AEROSOL INFLUENCES ON CLIMATE
RADIATIVE FORCING AND BEYOND

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Symposium on

Impacts of Clouds and Aerosols on Terrestrial Carbon
and Hydrological Cycles (ICATCH)

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These viewgraphs available at

http://www.ecd.bnl.gov/steve/pubs.html

OUTLINE

Attribution of excess atmospheric CO_2 to fossil fuel emissions and land use changes

Time constant of CO_2 emissions and CO_2 residence time

Time constant of climate change

Aerosol influences on climate change

Residence time of tropospheric aerosols

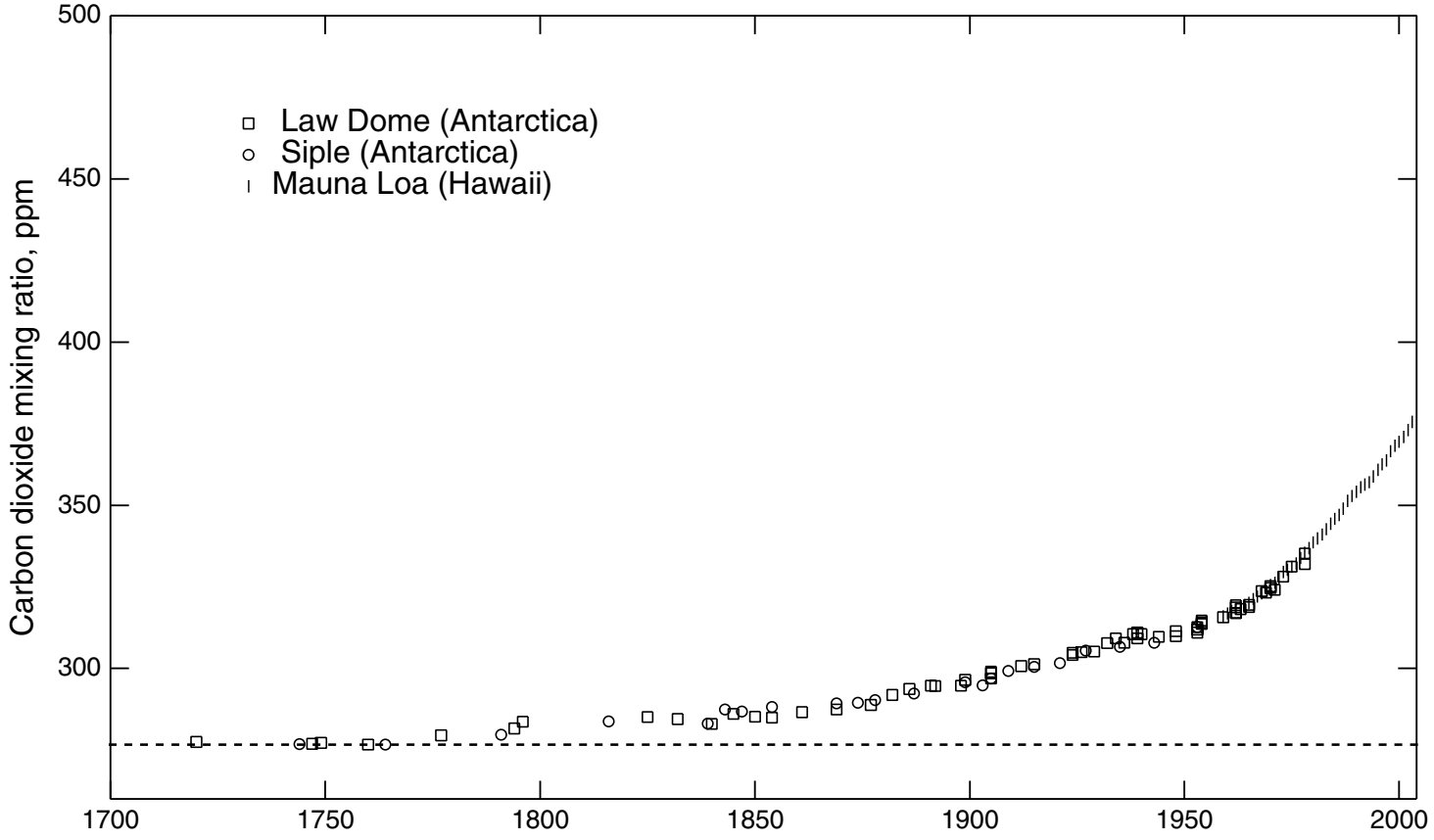
Integrated forcing of greenhouse gases and aerosols

Concluding remarks

INCREASES IN CO_2 OVER THE INDUSTRIAL PERIOD

ATMOSPHERIC CARBON DIOXIDE

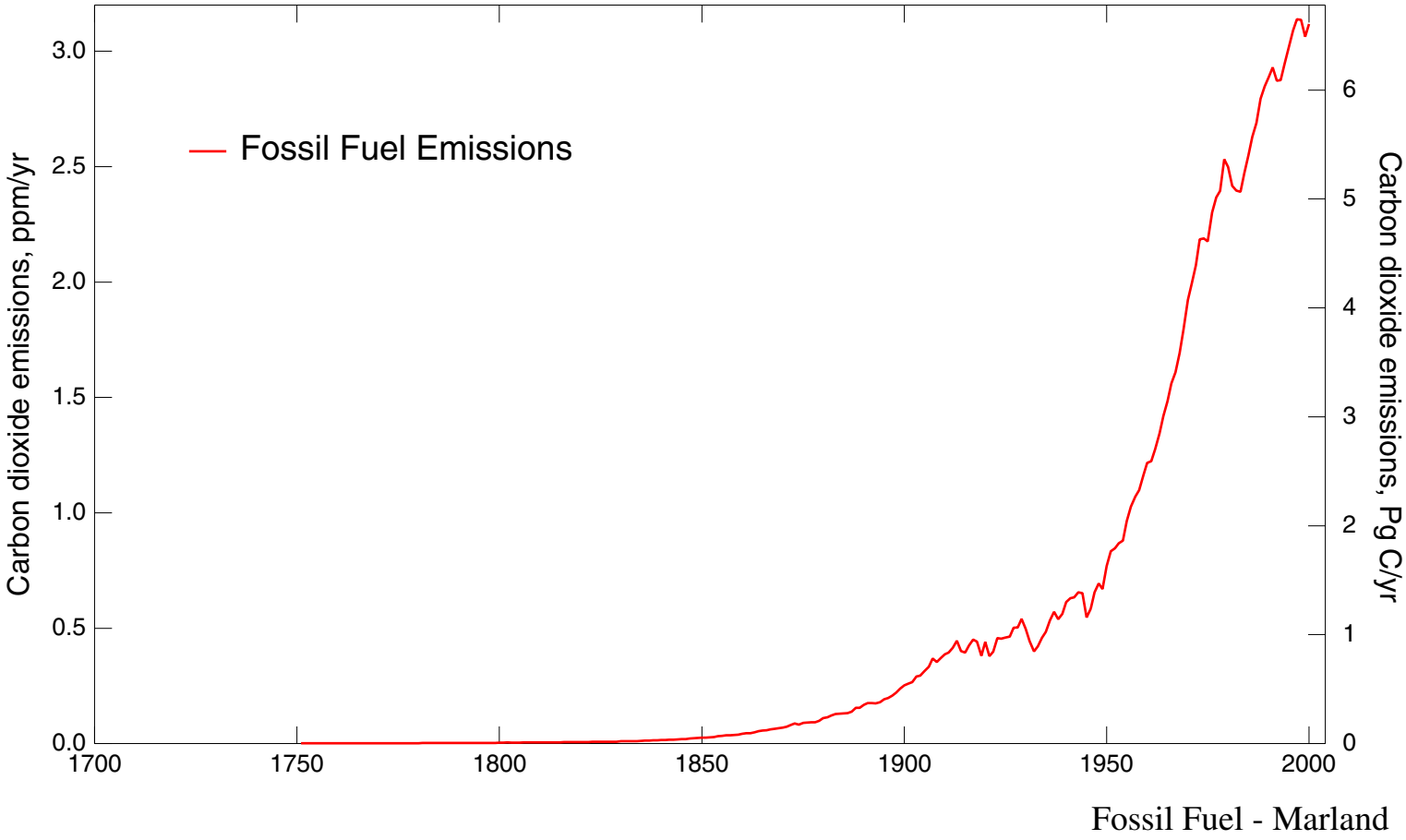
Time series 1700 - 2003



Law - Etheridge et al.
Siple - Friedli et al.
Mauna Loa - Keeling

ATMOSPHERIC CO_2 EMISSIONS

Time series 1700 - 2003



Fossil Fuel - Marland

ATMOSPHERIC CARBON DIOXIDE

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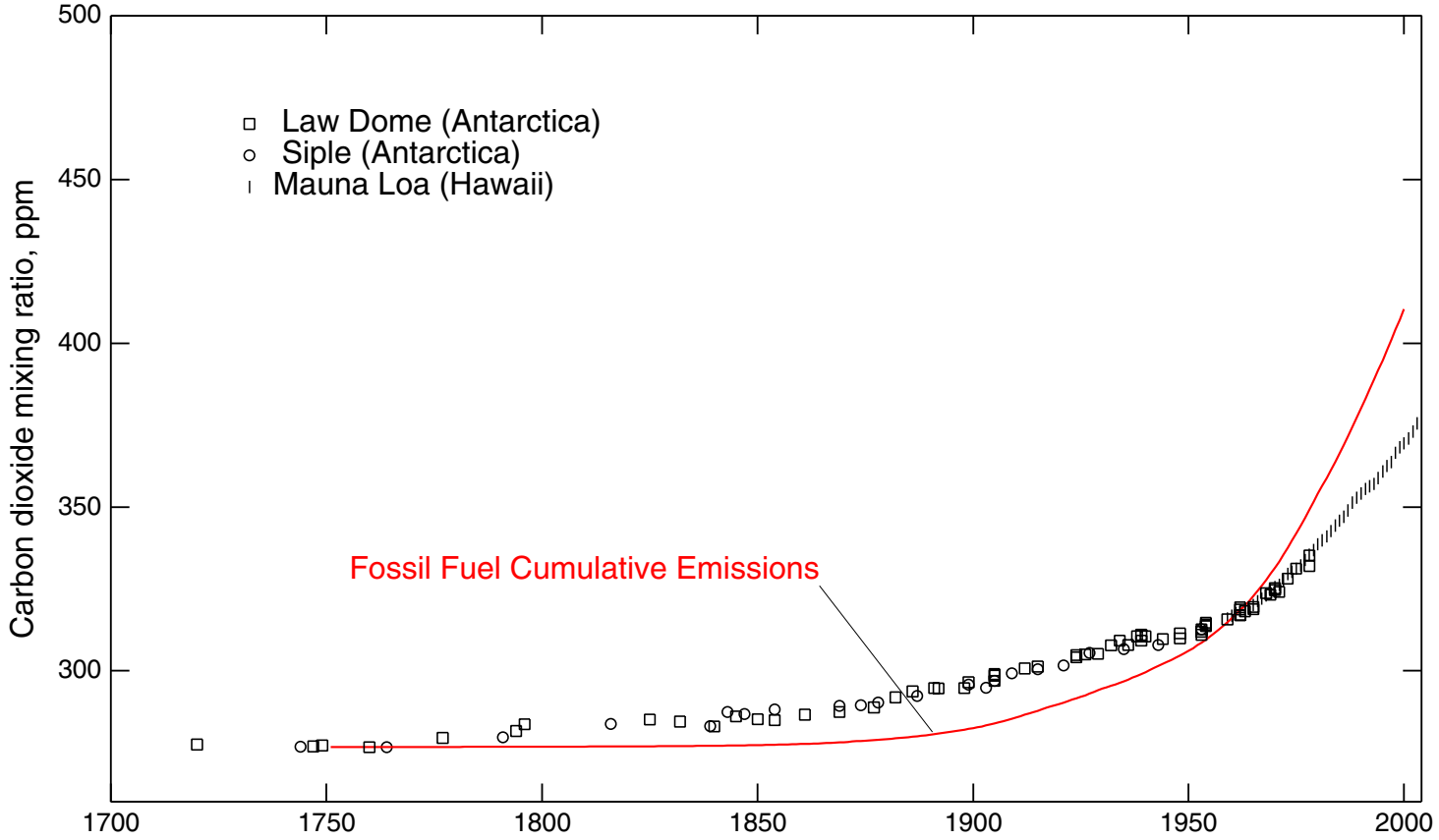

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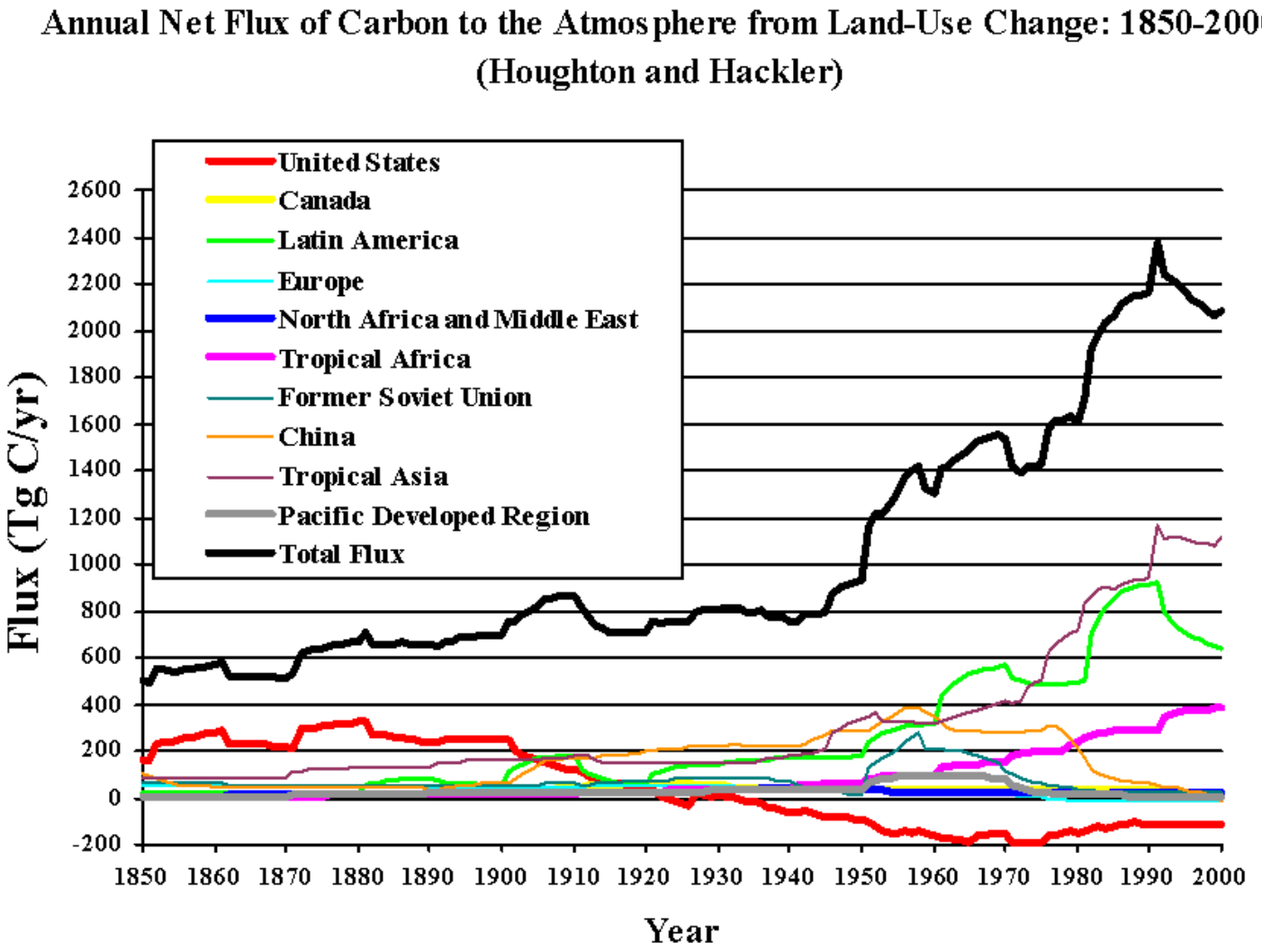
What's missing?

LAND USE CARBON EMISSIONS BY SOURCE REGION



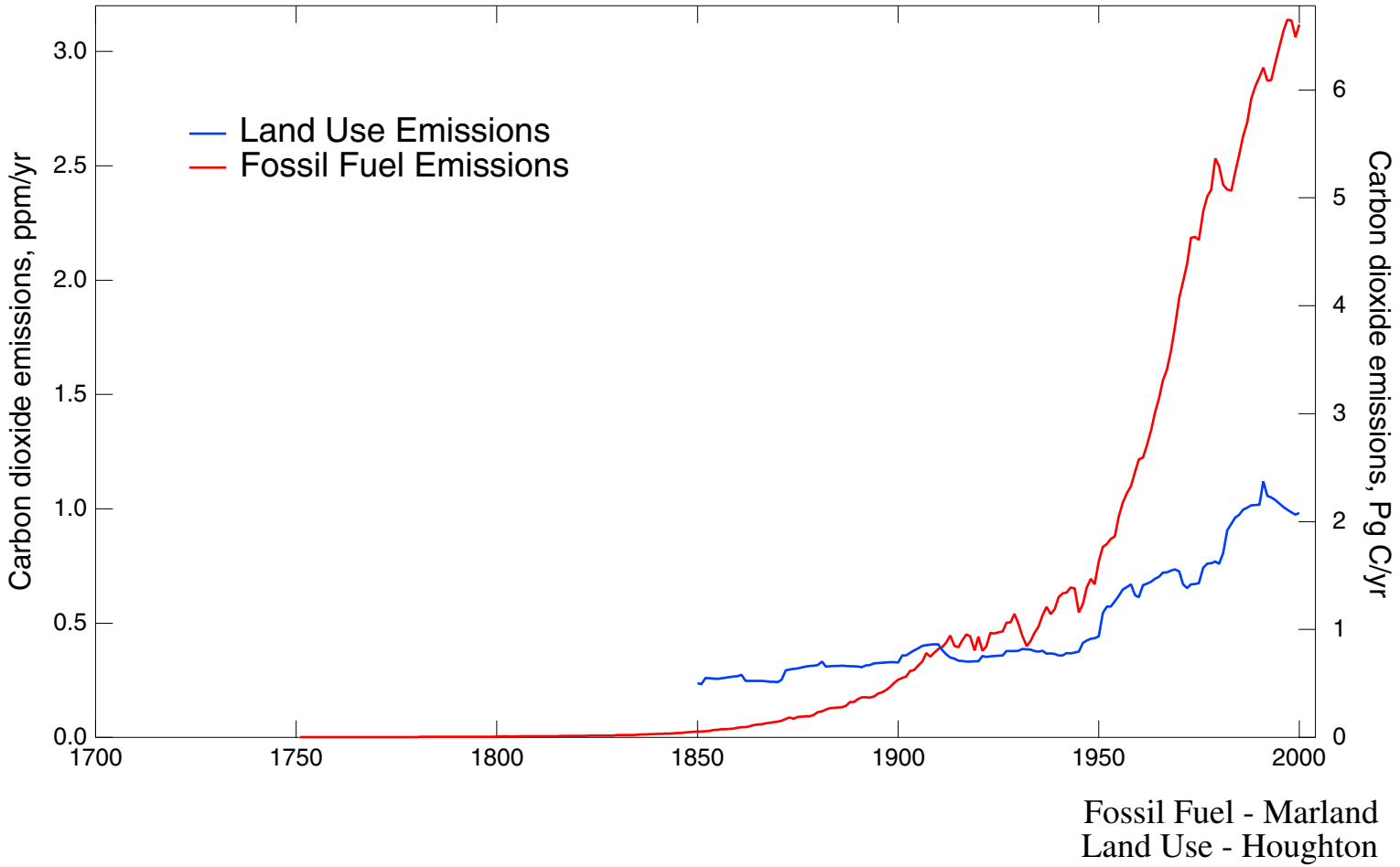
1000 Tg = 1 Pg
= 10^{15} g,
Equivalent to
0.47 ppm

Carbon flux estimated as land area times carbon emissions associated with deforestation (or uptake associated with afforestation).

United States dominates emissions before 1900 and uptake after 1940.

ATMOSPHERIC CO_2 EMISSIONS

Time series 1700 - 2003

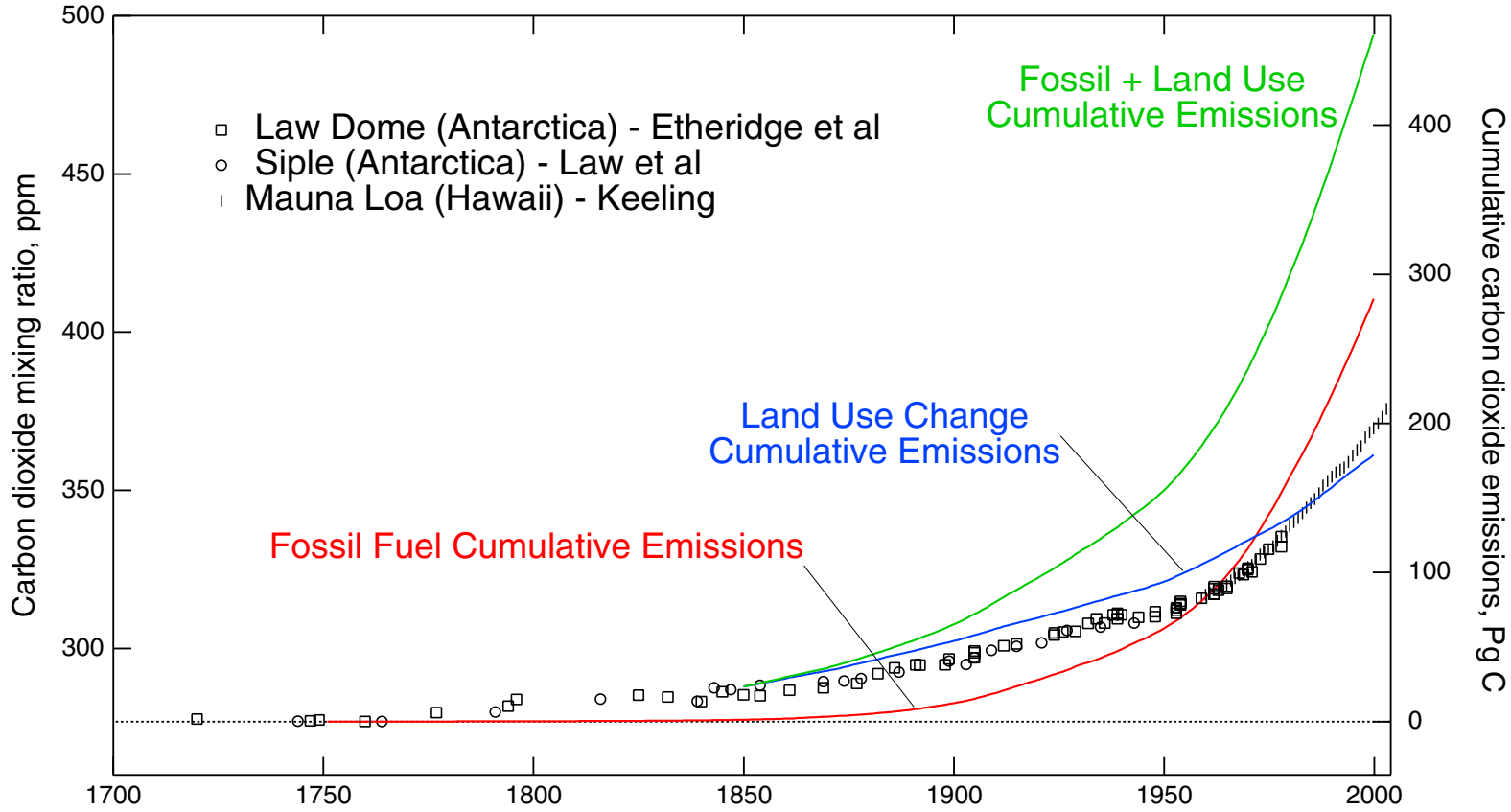


Prior to 1910 CO_2 emissions from land use changes were dominant.

Subsequently fossil fuel CO_2 has been dominant and rapidly increasing!

ATTRIBUTION OF INCREASE IN ATMOSPHERIC CO_2

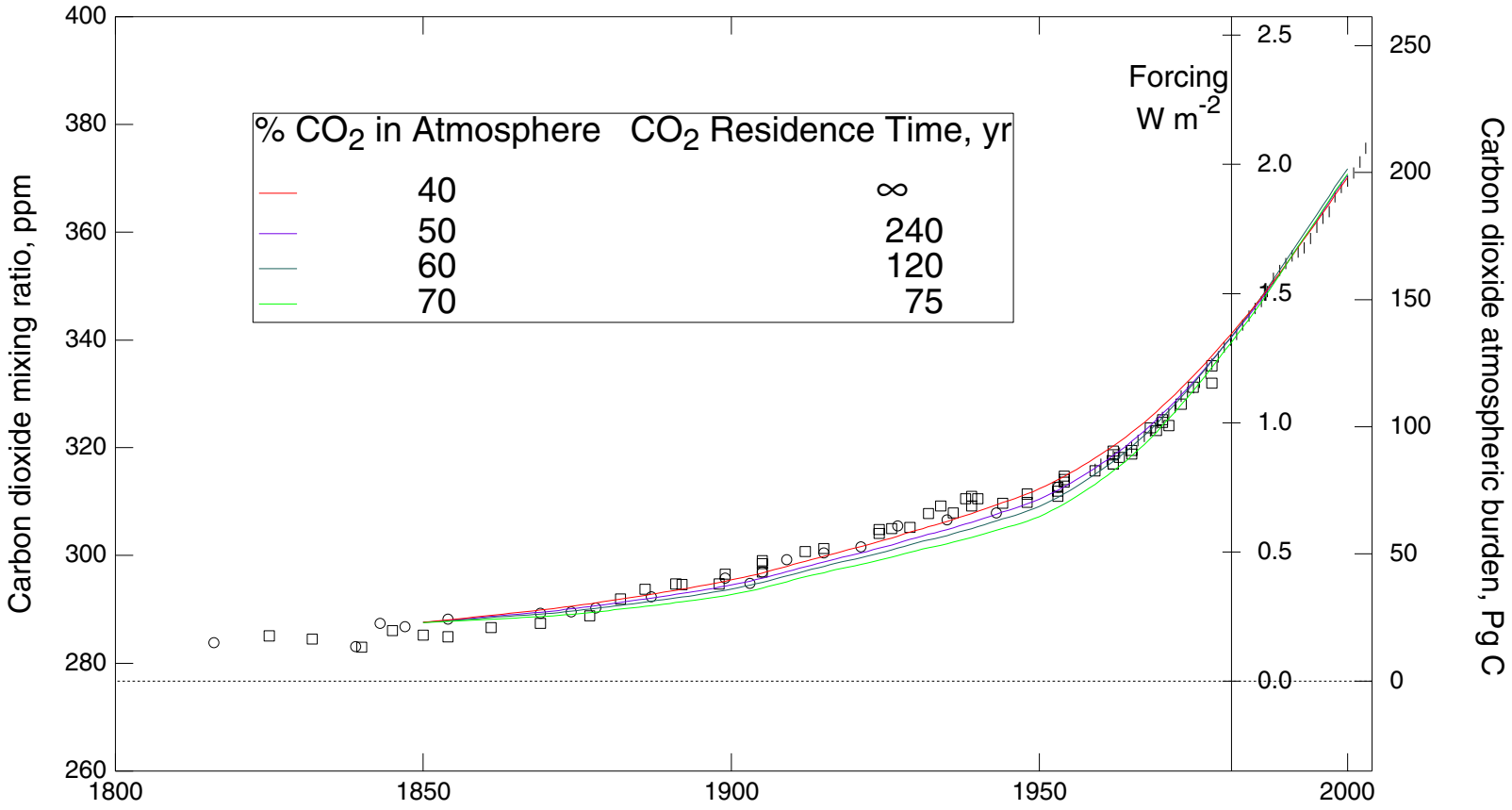
Comparison of ***cumulative*** CO_2 emissions from fossil fuel combustion and land use changes with measured increases in atmospheric CO_2.



Prior to 1970 the increase in atmospheric CO_2 was dominated by emissions from land use changes, not fossil fuel combustion.

ATTRIBUTION OF ATMOSPHERIC CO_2

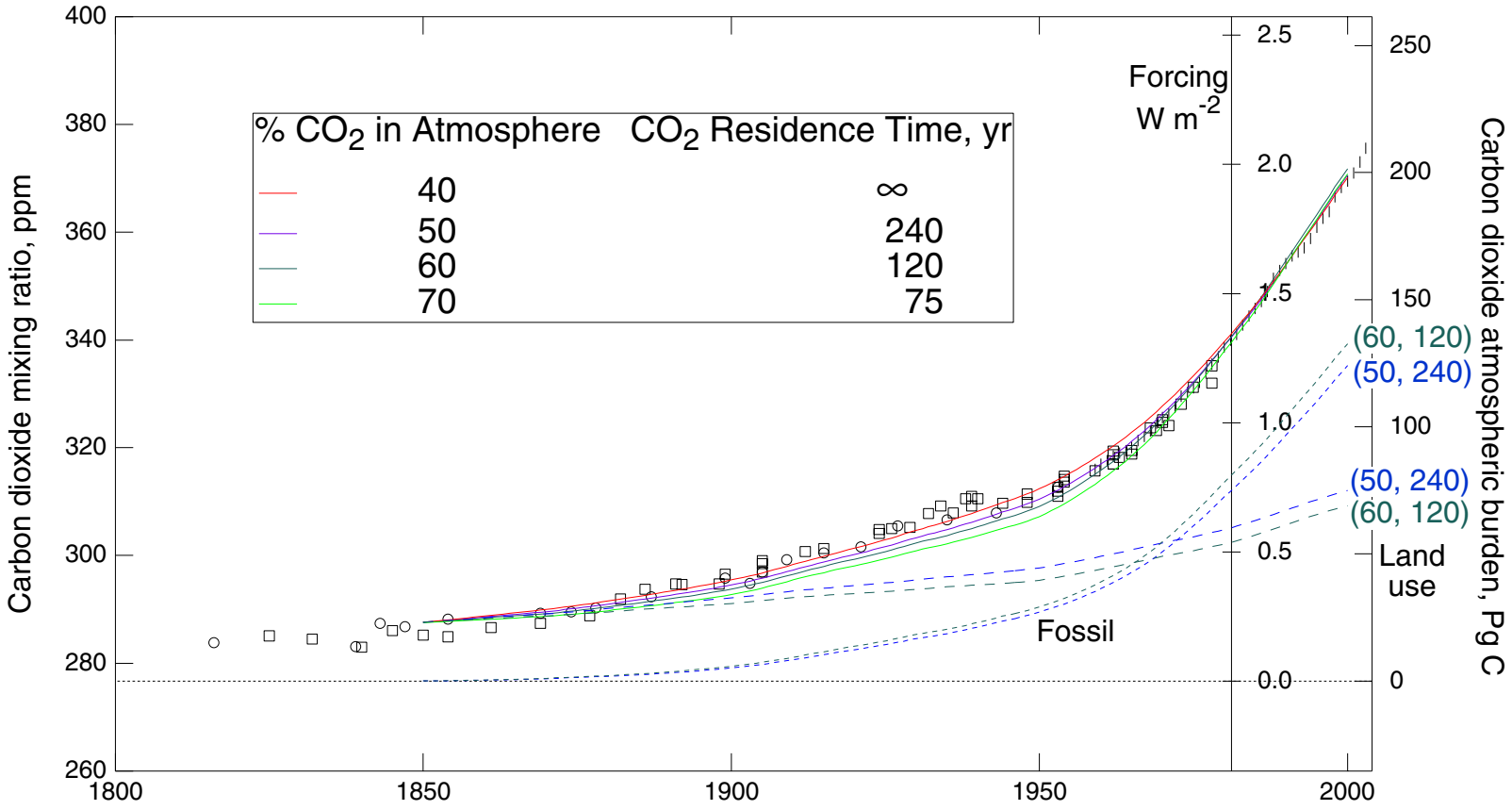
Comparison of CO_2 ***mixing ratio and forcing*** from fossil fuel combustion and land use changes



Partition-decay model: $$\frac{d\Delta CO_2}{dt} = f_A Q - \Delta CO_2 e^{-t/\tau}$$

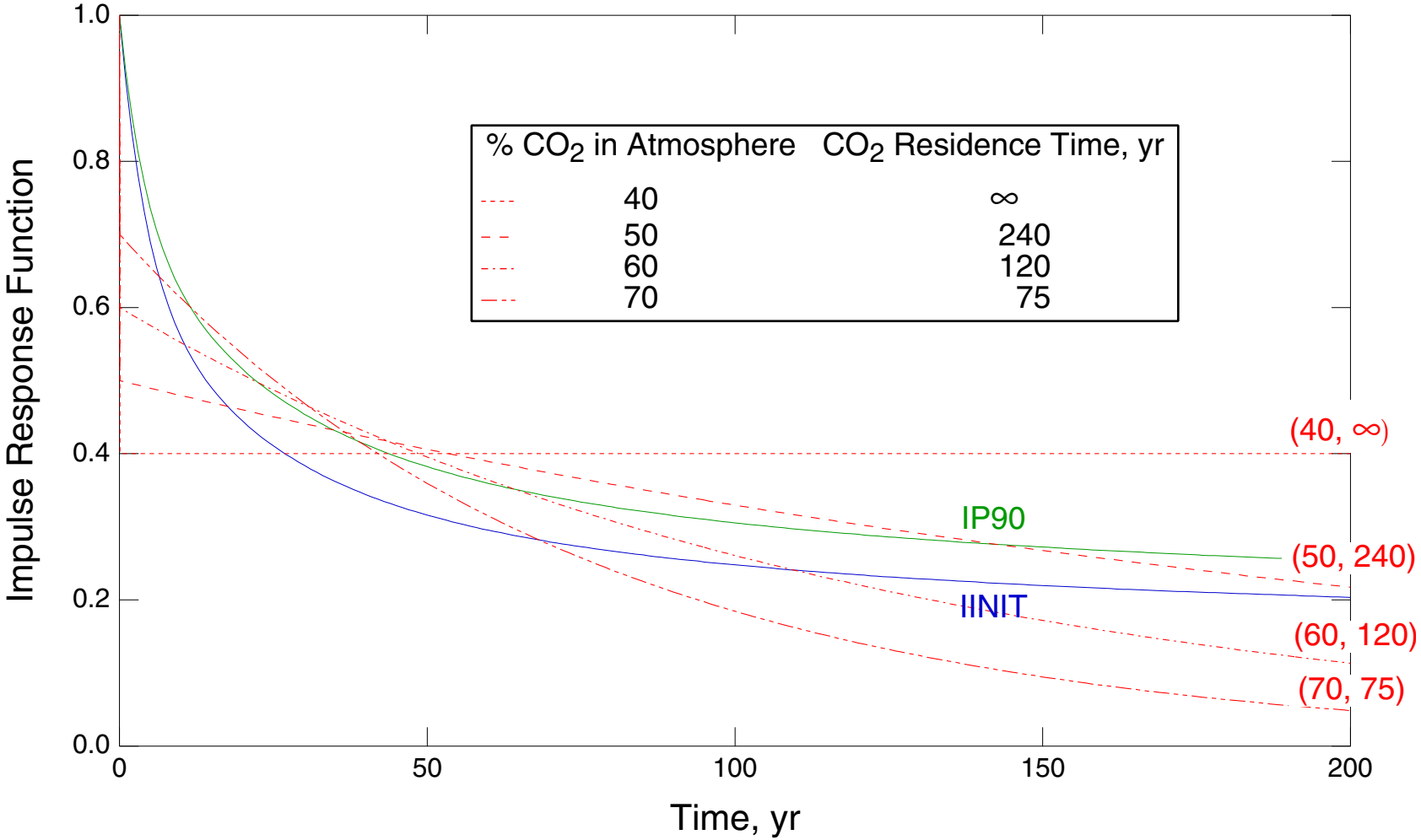
ATTRIBUTION OF ATMOSPHERIC CO_2

Comparison of CO_2 ***mixing ratio and forcing*** from fossil fuel combustion and land use changes



CO_2 from land use emissions – ***not fossil fuel combustion*** – was the dominant contribution to atmospheric CO_2 and forcing over the 20th century. ***This conclusion is not sensitive to the parameters***.

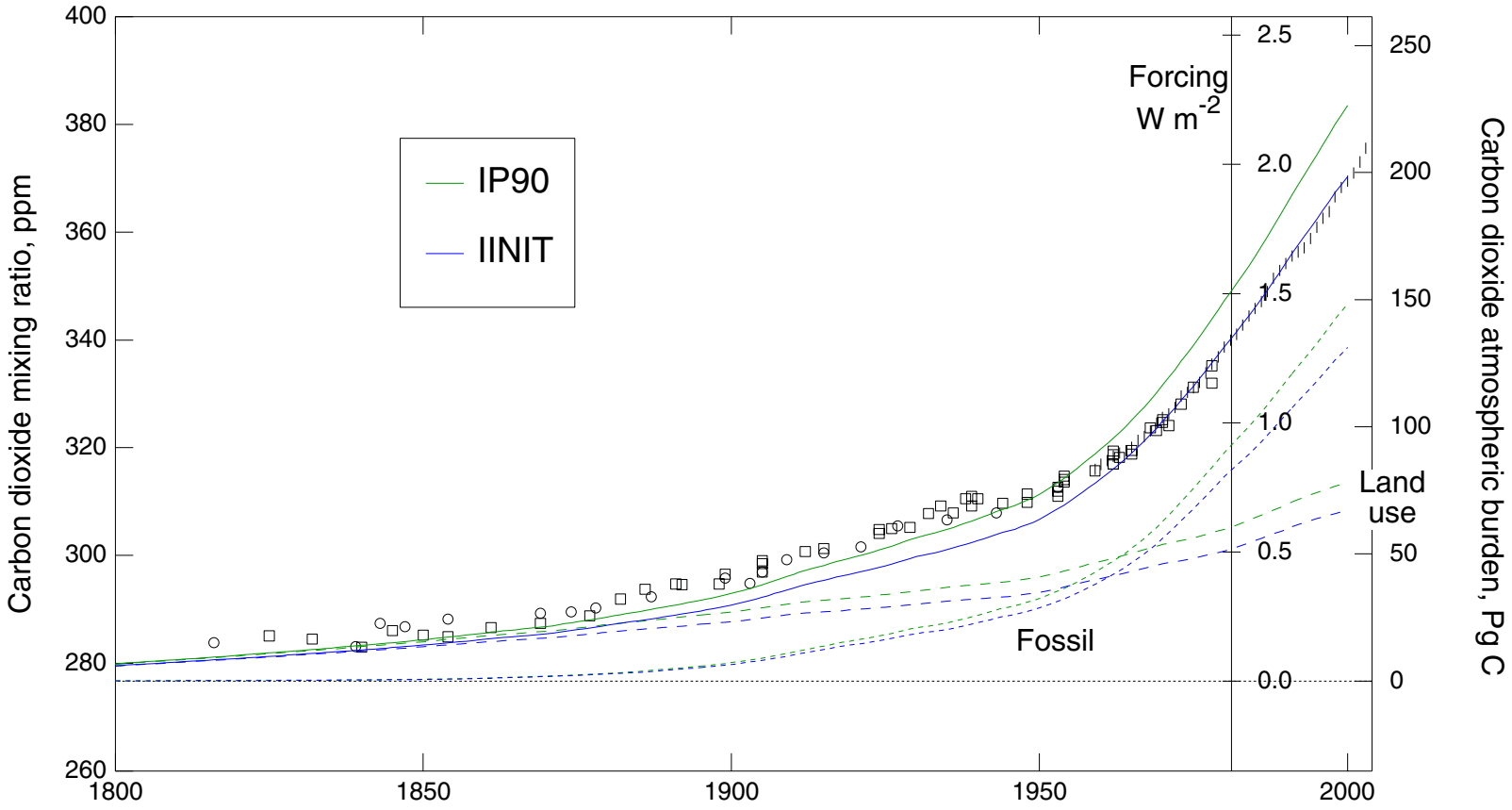
IMPULSE RESPONSE PROFILES OF ATMOSPHERIC CO_2



Preindustrial (IINIT) and IPCC-1990 (IP90) profiles from Enting et al., 1994.

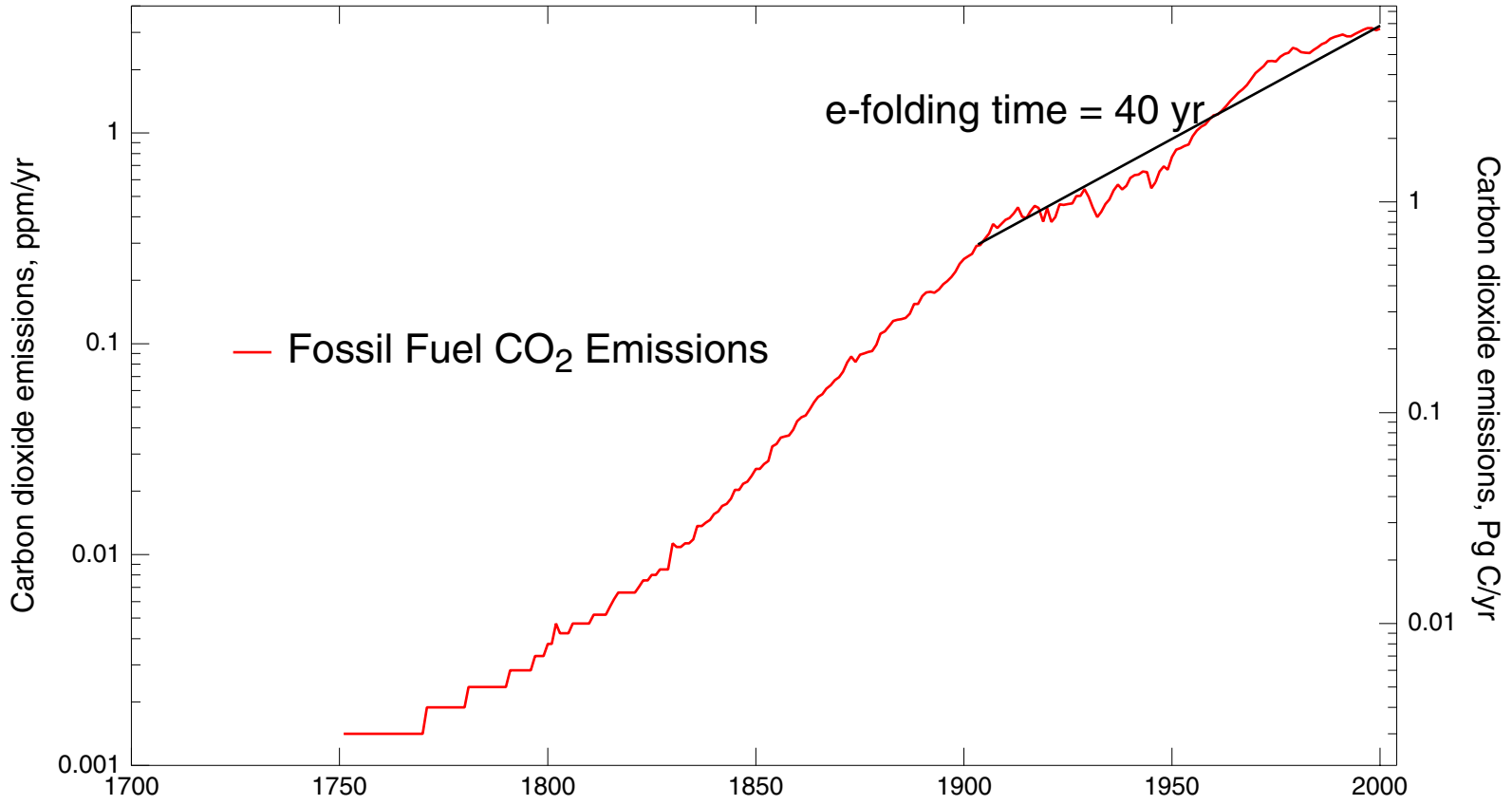
ATTRIBUTION OF ATMOSPHERIC CO_2

Comparison of CO_2 ***mixing ratio and forcing*** from fossil fuel combustion and land use changes



CO_2 from land use emissions – ***not fossil fuel combustion*** – has been the dominant contribution to atmospheric CO_2 and forcing over the 20th century. ***This conclusion is not sensitive to the model.***

INCREASE OF CO_2 EMISSIONS IS ROUGHLY EXPONENTIAL



The time constant for emissions growth is well less than time constant for decrease of excess CO_2.

The mean age of fossil fuel CO_2 in the atmosphere is ~ 40 years.

The climate influence of excess fossil fuel CO_2 already in the atmosphere will continue well into the future.

OBSERVATIONS ABOUT CO_2

The residence time of excess atmospheric $CO_2 \gtrsim 100$ years.

CO_2 from ***land use emissions*** was the dominant contribution to excess CO_2 and its climate forcing over the 20^{th} century.

CO_2 from ***fossil fuel combustion*** now the dominant contribution to excess CO_2 and its climate forcing.

Fossil fuel CO_2 emissions are increasing with time constant of ~40 years.

Excess CO_2 ***now in the atmosphere*** is 100% of ~40 years' emissions.

The forcing of present excess CO_2 will remain for a long time.

TIME CONSTANTS OF EARTH'S CLIMATE SYSTEM

Consider a perturbation to the climate system

How long does it take for the system to adjust to the new state?

There are many time constants:

Minutes. It gets cooler when the sun goes "behind a cloud."

Hours. It is cooler at night than during the day; but there is a lag.

Months. It is colder in winter than in summer, but there is a lag.

Years. Thermal buffering of the ocean mixed layer.

Thousands of years. The deep oceans.

Millions of years. Thermal mass of the whole planet (Kelvin and the age of Earth)

TIME CONSTANT OF THE CLIMATE SYSTEM

For the ***relevant climate system*** consisting of the ***atmosphere and the mixed layer of the ocean***, the time constant for relaxation of a perturbation is $\tau = C_0 / \beta$,

where $\beta = \frac{4J_0}{T_0}\left(1 - \frac{1}{4}\frac{d\ln(1-\alpha)}{d\ln T}\bigg|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\bigg|_0\right)$,

C_0 is the thermal mass of the system, J_0 is the emitted longwave flux at the TOA, and T_0 is temperature at the TOA.

For $\left(\quad\right)$ taken as unity and C_0 given by the thermal mass of the ocean mixed layer (100 m), $\tau \approx 4$ yr.

Climate response is essentially instantaneous! Warming due to excess CO_2 will diminish as the excess CO_2 decays.

AEROSOL INFLUENCES ON RADIATION AND CLIMATE

Direct Effect (Clear sky)

Light scattering → Cooling influence

Light absorption → Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)

More droplets → Brighter clouds (Twomey)

More droplets → Enhanced cloud lifetime (Albrecht)

More droplets → Broadening of drop distribution → warming (Liu)

Semi-Direct Shortwave Radiative Effect

Absorbing aerosol → Cloud evaporation (Hansen)

Longwave Radiative Effect (Clear sky)

Greenhouse effect of aerosol particles (Vogelmann)

Hydrological Effects

Suppressed surface evaporation → Spinning down the water cycle

Longer-lived clouds → Displaced precipitation (Rosenfeld)

Ecological Effects

Decreased surface irradiance affects primary productivity

Increase in diffuse/direct ratio affects primary productivity

ELEMENTS OF AEROSOL FORCING

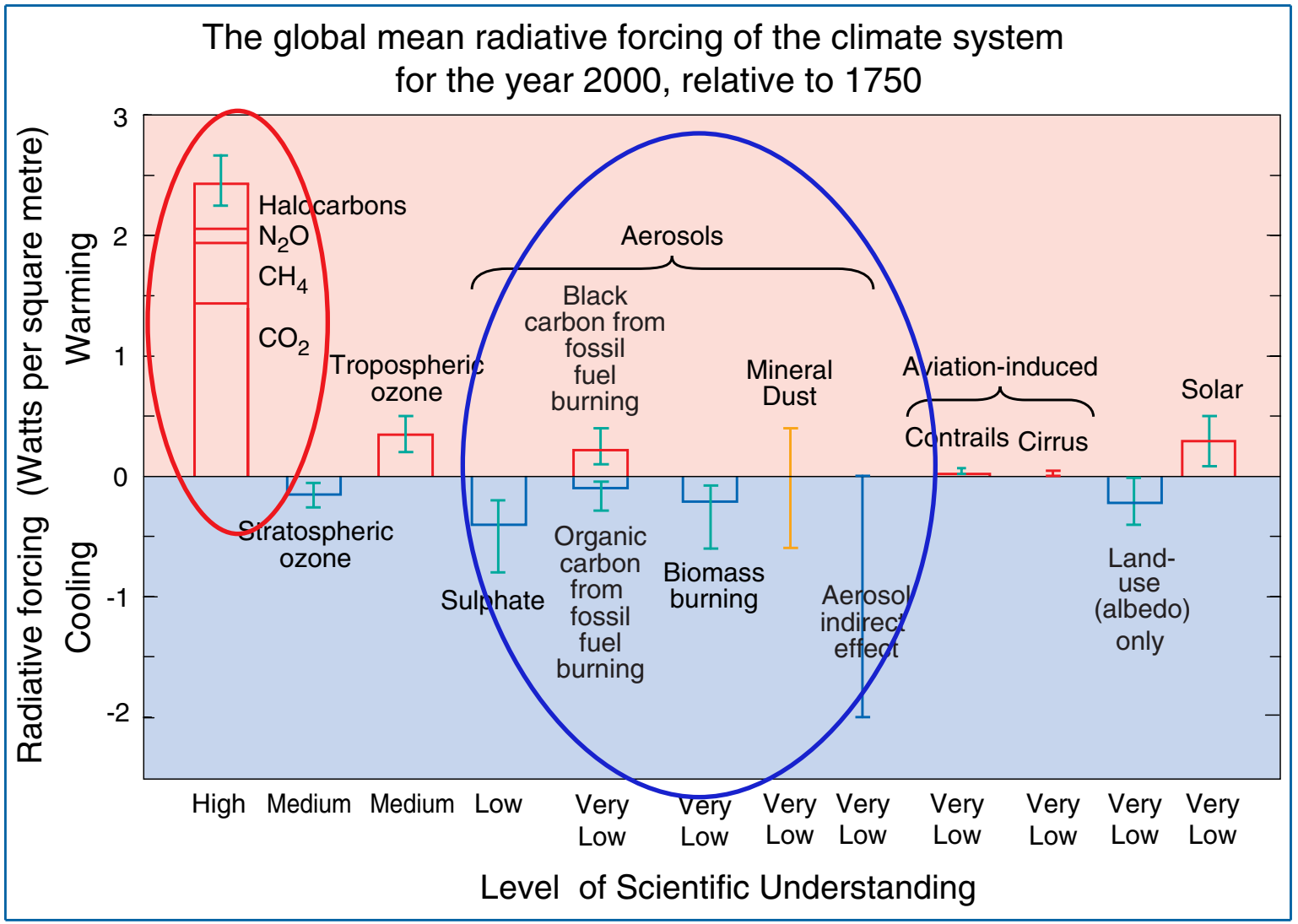
Forcing depends on ***amount of material*** present and on aerosol ***microphysical and optical properties*** (size, single scattering albedo, ability to nucleate cloud drops).

Amount of material present depends on ***emissions***, ***atmospheric chemistry***, and ***removal***.

Anthropogenic emissions are associated largely with ***fossil fuel combustion*** (sulfate, soot, secondary organics), ***biomass burning*** (organics and soot), ***mineral dust*** from disturbed soils.

Removal occurs mainly by precipitation with ***residence time of about a week***.

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

IMPLICATIONS OF AEROSOL FORCING

- Aerosol negative (cooling) forcing is likely ***offsetting*** and ***masking*** a substantial fraction of positive (warming) forcing by greenhouse gases.
- A substantial fraction of the forcing of 40 years of CO_2 emissions is being offset by ***a week's worth of aerosol***.
- The global warming due to CO_2 and other GHGs is almost certainly ***substantially greater*** than has been experienced thus far.
- Quantifying aerosol forcing is essential because the uncertainty in aerosol forcing ***precludes meaningful empirical inference of climate sensitivity and evaluation of climate models***.
- Aerosols influence hydrological cycles, vertical heating profiles, surface heating, vegetation, etc., and these influences must also be understood and quantified.

INTEGRATED FORCING

A MEASURE OF THE IMPACT OF INCREMENTAL GREENHOUSE GASES OR AEROSOLS

$$\Phi(T) = \int_0^T F(t)dt = \int_0^T \alpha(c)c(t)dt \approx \alpha \int_0^T c(t)dt = \alpha c_0 \int_0^T I(t)dt$$

Where

$\Phi(T)$ = Integrated forcing over time horizon T [Unit: W m^{-2} yr]

$F(t)$ = Time dependent forcing of incremental gas or aerosol species

$\alpha(c) \equiv F(c)/c$ = Forcing intensity of incremental gas or aerosol species (may depend on concentration c)

c_0 = Initial incremental concentration of gas or aerosol species

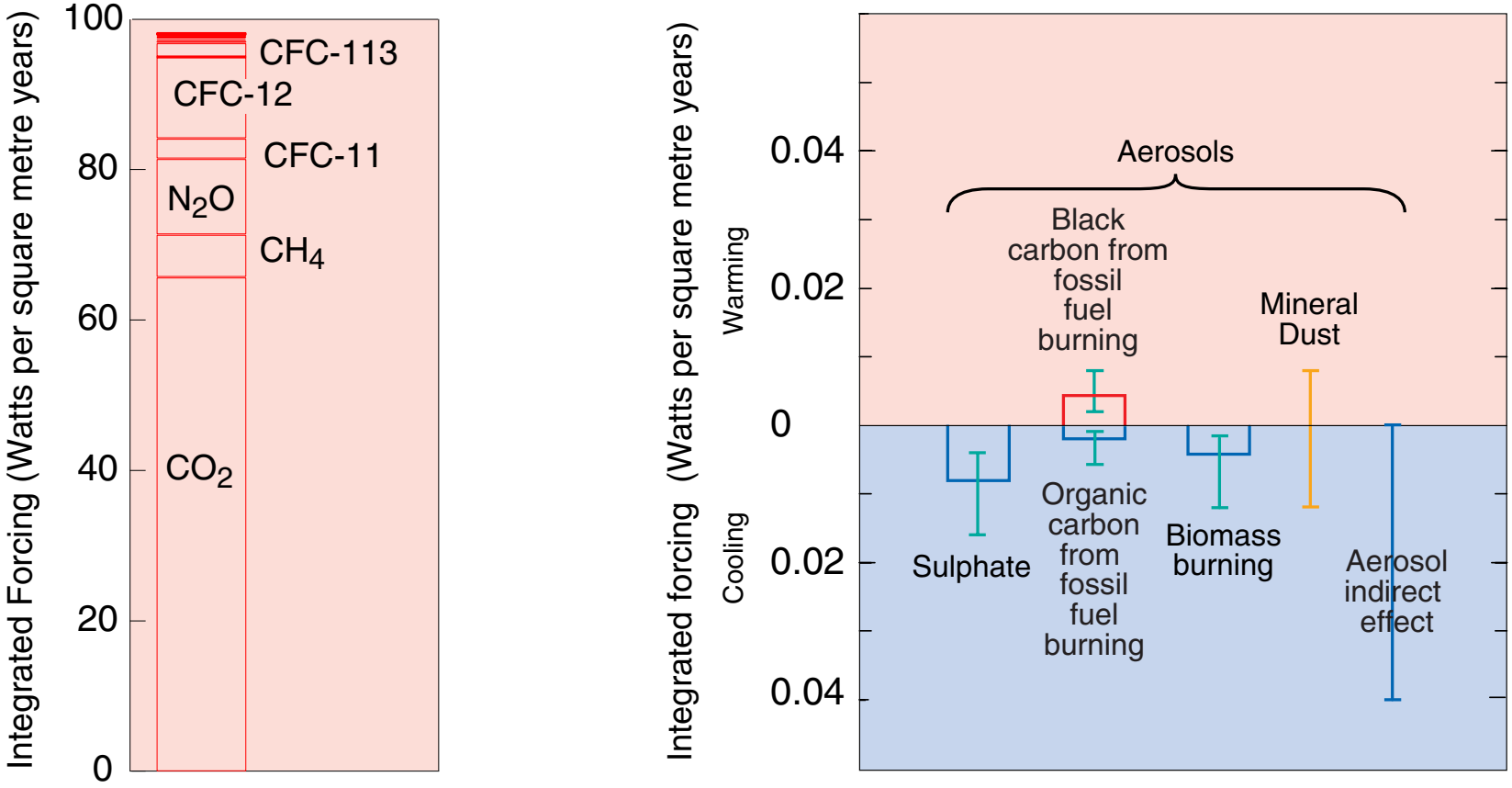
$I(t)$ = Impulse response function of gas or aerosol species

Integrated forcing is akin to absolute greenhouse warming potential *AGWP*.

$$\Phi = c_0 AGWP(T)$$

COMMITTED INTEGRATED FORCING OF ANTHROPOGENIC GASES AND AEROSOLS IN PRESENT ATMOSPHERE

Evaluated for 100-year time horizon



Note vastly different scales, 1000 ×, greenhouse gases >> aerosols.

Despite comparable forcings, ***greenhouse gases exert much greater integrated forcings because of long atmospheric lifetimes***.

SOME CONCLUDING OBSERVATIONS

- GHG concentrations and forcing are increasing. GHGs persist in the atmosphere for ***decades to centuries***.
- Tropospheric aerosols remain in the atmosphere for ***about a week***.
- Increasing scattering aerosols is ***not a viable strategy*** for mitigating greenhouse warming.
- Decreasing absorbing aerosols would be of ***little long-term avail***.
- Integrated forcing is potentially useful for policymakers, e.g., ***Integrated Forcing Impact Assessment*** for new power plants and the like.