Carbon-climate-human interactions as a complex system

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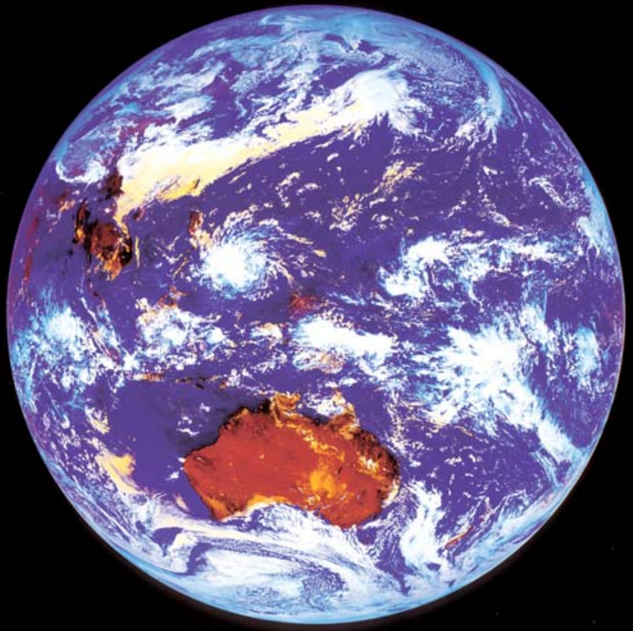
Two nested ecologies



- **Ecology of the biosphere**
  - Life is a complex adaptive system (CAS)
  - Imports (solar) energy, exports entropy, stores information
  - Evolves by sieving information (genome) about organisms (phenome)
  - Genomes and phenomes are both **carbon-based**
- **Ecology of the anthroposphere**
  - New evolutionary trick: use of exogenous (non-biotic) energy
  - Easiest energy source: detrital carbon from the biosphere
  - CAS with biological, technological, social, cultural levels
  - Emergence of impact of anthroposphere on planetary function

Outline

- **Carbon-climate-human interactions**
- **Trends in CO_2 emissions**
- **Land and ocean CO_2 sinks**
- **Attribution of trends in atmospheric CO_2**
- **Carbon, climate and the tragedy of the commons**

Past climate and greenhouse gases (mainly CO_2)

- Solar and orbital forcing of climate is amplified by three positive feedbacks:
  - water vapour
  - trace greenhouse gases
  - ice albedo effects

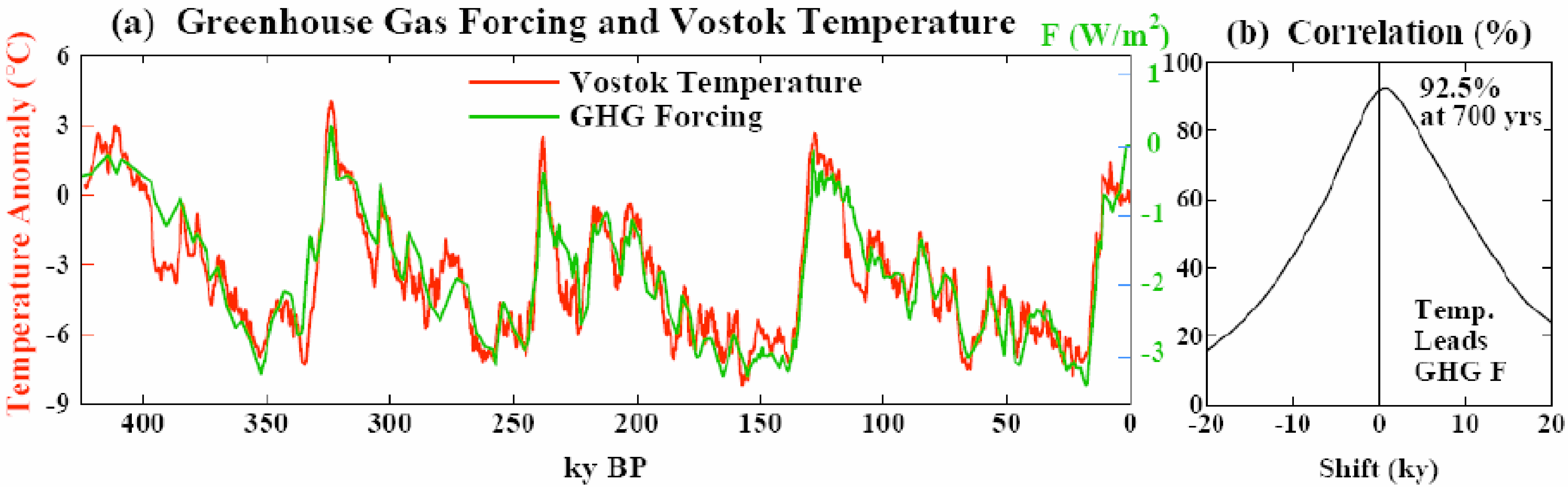
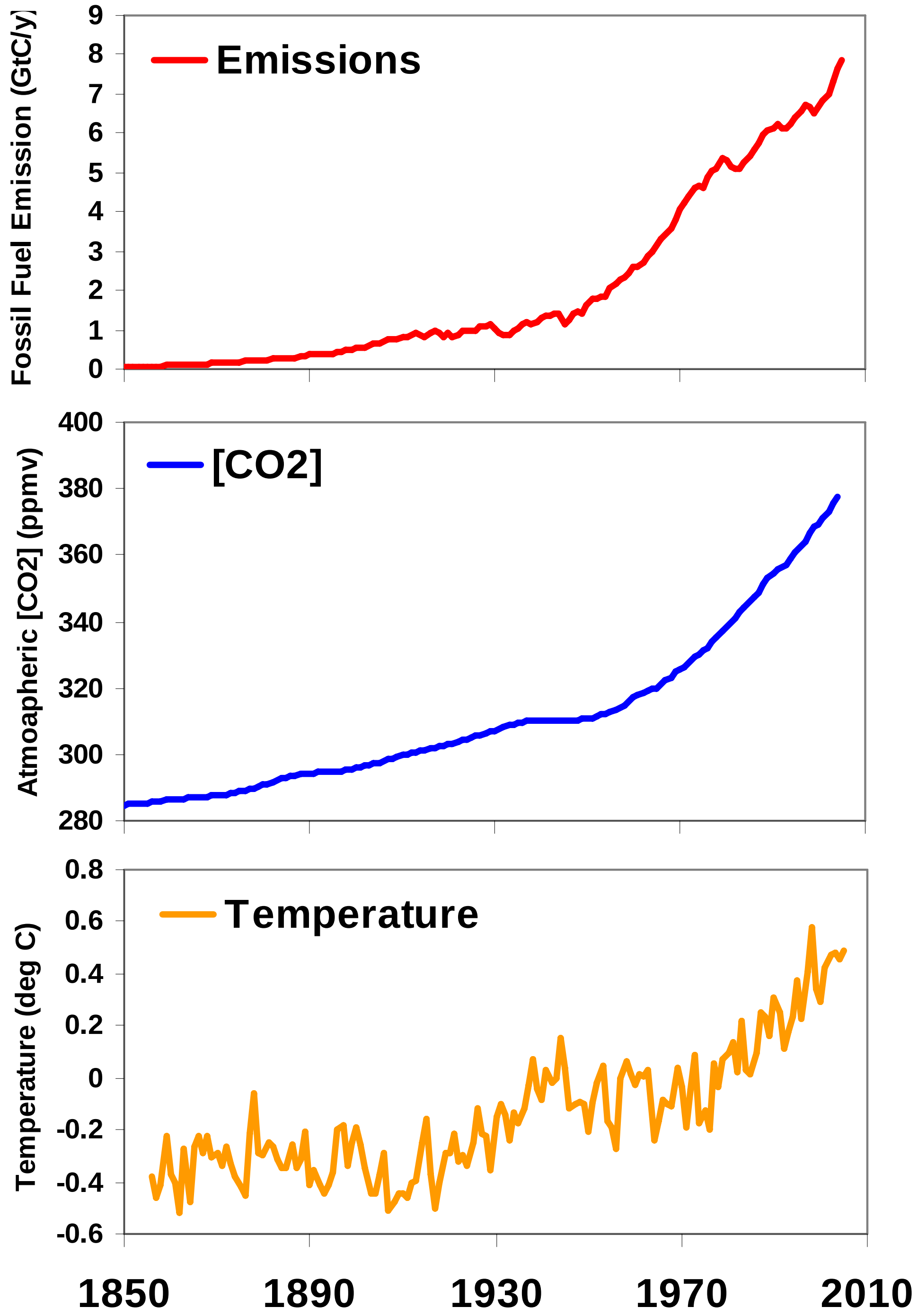


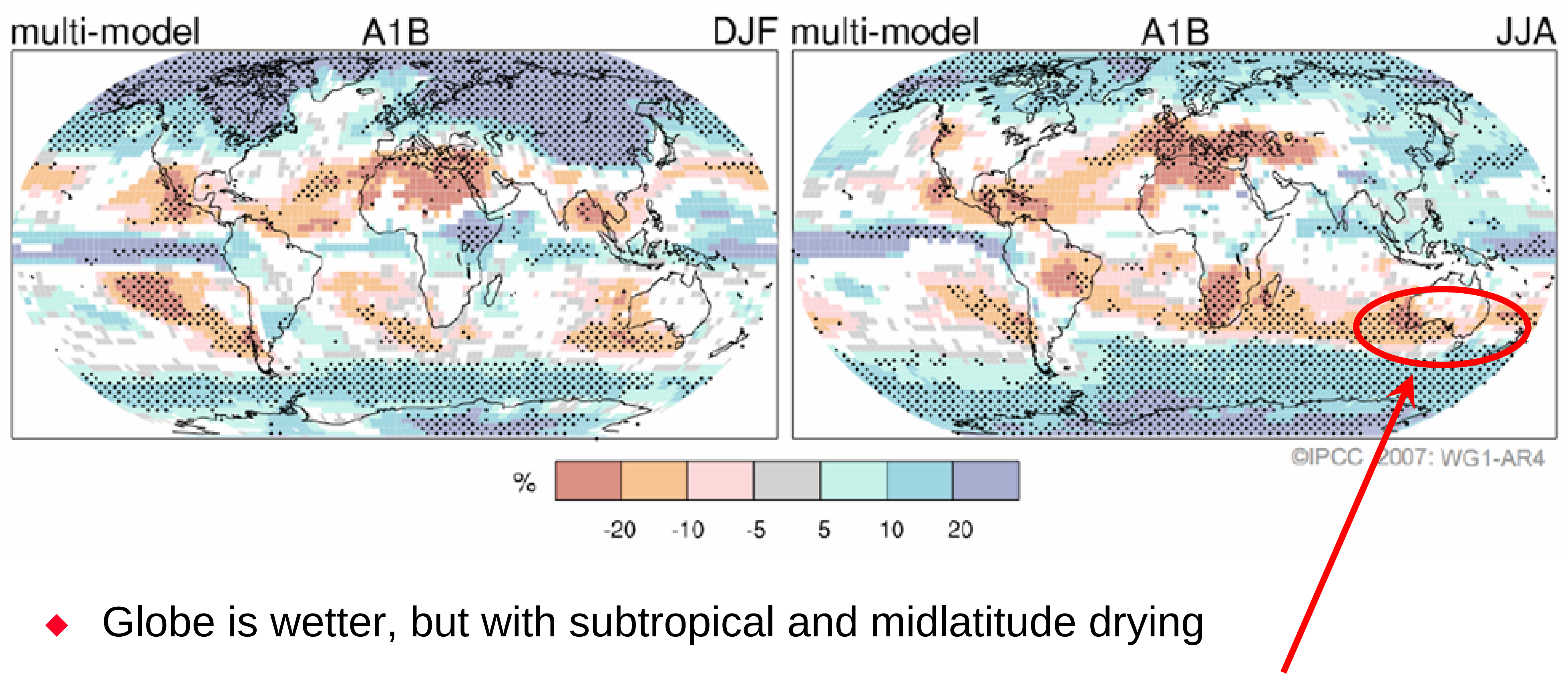
Figure 1. Antarctic temperature (left scale) from Vostok ice core (Vimeux et al. 2002) and global climate forcing (right scale) due to CO_2, CH_4 and N_2O. Flux zero point is for 1850 gas amounts specified by Hansen and Sato (2004). Temperature zero point is "present" value from the Vostok ice core (Vimeux et al. 2002). Ratio of temperature and flux scales (3.02°C per W/m^2) is chosen such that their standard deviations in this figure are equal.

Recent climate and CO_2

- Factors explaining observed warming from 1850 to present:
  - fluctuations in solar and volcanic forcing
  - enhanced greenhouse gases
- From 1970 onward, enhanced greenhouse forcing is dominant



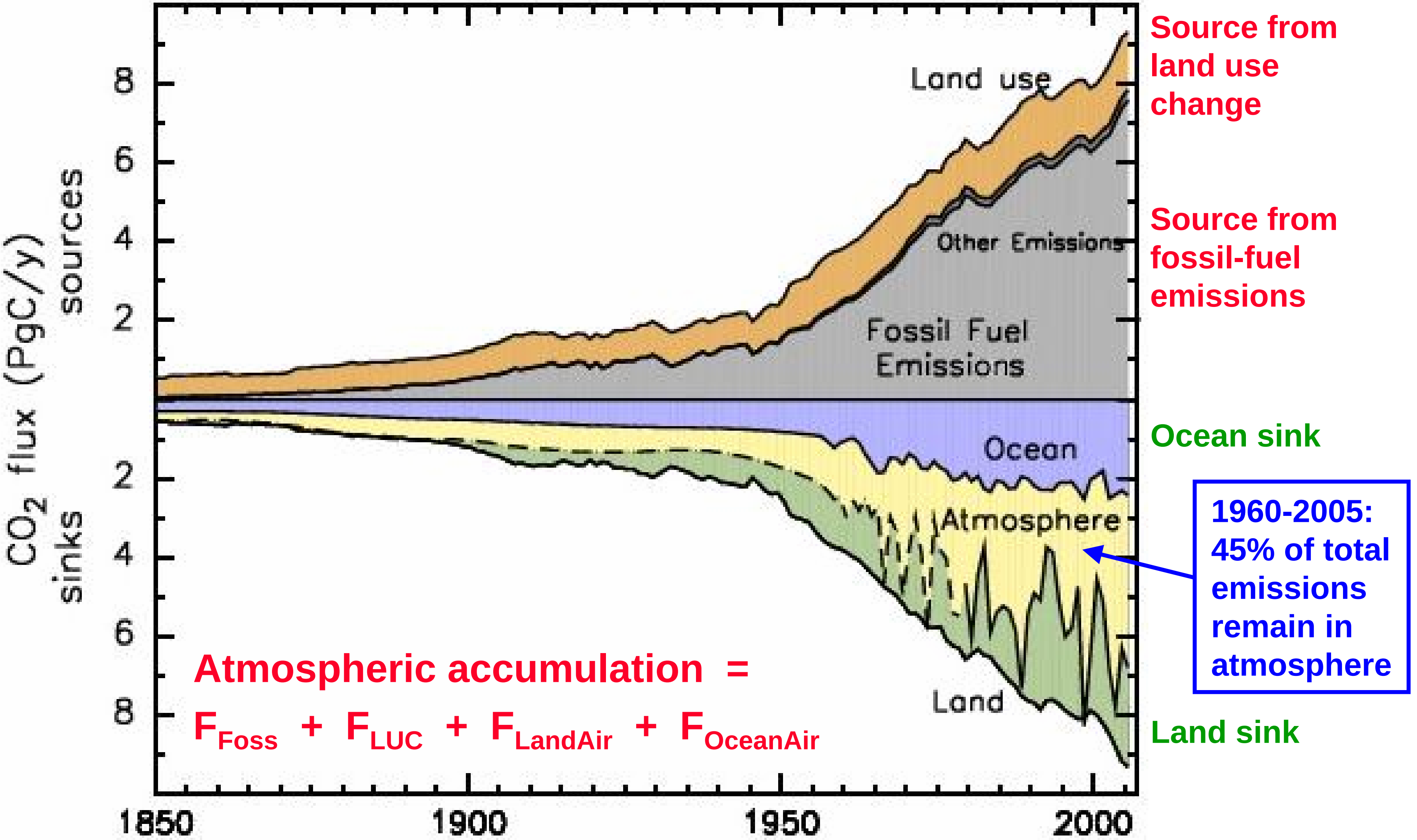
Rainfall predictions for 2100



- Globe is wetter, but with subtropical and midlatitude drying
- Southern Australia: winter rainfall declines by 10% to 20%
  => runoff and streamflow decline by ~20% to ~60%

IPCC (2007) Fourth Assessment, WG1 SPM, Fig 6

Budget of atmospheric CO_2



Atmospheric accumulation =

$$F_{Foss} + F_{LUC} + F_{LandAir} + F_{OceanAir}$$

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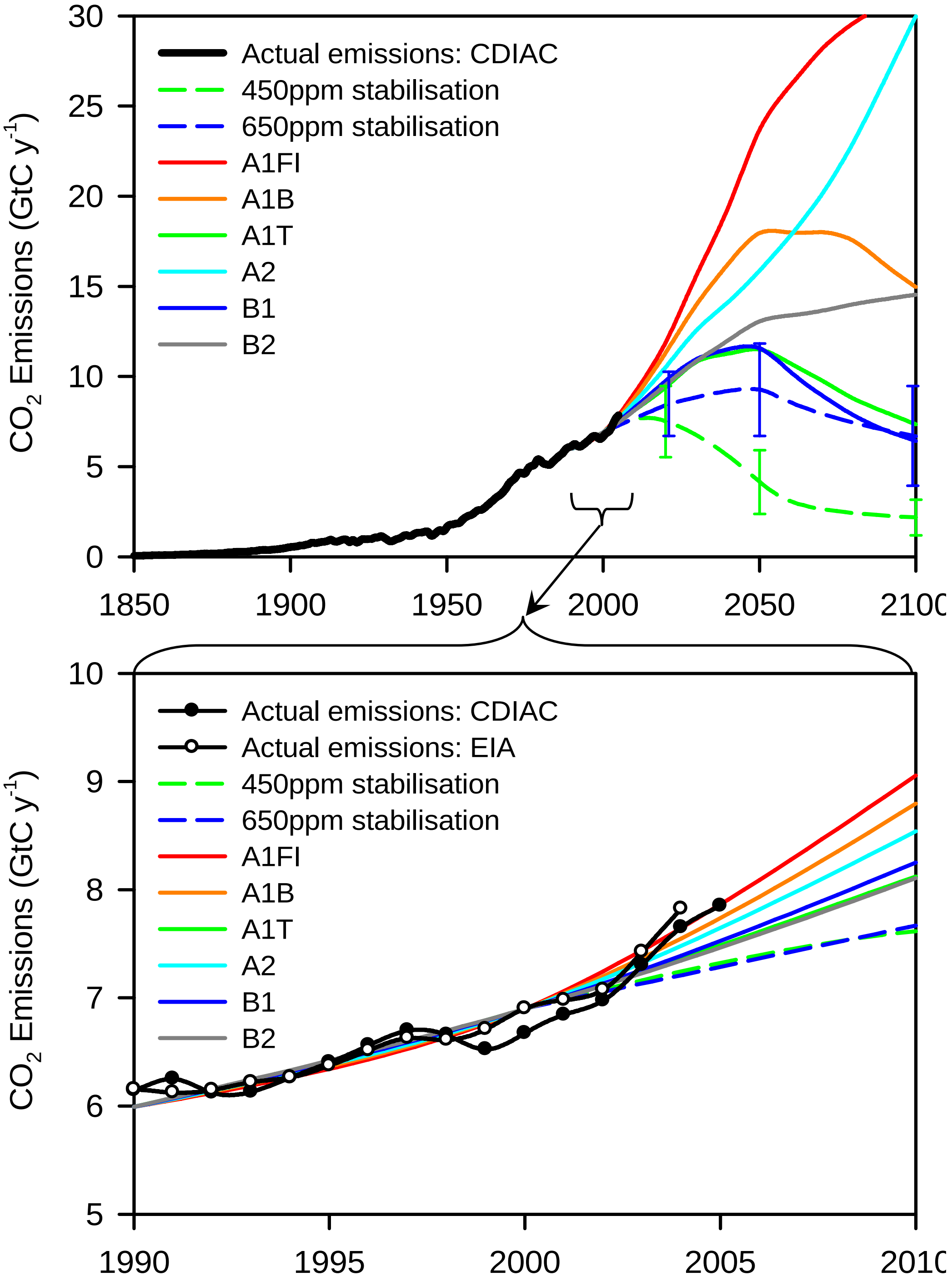
CO_2 from fossil fuels: global trends

- **Growth rate in fossil-fuel CO_2 emissions:**
  - **1990-1999: ~1% y^{-1}**
  - **2000-2005: ~3% y^{-1}**

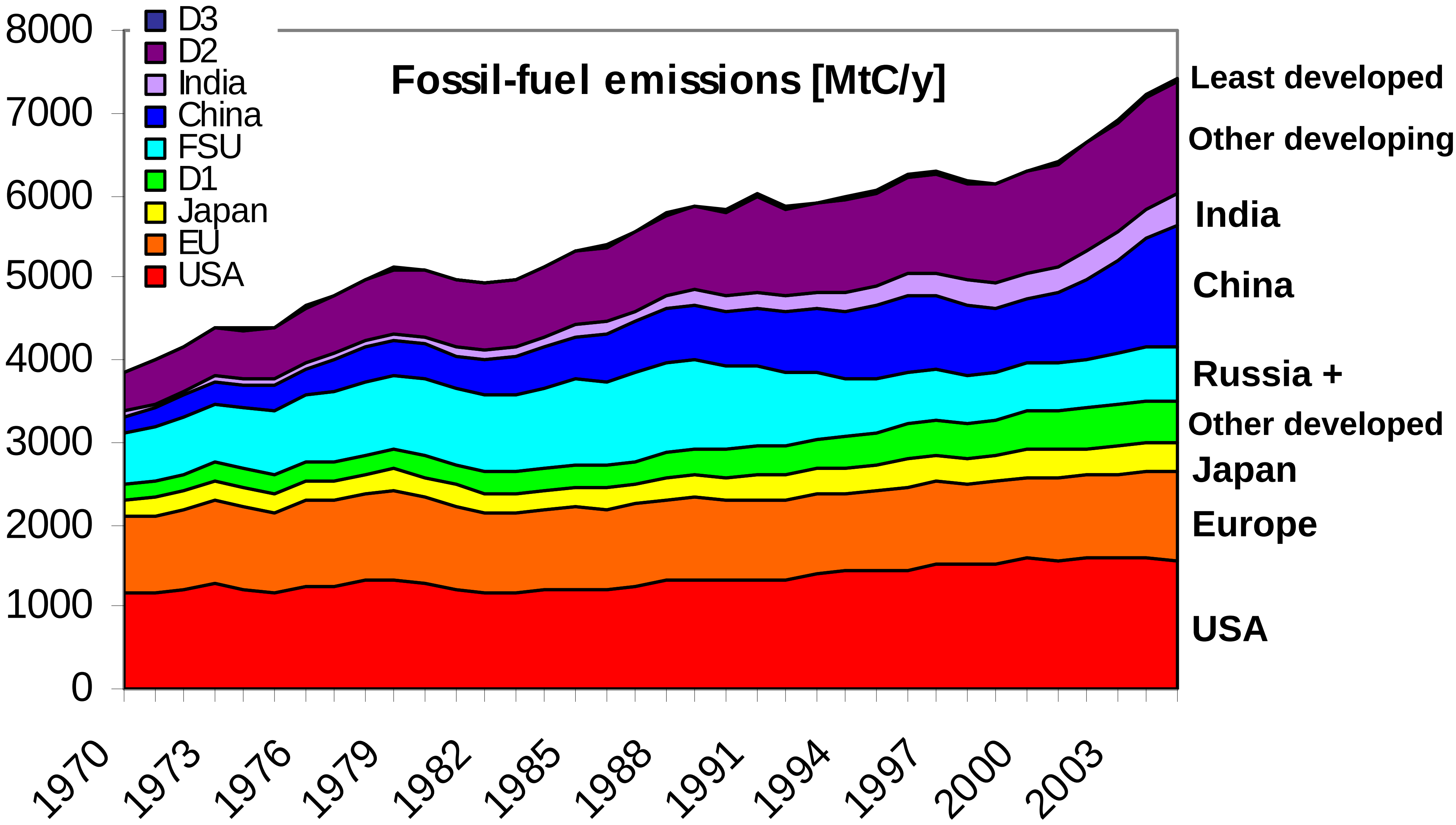
- **Scenarios underestimate growth rate in actual emissions since 2000**



Raupach et al. (2007) PNAS

Raupach et al. (2007) PNAS

CO_2 from fossil fuels: regional trends



Kaya identity

- **Extensive variables:**

  F = fossil-fuel CO_2 emission
  P = population
  G = GDP
  E = primary energy use

- **Kaya identity:**
  - **F = P * (G/P) * (E/G) * (F/E) = P * (G/P) * (F/G)**
  - **F = Pgef = Pgh**

- **Intensive variables:**

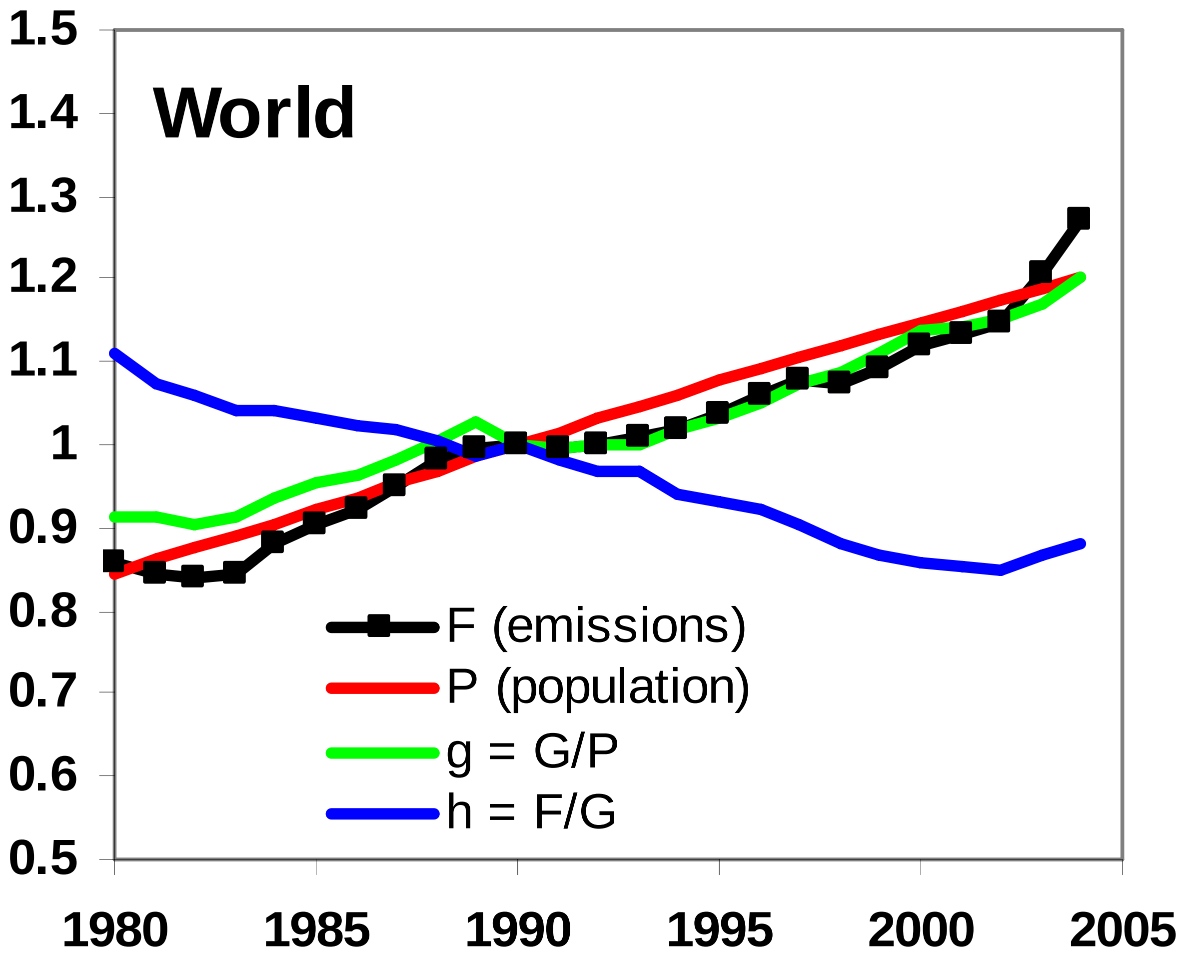
  g = G/P = percapita GDP
  e = E/G = energy intensity of GDP
  f = F/E = carbon intensity of energy
  h = F/G = carbon intensity of GDP

Drivers of global emissions

- **Kaya Identity**

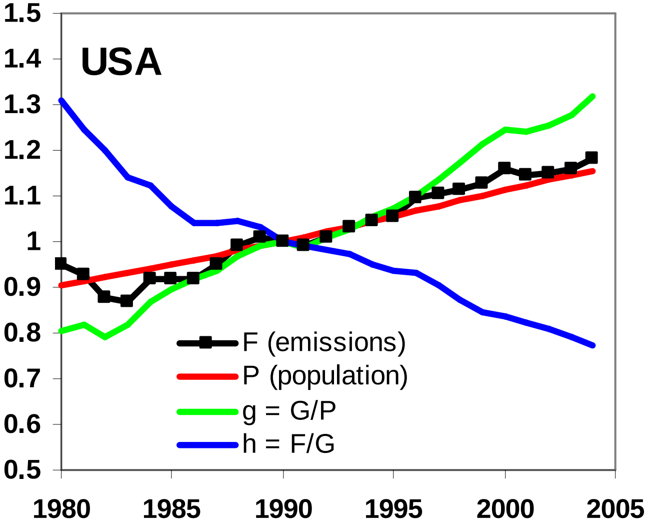
$$F = P \times \frac{G}{P} \times \frac{F}{G}$$

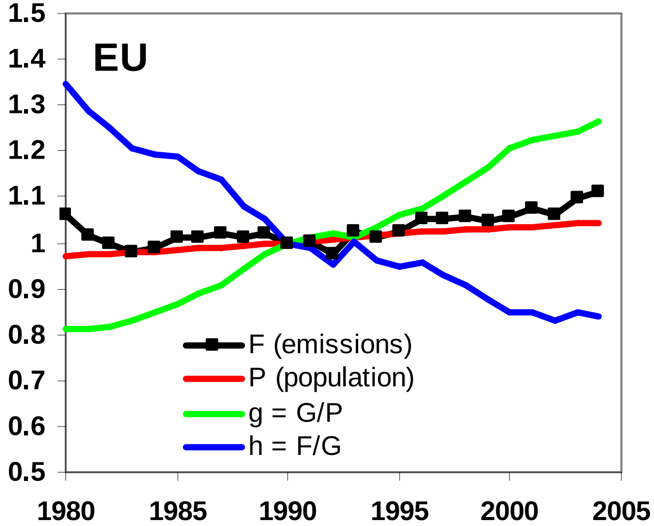
- F: Fossil-fuel CO_2 emission
- P: Population
- G/P: Per-capita GDP
- F/G: Carbon intensity of GDP

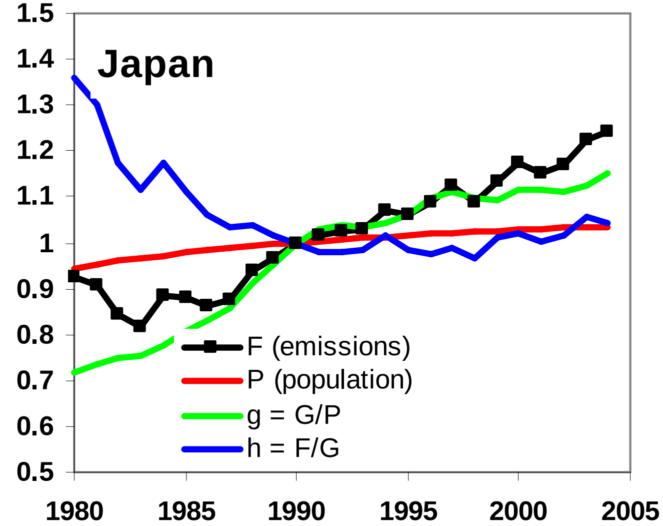


Raupach et al. (2007) PNAS

Drivers of emissions for 4 developed regions

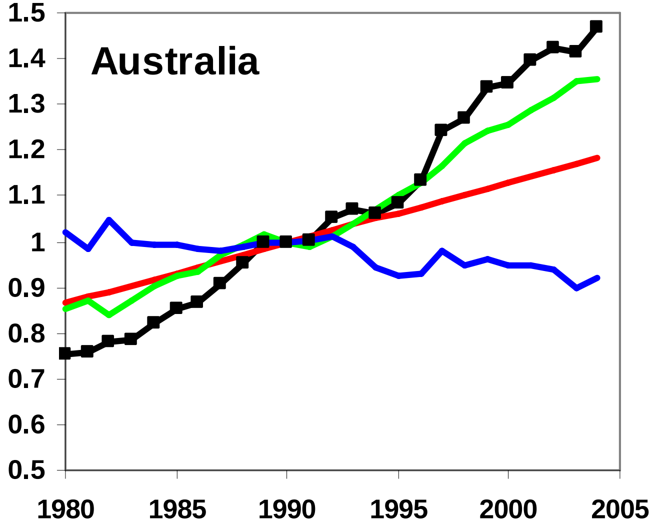


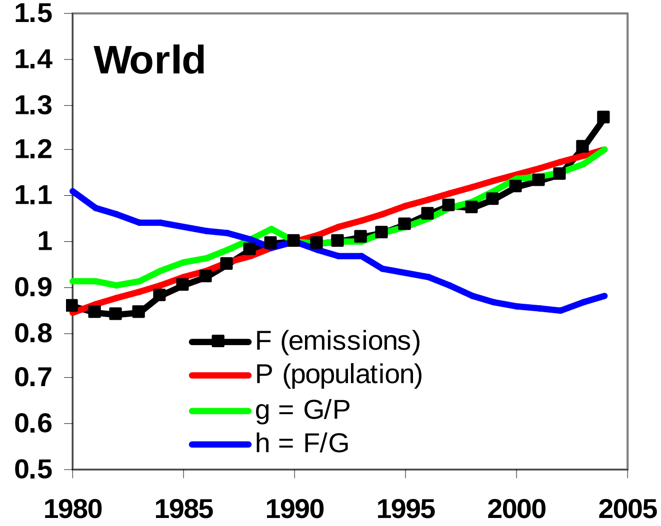




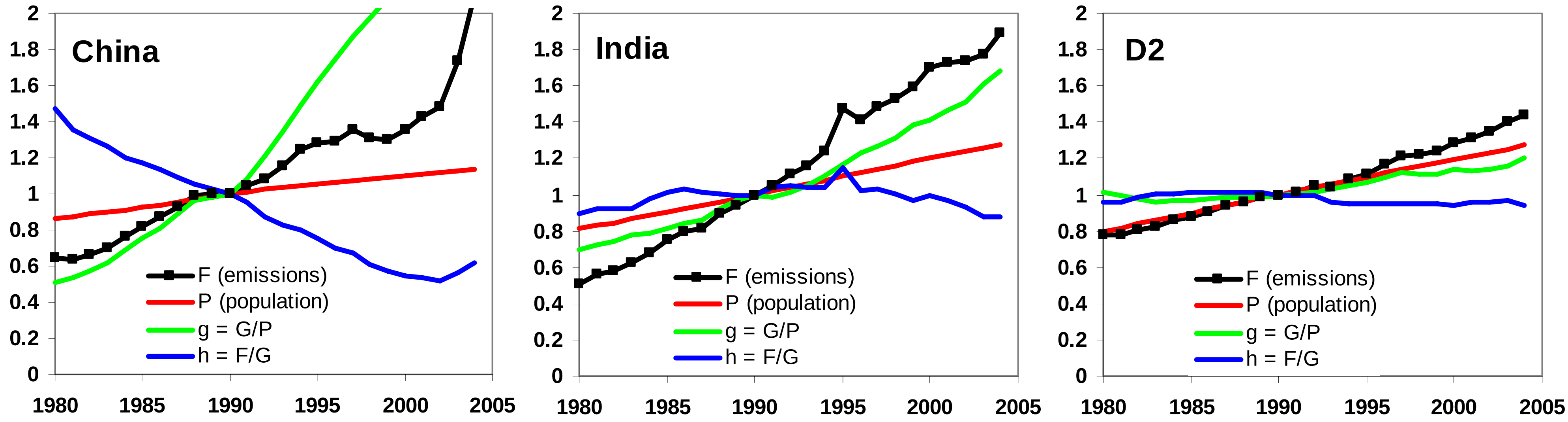
- **Kaya identity:**

$$F = P \times \frac{G}{P} \times \frac{F}{G}$$





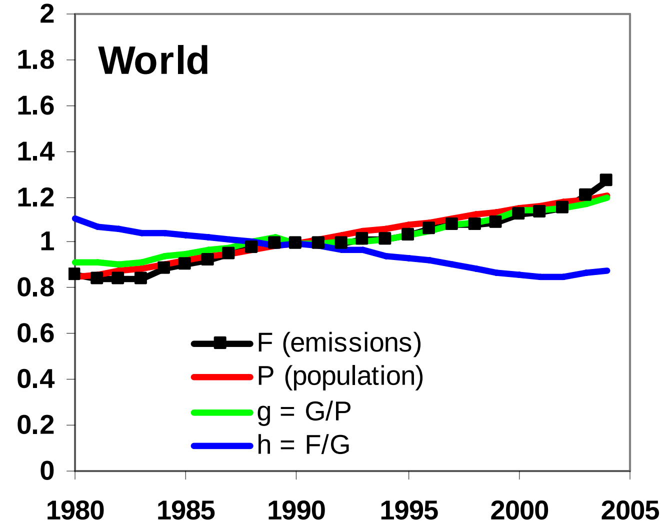
Drivers of emissions for 3 developing regions



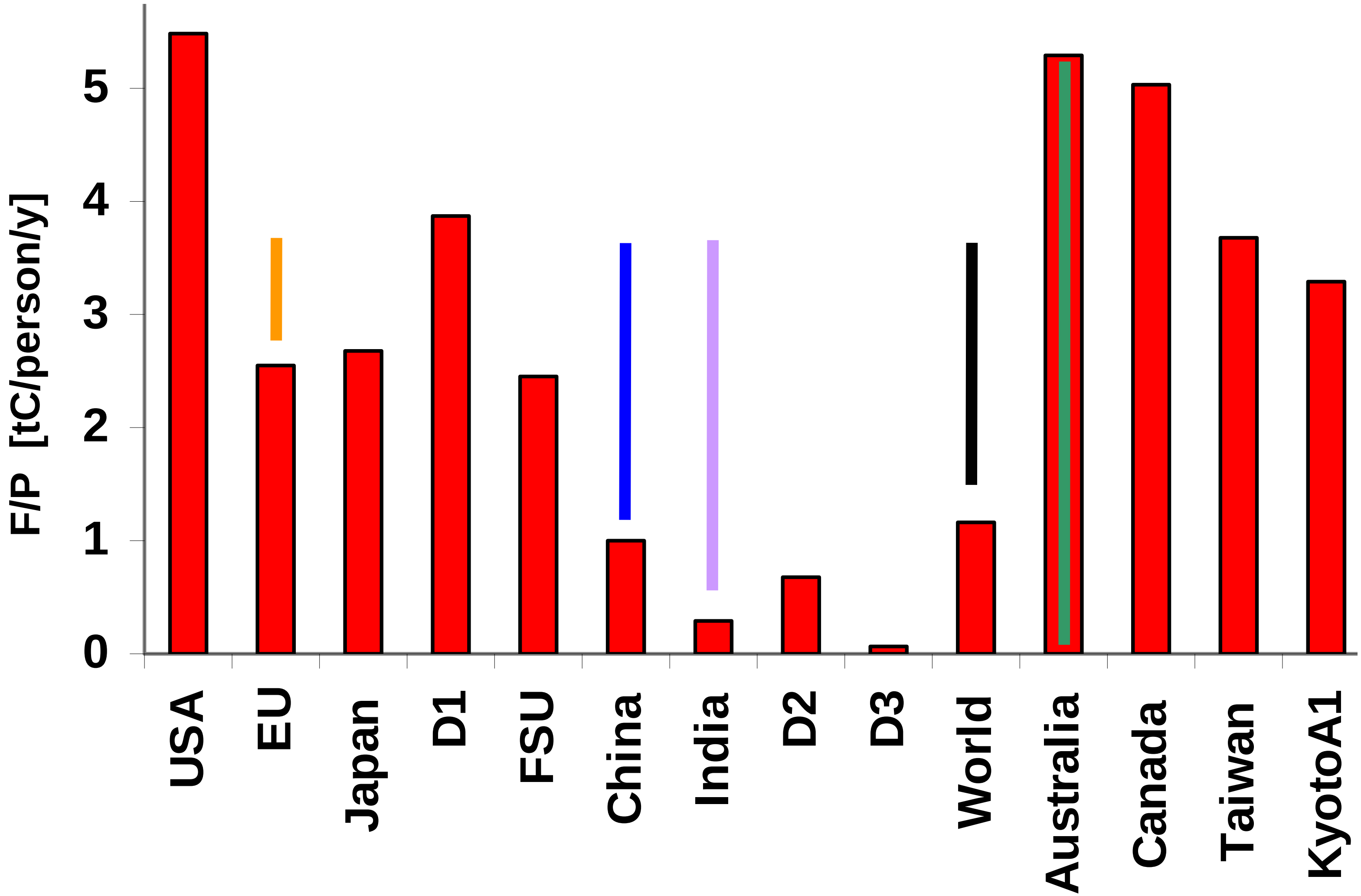
- **Kaya identity:**

$$F = P \times \frac{G}{P} \times \frac{F}{G}$$

- **Note change of scale**

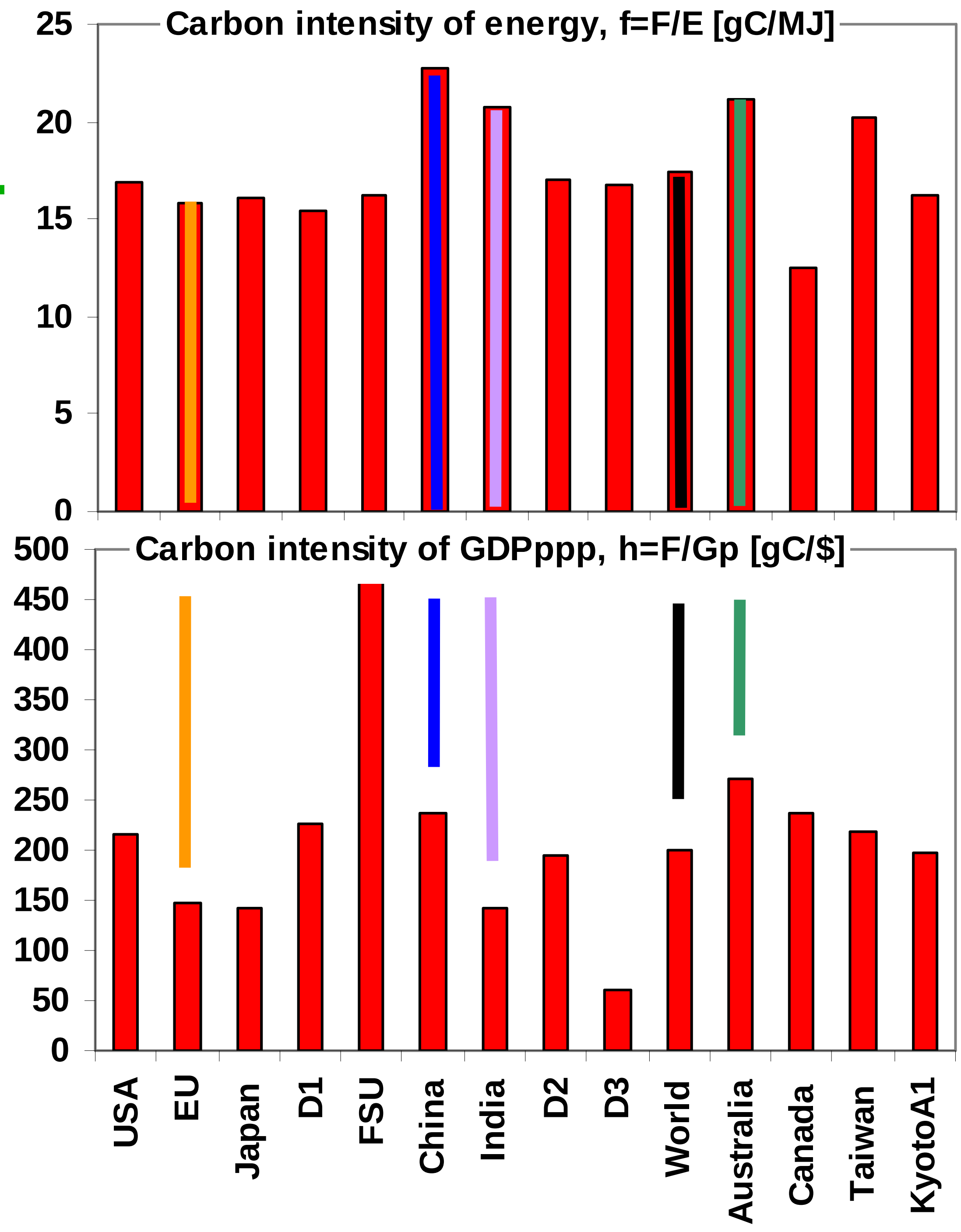


Per capita CO_2 emissions in 2004



Intensities in 2004

- Carbon intensity of energy (f = F/E)
- Carbon intensity of GDP-PPP (h = F/G_p)



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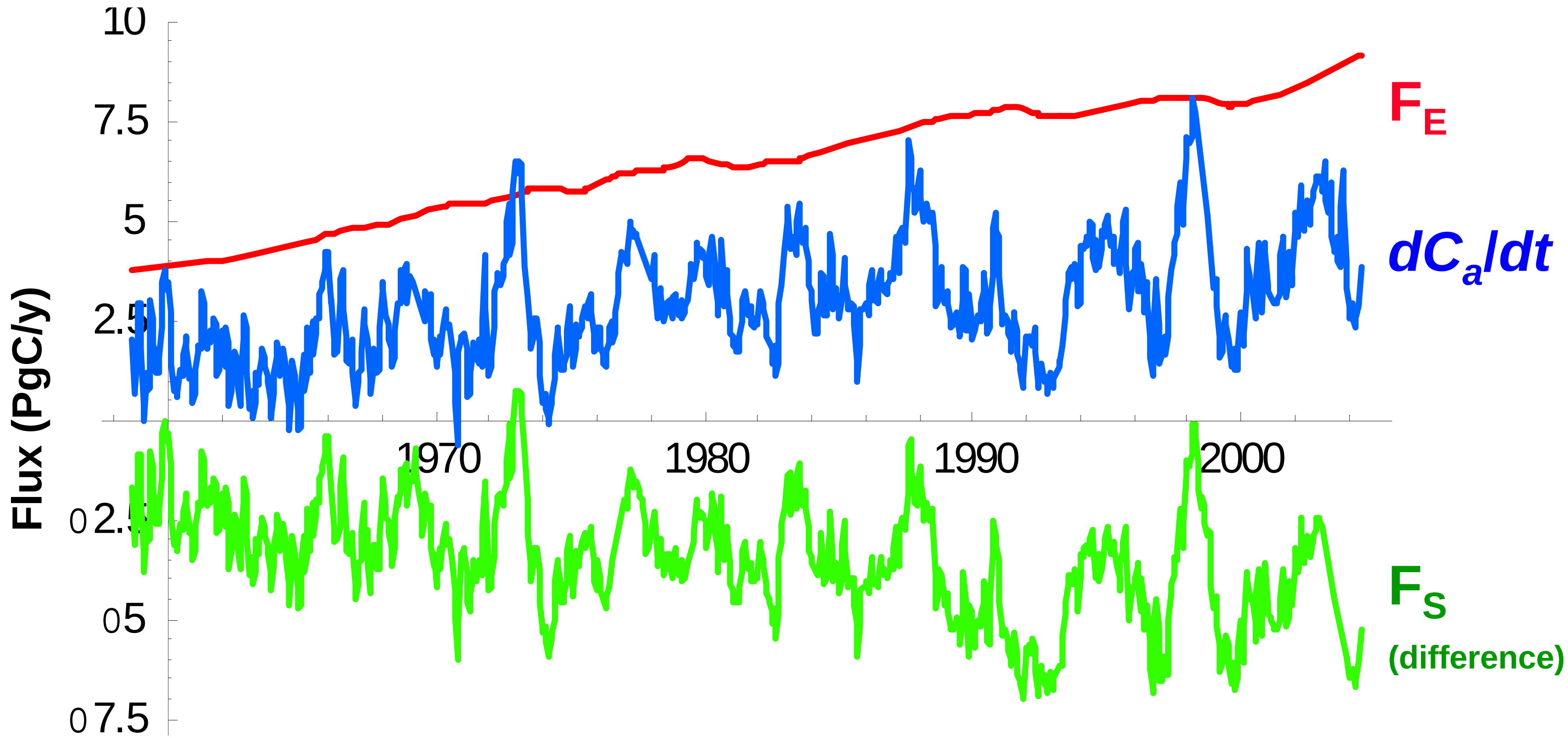
Atmospheric CO_2 growth = emissions + natural sinks

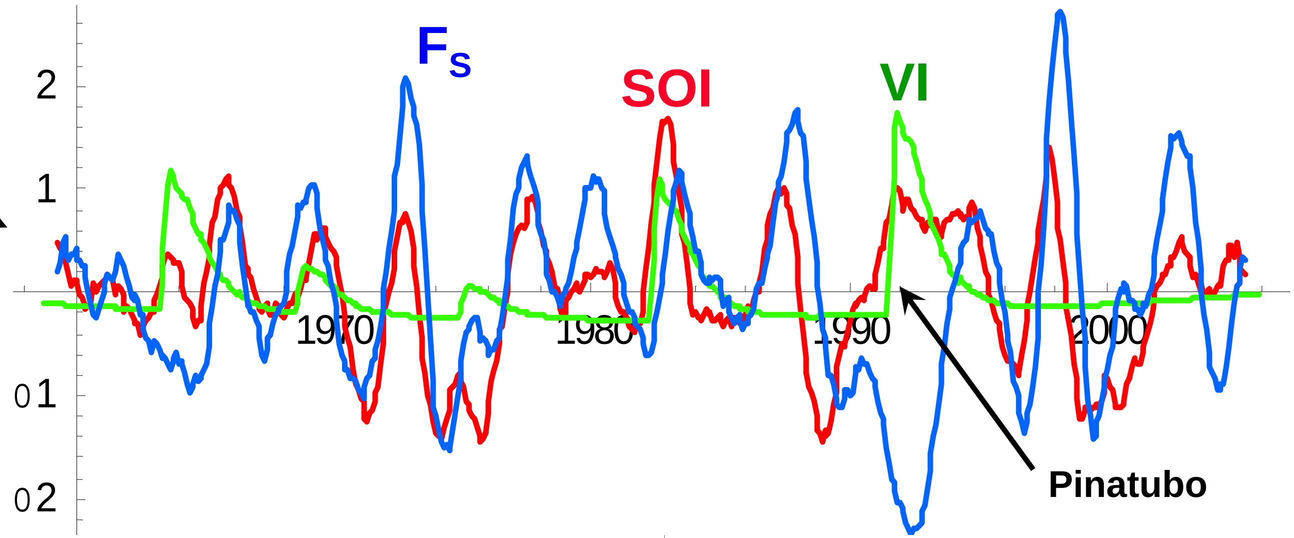
$$dC_a/dt = F_{Foss}(t) + F_{LUC}(t) + F_{LandAir}(t) + F_{OceanAir}(t)$$

$$= \underbrace{F_E(t)}_{\text{Total anthropogenic emissions}} + \underbrace{F_S(t)}_{\text{Total surface-atmosphere exchange}}$$

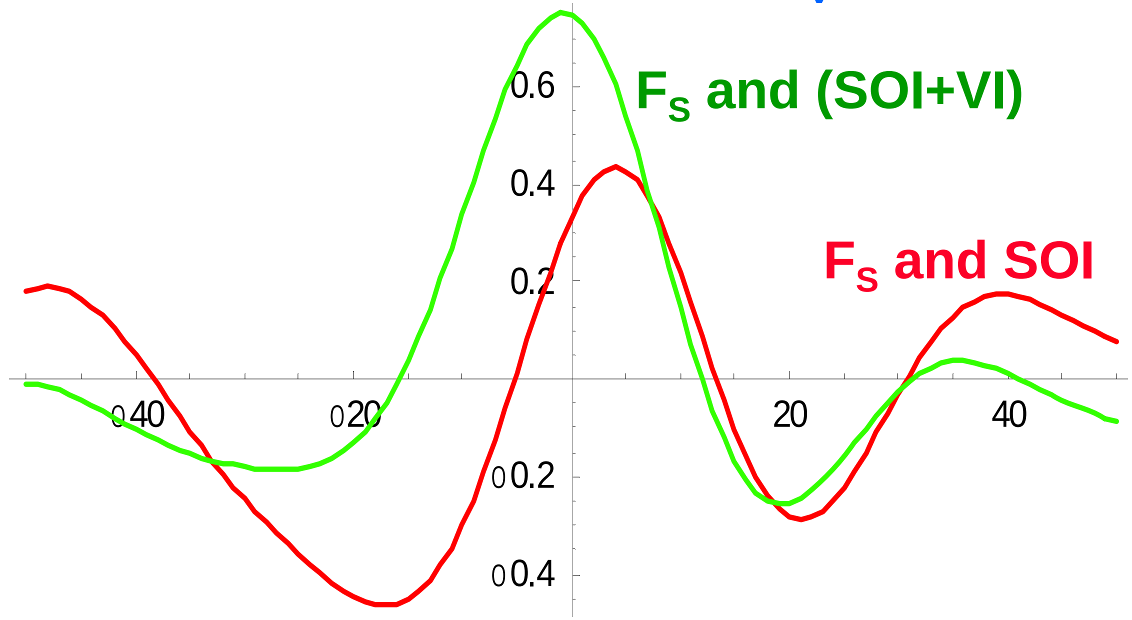


Interanual variation in CO_2 growth rate is correlated with ENSO and volcanic forcing

Time series of perturbations about long-term trends



- **surface flux**
  $F_S = F_{LandAir} + F_{OceanAir}$
- **ENSO (as SOI)**
- **VI = volcanic index (Amman et al 2003)**
- Note: low-pass filter applied to F_S, SOI

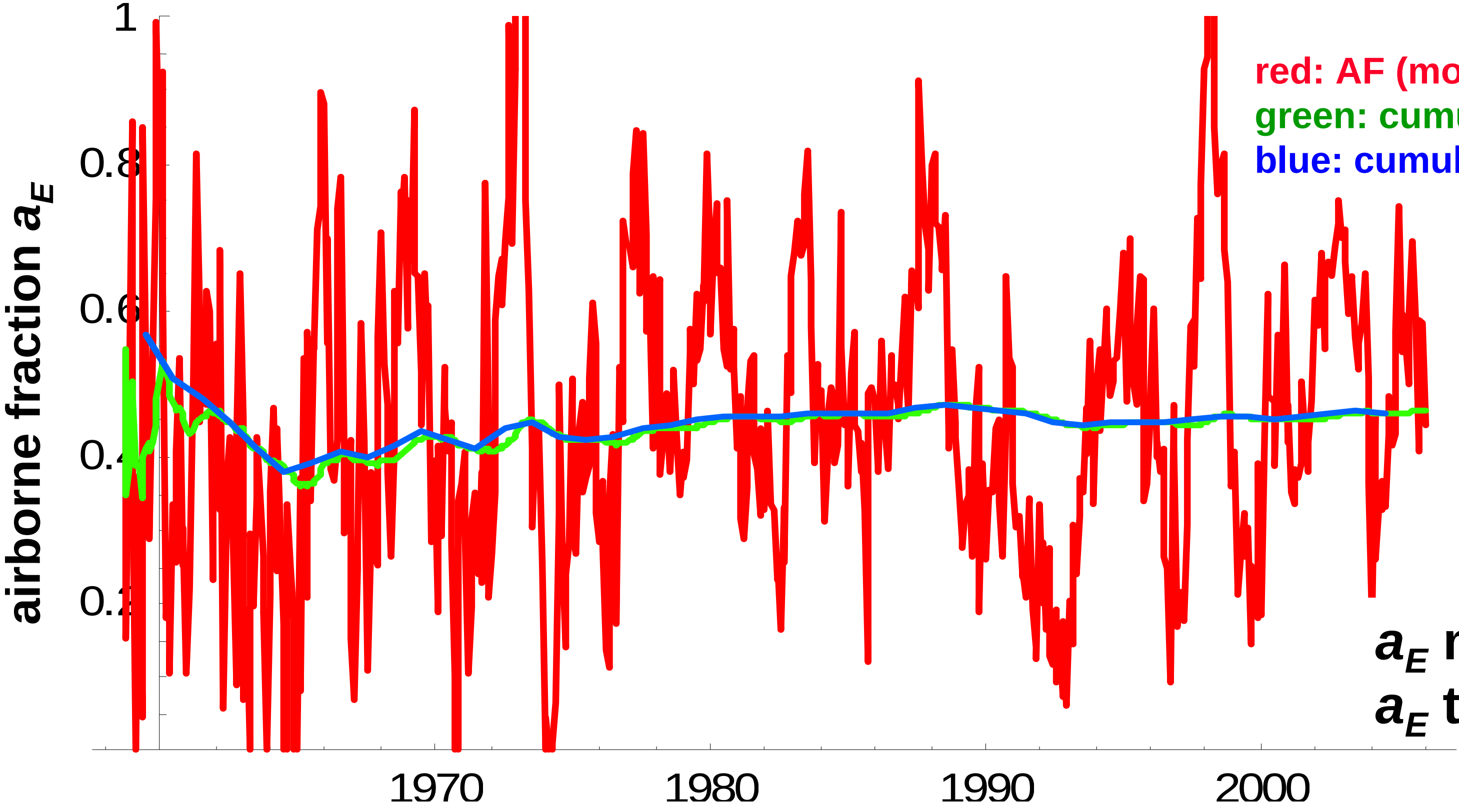


Lagged correlations

Airborne fraction

- Airborne Fraction (a_E) = fraction of total emissions that remain in the atmosphere (the rest are taken up by land and ocean CO_2 sinks)

$$a_E = (dC_a/dt) \,/\, F_E(t)$$



a_E mean: ~ 0.45

a_E trend: 0.3 % y^{-1}

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Attribution of changes in atmospheric CO_2 growth rate

- Kaya identity:

$$\begin{bmatrix}\text{Total CO}_2\\ \text{emission}\end{bmatrix} = [\text{Population}] \times \begin{bmatrix}\text{Per-capita}\\ \text{GDP}\end{bmatrix} \times \begin{bmatrix}\text{Carbon intensity}\\ \text{of GDP}\end{bmatrix}$$

$$F_E = Pgh_E, \quad \text{with} \quad g = G/P, \; h_E = F_E/G$$

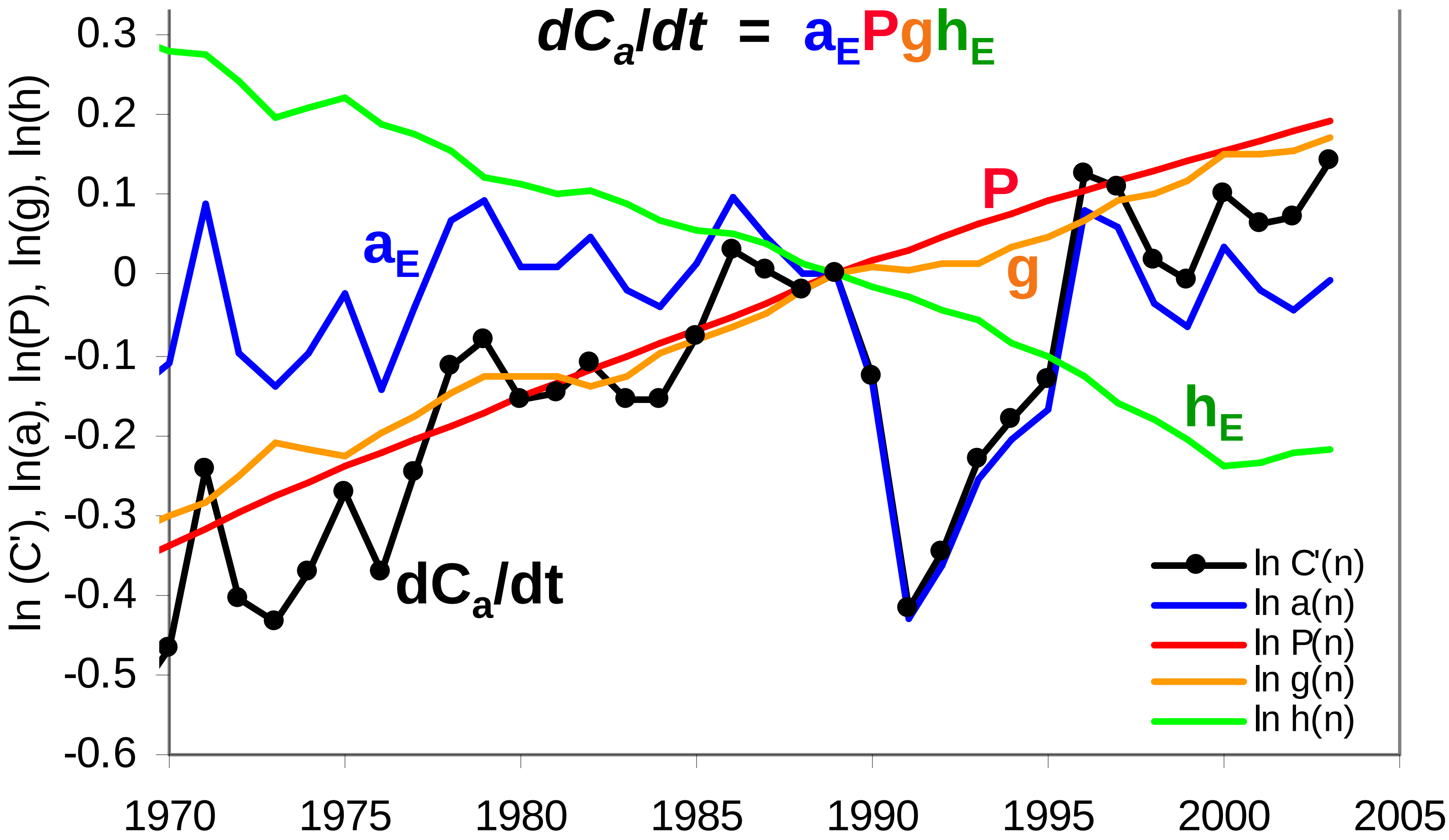
- Introduce airborne fraction: $a_E = \dfrac{dC_a/dt}{F_E}$

- Obtain an **extended Kaya identity** (also an atmospheric CO_2 budget):

$$\boxed{dC_a/dt = a_E P g h_E}$$

Attribution of changes in atmospheric CO_2 growth rate

- Terms in global extended Kaya identity



Attribution of changes in atmospheric CO_2 growth rate

Contributions to growth rate of dC_a/dt = growth in CO_2 accumulation:

- Growth rates for 1970-2000:

a_E	(airborne fraction)	+0.3 ß 0.2 % y^{-1}	(high variability)
P	(population)	+1.6 ß <0.1 % y^{-1}	
g	(per capita GDP)	+1.4 ß <0.1 % y^{-1}	
h_E	(C intensity of GDP)	–1.6 ß <0.1 % y^{-1}	
---------------			
dC_a/dt	(CO_2 accumulation)	+1.5 ß 0.4 % y^{-1}	(high variability)

- Since 2000, and immediate future:
  - growth rates of P and g do not change significantly
  - growth of a_E continues at 0.3 %/y (high variability)
  - **Growth in carbon intensity (h_E) turns from –1.6 to >0 % y^{-1}**

  ... so ...

  - **Growth in CO_2 accumulation increases from around 1.5 to 3 % y^{-1}**

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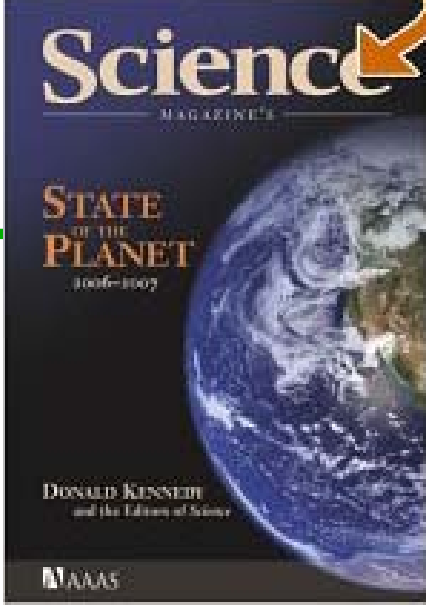
The tragedy of the commons – and beyond

- Hardin (1968) - model of herders on a common pasture
  - problem has no purely technical fi
- Dietz, Ostrom and Stern (2003):
  - Tragedy-of-commons problems can be solved with ***adaptive governance in complex systems***
  - Requires: Information
    Conflict resolution
    Rule compliance
    Infrastructure
    Readiness for change
  - These factors need to act at compatible scales
- Pretty (2003):
  - natural, physical, financial, human, social capital
  - social capital is a prerequisite for collective resource management



Hardin G (1968) The tragedy of the commons. Science **162**, 1243.

Dietz T, Ostrom E, Stern PC (2003) The struggle to govern the commons. Science **302**.

Pretty J (2003) Social capital and the collective mangement of resources. Science **302**.

Reprinted in Kennedy D et al. (2006) Science Magazine's State of the Planet 2006-2007. Island Press, Washington DC.

Carbon-climate-human interactions and the tragedy of the commons

- Danger and challenge are well known (IPCC 1991, 1996, 2001, 2007)
  - We must cap future emissions at ~ 500 GtC
    - about equal to cumulative emissions (fossil + land use) since 1750
    - "peak CO_2" is about now

- "If Australia stopped all its fossil fuel emissions today, the benefit would be wiped out by growth of Chinese emissions in just 9 months" (Australian Prime Minister, J. W. Howard, 2006)
  - ***this is true of everyone, including any Australia-size part of China!***

- After over 15 years of climate change awareness:
  - No agreed global emissions caps
  - No agreed global regulatory institution
  - Exploitation of individual commons benefit is accelerating

Four essential response components

- **Technical**
  - Broad portfolio: conservation, renewables, cleaner fossil fuels, ...
  - A workable transition pathway
- **Economic**
  - Market drivers: greenhouse accounting and trading mechanisms
- **Policy**
  - Agreed cap on cumulative emissions
  - Agreed rules to govern national emission flux trajectories
  - Policies to make greenhouse costs visible (carbon price signal)
  - Support for innovation
- **Cultural and social: building social capital across connected scales**
  - Global: protection of the shared earth system as a global imperative
  - Local: decoupling quality of life from consumption

Bifurcations, crossroads, choices

- **The Crossroads of Gaia**
  - Humans are now major participants in the evolution of Planet Earth
- **The Crossroads of Kyoto**
  - Carbon-climate-human interactions are now driven by tragedy-of-the-commons dynamics
  - We need global social capital
- **The Crossroads of Robert Johnson**
  - We have a few decades to reshape our unwitting Faustian bargain with a Gaian inheritance of detrital carbon