Integrated Economic and Climate Modeling

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http://www.econ.yale.edu/~nordhaus/homepage/recent_stuff.htm

*I am Professor of Economics at Yale University. I have received support for research on the economics of climate change during the last decade from the National Science Foundation, the Department of Energy, and the Glaser Foundation.

Topics for today

- The need for Integrated Assessment Models (IAMs)
- Some scientific and emissions background
- The RICE-DICE models
- Modeling the 2 °C / Copenhagen target
- The social cost of carbon
- Is disaggregation always desirable?
- The scary problem of computational complexity

The Contribution of Economics: Integrated Assessment Models (IAMs)

What are IA models?

These are models that include the full range of cause and effect in climate change ("end to end" modeling).

Major goals of IA models:

Project trends in consistent manner

Assess costs and benefits of climate policies

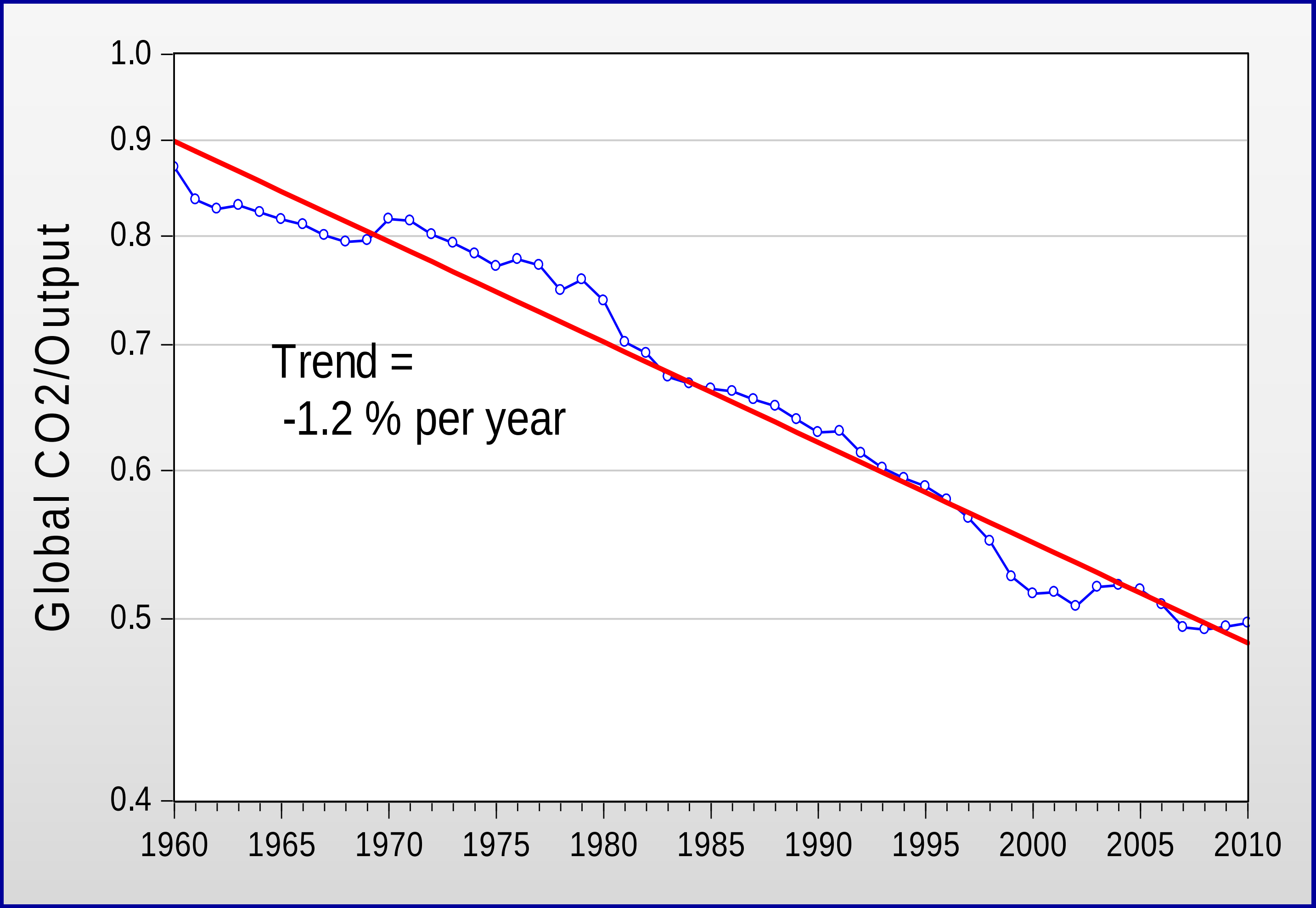
Estimate the carbon price and efficient emissions reductions for different goals

Why do we need IAMs?

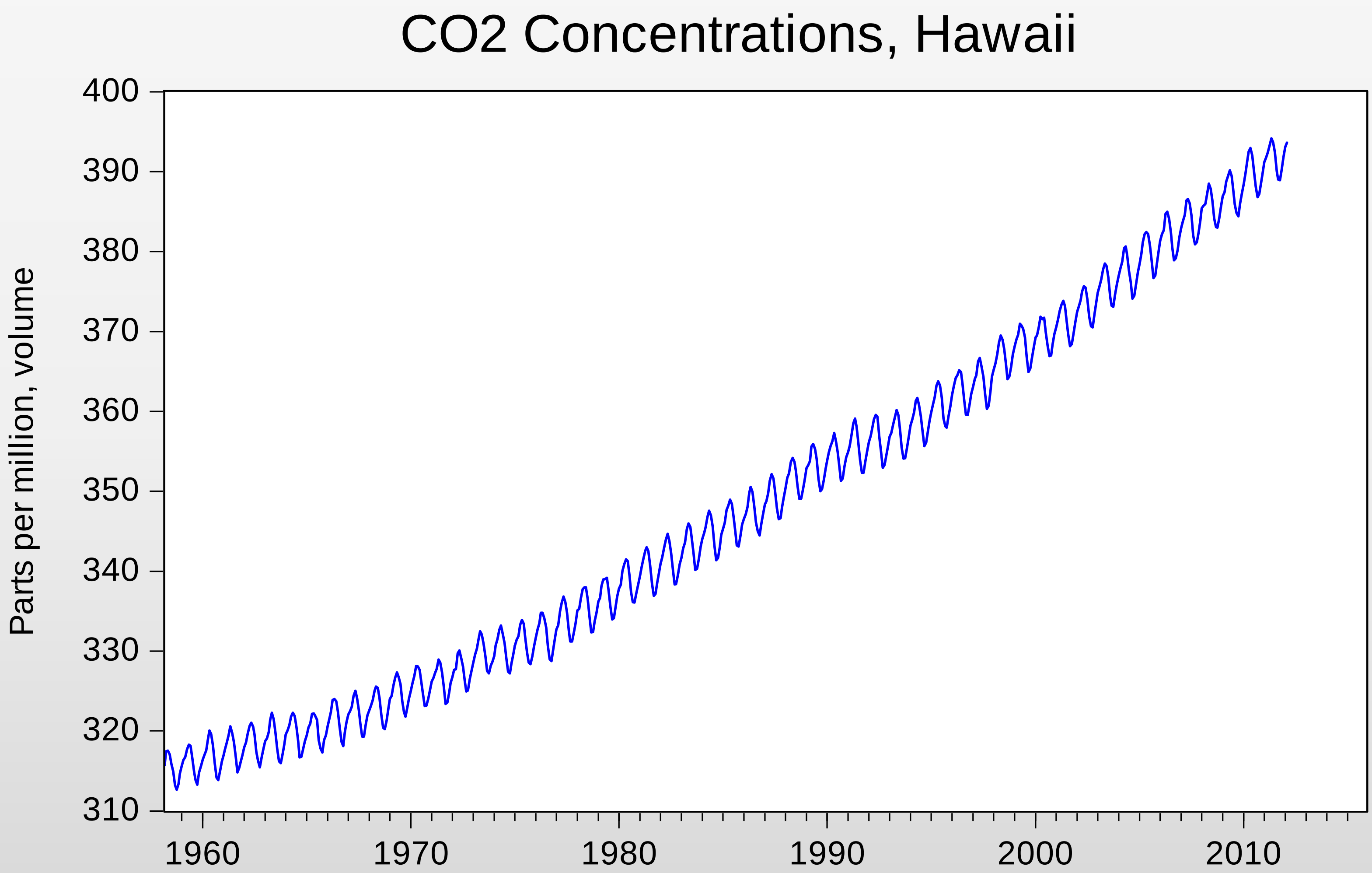
- Many areas of the natural and social sciences involve complicated interrelated systems cannot be intuitively understood.
- The example here is climate change, involving geophysical and social sciences.
- As understanding progresses in the different areas, it is increasingly necessary to link together the different areas to develop effective understanding and efficient policies.
- Integrated assessment models (IAMs) can be defined as approaches that integrate knowledge from two or more domains into a single framework.
- However, the scientific and computational complexity is rising rapidly, and this poses a major challenge for the modeling and scientific community

Some Scientific Background

Trend in global CO2 emissions relative to GDP



Sources: [23, 27]


CO2 Concentrations, Hawaii
Parts per million, volume
400
390
380
370
360
350
340
330
320
310
1960
1970
1980
1990
2000
2010

Sources: [24]

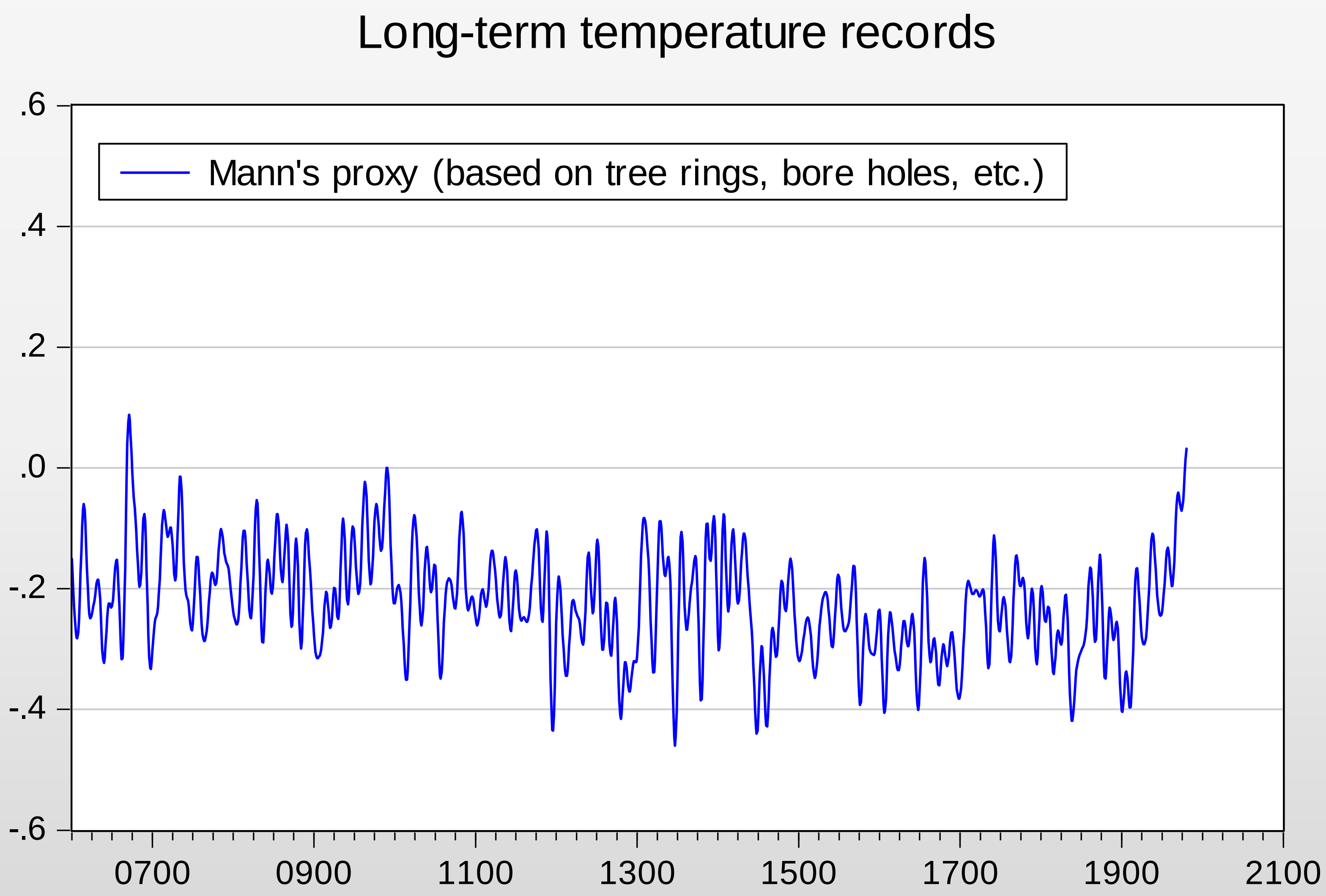
Global emissions trend, 1950 – 2010

Kaya identity: CO_2 = Pop * (GDP/Pop) * (CO_2/GDP)

	1950	2010	Growth rate (% per year)
	Global		
GDP/Pop (2005 $/person)	2,744	9,856	2.2
CO2/GDP (tons/1,000,000 $)	852	497	-0.9
Population (millions)	2,557	6,869	1.7
Total CO2 Emissions (million tons CO2)	5,976	33,678	2.9

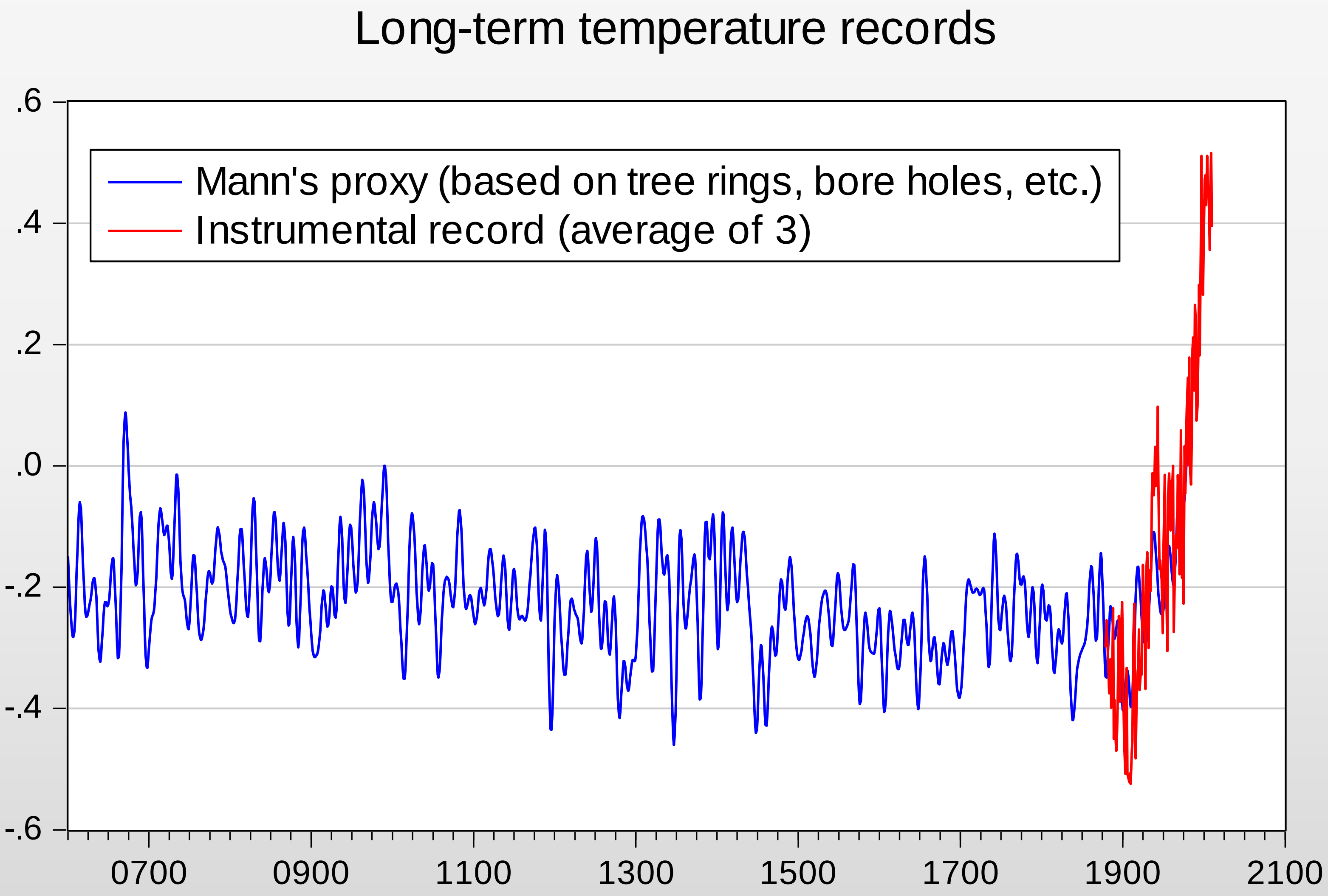
Sources: [27, 23]

Temperature record (°C), 200 - 1980



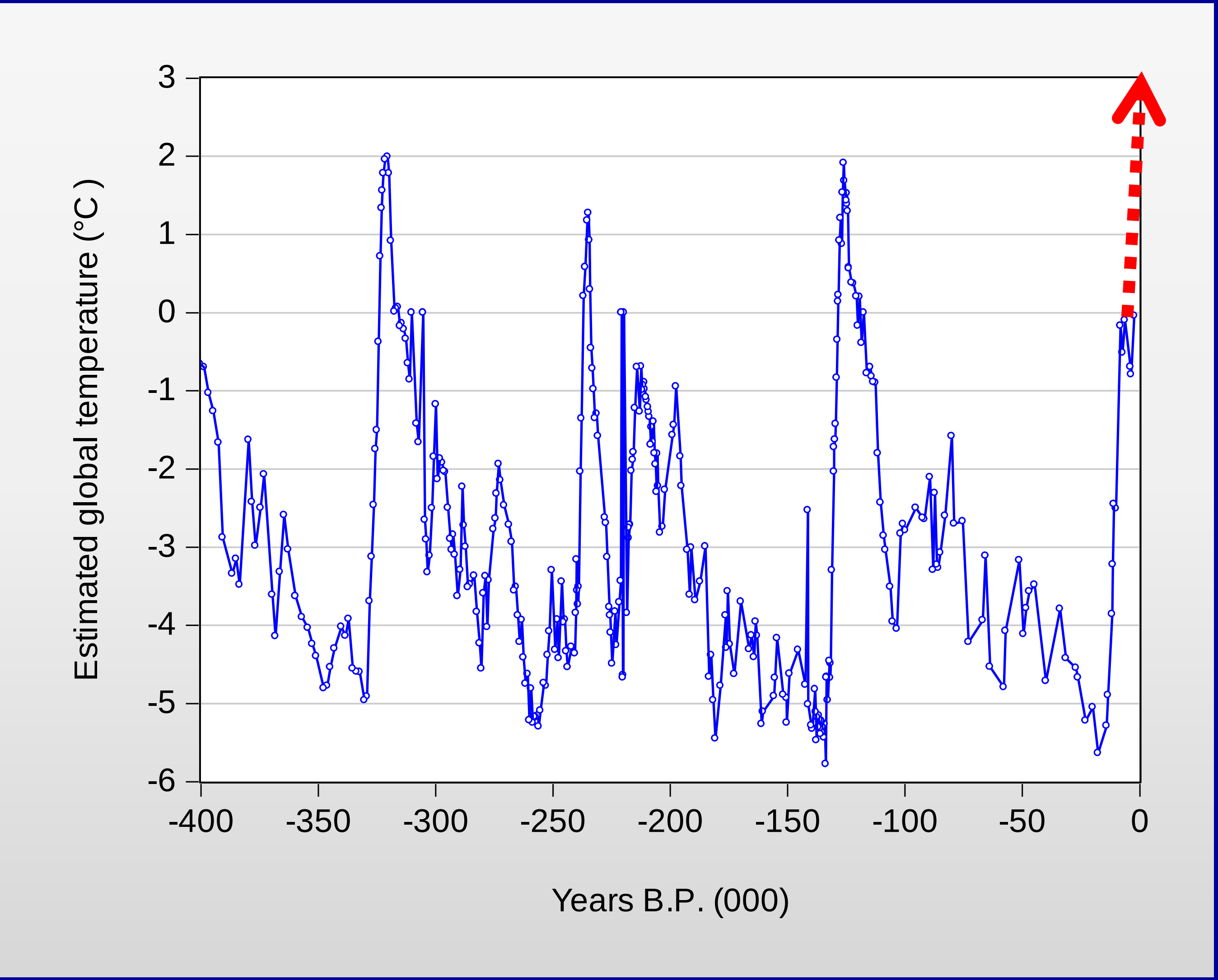
Sources: [25]

Merged temperature record (°C)



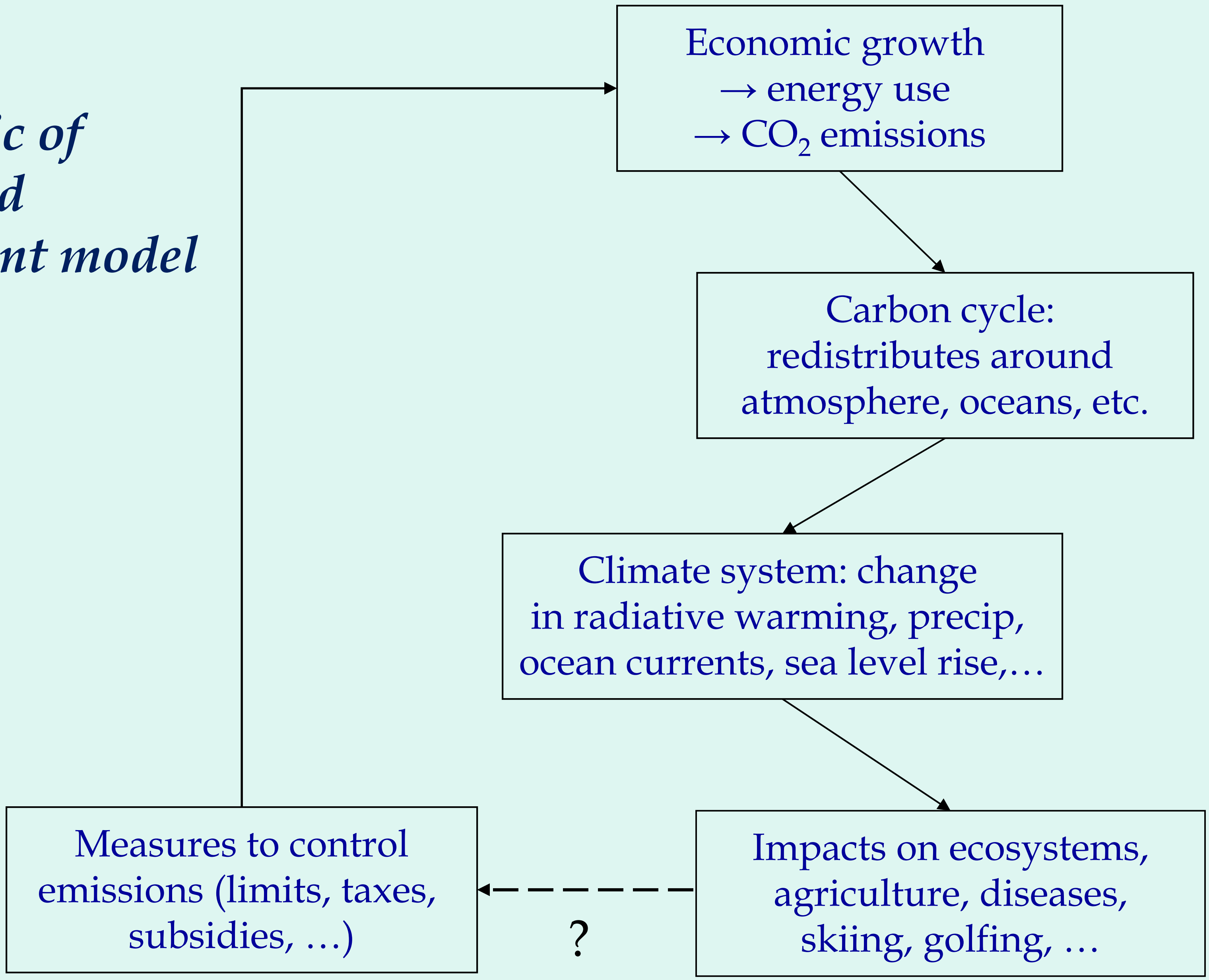
Sources: [25, 28]

Projections and the paleoclimatic record



Sources: Vostok core scientists for history; standard projections to 2100 or so for arrow. Uses conversion of 5:8 for global to Antarctica temperature. Sources [26, 2]

Schematic of integrated assessment model



The DICE-RICE family of IAMs

History:

- First vintage 1992
- Latest full versions:
  - Global aggregate (DICE 2007)
  - Regional (RICE-2010)
- Special cases (probabilistic, with R&D, with learning, with catastrophic thresholds)
- Work in progress: RICE-2012 (in development)

DICE/RICE-2010 model structure

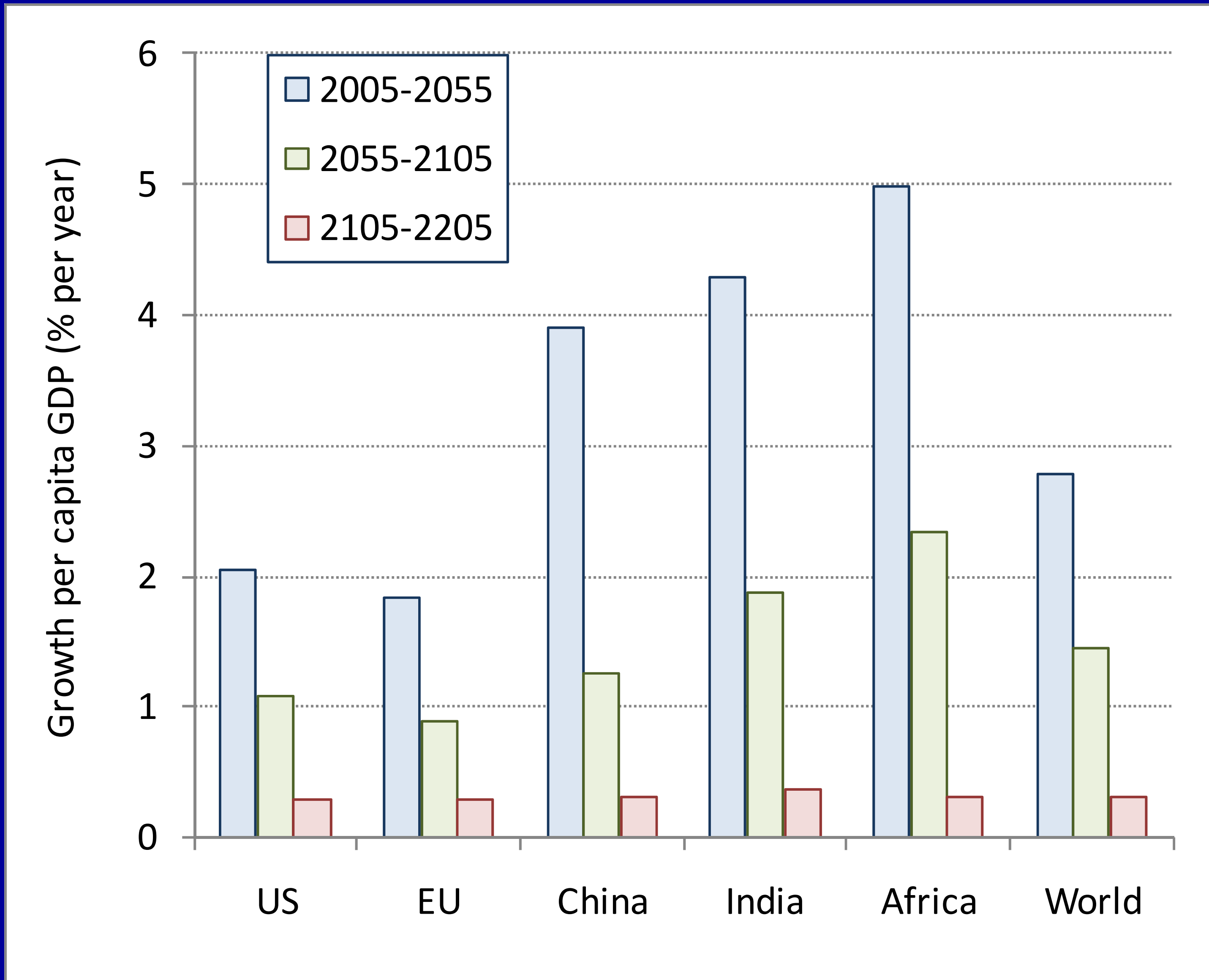
Economic module:

- Ramsey-Cass-Koopmans model with labor, capital, cabron capital, abatement, damage
- Climate variable is externality and market underinvests in climate capital
- 12 regions, no trade, limited carbon energy

Environmental module:

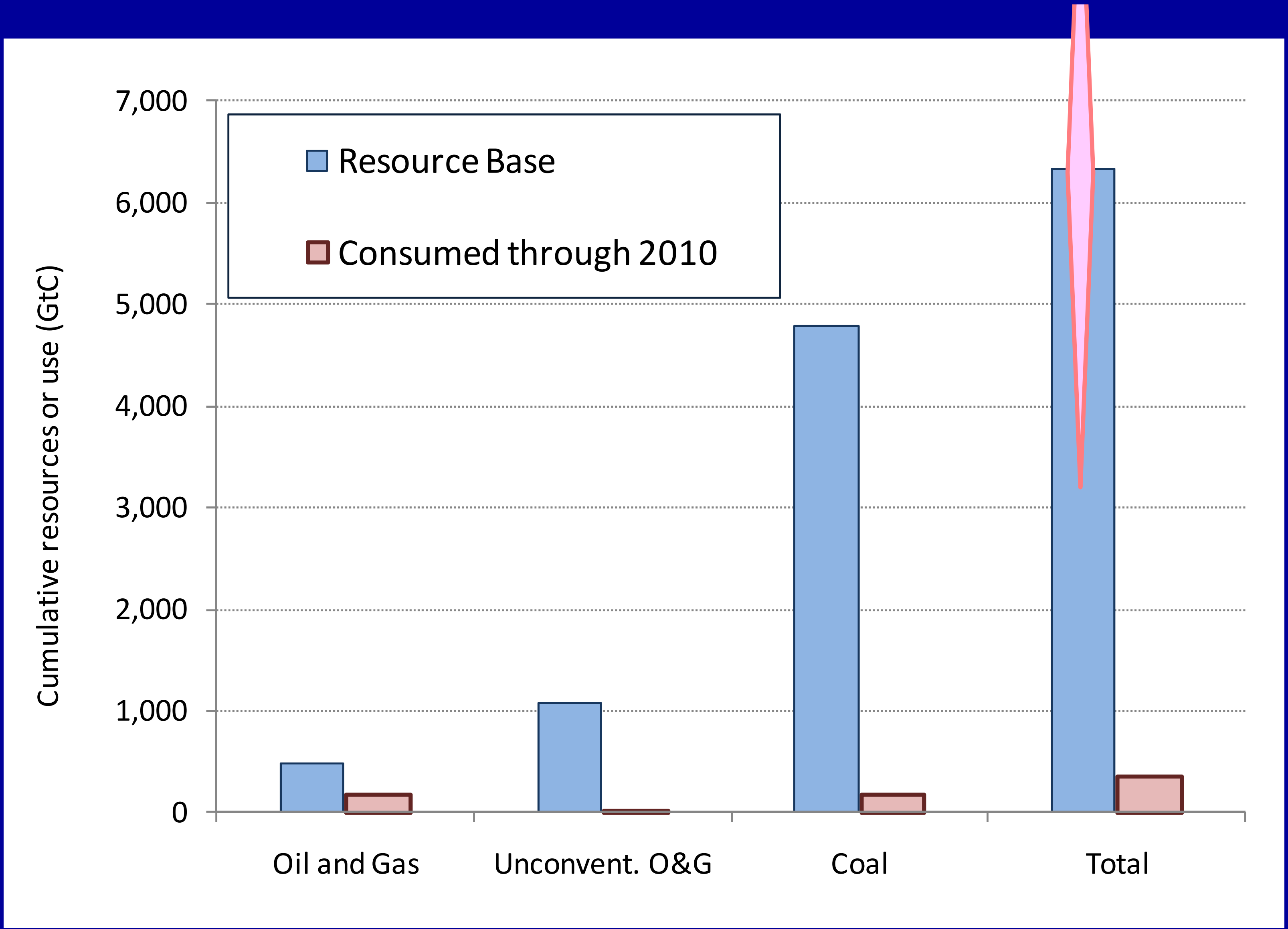
- Emissions = f(output, carbon price, time)
- Concentrations = g(emissions, 3 C reservoirs)
- Temperature change = h(GHG forcings, lag T, …)
- Economic damage = F(output, T, CO2, sea level rise)

Output growth by RICE region



Source: [2]

Cumulative resources and use of carbon fuels



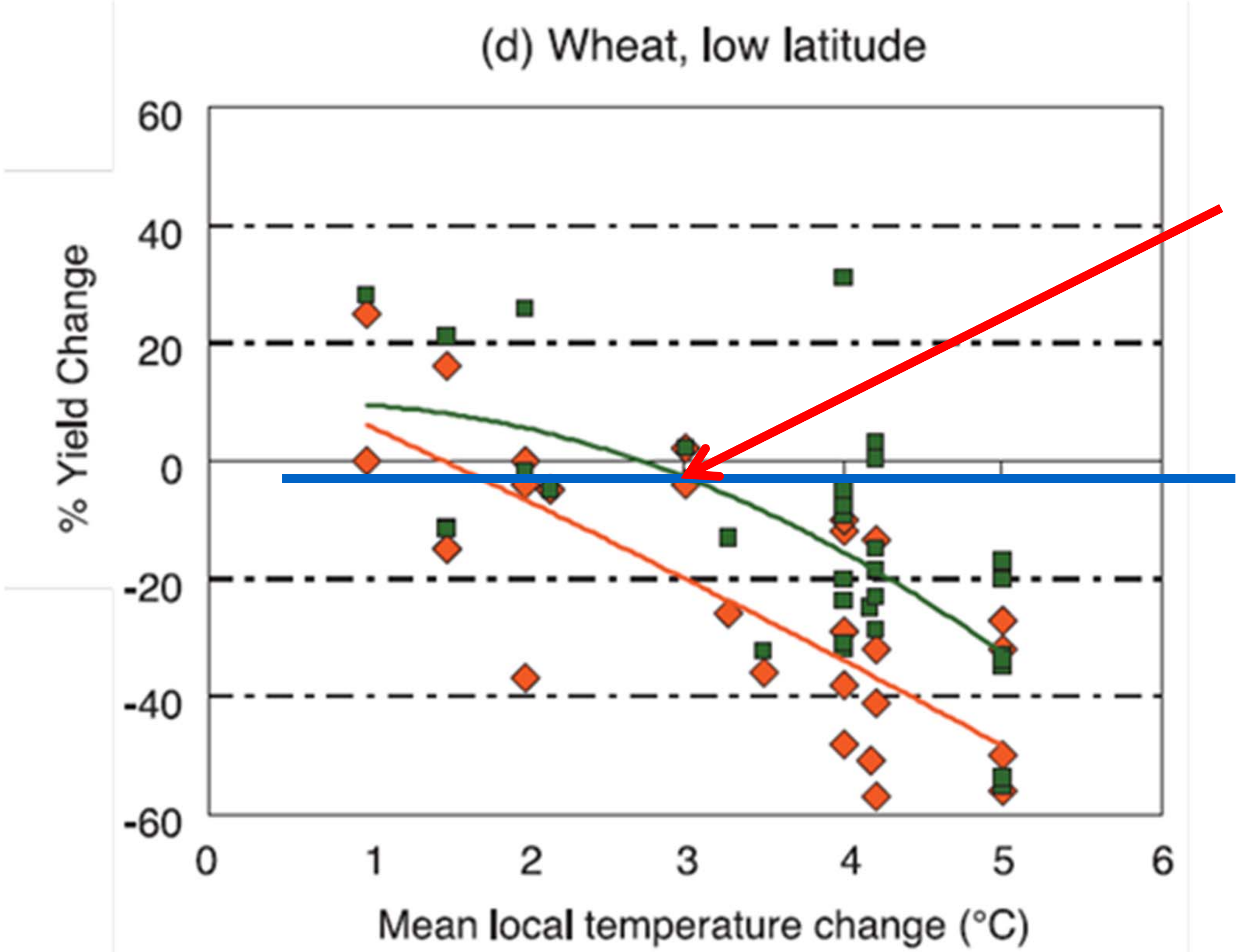
Sources: [2]

The Impacts of Climate Change

The Copenhagen Accord recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius."

How solid is this?

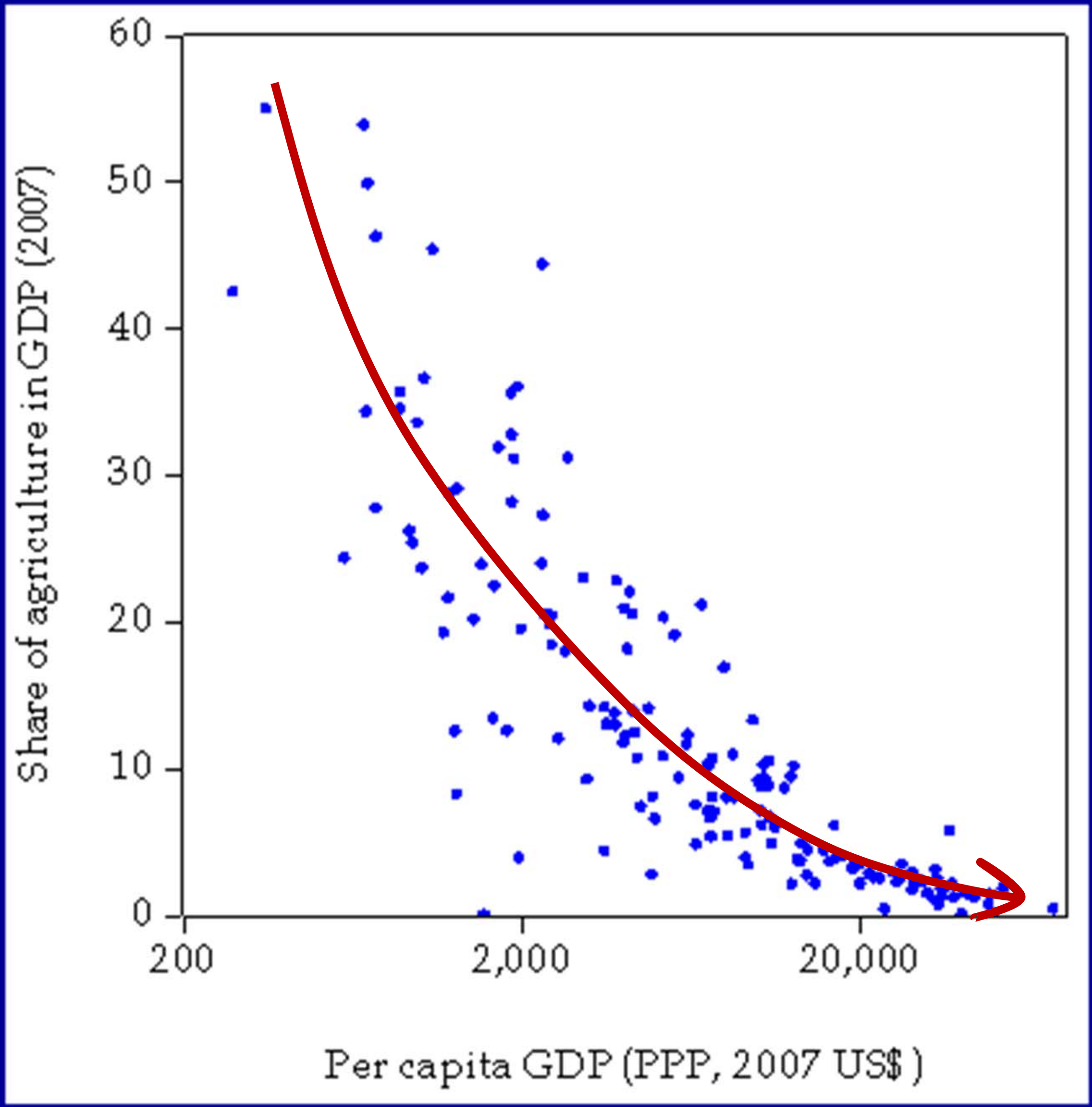
But the actual science and economics are complex: The example of low-latitude wheat



Note zero impact T at 2 °C

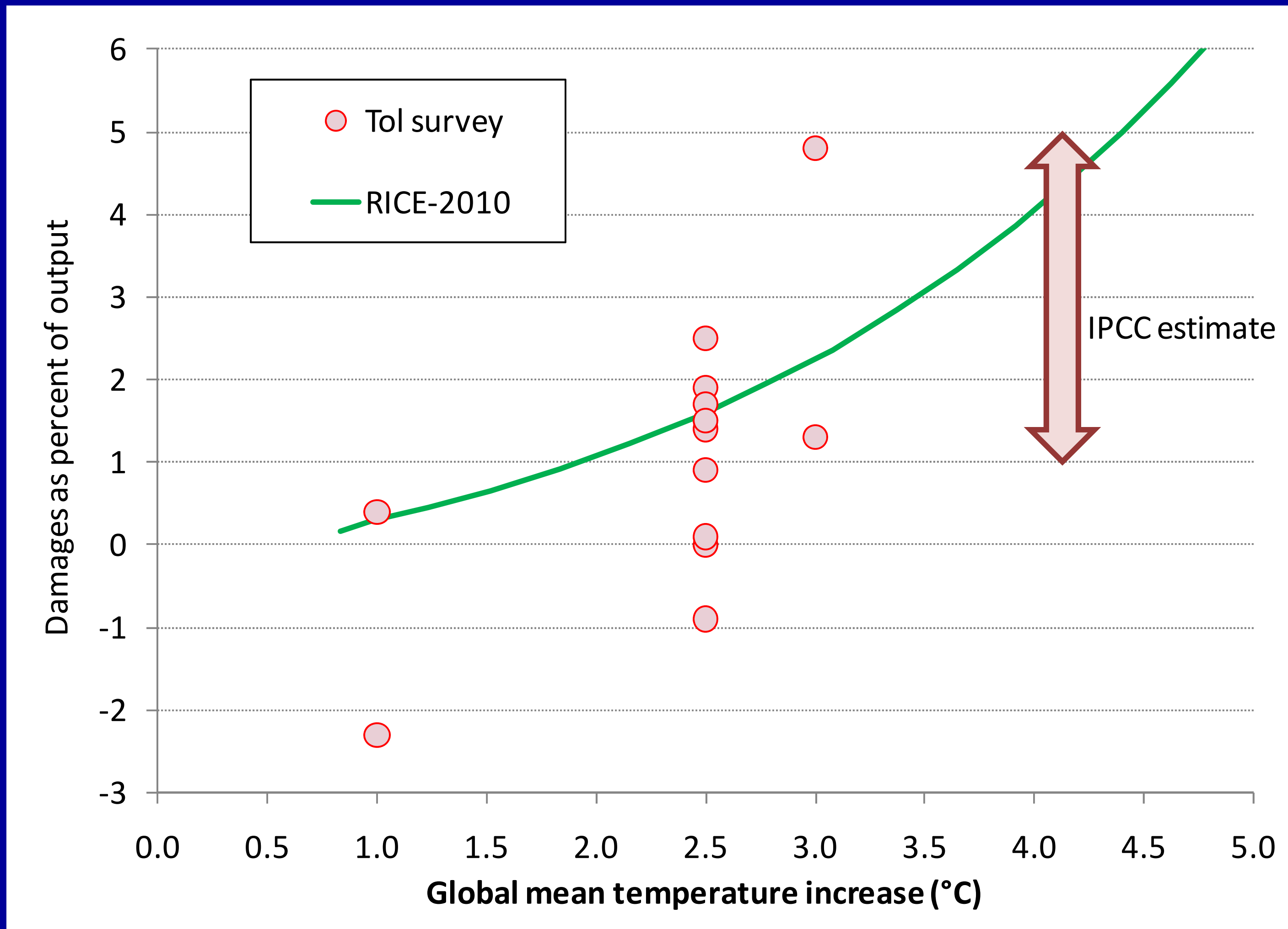
Sources: [4]

But future farming will be in a different world…



Sources: [29]

Aggregate damage estimates from different studies



Source: [16]

The Impacts of Climate Change

Summary

- Estimating impacts has been the most difficult part of all climate science: house-to-house combat for analysts.
- Economic studies do not suggest catastrophic economic damages in near term (< 50 years).
- Major concerns are species loss, ocean acidification, long-term sea-level rise, and ecosystems.

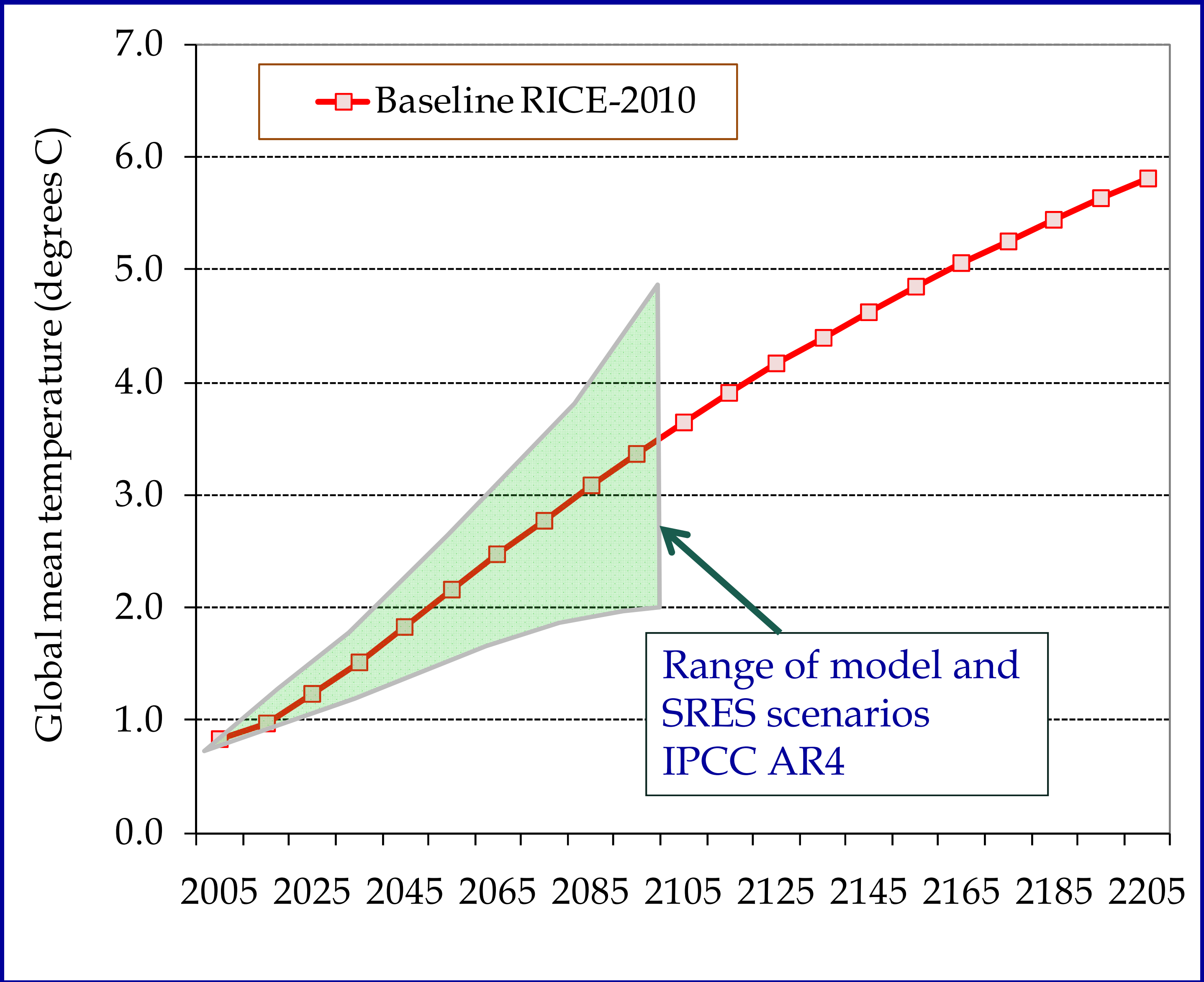
Policy Scenarios for Analysis using the RICE-2010 model

1. Baseline.
2. Economic cost-benefit "optimum."
3. Limit to 2 °C.
4. Copenhagen, all countries.
5. Copenhagen, rich only.

Scenario	**Description**
Baseline	No emissions controls.
Economic optimum	Emissions and carbon prices to maximize discounted economic welfare.
Limit 2 °C	Climatic constraints with global temperature increase limited to 2 °C above 1900
Copenhagen all	Uses US emissions targets joined by other rich countries, with developing countries entering after 1 -3 decades.
Copenhagen rich	Uses US emissions reductions joined by other rich countries, with developing countries staying out.

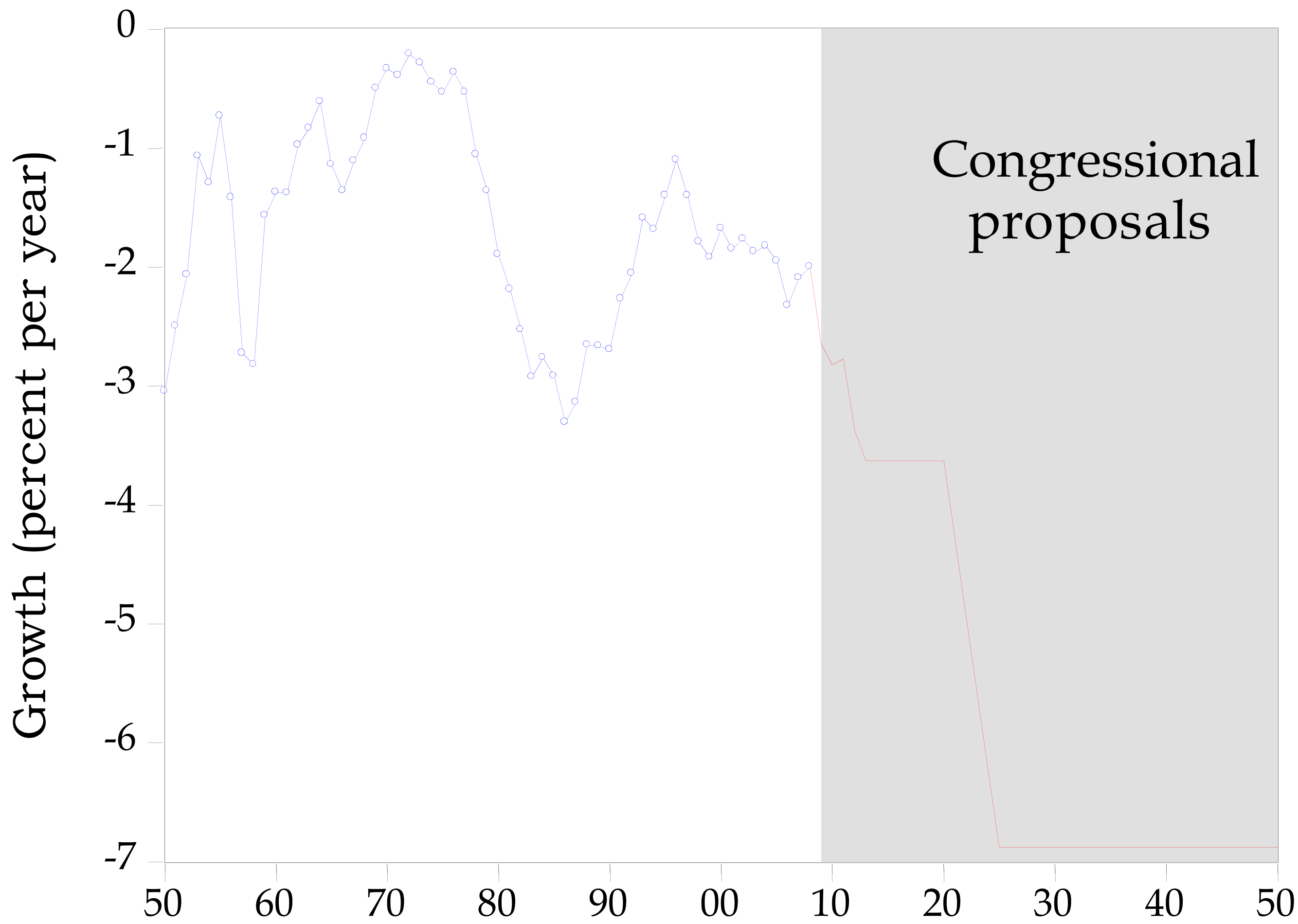
Sources: [2]

Temperature profiles for baseline RICE and IPCC

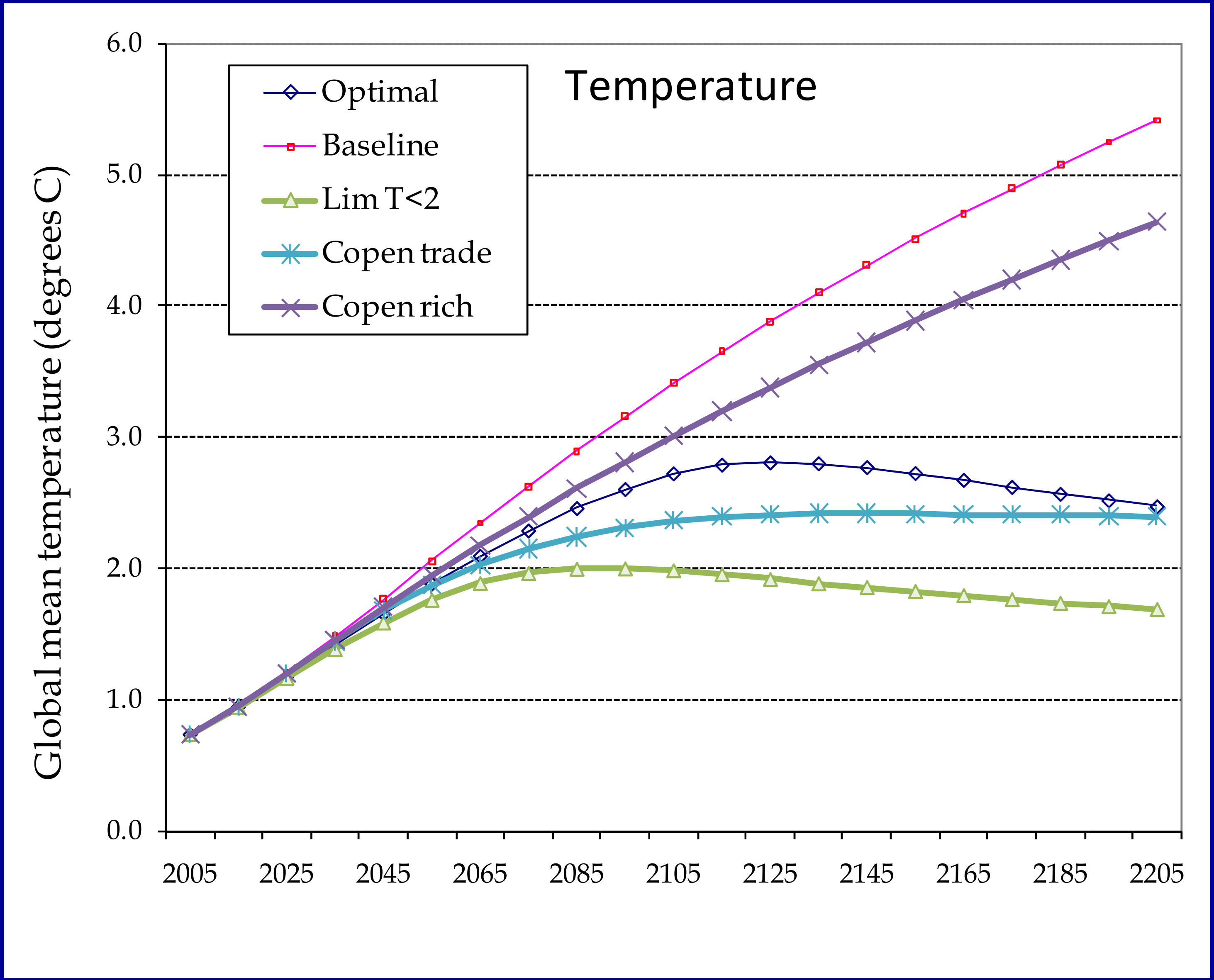


Sources: [2, 4]

Rate of growth of CO2-GDP ratio: history and Congressional proposals

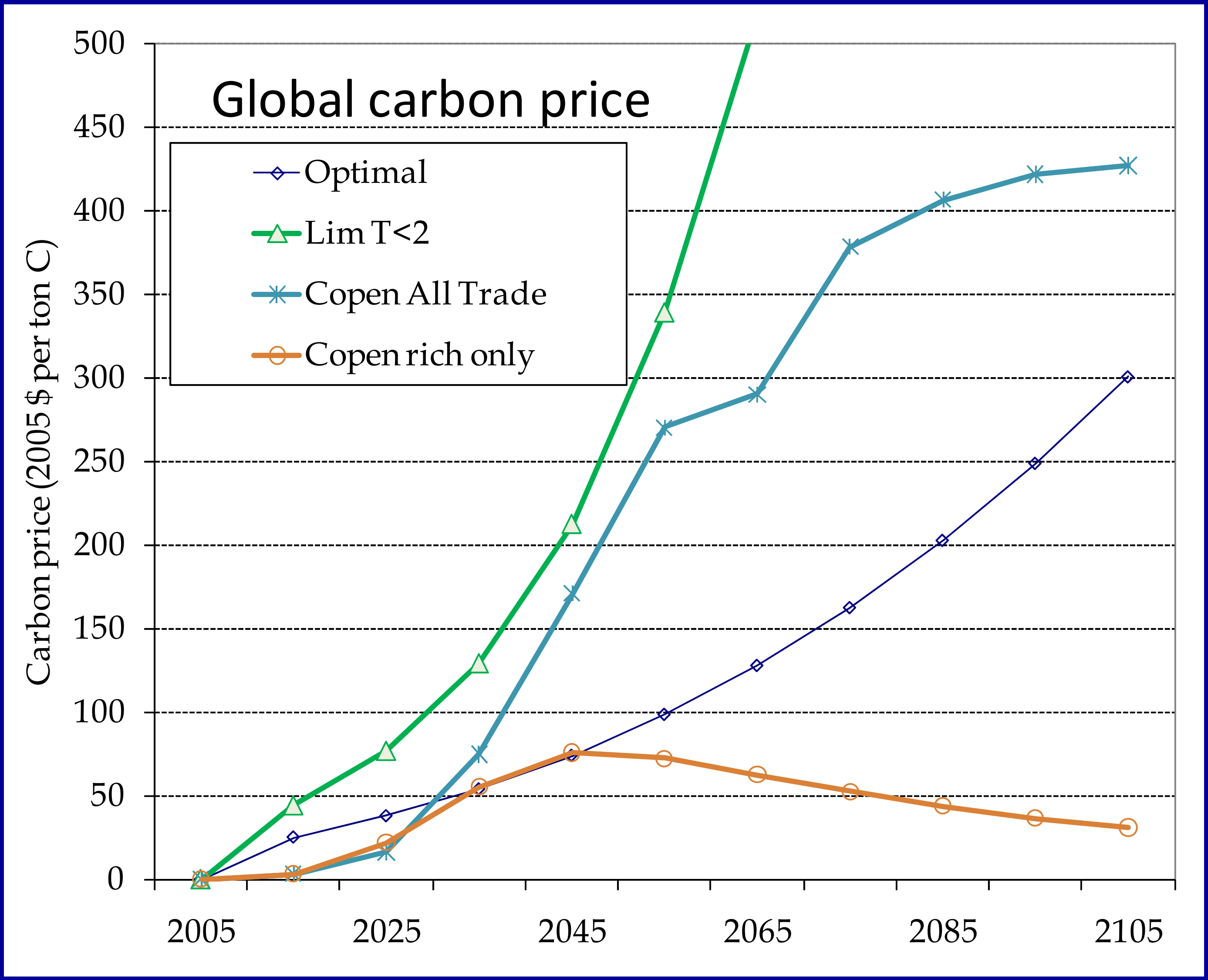


Temperature profiles: RICE -2010



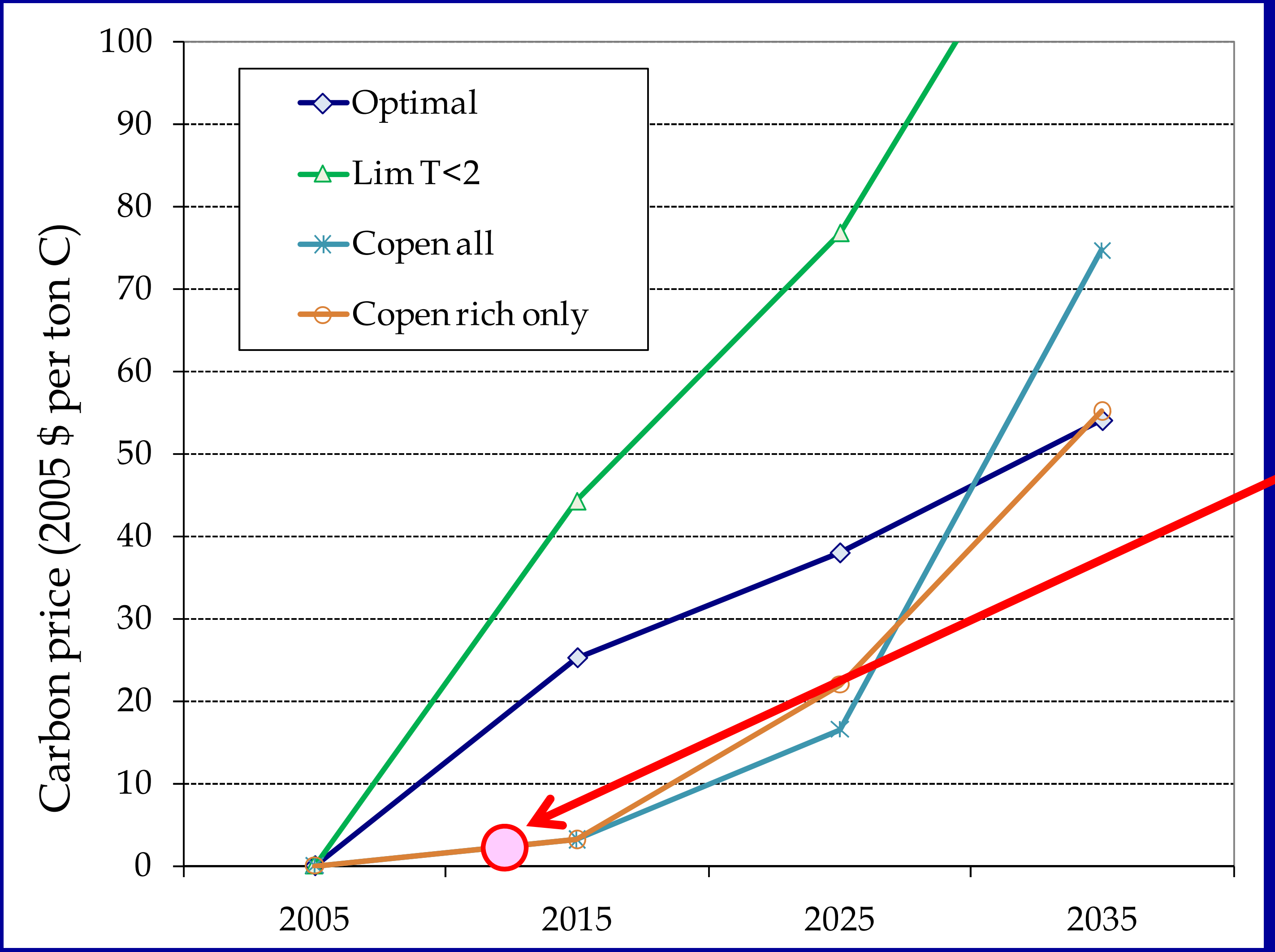
Sources: [2]

Carbon prices for major scenarios



Sources: [2]

Carbon prices for major scenarios



Actual equivalent global carbon price = $2 / tC

Sources: [2]

Prospects for reaching 2 °C target

Robust conclusions across many models:

- Cannot reach 2 °C target unless virtually all countries participate very soon.

- Reaching target will also require very high and virtually universal carbon prices:
  - 11/13 models find it infeasible in EMF-22 exercise
  - Carbon prices probably $200+/tCO2 by mid-century

Sources: [2, 17]

Social cost of carbon

An important concept from IAMs is the "social cost of carbon" or SCC. This concept represents the additional damage caused by an additional ton of carbon emissions.

In a more precise definition in a modeling framework, it is the change in the discounted value of the change in the utility of consumption denominated in terms of current consumption per unit of additional emissions.

Unique contribution of IAMs that can calculate the SCC taking into account all elements of system.

Alternative Estimates of SCC
[US$ per ton C]

Year of discounting and emission	Social cost of carbon (2005 US $ per ton CO2)					
	US Working Group 2010			Tol survey median		RICE-2010
	Discount rate on goods (on goods, per year)					
	2.5%	3.0%	5.0%	3.0%	5.0%	5.50%
2015	35	22	5	36	12	12

Sources: [14]

Is disaggregation desirable?

Are disaggregated IAMs always desirable?
Assume there is a model structure as follows:

$$Y(t) = \sum y_i(t) = \sum f_i[z_i(t), \beta] + u_i(t)$$

Basic results on whether to disaggregate:

- ***Yes,*** when you need to know the micro outcomes, $y_i(t)$.
- ***Sometimes,*** when the micro relationships are known without error. [11]
- ***Probably not*** when either
  - (a) the micro relationships (f_i) are not known or
  - (b) measurement errors on the micro variables [$y_i(t)$, $z_i(t)$] are relatively large. [12]

Implications

Tentative hypotheses for climate-economic modeling:

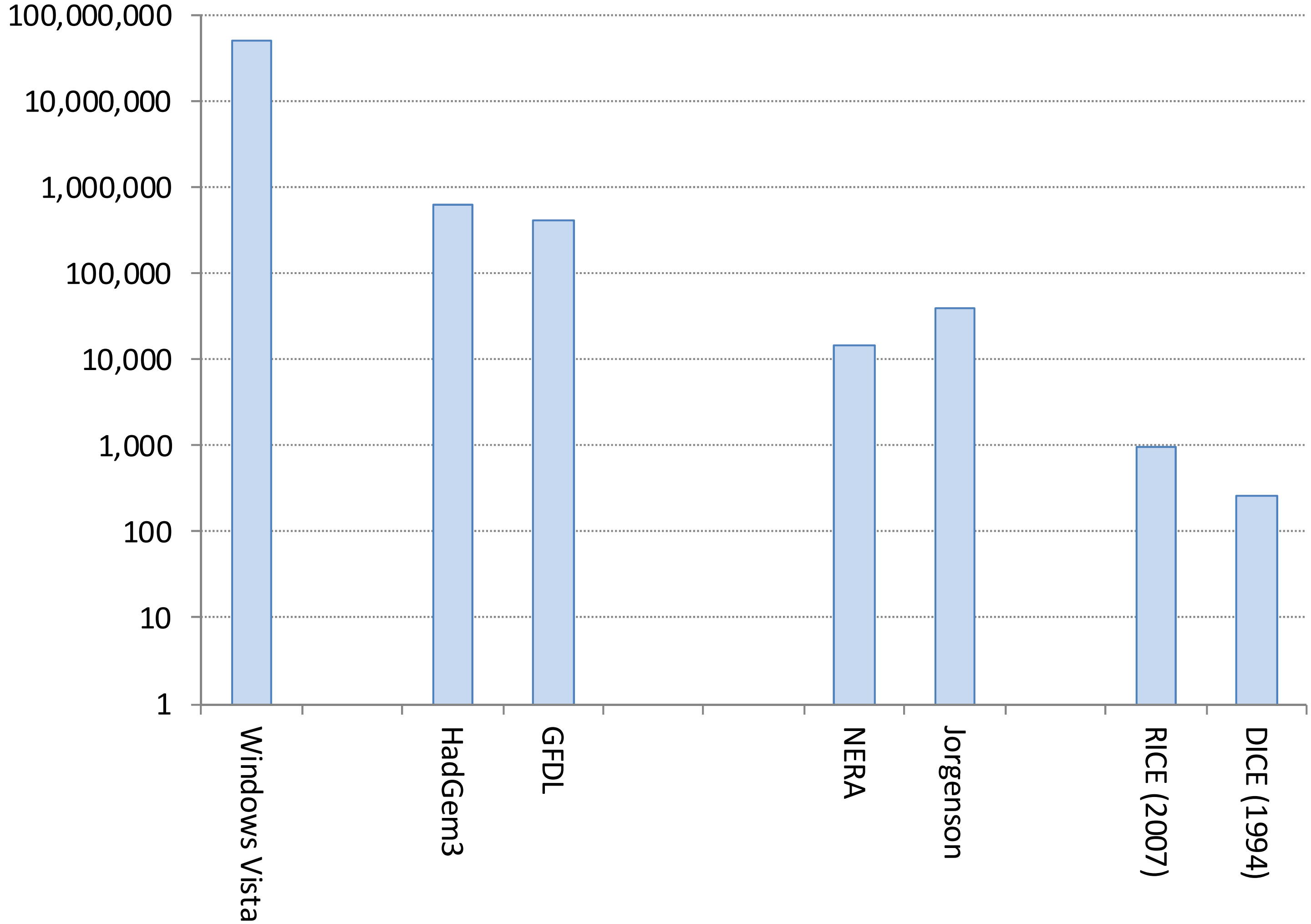
1. Presumptions are ***completely different*** for geophysical models and socioeconomic models.
2. Disaggregation is ***probably desirable for geophysical models*** where micro structure is well-understood and have good micro observations (laws of conservation, etc.).
3. Disaggregation is ***probably undesirable*** where have high negative correlation of errors in micro behavior (location of industry).
4. Sub-national disaggregation is ***probably undesirable*** for many economic variables where sub-national data are poorly measured (regional output and emissions).
5. ***Jury is out*** in other areas (mitigation costs in top-down or bottom-up approaches).

The scary problem of computational complexity

The problem of increasing complexity and errors

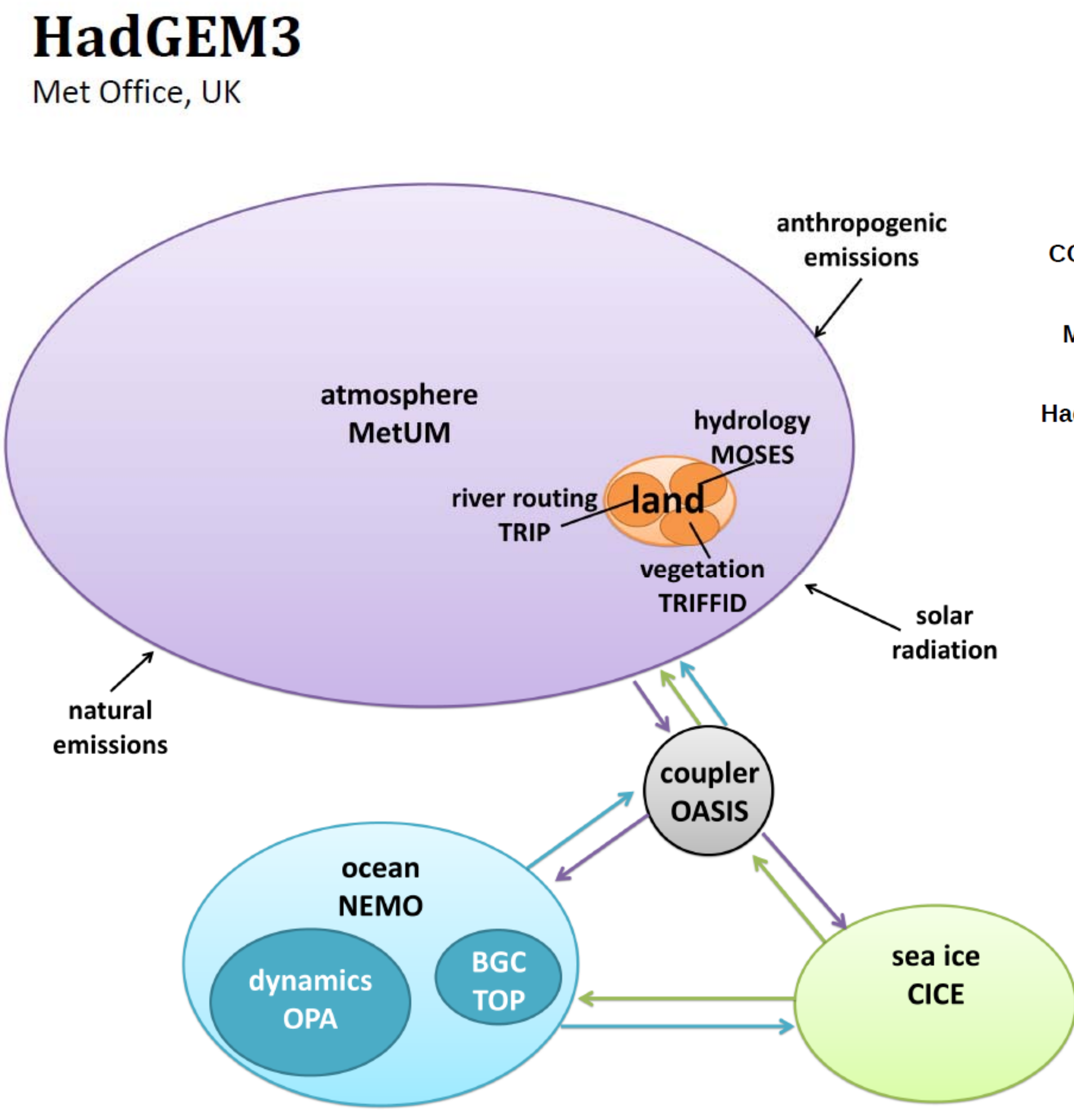
- IA models and code are getting very large.
- We know that the error rate in large software programs is very substantial.
- The fact is that scientists and economists are amateurs at software engineering.
- I suspect that there are multiple errors in our IAMs.

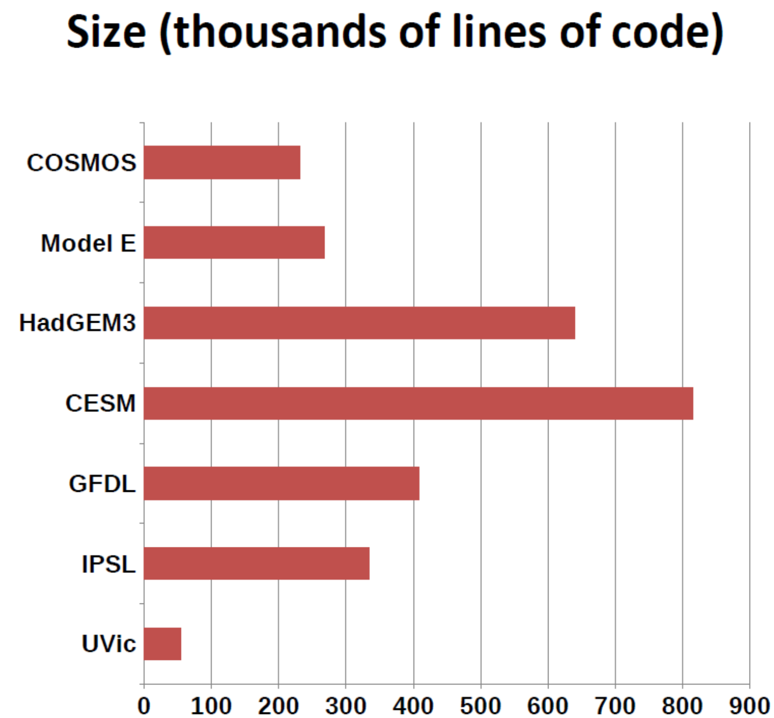
Software size: Source lines of code



Source: [6, Nordhaus, Zhimin Li]

Model size for climate models





Source: [6]

Error rate in software

Error rate in software

- Industry standard is 1 error per 1000 lines of code, and super-clean software has 0.1 bugs per line of code
- On release, Windows 2000 had about 65,000 bugs [9]
- Luxury car has > 10,0000,000 lines of code, and is estimated to have 150,000 bugs in software [8]

Catastrophic software bugs [not always well documented]

- Mars orbiter crashed because of mix-up of pounds and kilograms
- Loss of Mariner 1 probably due to period instead of comma in FORTRAN DO-Loop
- Shutdown of 5 nuclear reactors in 1985 due to use of arithmetic sum of variables instead of the square root of the sum of the squares of the variables
- Cyberweapon wrecked Iranian enrichment machines.

Error rate in IAMs

Green Model:

- Fundamental error in calculation of equilibrium prices discovered when MIT recoded it. [3]

FUND model:

- Damage estimates are unreliable because of model error in which a variable is potentially divided by zero. [15]
- Estimates in US Working Group for SCC are probably incorrectly calculated for FUND model.

RICE 2012-beta version:

- Approximately 120,000 Excel cells of code (high redundancy)
- Careful scrutiny of random block of code found:
  - Non-substantive errors (stranded code, poor labels, bad variable definitions, etc.): 270/1000 LOC
  - Substantive error: 0/1000 LOC

Conclusion on computational complexity

- Because of rapid increase in computer and software power, computational complexity of systems is increasing very rapidly.
- Standard procedures for quality control are very rudimentary or lacking in economic modeling
- Modelers should pay close attention to standards of good software architecture.

Conclusion on IAMs

- Integrated assessment models of climate change show great progress over the two decades since its emergence. The progress is made possible by the parallel developments in fundamental science and economics across a broad range of areas.
- The single most important set of results from IAMs has been the development of the idea of efficient paths of abatement and carbon pricing required for slowing climate change. Today, in part because of developments in IAMs, carbon prices and estimates of the social cost of carbon are actually integrated into the regulatory decisions of major countries.
- Looking forward, there is much work for modelers. Among the areas are further refinement and better modeling, particularly issues surrounding uncertainty, technological change, and the need for mechanisms to break the non-cooperative trap of climate policy that is gripping the globe.

References

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On software architecture and bugs: [6] Kaitlin Alexander and Steve Easterbrook, "The Software Architecture of Global Climate Models"; [7] Paul Clements et al., *Documenting Software Architectures: Views and Beyond, Second Edition*. Addison-Wesley, 2010; [8] "Cars and Software Bugs," *The Economist,* http://www.economist.com/blogs/babbage/2010/05/techview_cars_and_software_bugs; [9] Bugs fixed in Windows 2000 at http://support.microsoft.com/kb/327194.

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