Global warming and local dimming: the statistical evidence

Chris Muris

Joint work with
Jan Magnus
Bertrand Melenberg

ETH Zürich

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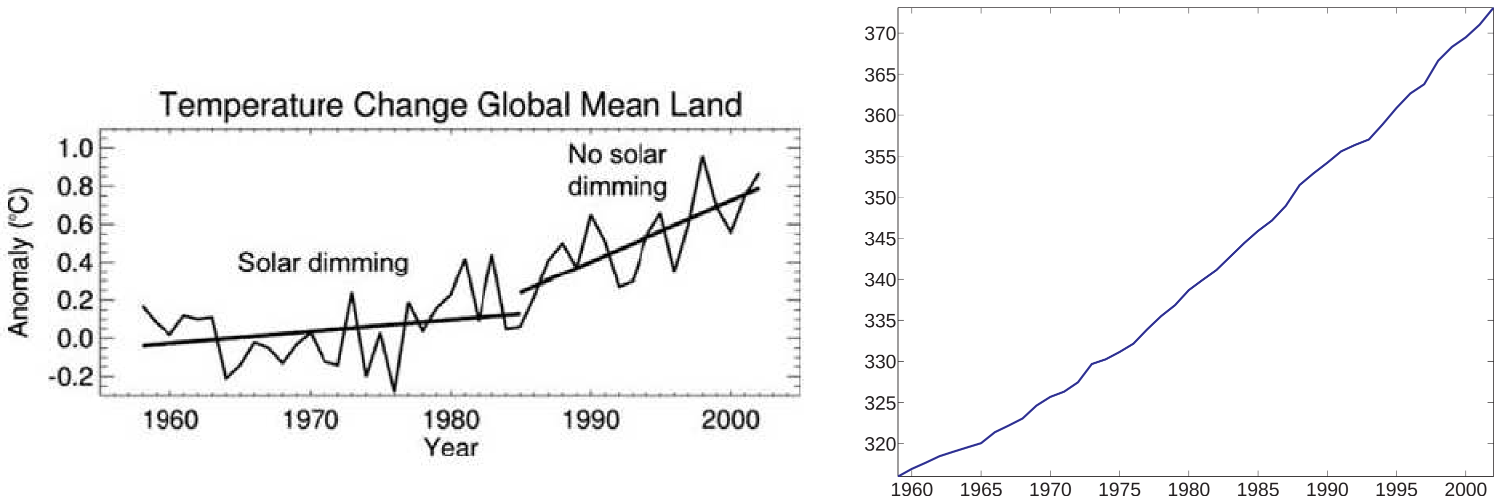
Tilburg School of Economics and Management

Introduction

Warming and CO2



(a) Temperature. Source: Wild et al. (2007)

(b) Carbon dioxide concentration

Figure 1: Temperature and carbon dioxide concentration

Potential other causes

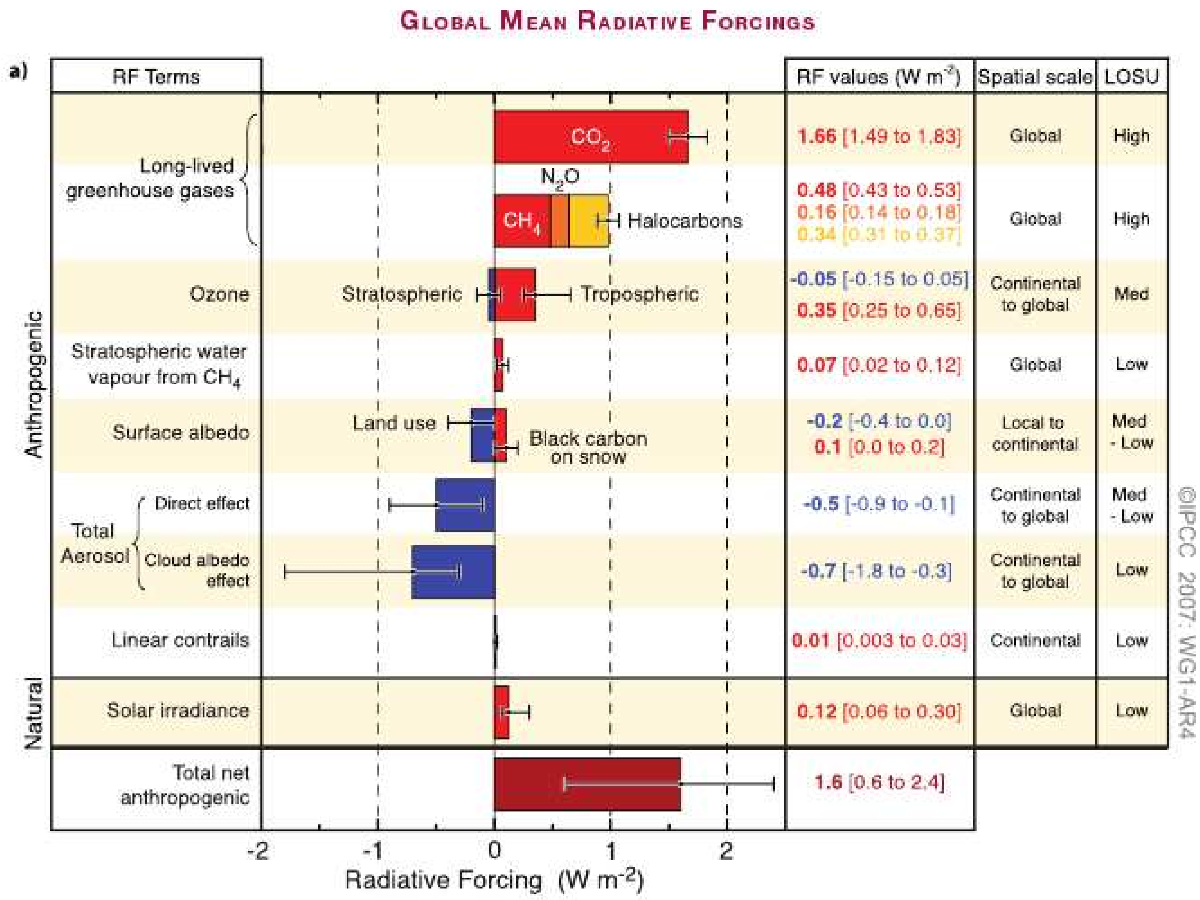


Figure 2: Alternative drivers of temperature. Source: IPCC (2007)

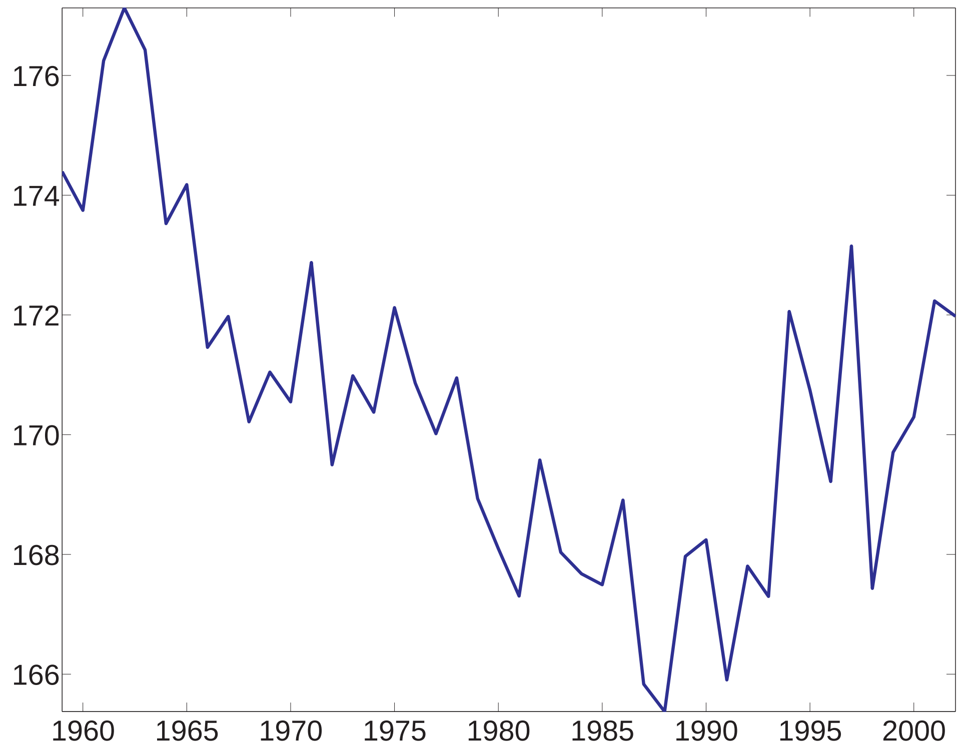


Figure 3: Solar radiation over time

Due to measures that target the adverse health effects of aerosols, and acid rain.

Motivation

- Andreae et al., “Strong present-day aerosol cooling implies hot future” (*Nature,* 30 June 2005)
- Arneth et al., “Clean the air, heat the planet” (*Science,* 30 October 2009)

- Uncertainty about the magnitude of dimming...
- ... has a potentially large effect on projected temperature ...
- ... and is therefore important in assessing environmental policy.

Goal

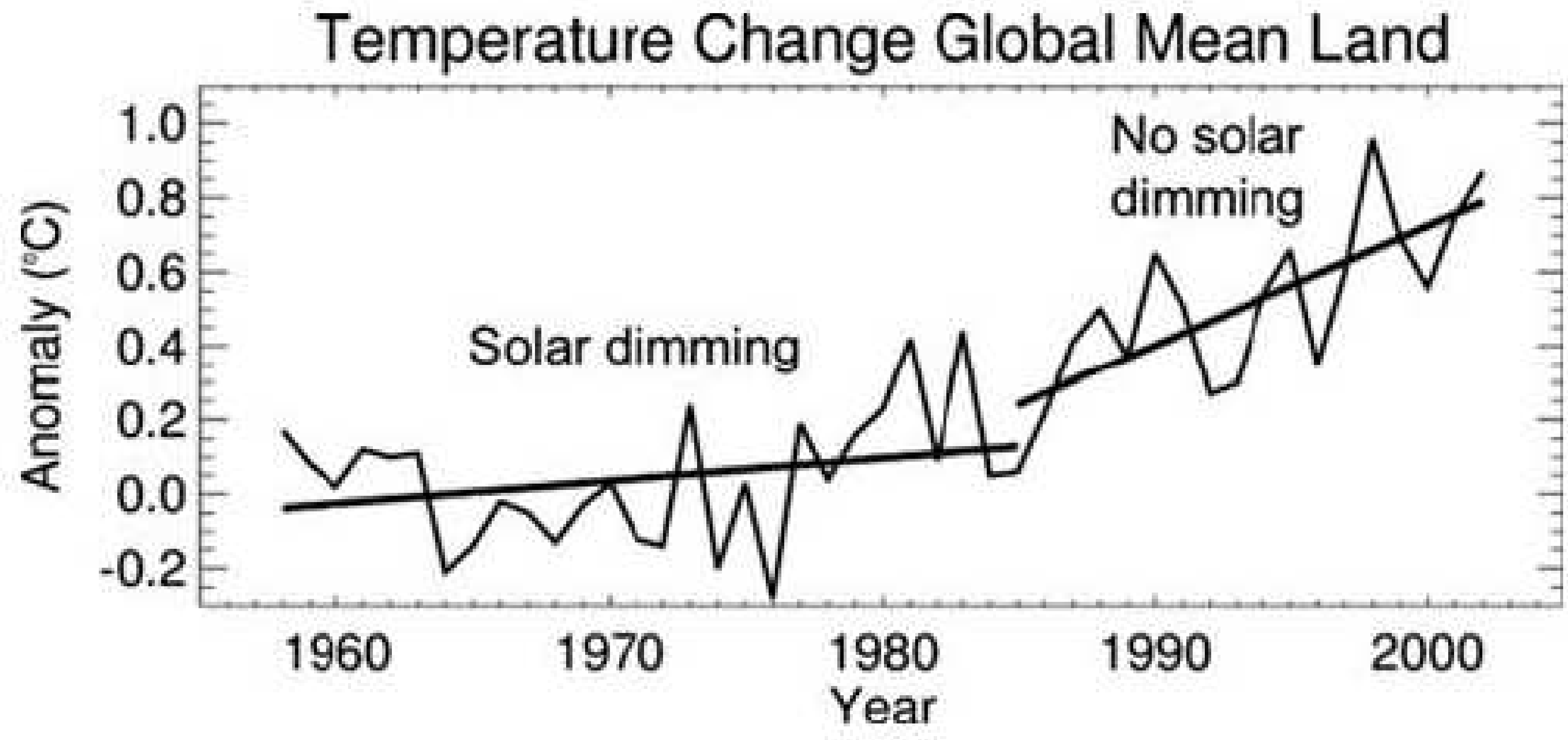


Figure 4: Temperature. Source: Wild et al. (2007)

- How much temperature increase due to warming?
- How much temperature decrease due to dimming?

Outline

1. Modelling the climate system
2. Data
3. Econometric model: dynamic panel data
4. Results

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1. Modelling the climate system

2. Data

3. Econometric model: dynamic panel data

4. Results (dimming offsets more than 50% of warming!)

Climate modelling

Modelling approaches

- Climate scientists: simulations with General Circulation Models

- Statistics: no integrated approach that incorporates dimming

- Optimal fingerprinting: matching GCM simulations to data (e.g. Stott et al., 2006)

- Our approach: simple climate model + extensive statistical analysis.
  No GCM

GCM

- GCM: parameter in, “data” out.
  Parameter by guess, expertise, calibration.

- Our approach: data in, parameter estimate out.
- Advantage:
  - parameter uncertainty quantified
  - no identification problem
- Cost: simplified climate model

Climate model (1): Longwave and shortwave radiation

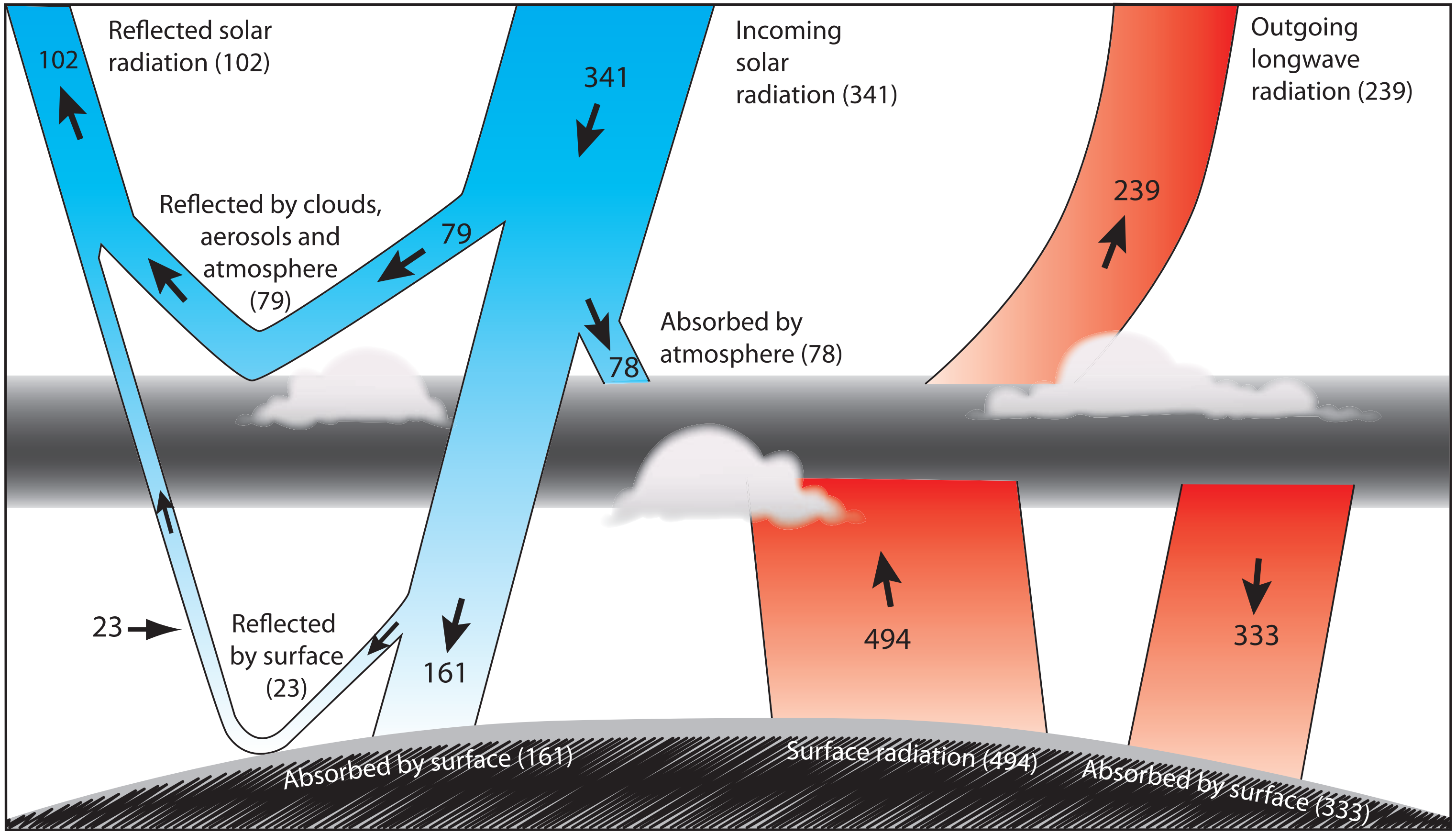


Figure 5: An energy balance model. Based on Trenberth et al. (2009)

Climate model (2): Energy balance surface

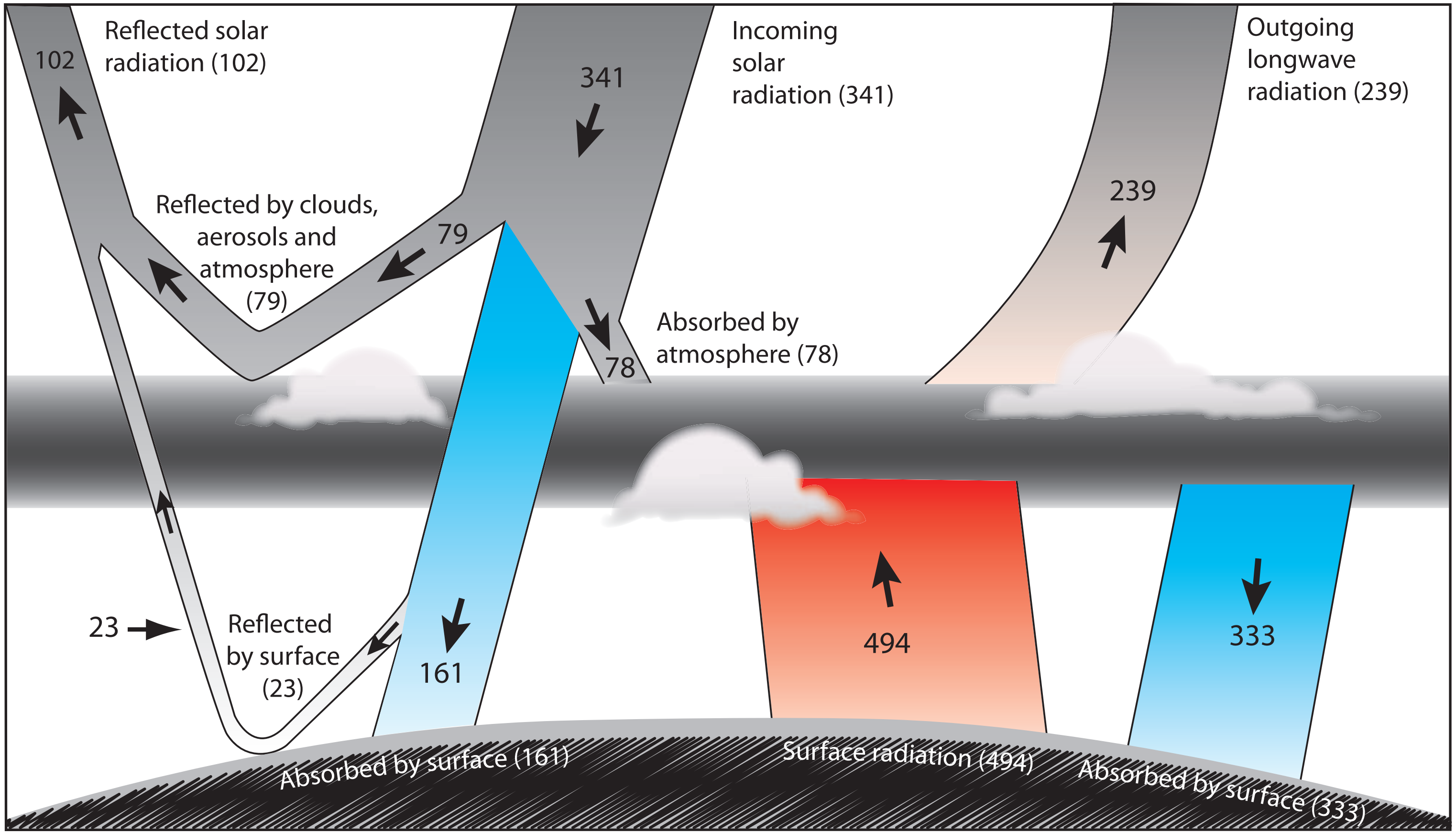


Figure 6: An energy balance model. Based on Trenberth et al. (2009)

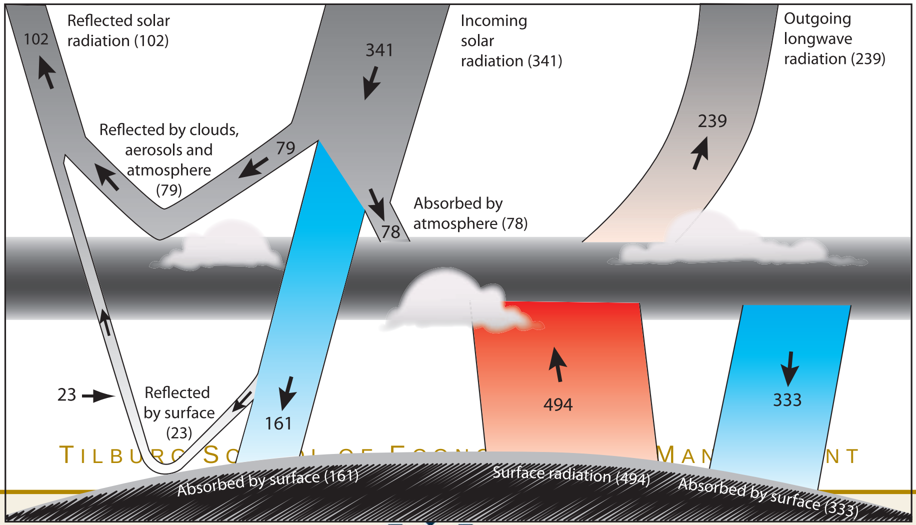
Energy balance

Equilibrium model:

- Global balance: Outgoing energy = Incoming energy
- Temperature restores balance: $c\Delta$TEMP = Incoming - Outgoing
  - Mechanism: surplus energy increases future temperature; higher temperature increases the amount of outgoing energy
  - c converts energy to temperature
- Local: $c\Delta$TEMP $=$ Incoming - Outgoing + Exchange

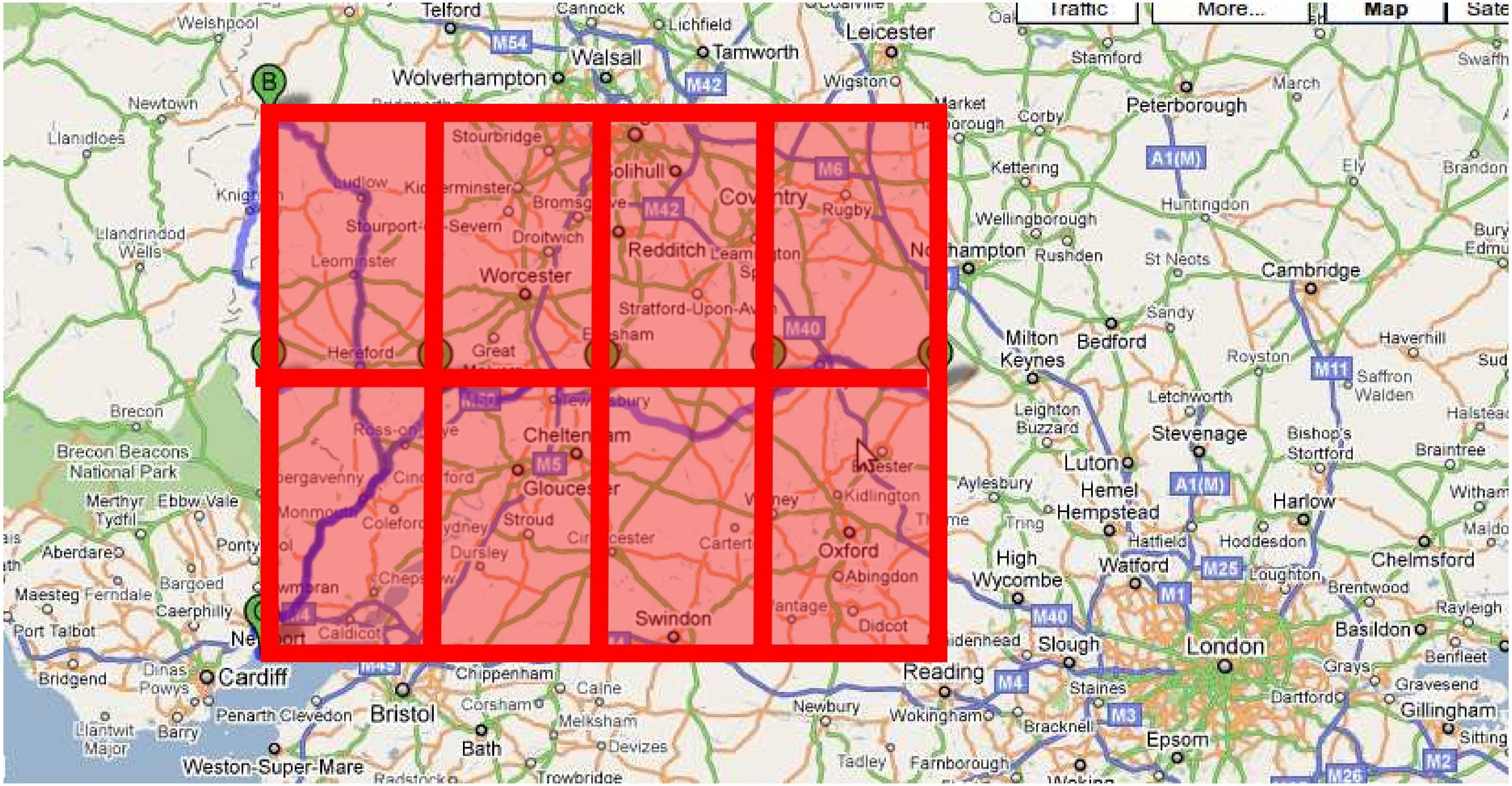
Data needs

- Incoming, blue, left: RAD, Solar radiation
- Incoming, blue, right: Concentration of greenhouse gases, as represented by CO2 (carbon dioxide)
- Outgoing: TEMP, Temperature
- Exchange: TEMP and average temperature



Data

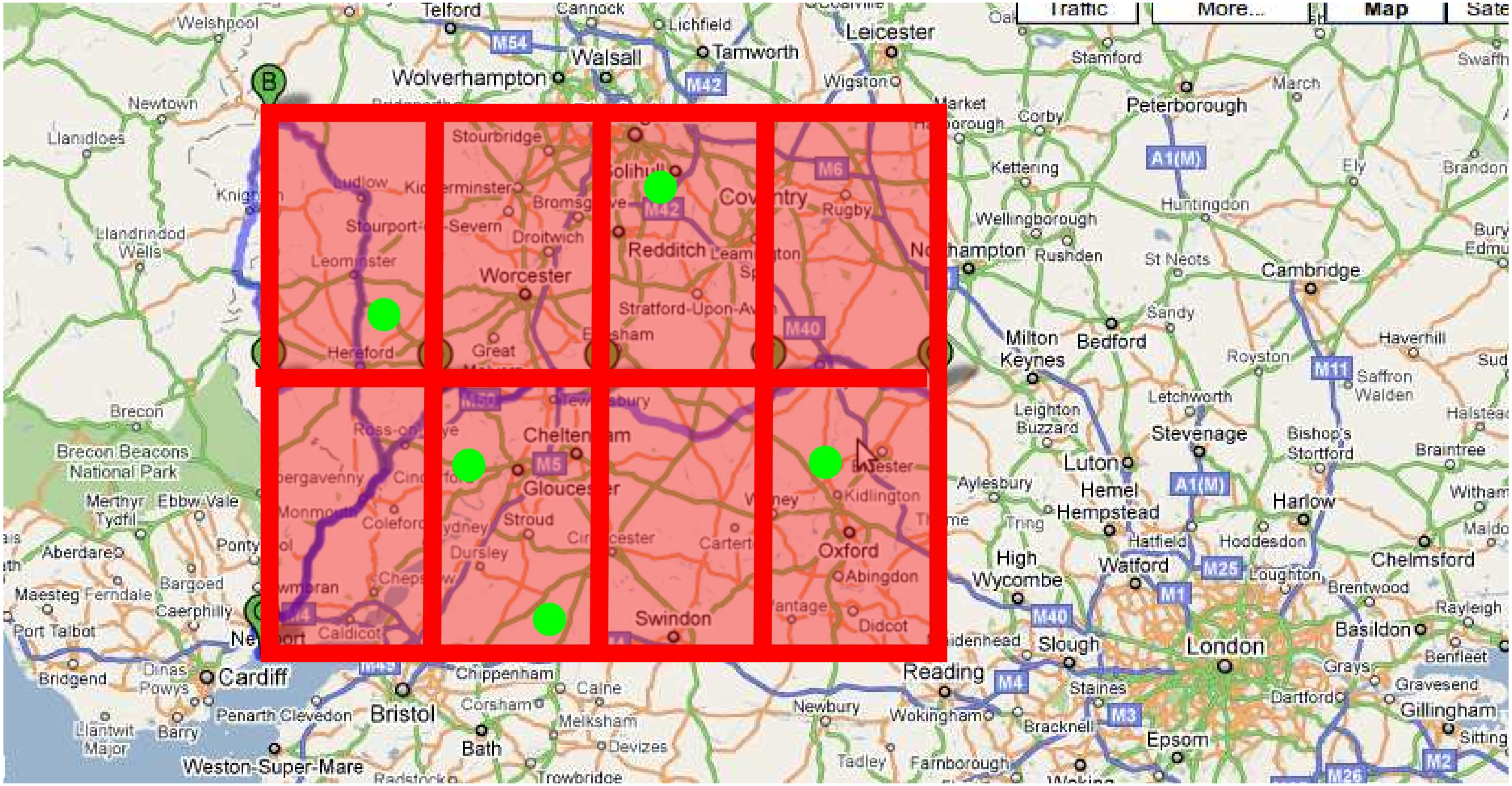
Construction (1)



■ One temperature measurement for every grid cell

■ Annual data for 1959-2002.

Construction (2)



- 1337 weather stations
- Unbalanced panel of 18000 data points

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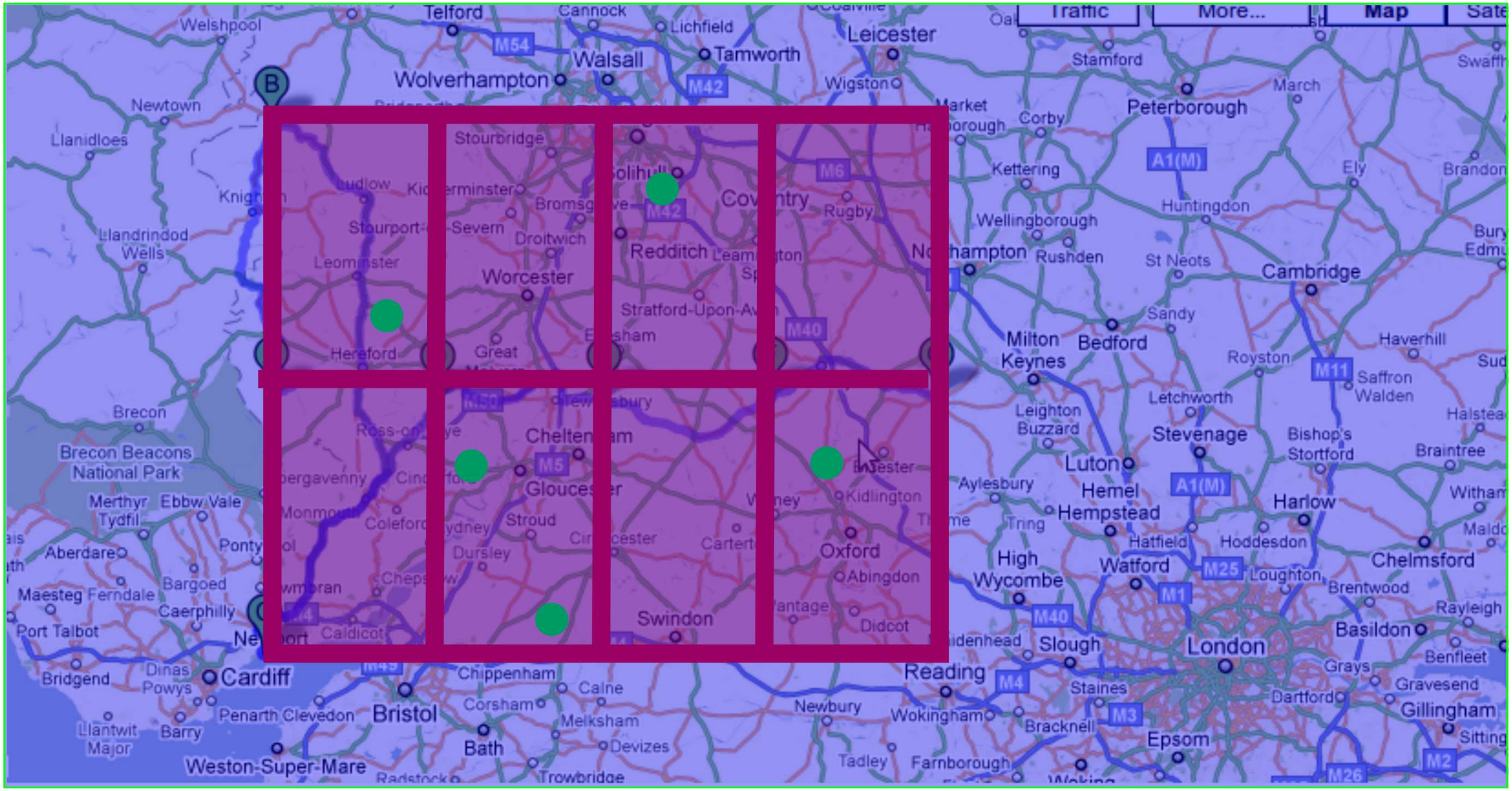
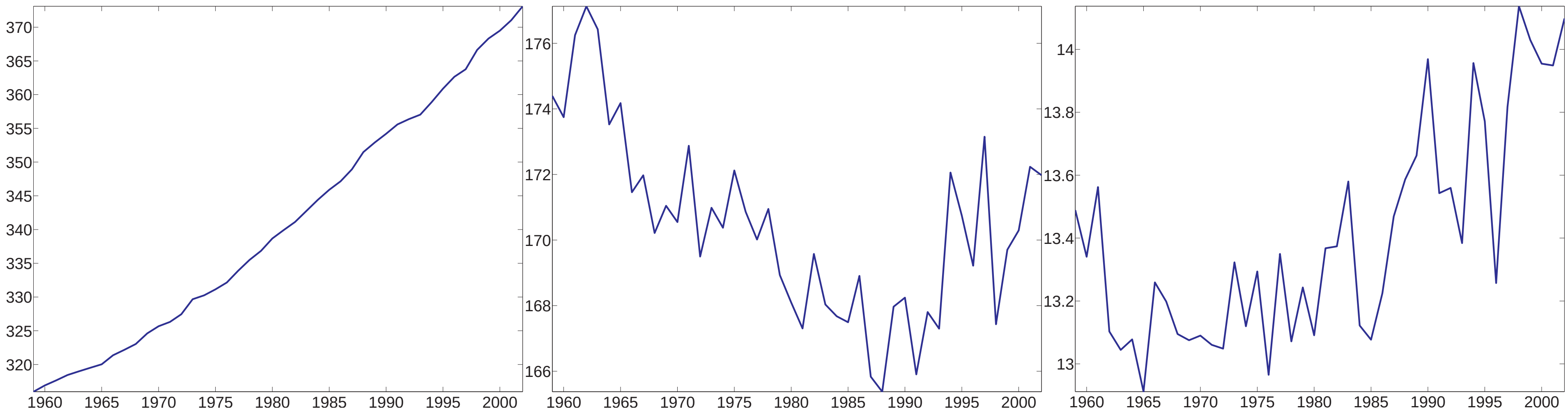
Construction (3)



■ Carbon dioxide concentration is everywhere the same

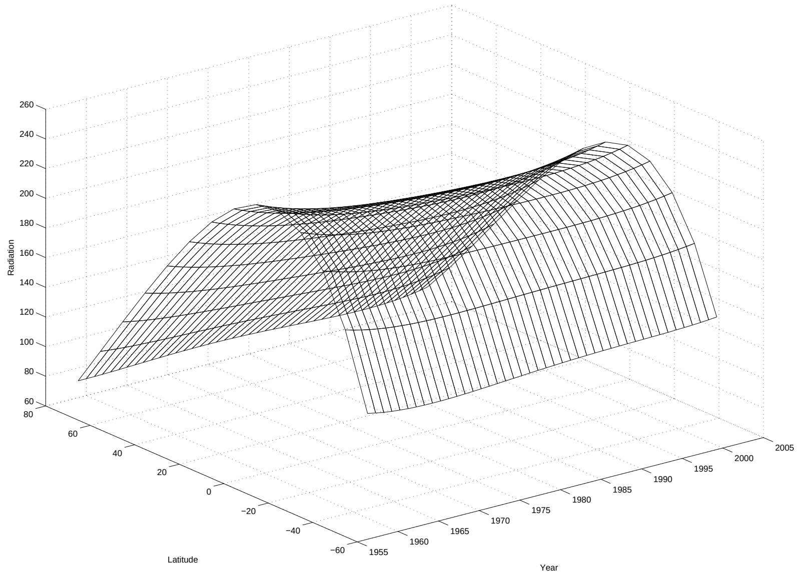
Aggregated data plots



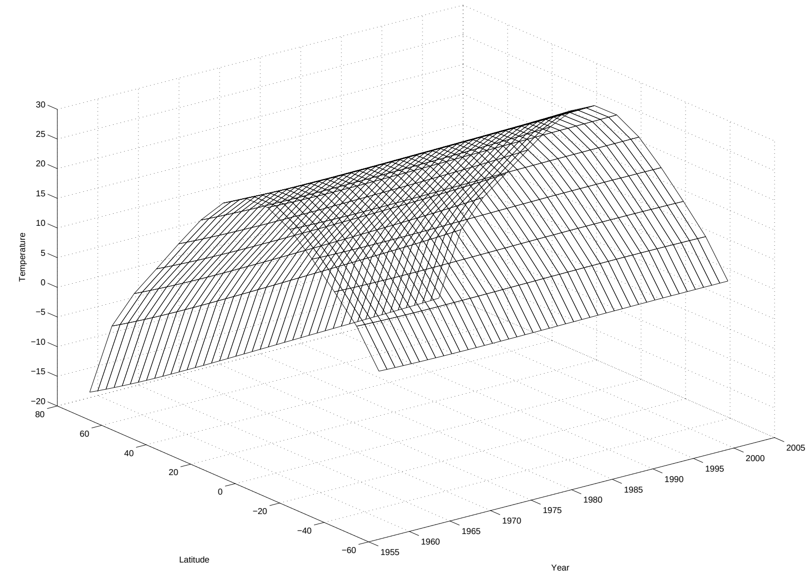
(a) CO_2 (b) RAD (c) TEMP

Figure 7: Data, (aggregated to) global means

- Interpolation using polynomial of order 4



(a) RAD



(b) TEMP

Figure 8: TEMP and RAD at the weather station level

Econometric model

Translating from climate model

$$c\Delta \text{TEMP}_{it} = \text{Incoming} - \text{Outgoing} + \text{Exchange}$$
$$= \text{from Sun} + \text{greenhouse} - \text{outgoing} + \text{exchange}$$

$$\begin{aligned} &= a_0 + a_1 \overline{\text{RAD}}_t + a_2(\text{RAD}_{it} - \overline{\text{RAD}}_t) \\ &\quad + b_0 + b_1 \log(\text{CO2}_t) \\ &\quad - (c_0 + c_1 \overline{\text{TEMP}}_t + c_2(\text{TEMP}_{it} - \overline{\text{TEMP}}_t)) \\ &\quad + d_0 - d_1(\text{TEMP}_{it} - \overline{\text{TEMP}}_t) \end{aligned}$$

$\overline{\text{RAD}}_t$ is average radiation

Rewriting...

Reduced form:

$$\text{TEMP}_{i,t+1} = \beta_1 \text{TEMP}_{it} + \beta_2 \text{RAD}_{it} + \lambda_t + \varepsilon_{it} \quad (1)$$

$$\lambda_t = \gamma_0 + \gamma_1 \overline{\text{TEMP}}_t + \gamma_2 \overline{\text{RAD}}_t + \gamma_3 \log(\text{CO2}_t) + v_t \quad (2)$$

- Error terms allow for flexibility, absorb part of latent and sensible heat
- Estimates of the reduced form parameters are sufficient

Estimation

Estimation. . .

- Linear trend estimation:

$$y_t = \beta_0 + \beta_1 t + u_t.$$

  Allows parameter β_1 and its uncertainty to be estimated.

- Same here, but more complicated.

Results

+5) Coefficients

TEMP_{it} (β_1)	RAD_{it} (β_2)	$\overline{\text{TEMP}}_t$ (γ_1)	$\overline{\text{RAD}}_t$ (γ_2)	$\log \text{CO2}_t$ (γ_3)
0.9063	0.0087	-0.8235	0.0614	10.6955
(0.0046)	(0.0008)	(0.1839)	(0.0219)	(2.3958)

Table 1: Coefficient estimates

Effects: definition

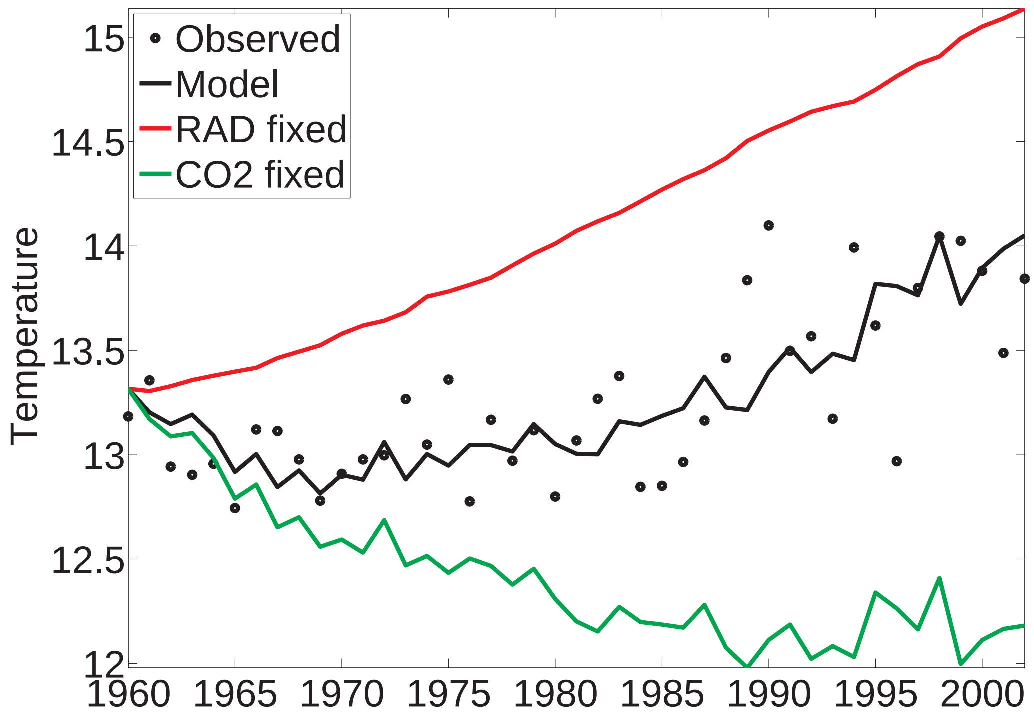


Figure 9: Results in terms of different scenarios

- black minus red: dimming
- black minus green: warming

Effects: estimates

We find:

- Dimming: $-1.09\,$°C (0.28)
- Warming: $1.87\,$°C (0.29)
- Warming offset by dimming: 58%

- Point estimate is 5.30
- 95%-confidence interval: (3.48, 7.12)

- Solomon et al (2007): (2.38, 5.14)

Policy (1)

- $> 2\,^{\circ}$C temperature increase is catastrophic

- Can this be avoided?

Policy (2)

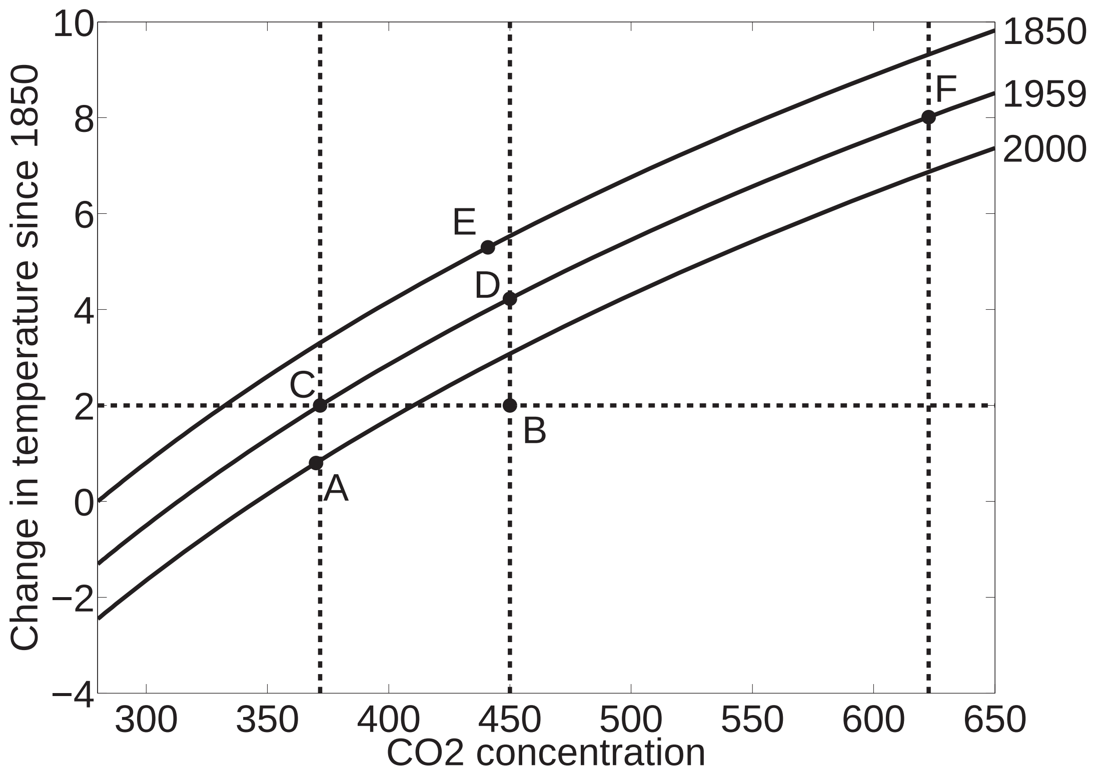


Figure 10: Iso-radiation curves

- If the current trend in dimming persists, greenhouse gas concentrations need to return to their 2000 levels to avoid catastrophe

Conclusions

Conclusions

- We detect a greenhouse effect and a radiation effect
- More action required to avoid dangerous climate change
- Findings robust to model changes
- Completely new approach, comparable results
- Many challenging improvements possible: modelling ocean, slower processes, strongly absorbing aerosols

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+4) Sensitivity analysis

	Method		Radiation	Greenhouse
1	Benchmark		−1.09 (0.31)	1.87 (0.32)
2a	Water vapor	Exogenous	−1.41 (0.84)	2.68 (1.45)
2b		Endogenous	−1.22 (0.87)	2.56 (1.63)
3	Cloud cover		−0.58 (0.37)	1.35 (0.43)
4	Albedo		−0.92 (0.34)	2.34 (0.41)
5	Different sample period		−0.61 (0.71)	1.27 (0.78)
6	Smoothing		−0.99 (0.29)	1.94 (0.33)
7	Definition of $\overline{\text{TEMP}}$		−1.16 (0.25)	1.78 (0.24)
8	Weights		−1.43 (0.28)	1.71 (0.25)
9a	Lags	Two lags	−1.05 (0.31)	1.84 (0.32)
9b		Four lags	−1.08 (0.31)	1.88 (0.32)
10	Arellano-Bond		−0.78 (0.29)	1.73 (0.30)
11	One round		−0.07 (0.03)	1.08 (0.03)

Table 2: Sensitivity analysis: radiation and greenhouse effects

+6) Emissions policy

- Link emissions to concentrations

$$\Delta \text{CO2}_t \approx 0.0213 - 0.0077\text{CO2}_{t-1} + 0.0038\text{Emissions}_t$$

- Carbon dioxide concentrations converge slowly: abrupt emission changes have effects in the future, not now

+7) Emissions policy (2)

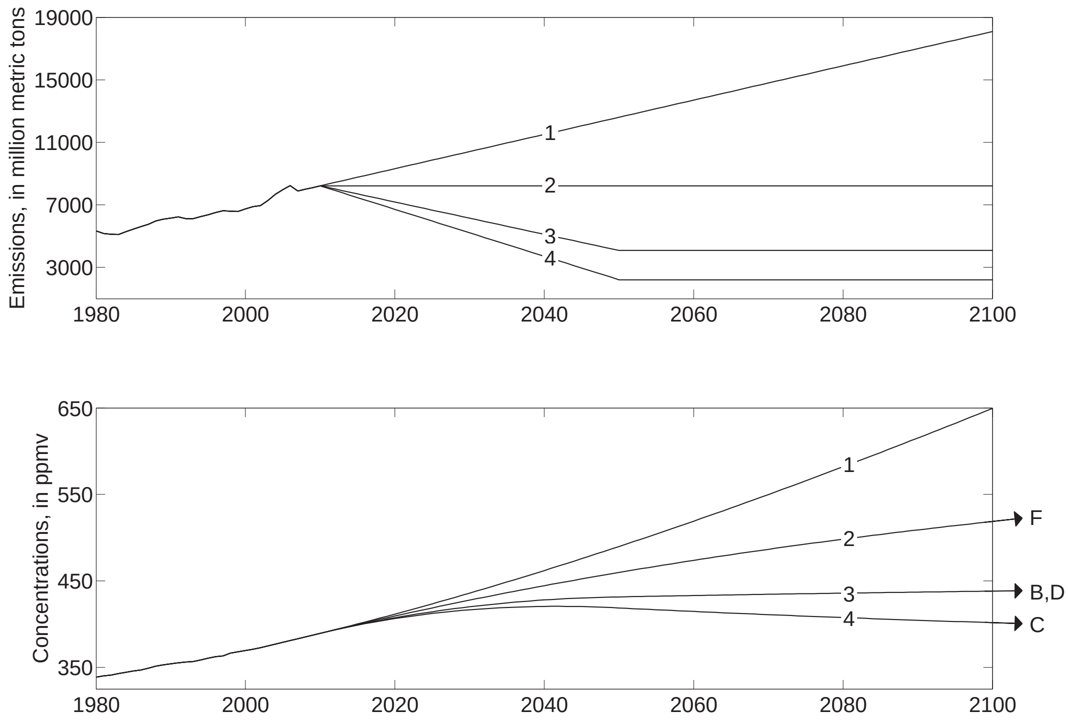

Figure 11: Emissions policies and effect on concentrations

- With brightening, we need to reduce emissions to pre-1980 levels to avoid $> 2\ ^\circ$C warming to avoid catastrophe