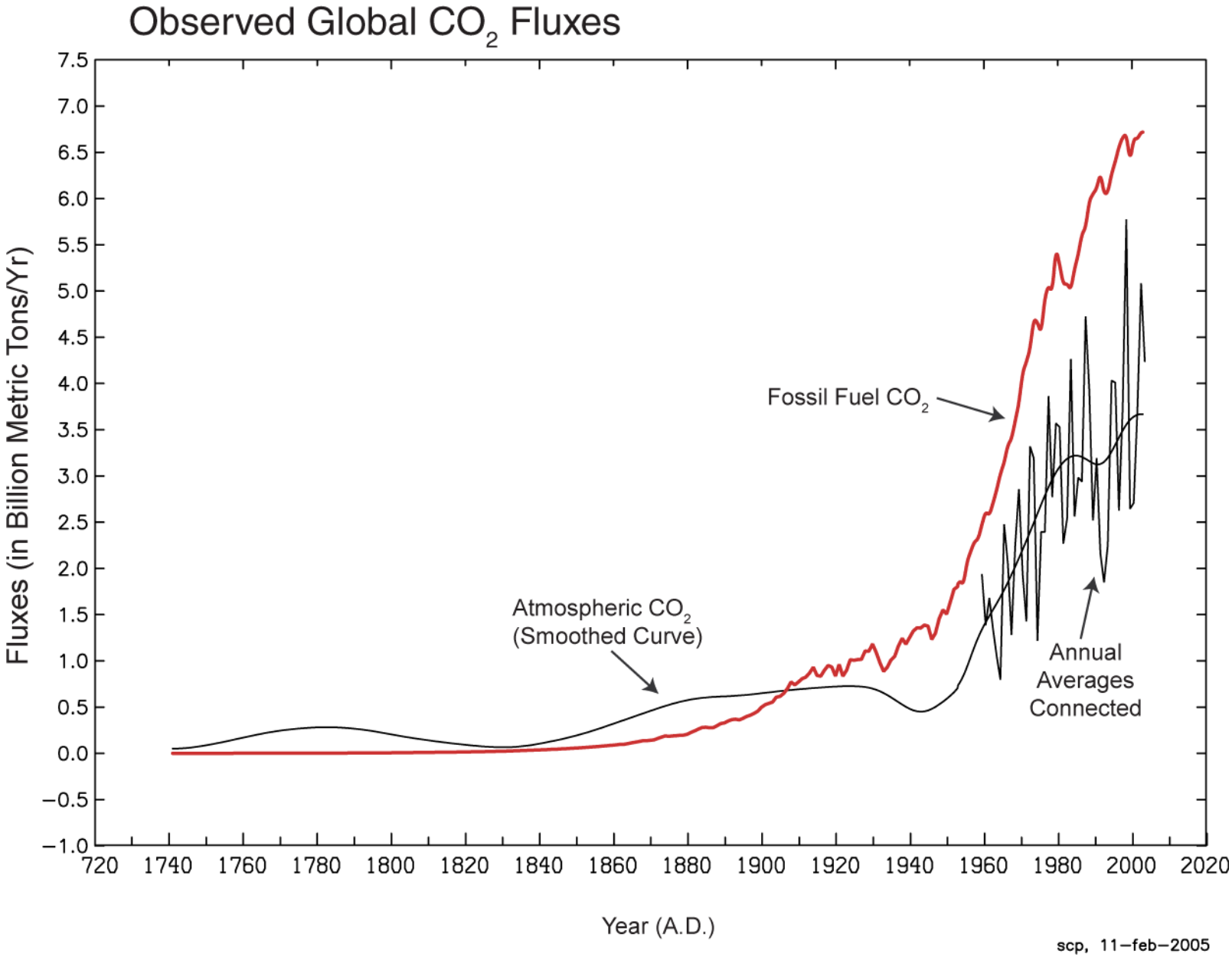
Location of stations of our station array for atmospheric CO_2 and O_2/N_2 sampling.
Solid circles: CO_2 sampling stations of the C. D. Keeling laboratory.
Open circles: O_2/N_2 and CO_2 sampling stations of the R. F. Keeling laboratory.

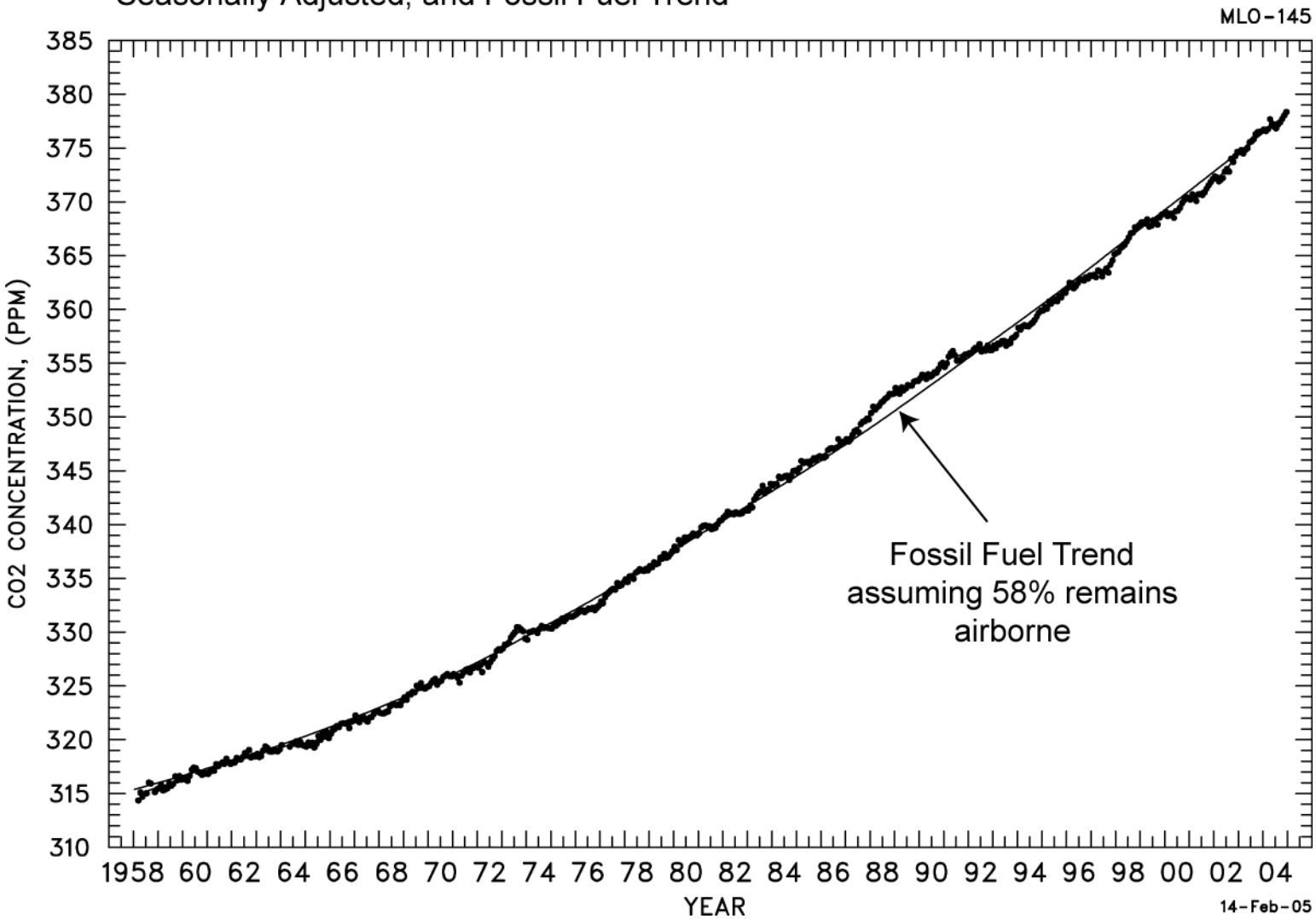
Interannual Variability in Atmospheric CO_2

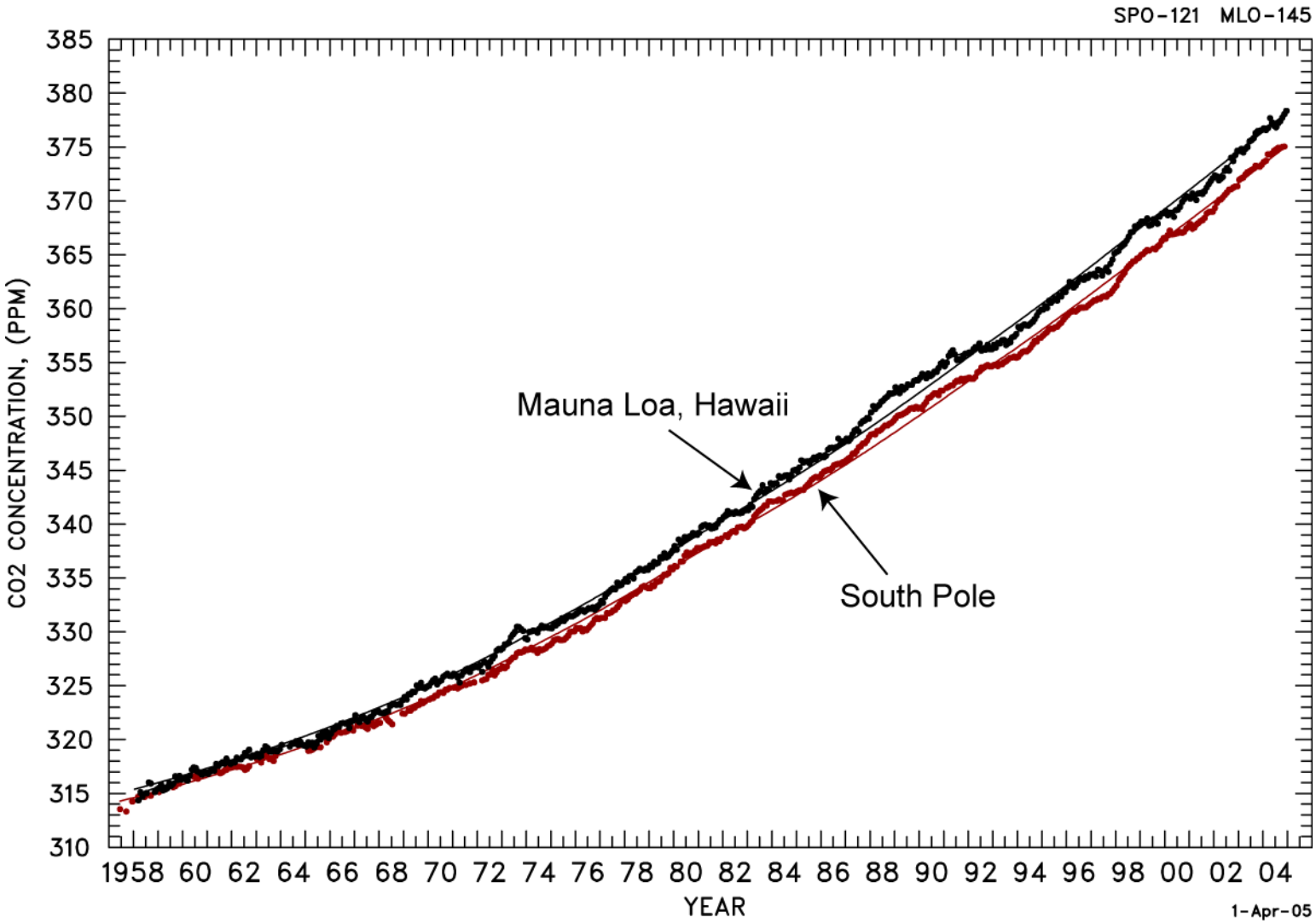


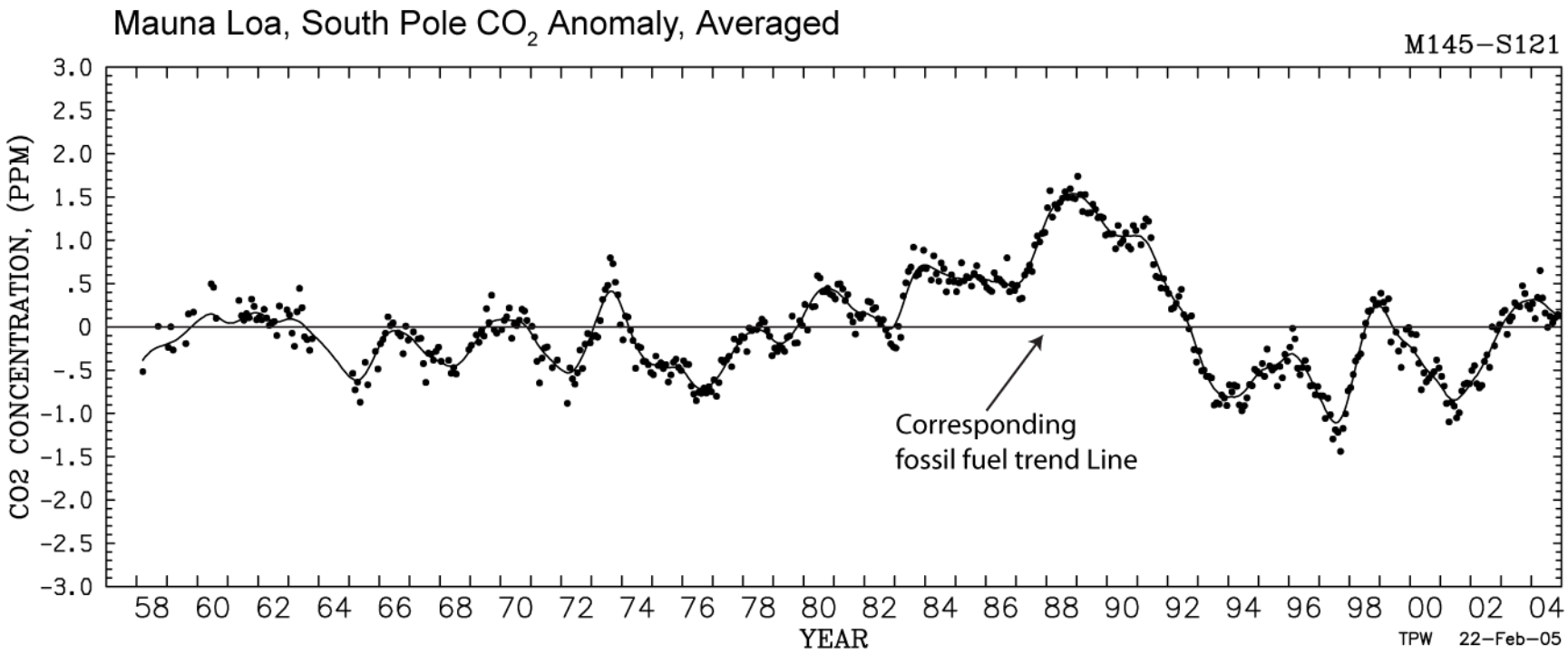

Trend in Atmospheric CO_2 Concentration over the Industrial Era till Present
CONCENTRATION CO2, (PPM)
380
370
360
350
340
330
320
310
300
290
280
270
1720
1740
1760
1780
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year (A.D.)
Seasonally Adjusted
Mauna Loa - South Pole
Annual Averages Merged
CO_2 Concentration in Air Extracted From
Antarctic Ice (*Tellus*, Vol51B, 1999)
TPW 11–Feb–05

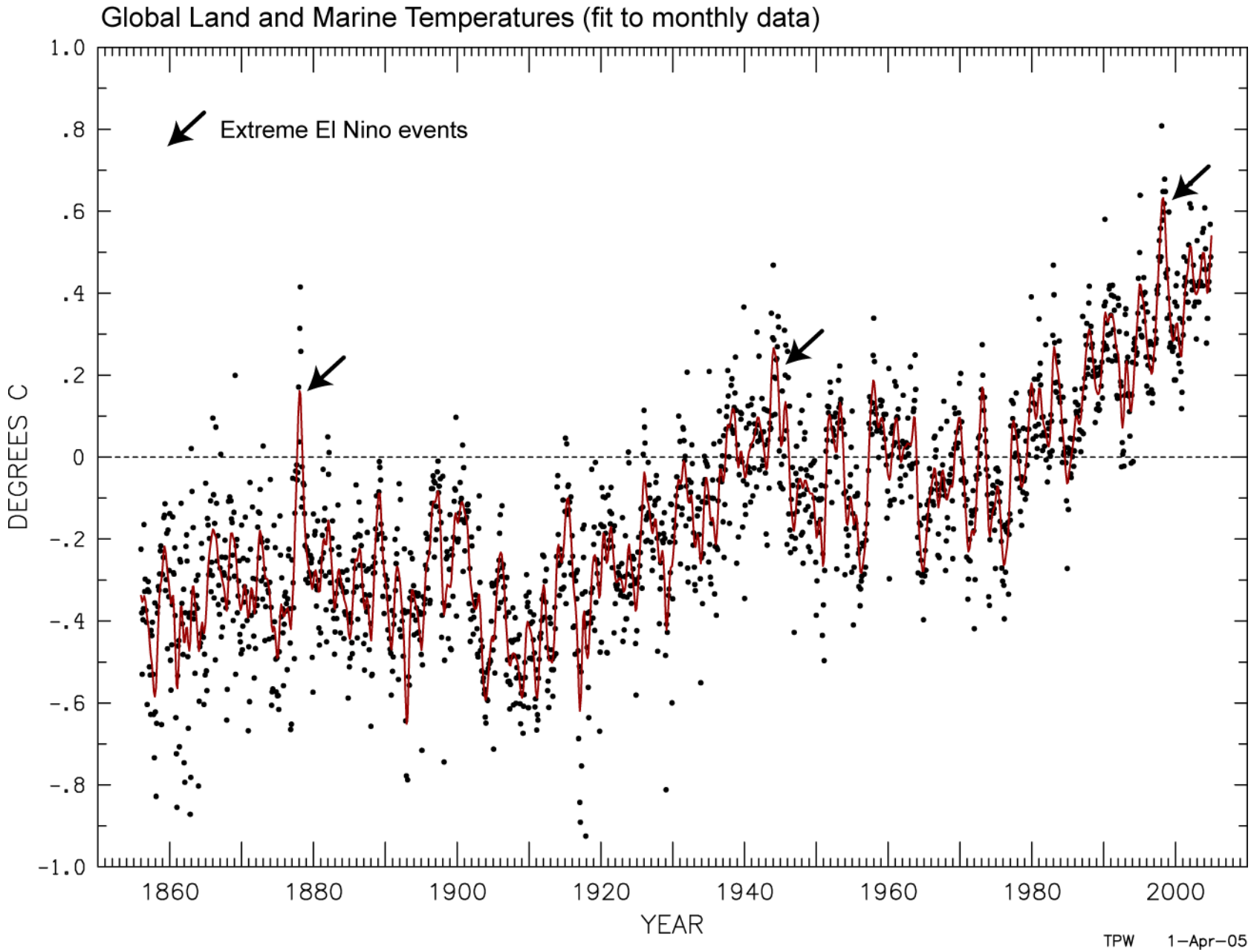

Cumulative fossil fuel and atmospheric CO_2 increase
amount of CO2 (PgC)
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
−20
1720
1760
1800
1840
1880
1920
1960
2000
year
ATM CO_2
Fossil Fuel
Fossil Fuel Flux: 1800 - 1994: 245 PgC/yr
ATM Increase: 1800 - 1994: 162 PgC/yr
scpiper, 9−aug−2004
xy−cum−ff−atm−1.job

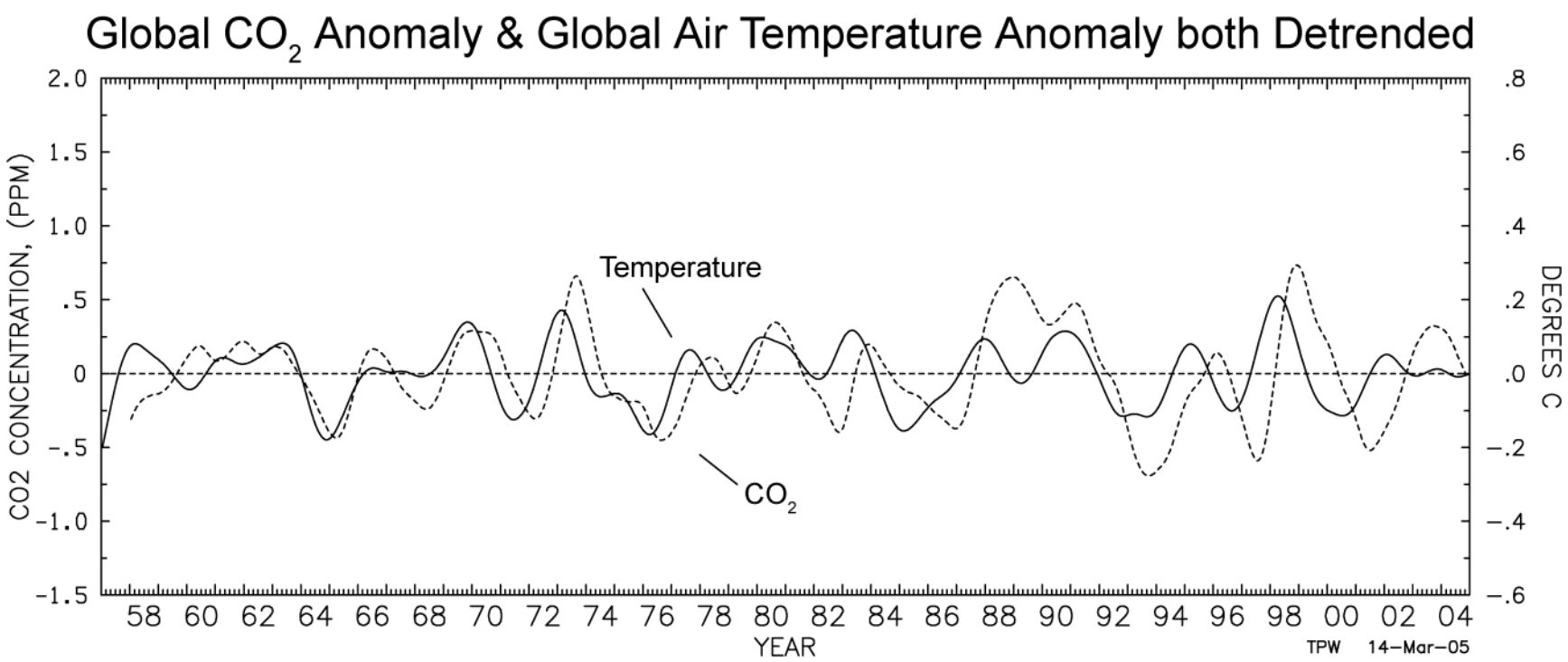

Observed Global CO_2 Fluxes
Fluxes (in Billion Metric Tons/Yr)
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
720
1740
1760
1780
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year (A.D.)
Fossil Fuel CO_2
Atmospheric CO_2
(Smoothed Curve)
Annual
Averages
Connected
scp, 11−feb−2005

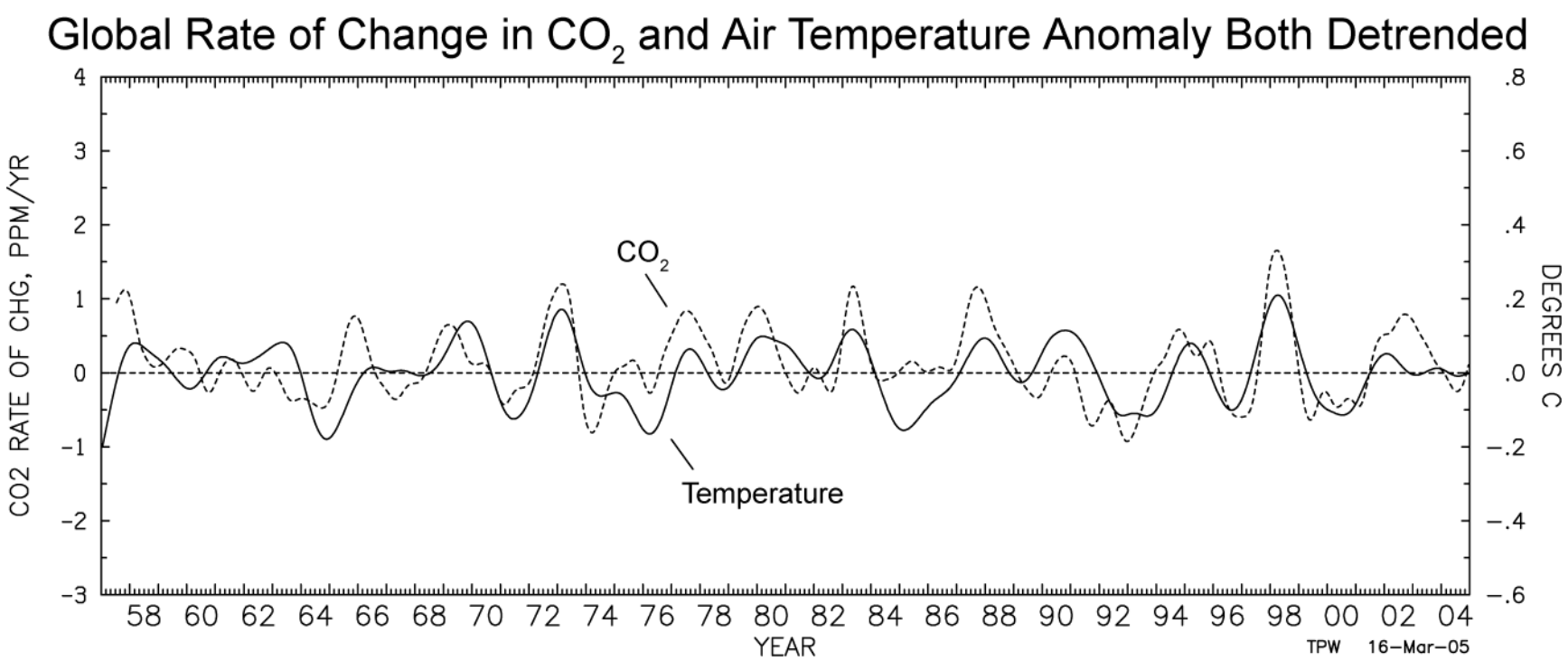

Mauna Loa Observatory, Hawaii Monthly Average CO_2 Concentration,
Seasonally Adjusted, and Fossil Fuel Trend
MLO-145
CO2 CONCENTRATION, (PPM)
385
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
Fossil Fuel Trend
assuming 58% remains
airborne
14-Feb-05

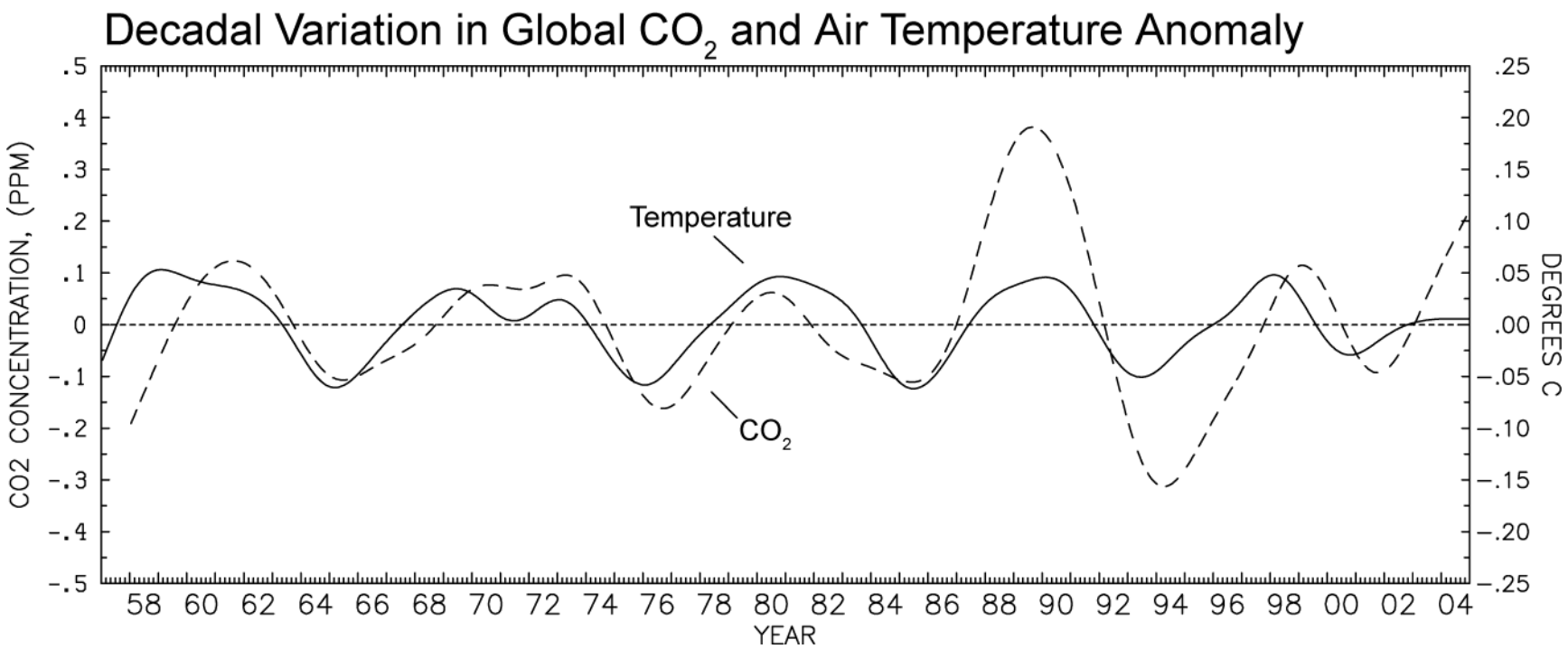

Mauna Loa Observatory, Hawaii and South Pole Antarctica
Monthly Average CO_2 Concentrations, Seasonally Adjusted, and Fossil Fuel Trends
SPO-121 MLO-145
CO2 CONCENTRATION, (PPM)
385
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
Mauna Loa, Hawaii
South Pole
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
1-Apr-05

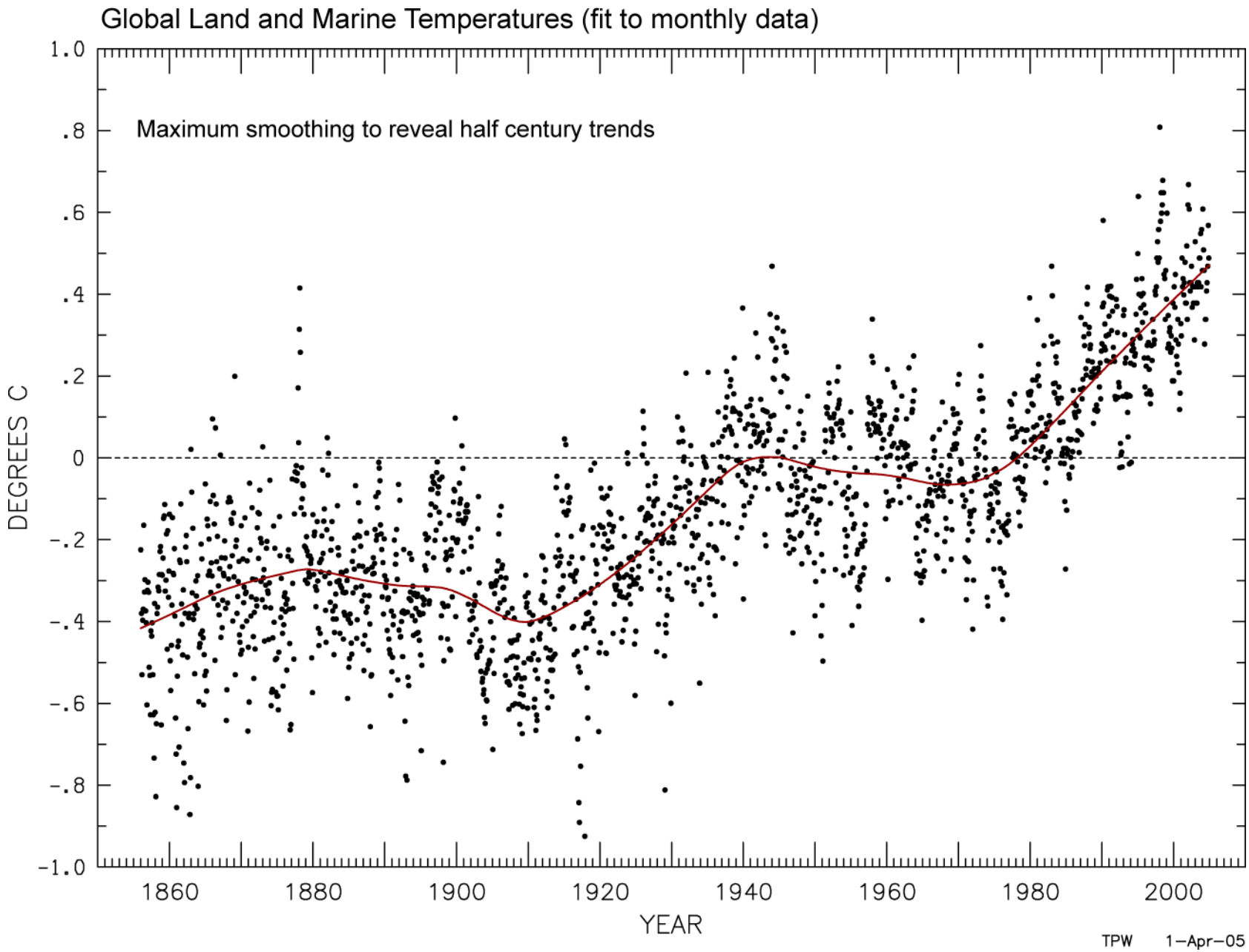

Mauna Loa, South Pole CO_2 Anomaly, Averaged
M145−S121
CO2 CONCENTRATION, (PPM)
3.0
2.5
2.0
1.5
1.0
.5
0
-.5
-1.0
-1.5
-2.0
-2.5
-3.0
58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
Corresponding
fossil fuel trend Line
TPW 22−Feb−05

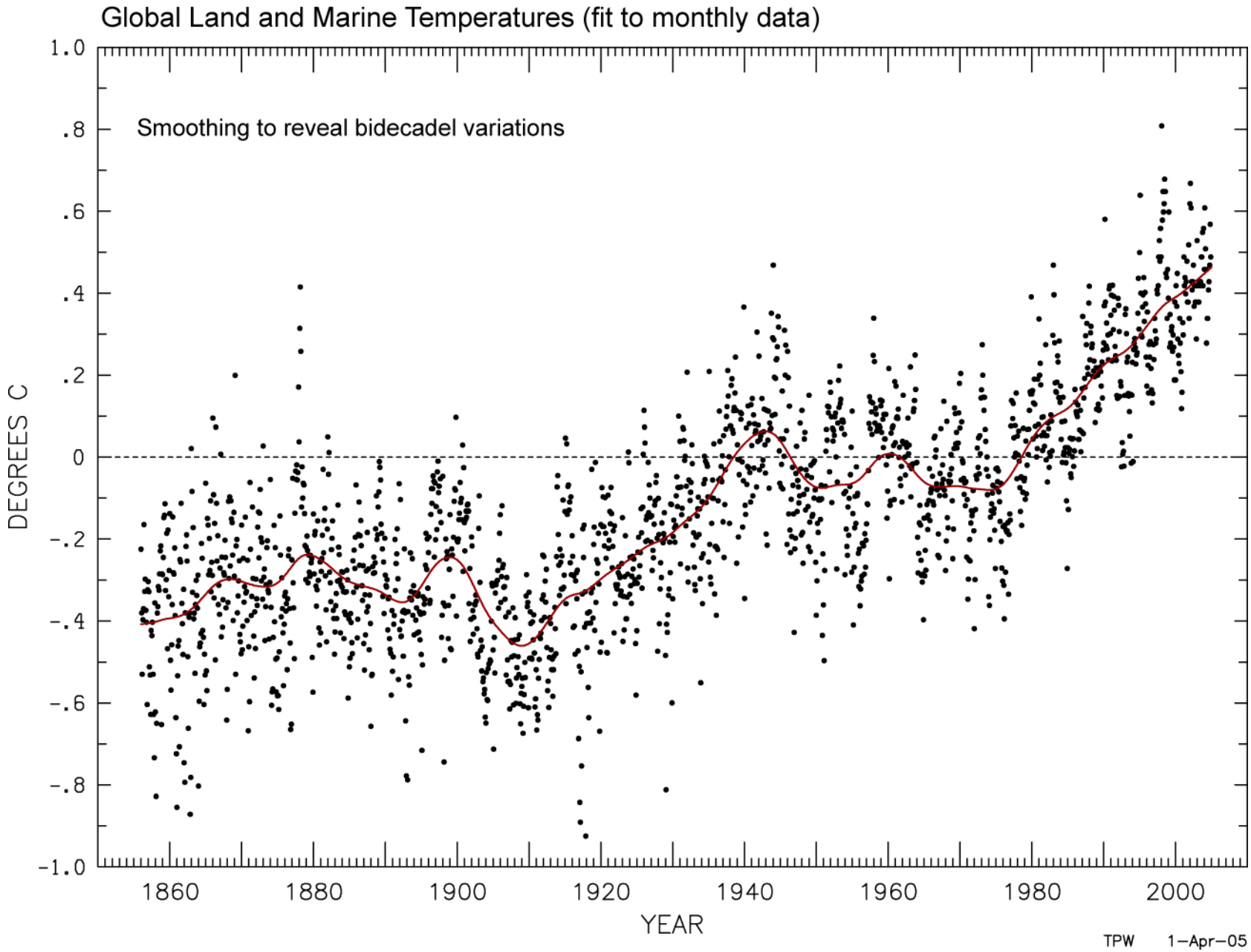

Global Land and Marine Temperatures (fit to monthly data)
Extreme El Nino events
DEGREES C
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
TPW 1-Apr-05

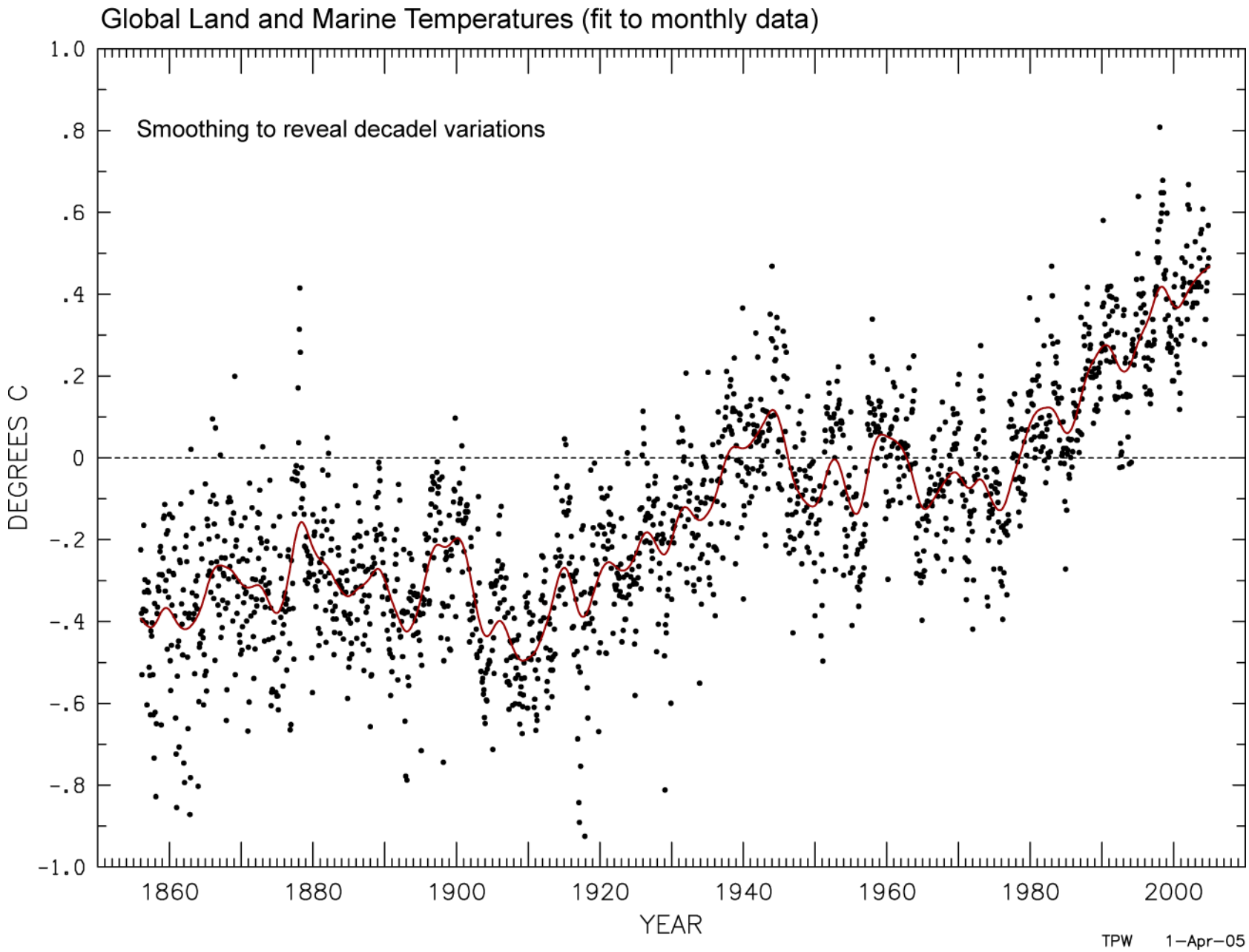

Global CO2 Anomaly & Global Air Temperature Anomaly both Detrended
CO2 CONCENTRATION, (PPM)
DEGREES C
Temperature
CO2
YEAR
TPW 14-Mar-05
2.0
1.5
1.0
.5
0
-.5
-1.0
-1.5
.8
.6
.4
.2
.0
-.2
-.4
-.6
58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04

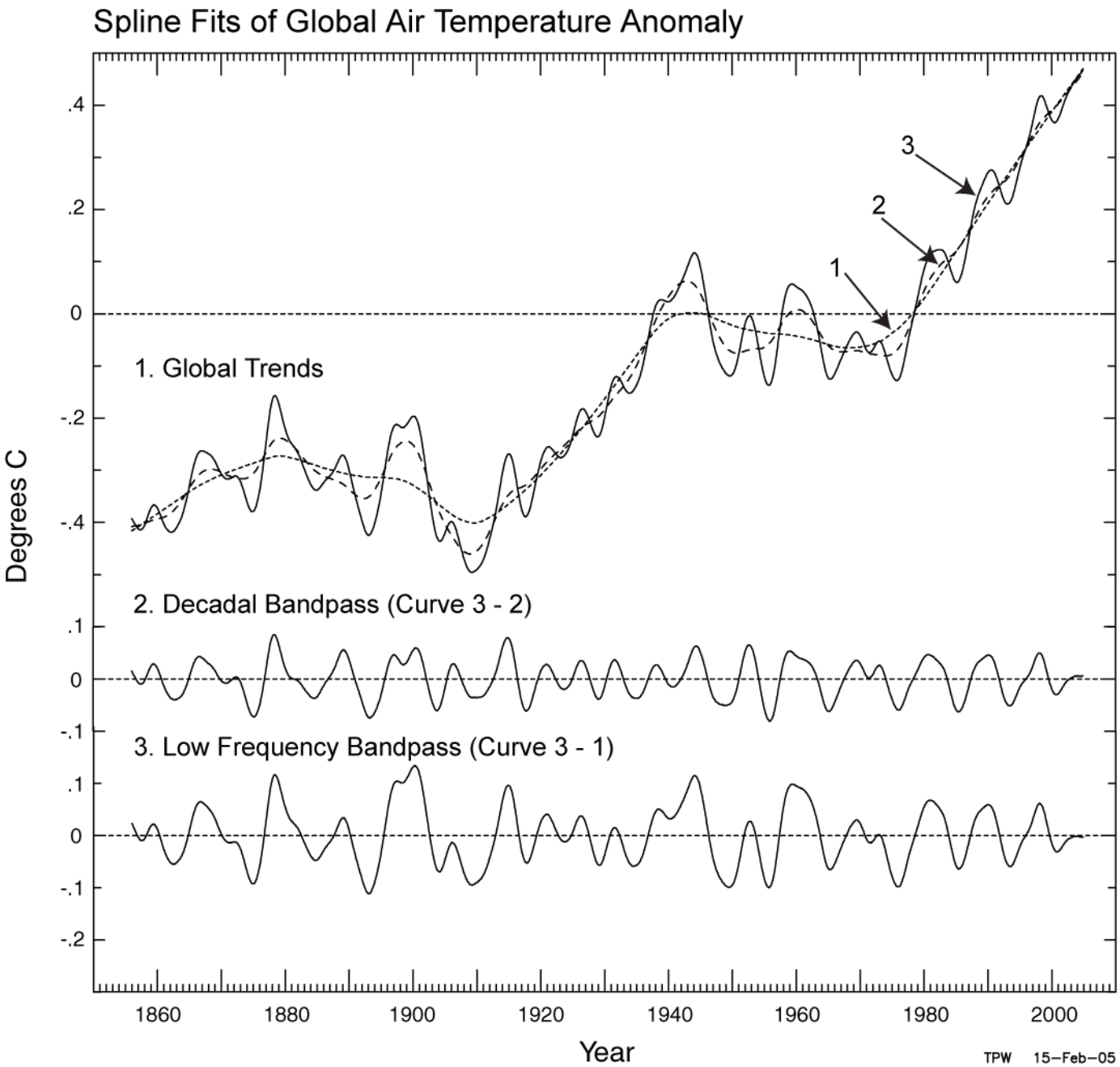

Global Rate of Change in CO2 and Air Temperature Anomaly Both Detrended
CO2 RATE OF CHG, PPM/YR
DEGREES C
CO2
Temperature
YEAR
TPW 16-Mar-05
4
3
2
1
0
-1
-2
-3
.8
.6
.4
.2
.0
-.2
-.4
-.6
58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04

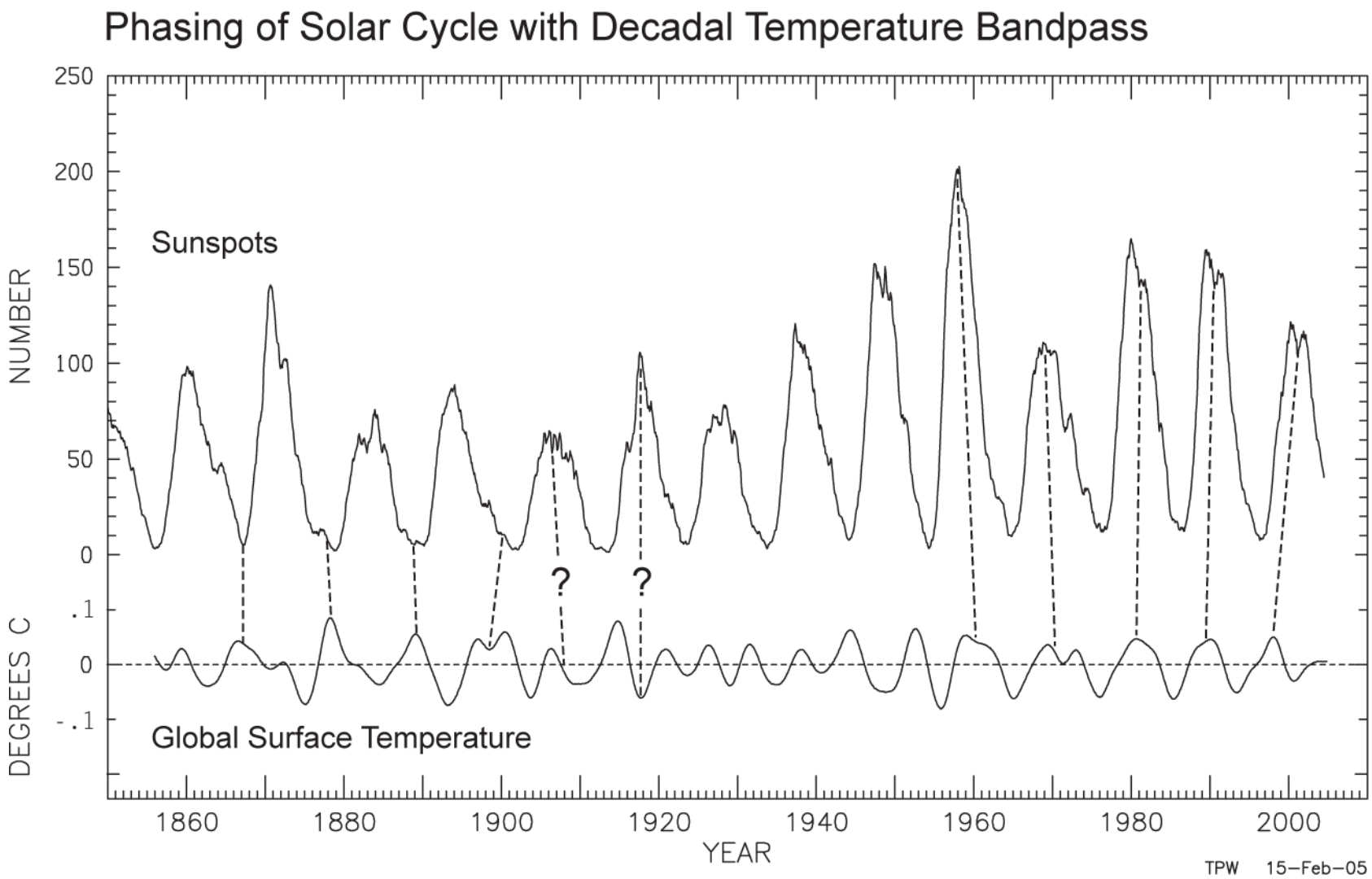

Decadal Variation in Global CO_2 and Air Temperature Anomaly
CO2 CONCENTRATION, (PPM)
DEGREES C
YEAR
Temperature
CO_2
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
.25
.20
.15
.10
.05
.00
-.05
-.10
-.15
-.20
-.25
58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04

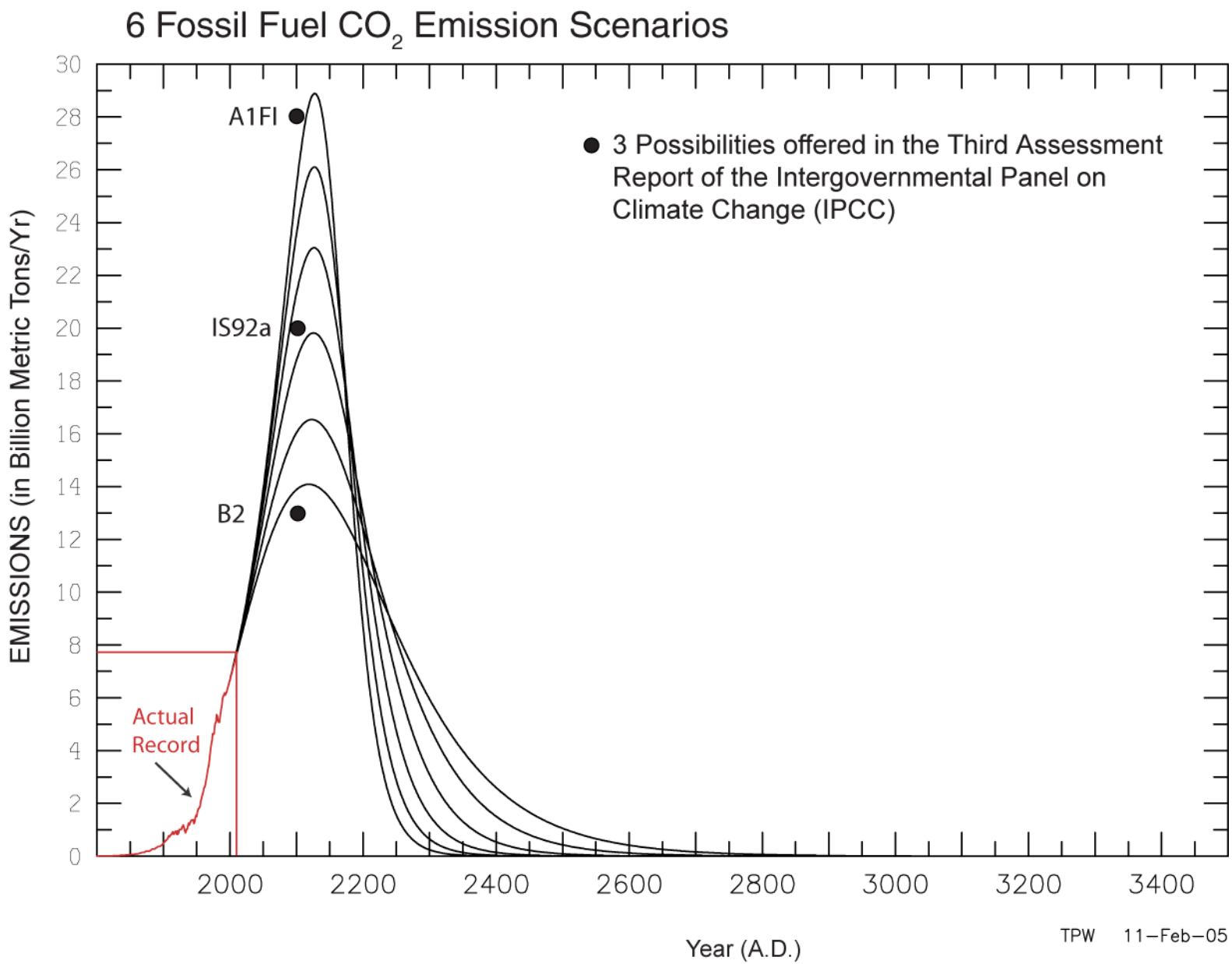

Global Land and Marine Temperatures (fit to monthly data)
Maximum smoothing to reveal half century trends
DEGREES C
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
TPW 1-Apr-05


Global Land and Marine Temperatures (fit to monthly data)
Smoothing to reveal bidecadel variations
DEGREES C
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
TPW 1-Apr-05

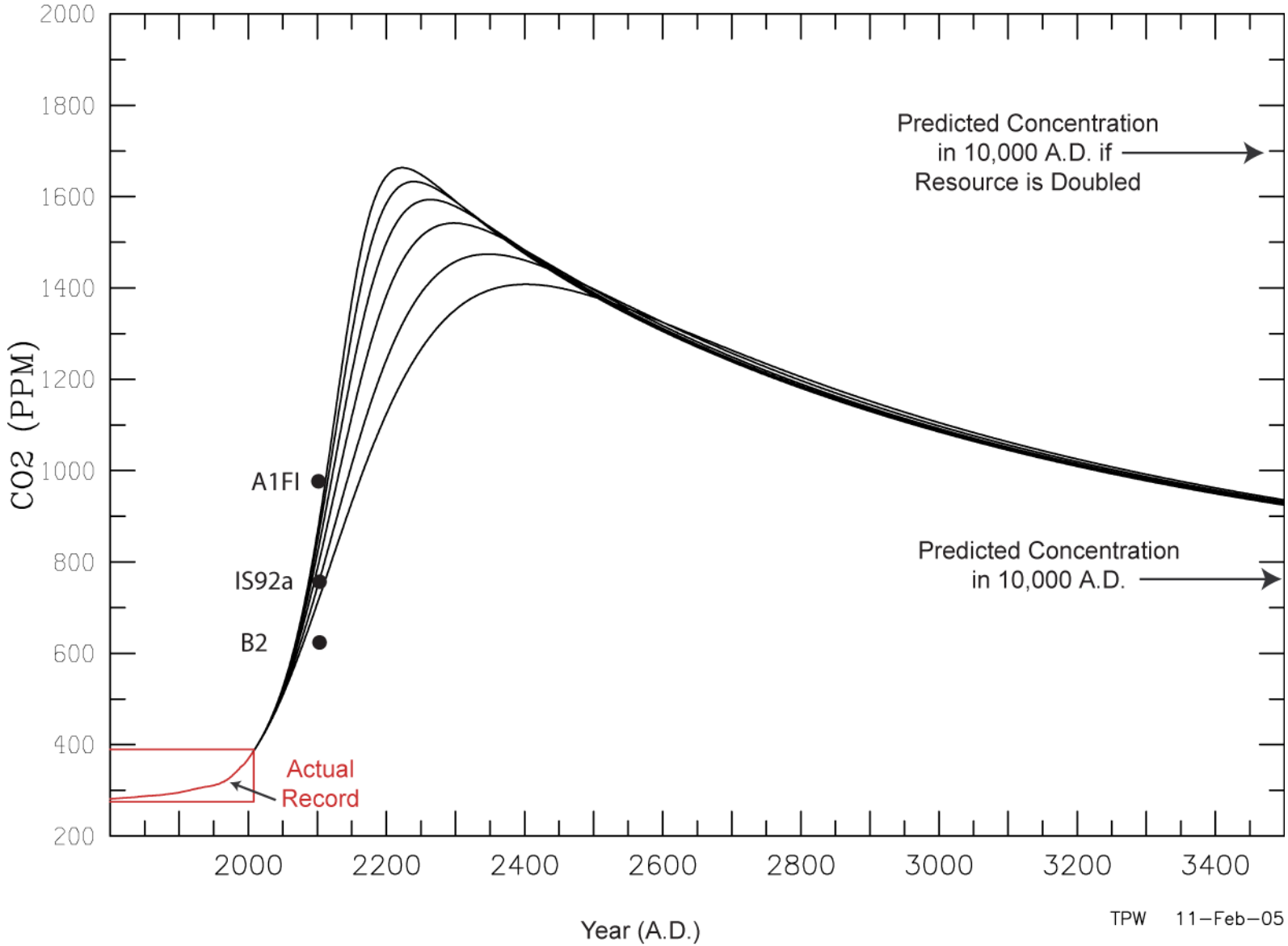

Global Land and Marine Temperatures (fit to monthly data)
Smoothing to reveal decadel variations
DEGREES C
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
TPW 1-Apr-05


Spline Fits of Global Air Temperature Anomaly
Degrees C
.4
.2
0
-.2
-.4
1. Global Trends
1
2
3
2. Decadal Bandpass (Curve 3 - 2)
.1
0
-.1
3. Low Frequency Bandpass (Curve 3 - 1)
.1
0
-.1
-.2
1860
1880
1900
1920
1940
1960
1980
2000
Year
TPW 15-Feb-05


Phasing of Solar Cycle with Decadal Temperature Bandpass
250
200
150
100
50
0
NUMBER
Sunspots
?
?
.1
0
-.1
DEGREES C
Global Surface Temperature
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
TPW 15-Feb-05


6 Fossil Fuel CO_2 Emission Scenarios
EMISSIONS (in Billion Metric Tons/Yr)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
A1FI
IS92a
B2
Actual Record
3 Possibilities offered in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)
2000
2200
2400
2600
2800
3000
3200
3400
Year (A.D.)
TPW 11–Feb–05

6 CO_2 Concentration Scenarios Assuming a Total Resource of 4240 Billion Metric Tons of Carbon



A Recent Example

Last October a reporter of a London Newspaper (the Independent) asked me by telephone whether the atmospheric CO_2 rise during 2002 and 2003 might be "unprecedented". I stated that the rise itself had a character similar to previous rapid rises seen in the Mauna Loa record. The rise correlated with a climatic feature, the "Southern Oscillation Index", which typically attains a negative peak during such times, including 2002-2003.

I explained that these negative peaks correspond to weak trade winds of the tropical Pacific associated with what are called "El Nino" events. He told me that other scientists whom he had queried said that there was no El Nino event in 2002-2003. I agreed that, if so, the break down of a relation between the Southern Oscillation index and El Nino might be construed as "unprecedented". Nevertheless what was critical to the CO_2 record was its correlation with the Southern Oscillation index reflecting changes in weather which could affect CO_2.

He replied that this discussion was "too complicated to write up" for his newspaper.

His simplification turned out to be that "the POSSIBILITY of a 'feedback' impetus to global warming, greatly accelerating the process of climate change [may oblige] us to rip up our present forecasts [of climate change] as too optimistic." This message (and more) was picked up by other newspapers including the Guardian (see excerpt below).

Charles D. Keeling

GuardianUnlimited network

Climate fear as carbon levels soar

Scientists bewildered by sharp rise of CO2 in atmosphere for second year running

Paul Brown, environment correspondent
Monday October 11, 2004
The Guardian

An unexplained and unprecedented rise in carbon dioxide in the atmosphere two years running has raised fears that the world may be on the brink of runaway global warming.

Scientists are baffled why the quantity of the main greenhouse gas has leapt in a two-year period and are concerned that the Earth's natural systems are no longer able to absorb as much as in the past.

The findings will be discussed tomorrow by the government's chief scientist, Dr David King, at the annual Greenpeace business lecture.

Measurements of CO2 in the atmosphere have been continuous for almost 50 years at Mauna Loa Observatory, 12,000ft up a mountain in Hawaii, regarded as far enough away from any carbon dioxide source to be a reliable measuring point.

In recent decades CO2 increased on average by 1.5 parts per million (ppm) a year because of the amount of oil, coal and gas burnt, but has now jumped to more than 2 ppm in 2002 and 2003.

Above or below average rises in CO2 levels in the atmosphere have been explained in the past by natural events.

(London Newspaper)

When the Pacific warms up during El Niño - a disruptive weather pattern caused by weakening trade winds - the amount of carbon dioxide rises dramatically because warm oceans emit CO2 rather than absorb it.

But scientists are puzzled because over the past two years, when the increases have been 2.08 ppm and 2.54 ppm respectively, there has been no El Niño.

Charles Keeling, the man who began the observations in 1958 as a young climate scientist, is now 74 and still working in the field.

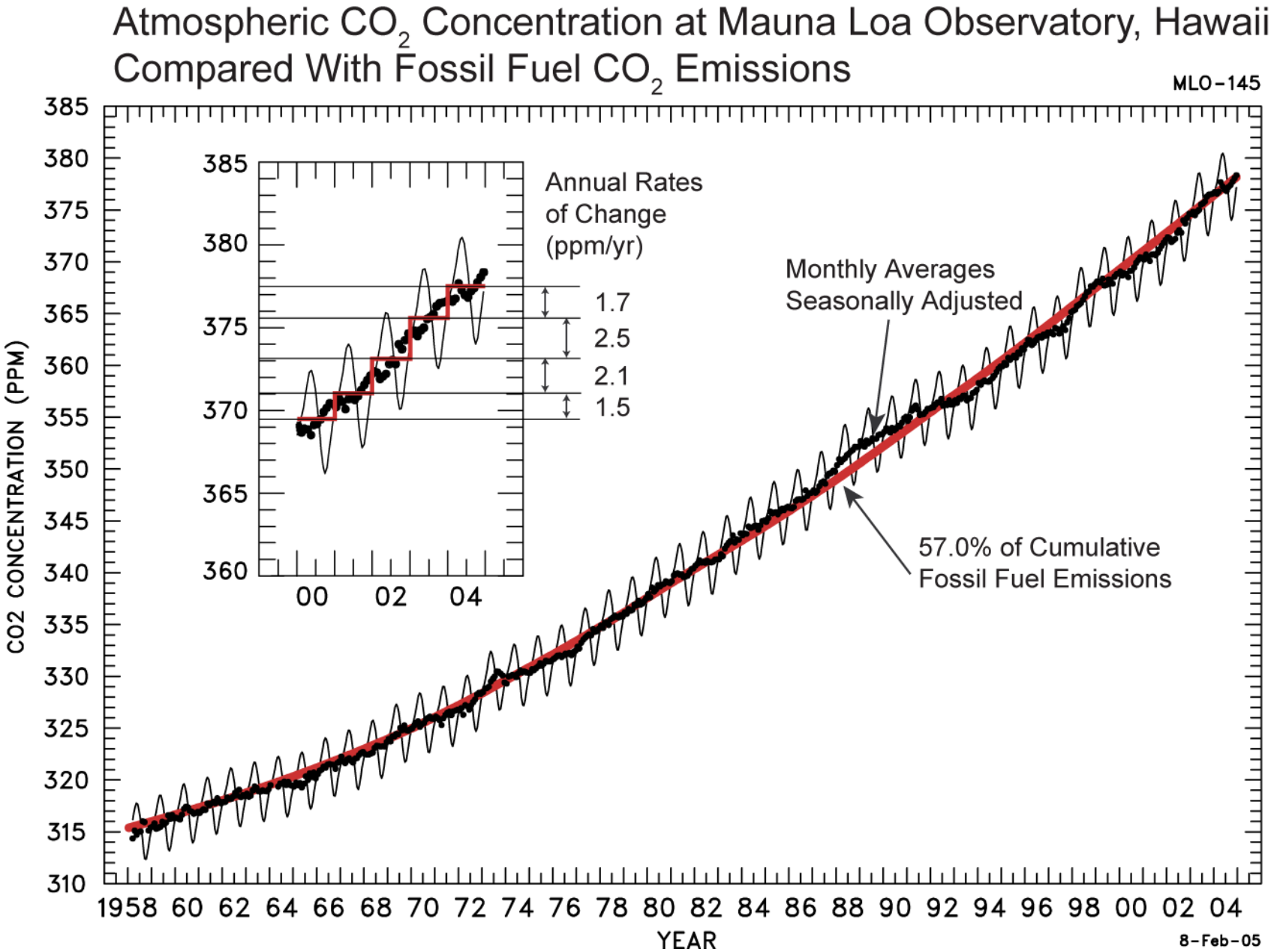
He said yesterday: "The rise in the annual rate to above two parts per million for two consecutive years is a real phenomenon.

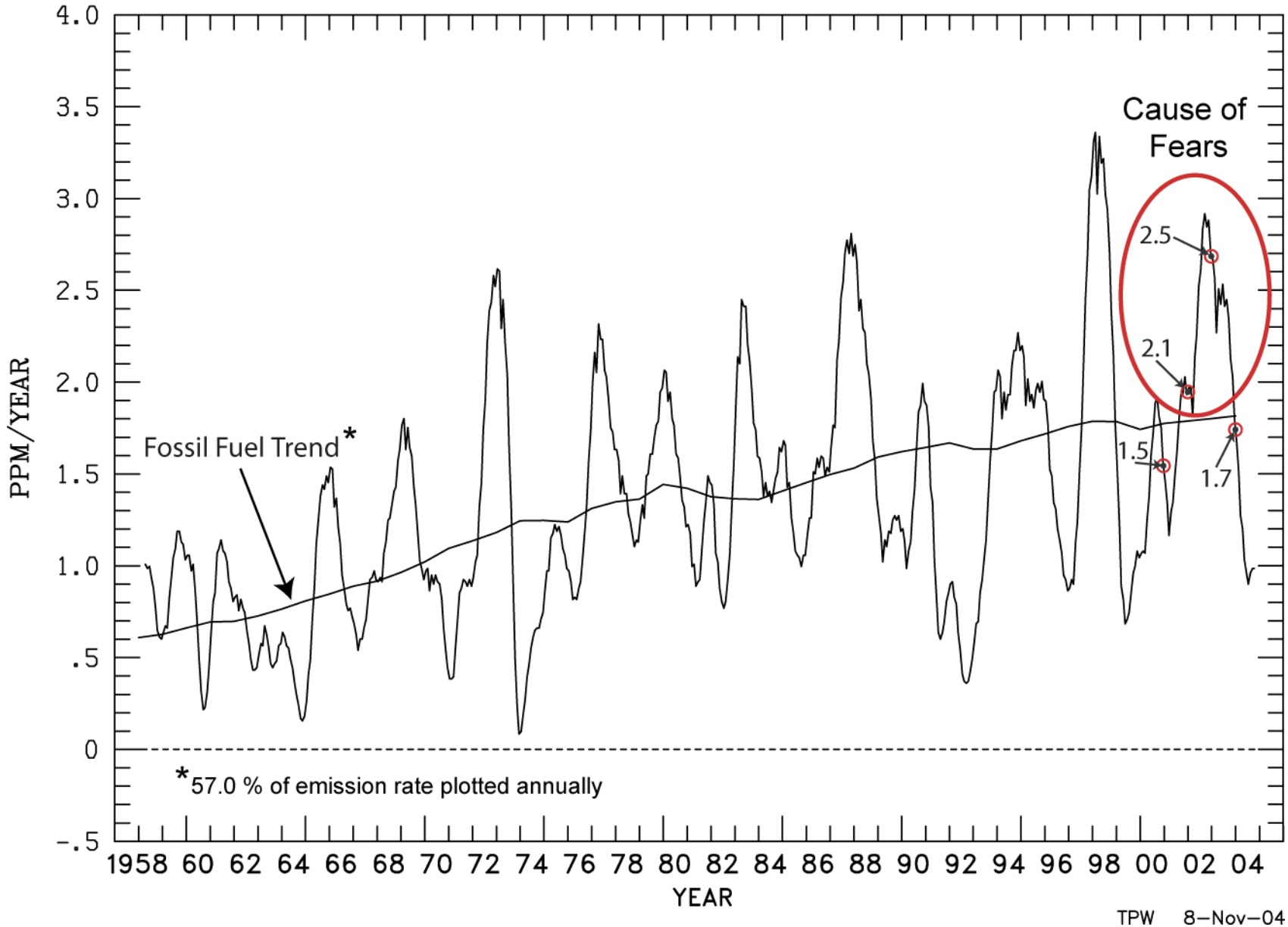
"It is possible that this is merely a reflection of natural events like previous peaks in the rate, but it is also possible that it is the beginning of a natural process unprecedented in the record."

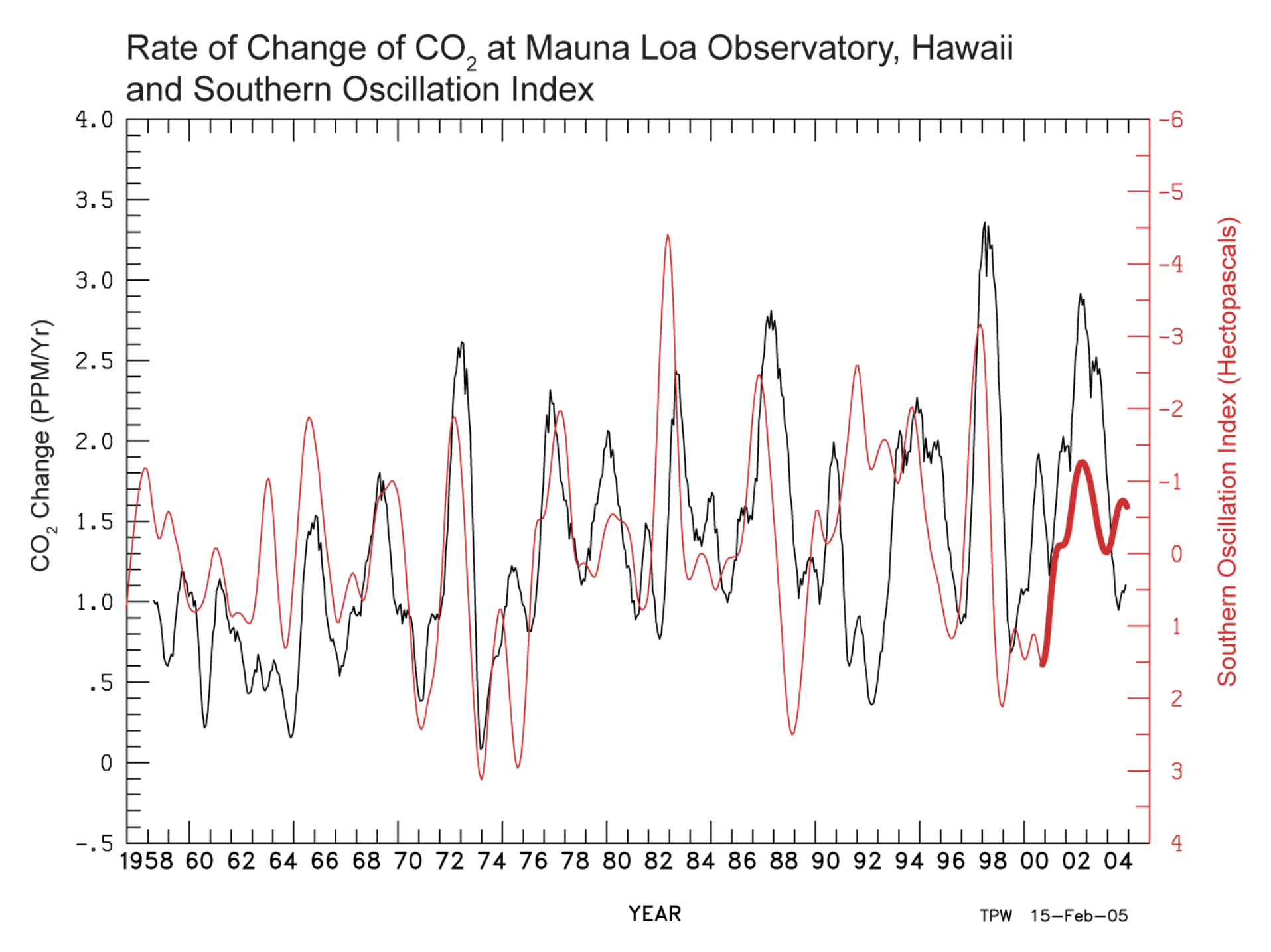
Analysts stress that it is too early to draw any long-term conclusions.

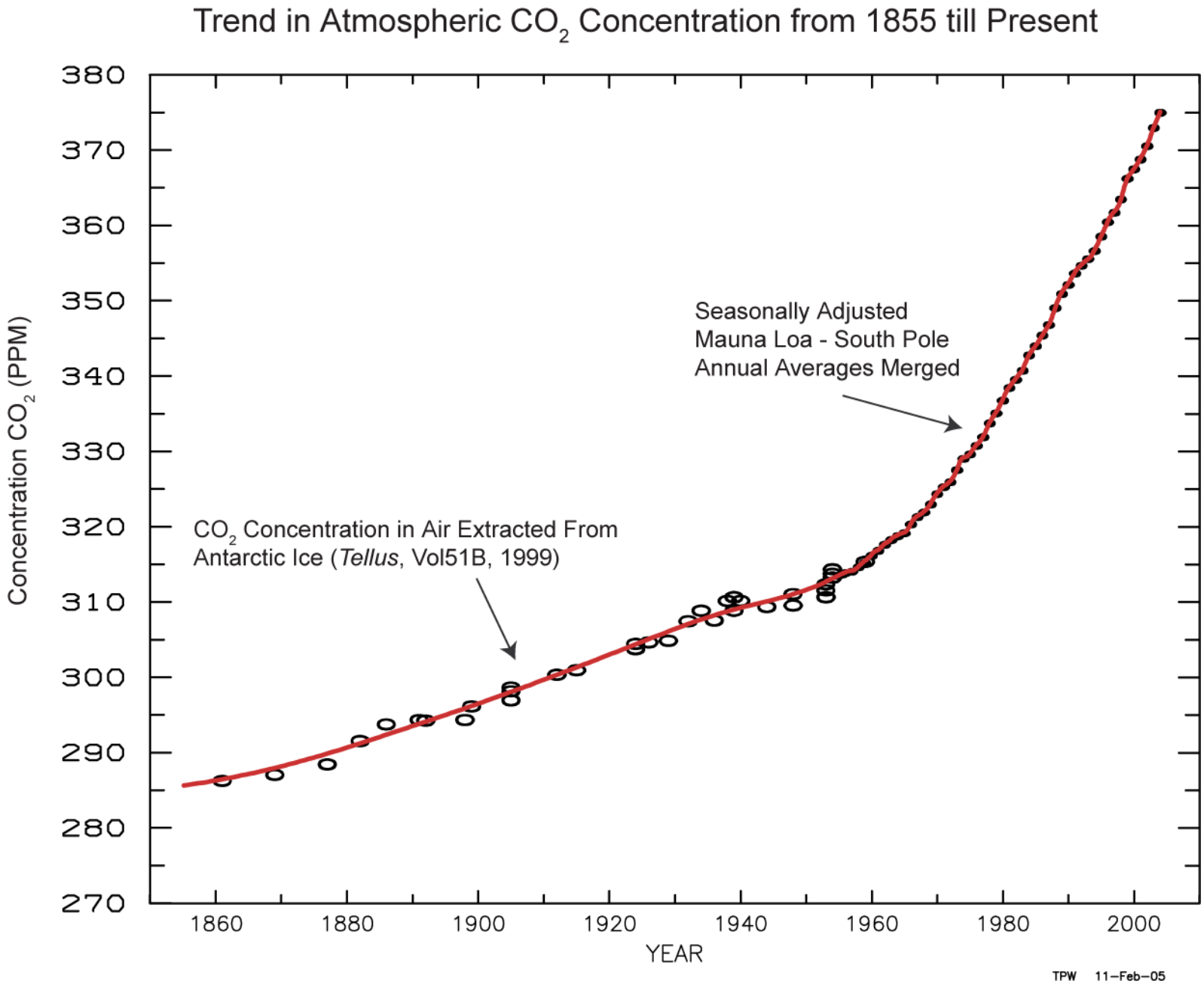
But the fear held by some scientists is that the greater than normal rises in C02 emissions mean that instead of decades to bring global warming under control we may have only a few years. At worst, the figures could be the first sign of the breakdown in the Earth's natural systems for absorbing the gas.

That would herald the so-called "runaway greenhouse effect", where the planet's soaring temperature becomes impossible to contain. As the icecaps melt, less sunlight is refected back into space from ice and snow, and bare rocks begin to absorb more heat. This is already happening.

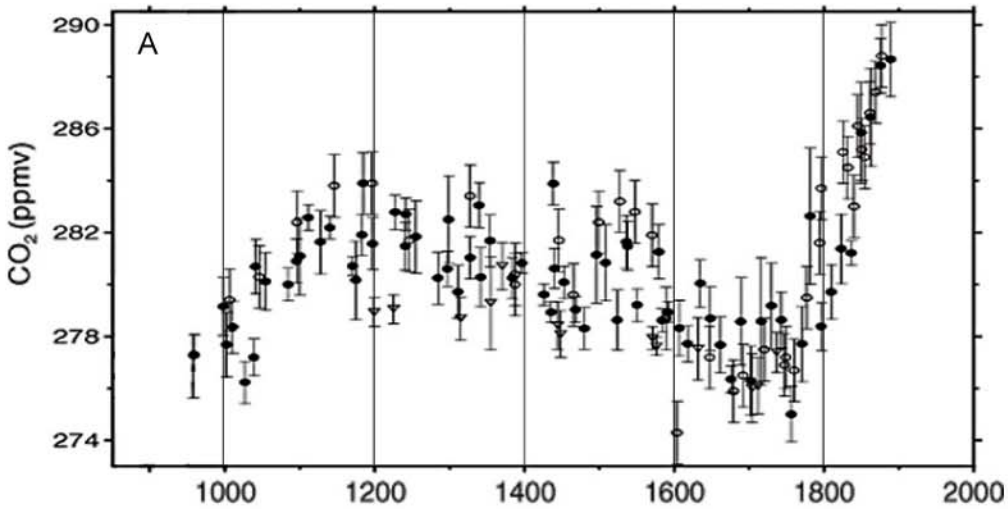

Atmospheric CO2 Concentration at Mauna Loa Observatory, Hawaii
Compared With Fossil Fuel CO2 Emissions
MLO-145
CO2 CONCENTRATION (PPM)
YEAR
8-Feb-05
Annual Rates
of Change
(ppm/yr)
1.7
2.5
2.1
1.5
Monthly Averages
Seasonally Adjusted
57.0% of Cumulative
Fossil Fuel Emissions


Rate of Change of CO_2 at Mauna Loa Observatory, Hawaii
and Associated Fossil Fuel Trend
PPM/YEAR
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
0
-.5
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
Cause of
Fears
2.5
2.1
1.5
1.7
Fossil Fuel Trend*
*57.0 % of emission rate plotted annually
TPW 8–Nov–04

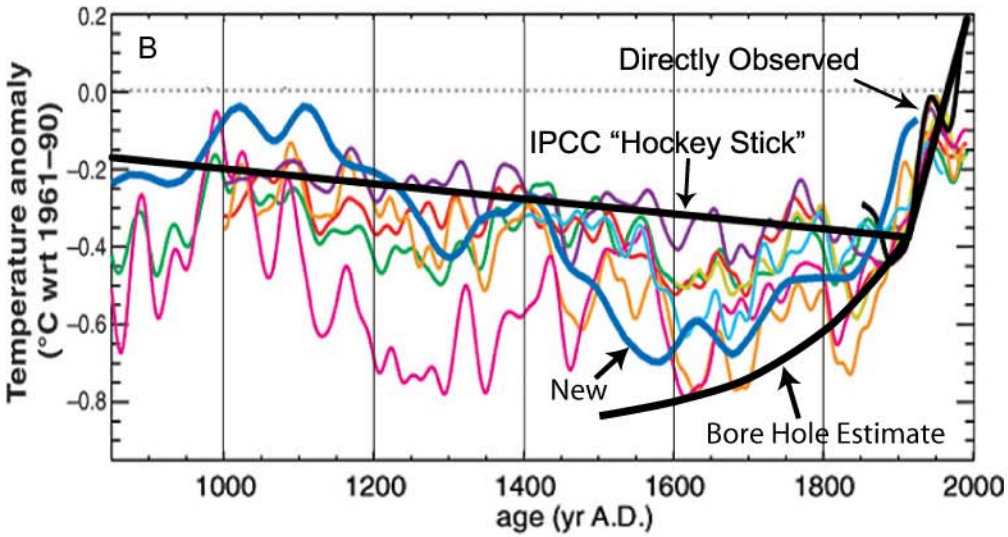

Rate of Change of CO_2 at Mauna Loa Observatory, Hawaii
and Southern Oscillation Index
CO_2 Change (PPM/Yr)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
0
-.5
Southern Oscillation Index (Hectopascals)
-6
-5
-4
-3
-2
-1
0
1
2
3
4
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
TPW 15-Feb-05


Trend in Atmospheric CO_2 Concentration from 1855 till Present
Concentration CO_2 (PPM)
380
370
360
350
340
330
320
310
300
290
280
270
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
Seasonally Adjusted
Mauna Loa - South Pole
Annual Averages Merged
CO_2 Concentration in Air Extracted From
Antarctic Ice (*Tellus*, Vol51B, 1999)
TPW 11–Feb–05

Carbon Dioxide and Temperature - Comparison over the Last Millennium



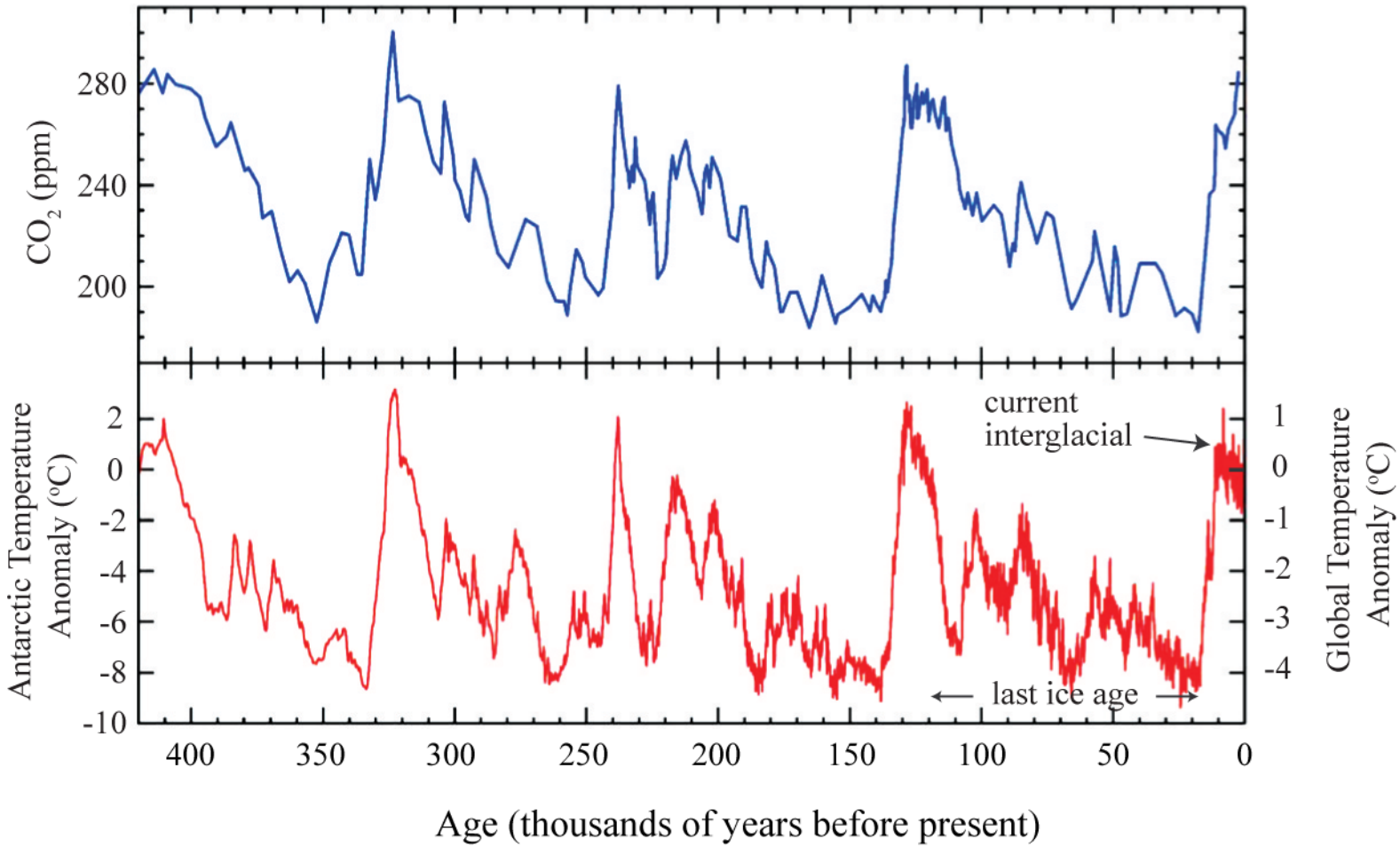
A) Atmospheric CO_2 data from Antarctica Ice Cores at 3 locations (Tellus, 57B.5, 2005).



B) Temperature records recovered from tree rings and other proxies.

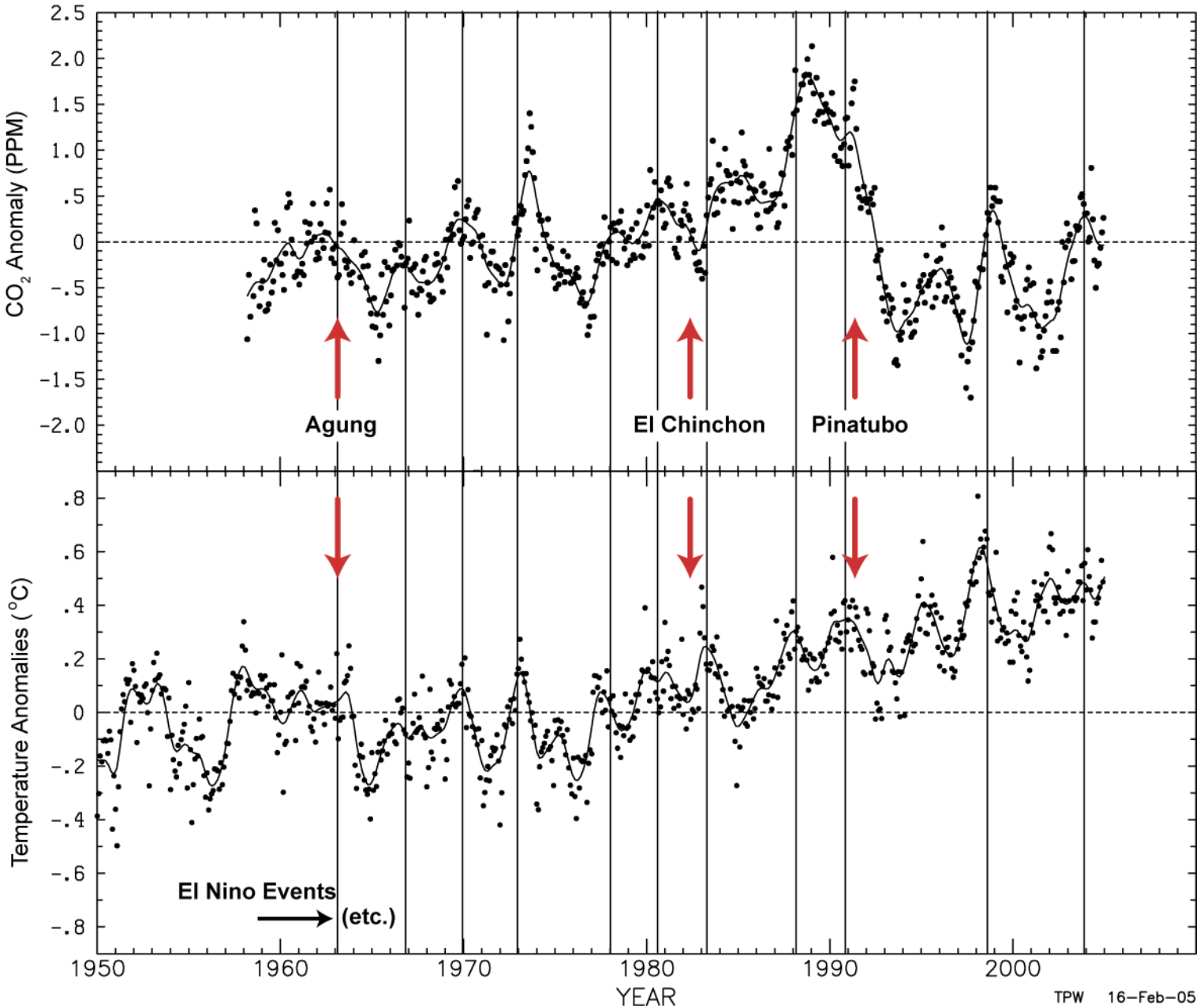
Dark Blue Line: new data from Moberg et al. (2005).
Ref: Science Vol. 387, 2005.

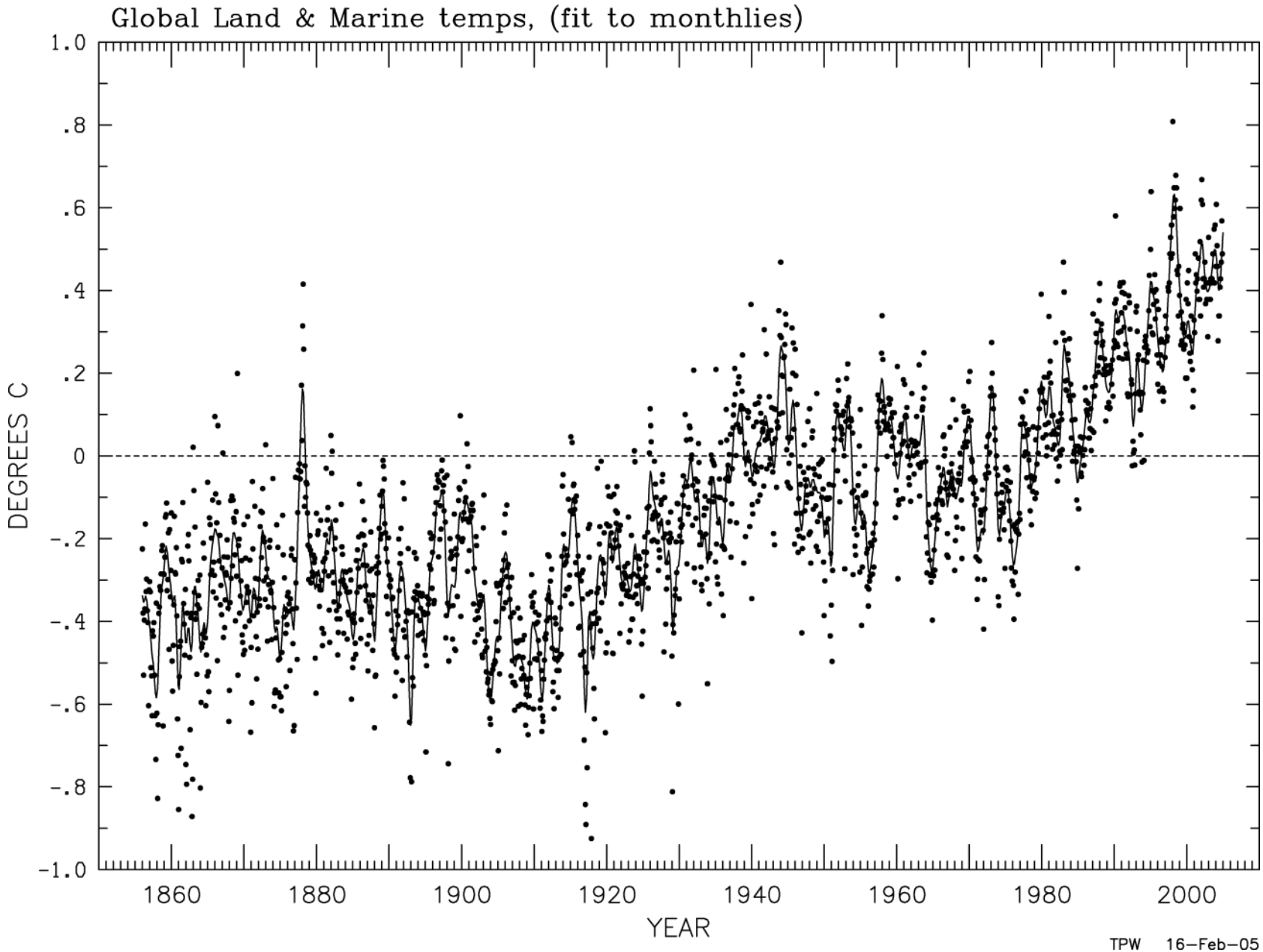
Vostok carbon dioxide, and temperature record for the past 420,000 years (*Nature*, Vol. 399, 1999).

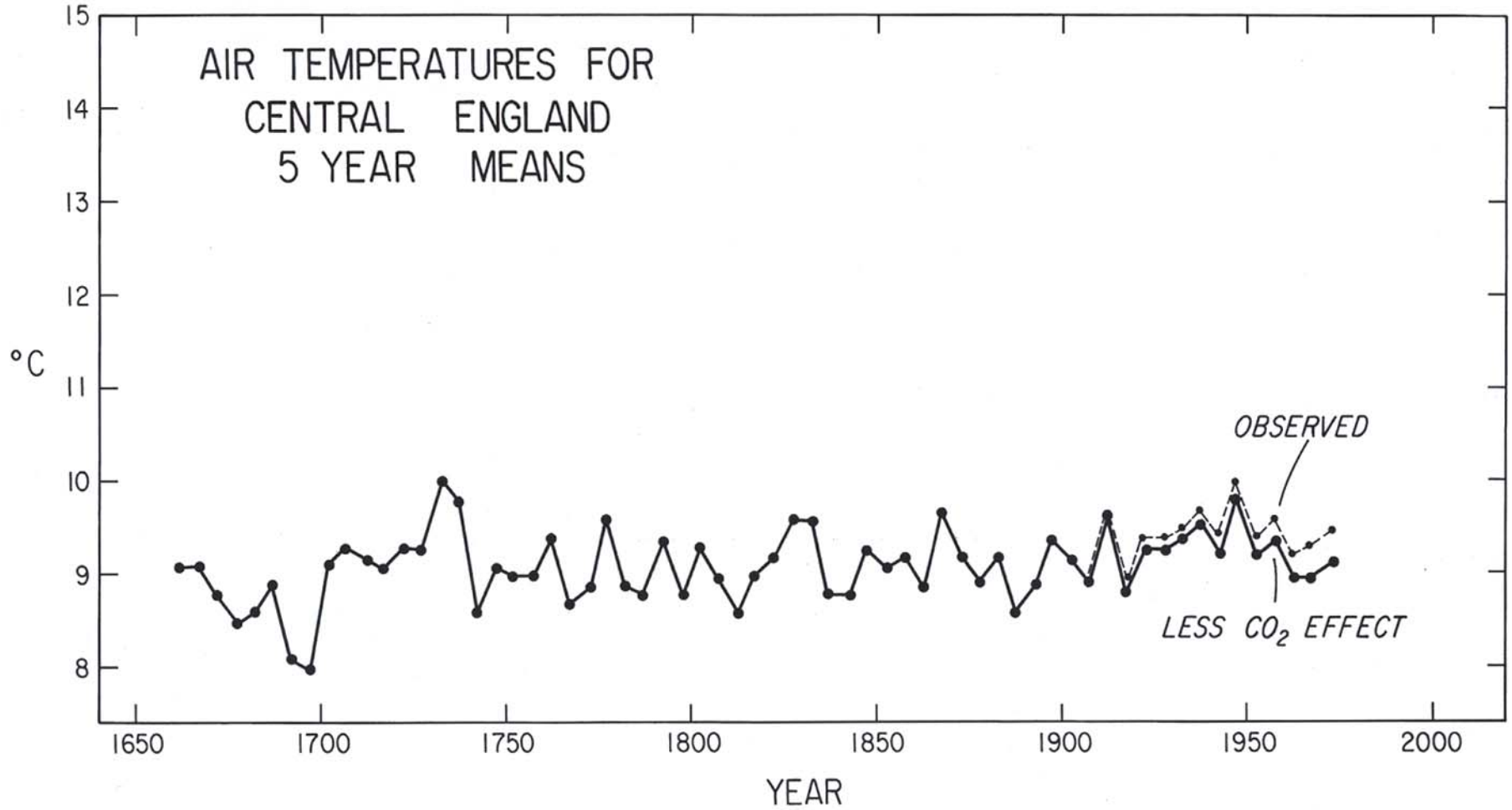


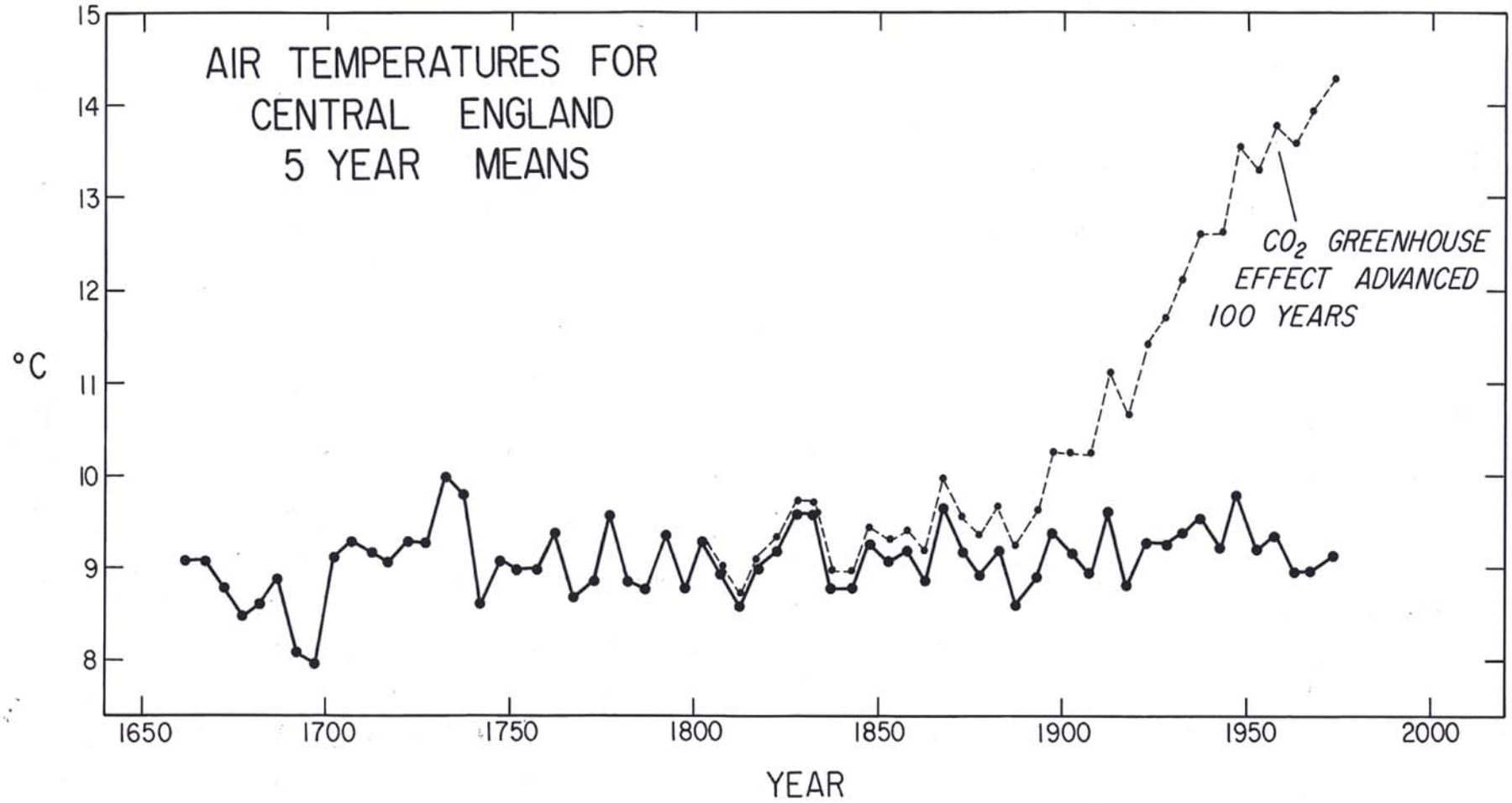
Data are from an Antarctic Ice Core.
Temperatures observed are estimates from variations in $^{18}O/^{16}O$ of the ice.

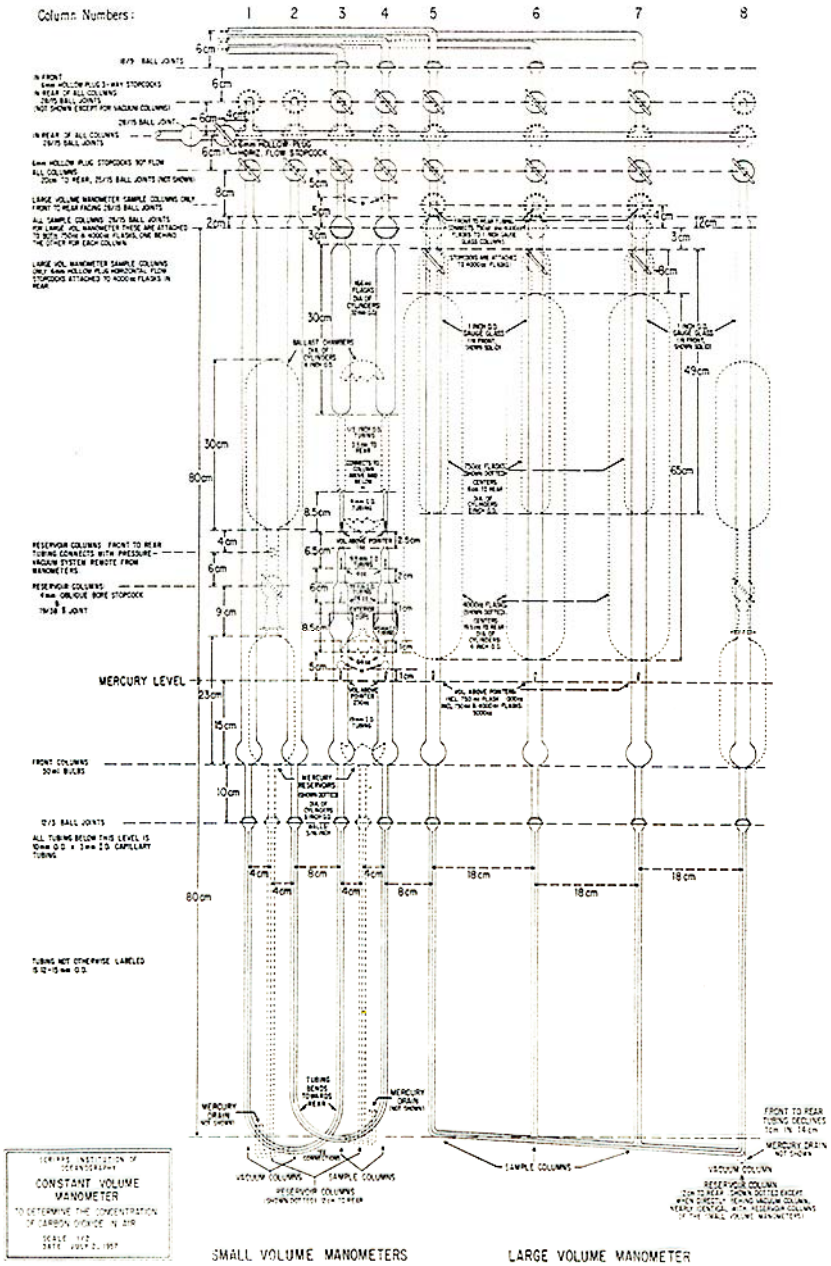
Carbon Dioxide and Temperature - Comparison over Past Half Century

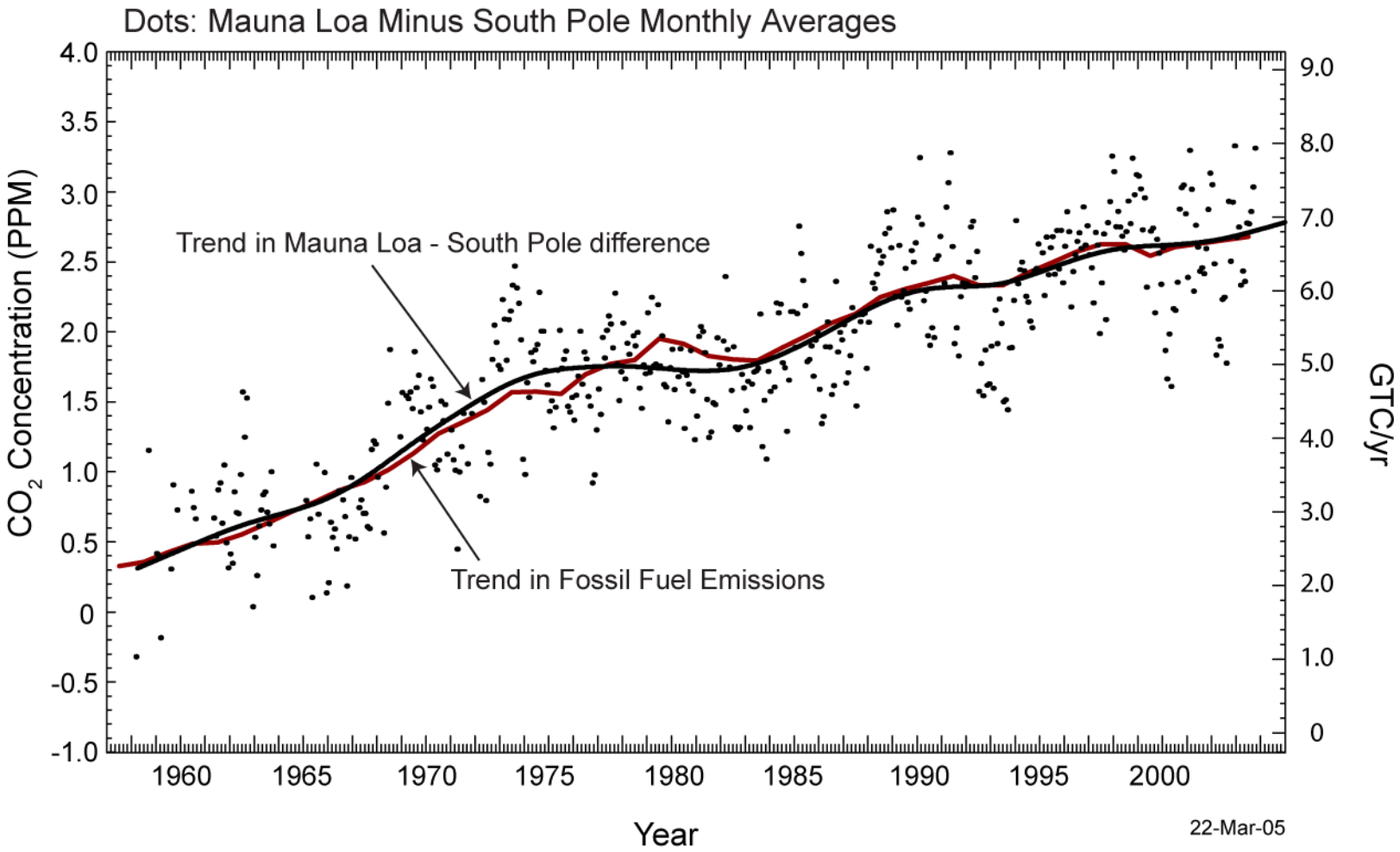



Global Land & Marine temps, (fit to monthlies)
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
DEGREES C
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
TPW 16-Feb-05


AIR TEMPERATURES FOR
CENTRAL ENGLAND
5 YEAR MEANS
°C
15
14
13
12
11
10
9
8
1650
1700
1750
1800
1850
1900
1950
2000
YEAR
OBSERVED
LESS CO_2 EFFECT


AIR TEMPERATURES FOR
CENTRAL ENGLAND
5 YEAR MEANS
CO_2 GREENHOUSE
EFFECT ADVANCED
100 YEARS
°C
15
14
13
12
11
10
9
8
1650
1700
1750
1800
1850
1900
1950
2000
YEAR


Column Numbers:
1
2
3
4
5
6
7
8
MERCURY LEVEL
SMALL VOLUME MANOMETERS
LARGE VOLUME MANOMETER
CONSTANT VOLUME MANOMETER
TO DETERMINE THE CONCENTRATION OF CARBON DIOXIDE IN AIR


Dots: Mauna Loa Minus South Pole Monthly Averages
Trend in Mauna Loa - South Pole difference
Trend in Fossil Fuel Emissions
CO2 Concentration (PPM)
GTC/yr
Year
22-Mar-05
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1960
1965
1970
1975
1980
1985
1990
1995
2000