29th Macaulay Lecture

Aberdeen, 14 Nov 2005

Planetary Co-Evolution: Where On Earth Are We Going

John Schellnhuber

P I K

Tyndall°Centre
for Climate Change Research

Climbing the co-evolution ladder

Co-evolution: Earth history involves tightly entwined transitions of information and the environment, but where is this process heading?

T. M. Lenton, H. J. Schellnhuber and E. Szathmáry

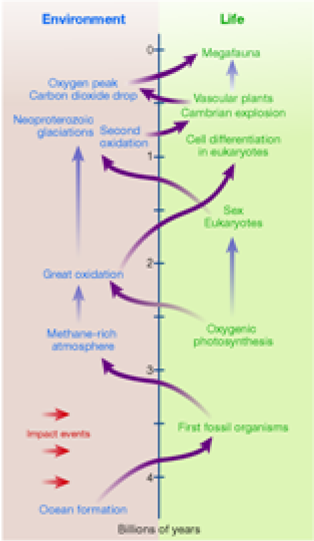
Stanislav Lem's science-fiction masterpiece, *Solaris*, tells the gripping — and scary — story of a super-intelligent super-organism that has transmuted into a vast ocean covering most of the surface of a distant planet. Thus information-processing (that is, active) life and force-driven (that is, passive) environment have finally merged into a single entity.

Here on Earth, we have yet to reach this vanishing point of evolutionary history. But modern civilization already perturbs — if not dominates — various large-scale processes and components of the planet. Most notably, the global 'metabolism' (the cycling of essential elements, including carbon, nitrogen, phosphorus and sulphur) and features of the global 'anatomy' (the landscape textures of the habitable continents) are largely a product of relentless socio-economic action.

Within the framework of Earth system analysis, this can be perceived as the latest step on the grand co-evolutionary ladder of entwined transitions of information and environment. Global industrialization, particulary since the Second World War, induced the transition into the Anthropocene. Its environmental consequences may in turn provoke a transition to an even higher form of worldwide socio-political organization.

Extending our concept of entwined transitions further back in time, we soon encounter the rise of the 'hydraulic societies' in the valleys of the Nile, Euphrat, Tigris and Indus, which were probably founded in response to the great drying of the African–Asian regions that took place in the sixth millennium before present (BP). Before this, organized *Homo sapiens* hunting caused mass extinctions of the prehistoric fauna. Language provided the novel inheritance system that allowed cumulative cultural and technological evolution, and a society resting on complex, negotiated division of labour. Further back, the evolution of hominins in the East African Rift valley was shaped by a rapidly changing environment.

Entwined environment–information transitions have characterized Earth's evolutionary history since its beginning some 4 billion years ago (4 Gyr). Life emerged remarkably soon after surface conditions became habitable, with the formation of oceans and cessation of sterilizing asteroid impacts. The first organisms would have drained the environment of energetically and structurally useful compounds and replaced them with degraded waste products, including methane. An ultimately dull fate for life, eking out a meagre existence on a lifeboat Earth, was averted when closed recycling loops developed, in which one life form's waste became another's food. These loops are large-scale manifestations of the auto-catalytic nature of the cell, locked in as the core of the global 'metabolism' that is still with us.



Earth's co-evolutionary ladder, as built so far…

Despite recycling, life remained energetically limited until the origin of oxygenic photosynthesis, sometime before 2.7 Gyr. This breakthrough in metabolic evolution greatly increased the free energy supply to the biota, giving life a truly global environmental impact. It facilitated the great oxidation of the atmosphere around 2.2 Gyr, but — as the long time lag indicates — other factors were required. Perhaps oxidation had to await tectonically driven changes in Earth's 'anatomy', including the appearance of shelf seas where reduced organic carbon could reach the sediments and be buried.

Although the energetic stage was now set for global dominance by eukaryotes, the emergence of a soft cell-boundary membrane coupled to an internal skeleton and a means for cellular division were also required. These transitions are thought to have been especially difficult, as they required the fixation of thousands of rare mutations.

Eukaryotes may be implicated in the worst crisis of past co-evolution: the extreme Neoproterozoic glaciations of 0.8–0.6 Gyr that were accompanied by a second rise in oxygen. Whenever eukaryotes started to colonize the land surface, there would have been strong selection for traits that accelerated weathering to access rock-bound nutrients. Weathering of silicates would have inadvertently drawn down atmospheric carbon dioxide and cooled the planet, and weathering of phosphorus would have increased global productivity and contributed to oxygen rise. The latter opened the door for the diversification of larger, hard-shelled, animal life in the Cambrian explosion. After that, the triumph of vascular land plants, causing a further rise in oxygen and fall in carbon dioxide, played its part in creating the environmental conditions in which active megafauna (including ourselves) evolved.

Pursing this concept of entwined evolution may reveal where we are ultimately heading — towards Solaris, or something even scarier. ■

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FURTHER READING

Schellnhuber, H. J. *et al.* (eds.) *Earth System Analysis for Sustainability* (Dahlem Workshop Reports 91, MIT Press, 2004).

Lovelock, J. E. *The Ages of Gaia — A biography of our living Earth* (Oxford Univ. Press, 1988).

Maynard Smith, J. & Szathmáry, E. *The Major Transitions in Evolution* (Freeman, 1995).

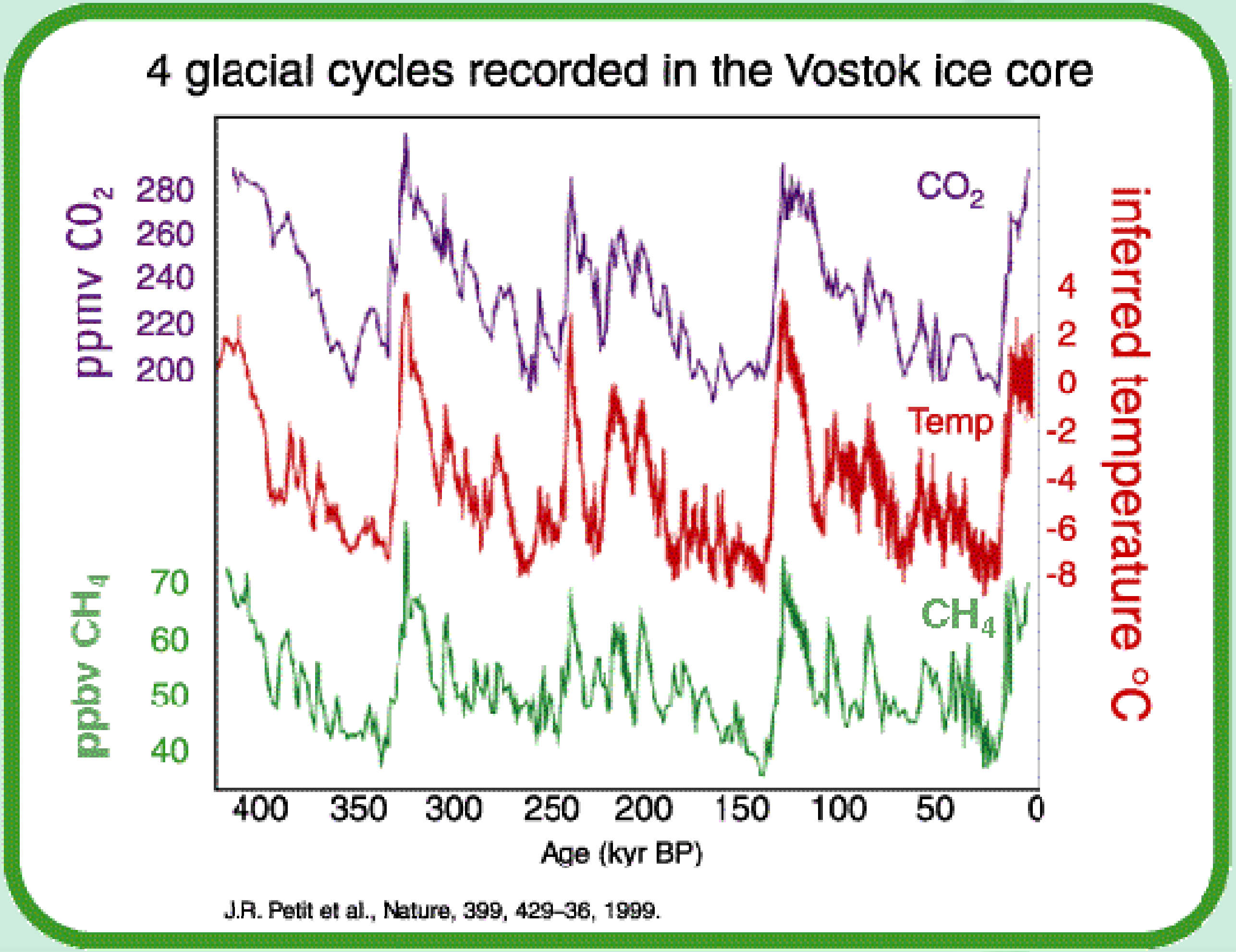
Lenton, T. M. & Watson, A. J. *Geophysical Research Letters* **31**, L05202 (2004).

Schellnhuber, H. J. *Nature* **402**, C19–C23, (1999).

Crutzen, P. J. *Nature* **415**, 23 (2002).

Based on the 91st Dahlem Workshop on Earth System Analysis for Sustainability, Berlin, 25-30 May 2003, with thanks to our fellow participants.

An Integrated Earth System



J.R. Petit et al., Nature, 399, 429–36, 1999.

GLOBAL IGBP CHANGE

H. J. SCHELLNHUBER & H. HELD

SCIENCE IN CULTURE

Inventing an icon

Hans Joachim Schellnhuber's map of global 'tipping points' in climate change.

Martin Kemp

Any public campaign benefits from having an iconic image — something that captures the essence of the message and engraves it indelibly on our memories. But it is almost impossible to predict which images will actually stick, so creating one on demand is extraordinarily difficult. For instance, who could have forecast that of all the news photographs emanating from the Vietnam war, it was Nick Ut's photograph of a napalmed child screaming naked on a road that would become the canonical image of innocent suffering during that unhappy episode in history?

Even so, finding an iconic image was one of the goals of a meeting, 'Changing the Climate', held in Oxford, UK, on 11 and 12 September (http://kron1.eng.ox.ac.uk/climate). Researchers and practitioners of the visual, literary, musical and performing arts came together to publicize the predicted perils of climate change, and there was much talk about a memorable image that would encapsulate the initiative. The challenge is considerable. Any icon inevitably involves condensation and simplification, but the issues surrounding climate change are extraordinarily complex. Can an image be found that is both simple and good science? Given the contentious nature of the debates, particularly in the United States, it is unwise to offer hostages to fortune by parading vulnerable predictions.

The data must come from the best science available, but the presentation for maximum impact is a matter of invention in art and design. Of the images produced by the scientists, one in particular seemed to have the potential to combine iconicity with complexity. This is the 'Tipping Points Map' devised by Hans Joachim Schellnhuber, director of the Potsdam Institute for Climate Impact Research in Germany and research director of the Tyndall Centre for Climate Change Research at the University of East Anglia, UK. This global map, shown here, outlines what Schellnhuber has identified as regions where the balance of particular systems has reached the critical point at which potentially irreversible change is imminent, or actually occurring.

The question marks that follow some of the labels acknowledge that it would be misleading to claim olympian certainty about the precise course of the Earth system in all respects. But what the tipping zones demonstrate vividly is the diversity and worldwide spread of climate-change threats. Some of the zonal features, such as the melting of ice and resulting rise of sea levels, have already passed the critical point and will have a literally global impact. A scientific meeting in Berlin on 5–6 October, 'Tipping Points in the Earth System', has since focused exclusively on topics highlighted in the map.

In its present state, the map has the character of a diagram synthesizing scientific predictions. It is still short of those elusive features that make an icon, and its language remains quite specialist. This is where the visual and verbal inventors need to step in, to take Schellnhuber's neat and ingenious graphic on to the next level of accessibility and memorability. The Oxford meeting provided access to creative people with the right range of artistic skills to hone the image into a potential icon.

The map could function as a poster, as an immediately recognizable symbol for a campaign, as a memory device in all kinds of education, as the map for a series of interactive explorations on the web and other digital platforms, and as the central image for media coverage. Its graphic density in its present form dictates that it cannot function well on small scales. Perhaps a more symbolic version is needed.

Schellnhuber's map can potentially be developed into a useful image for debates about climate change. What no one can tell, however skilfully the map is refined, is whether it will achieve the levels of indelibility that will give it iconic status.

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Earth systems engineering and management

Stephen H. Schneider

Imagine that we could let the world's economy continue to grow, bring the disadvantaged classes up from poverty and at the same time not threaten the atmosphere or global ecosystems with unprecedented build-up of greenhouse gases and the projected climatic risks of such growth. Earth systems engineering and management may just be such a panacea, some have suggested. But could we anticipate the costs or ever truly predict the consequences?

Few people would ask us to accept that a growing world economy based on greatly expanded per capita energy consumption would be free of environmental side effects. But many have claimed that the anticipated several-fold increase in greenhouse gases — and associated sea-level rises, intensified hurricanes, or drought and flood stresses — can be largely overcome by human ingenuity. Their optimistic vision depends greatly on what had been called 'geoengineering' and has more recently been relabelled Earth systems engineering. This describes the deliberate manipulation of the Earth system to manage the climatic consequences of human population and economic expansion[1].

To others, the notion of geoengineering — injecting dust in the stratosphere, for example, to reflect some sunlight back to space and counteract greenhouse warming — is an irresponsible palliative. It evades the need for a real cure, such as curbing the consumption of the rich and the population growth of the poor, and charging polluters for their use of the atmosphere as a free sewer.

In response, defenders of geoengineering retort that two-thirds of the world's people use a small fraction of the energy per capita of the rich. Cheap primary energy (mainly coal) is needed, they say, to build the economies of less developed countries and improve their well being. The negative environmental side effects of this will have to either be tolerated or be sidestepped by geoengineering in order to have it both ways — a materialistic growth-oriented world and relatively undisturbed climate.

At times this debate takes on an ideological tenor. Claims that the imperative of development cannot be impeded by the prospect of global warming are greeted with the assertion that creating inadvertent damage to nature is bad enough, but deliberately attempting to manipulate the climate just to let our old habits prevail is a violation of stewardship and an ethical transgression against the natural world. These sets of opposing world views — anthropocentric expansion versus stewardship — are not new. They flared in the 1970s with Club of Rome debates over the 'limits to growth' and matured with the publication of the Brundtland Commissions' middle path, aiming to pursue 'sustainable development'[2]. Today, they continue in arguments over whether nations must meet their emissions reductions agreed in the Kyoto Protocol by domestic cuts —even if not cost effective — or be permitted to shop around to buy their obligations elsewhere in the world at lower costs.

Let us return to the central question of what best characterizes Earth systems engineering. Is it a panacea for sustainable development built with vision and ingenuity or a palliative to avoid fundamental limits and maintain the privileged status quo for special interests? There is no easy answer to this question, but I do believe that both sides have merit in parts of their arguments. Here I will try to sketch out some opportunities and pitfalls that might help to clarify the role of geoengineering and carbon management strategies in the climate policy debate.

Figure 1 Some geoengineering projects, such as this plan for the irrigation of the Sahara by creating a 'second Nile' to refill Lake Chad, have become part of geoengineering folklore. (Reproduced from ref. 3.)

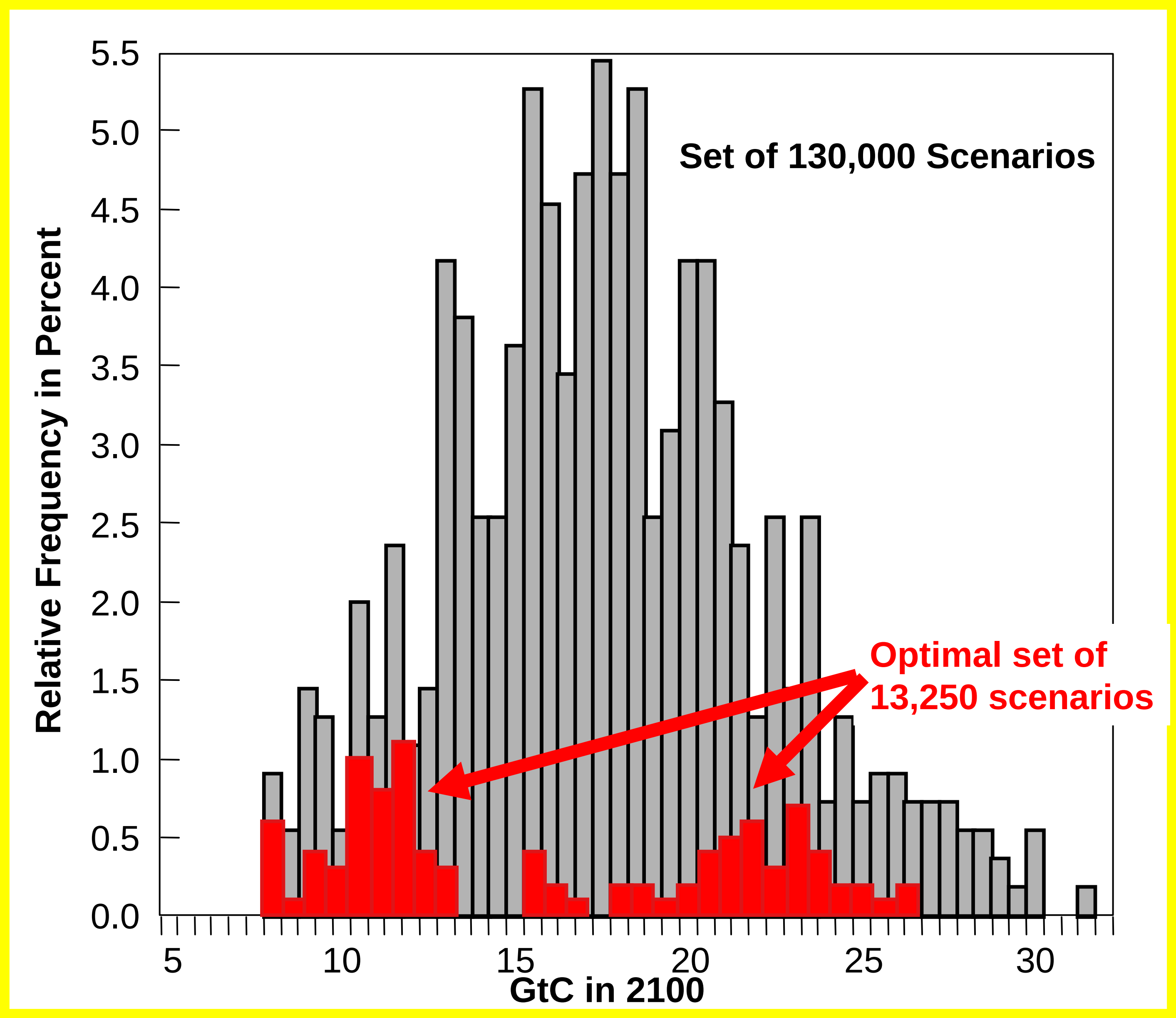
Historical perspective

In Homer's *Odyssey*, Ulysses is the frequent beneficiary (or victim) of deliberate weather modification schemes perpetuated by various gods and goddesses. In Shakespeare's *The Tempest*, Prospero, a mortal (albeit one with magical powers), conjures up a tempest to strand on his mystical island a passing ship's crew. In literature and myth, only gods and magicians could control the elements. But in the twentieth century, serious proposals for the deliberate modification of weather and/or climate came from engineers, futurists or those concerned with counteracting the inadvertent anthropogenic modification of the Earth's climate.

About 1960, Rusin and Flit[3] from the former Soviet Union published a long essay entitled *Man versus Climate* in which they suggested 'improving' our planet by, for instance, diverting rivers from the Arctic to the Russian wheat fields, or from the Mediterranean to irrigate areas in Asian USSR. One of their ambitious projects was to create a 'Siberian sea' with water taken from the Caspian Sea and Aral Sea areas. Of course, flowery rhetoric with images of blooming arid zones stands in stark contrast to the ecological disaster that surrounds the Aral Sea today, where environmental degradation is associated with much less radical geoengineering projects[4].

Other such proposals have become part of geoengineering folklore and include damming the Gulf Stream, the Bering Straits or the Nile, or creating a Mediterranean drain back into central Africa where a 'second Nile' would refill Lake Chad, turning it into the 'Chad Sea' after the Straits of Gibraltar were dammed (Fig. 1). But the potential side effects if these projects misfire are rarely discussed — which is not unlikely, given the complexity of the highly nonlinear climate system.

CO_2 Emissions from Scenarios with Technological Uncertainty



Gritsevkyi&Nakicenovic

IIASA 2000

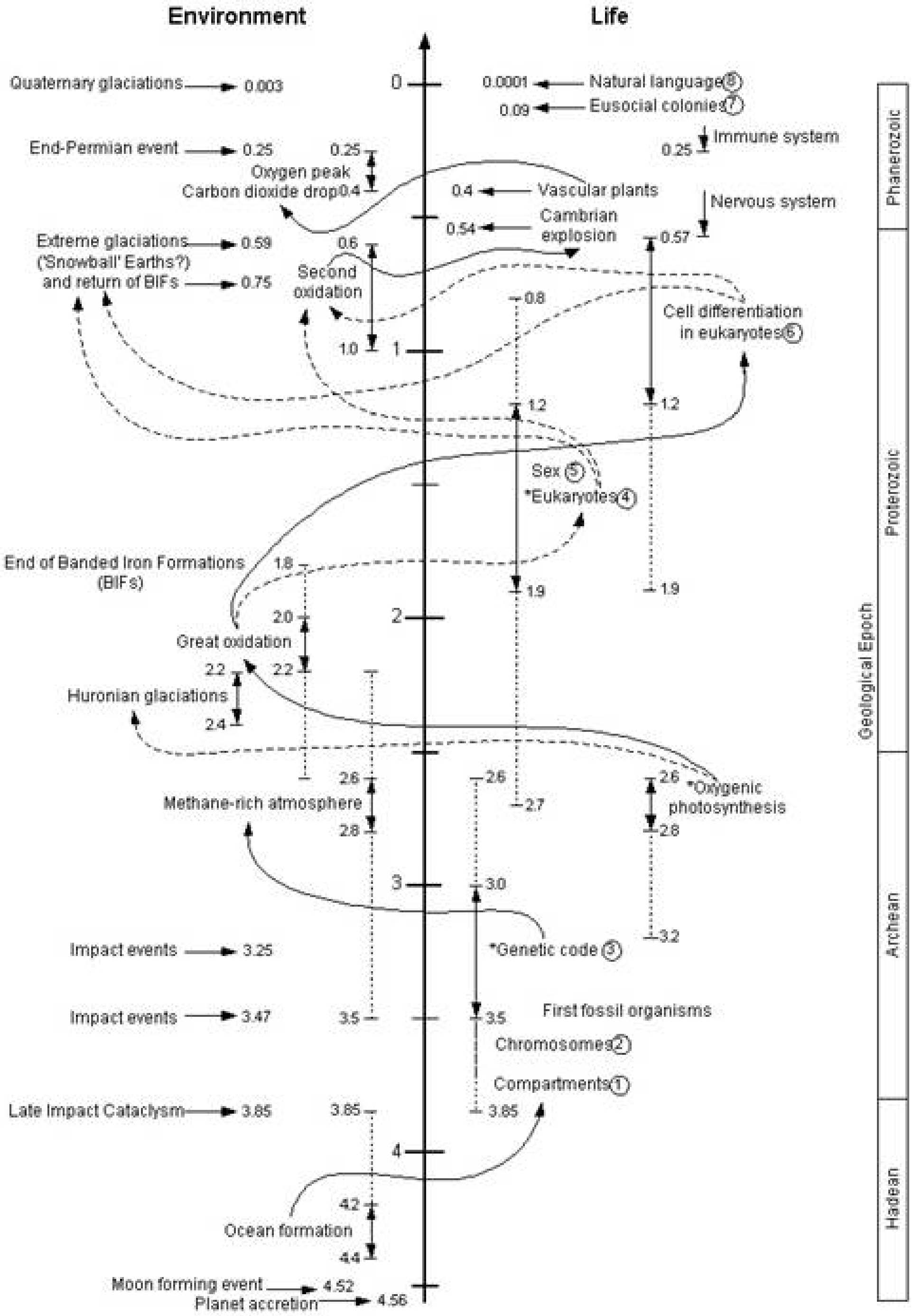
Co-evolution Timeline

Ages in Ga (10^9 yr BP)

Global tipping points:

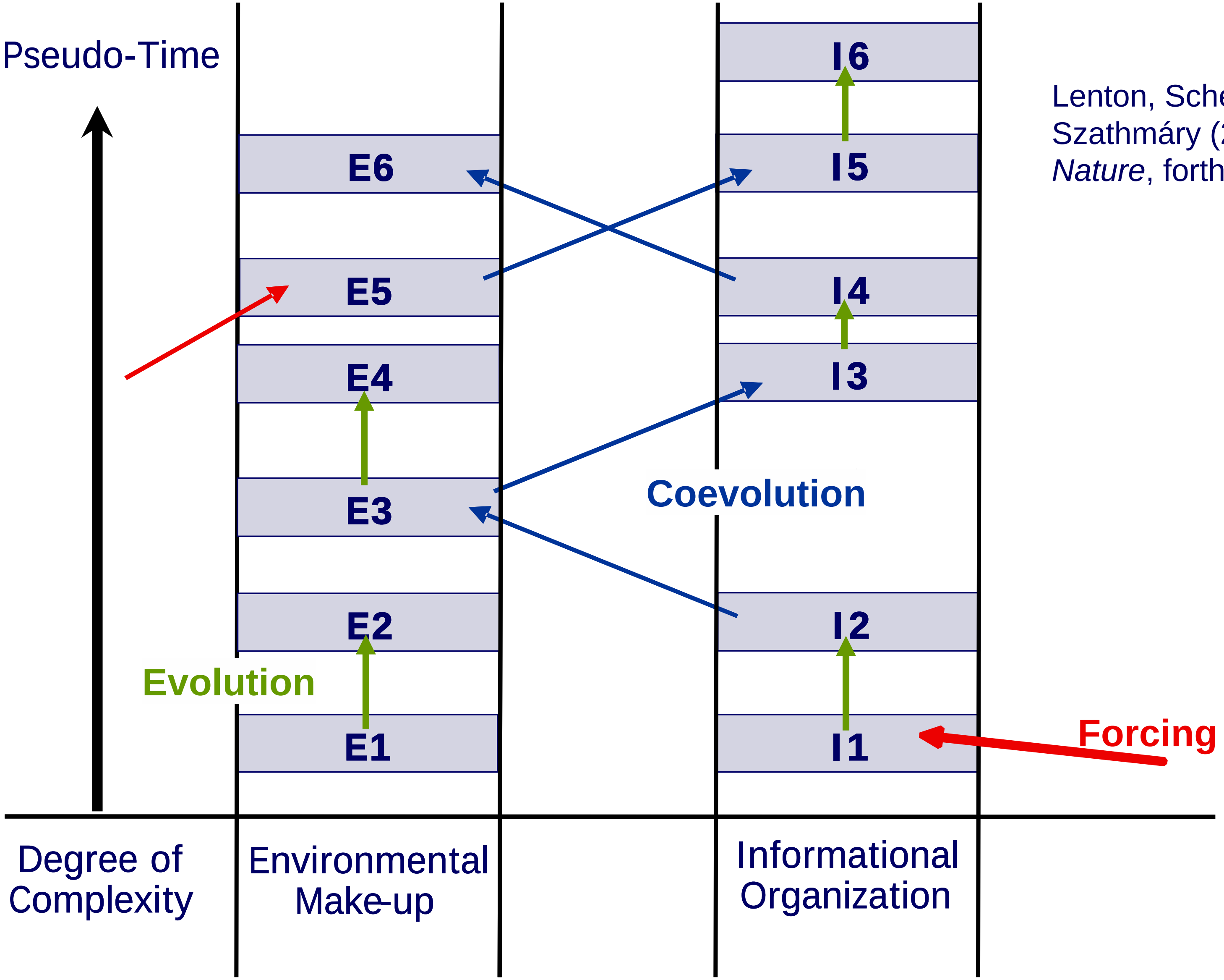
- Great oxidation
- Snowball Earths
- Cambrian explosion

T. M. Lenton et al. (Working Group 1)
91st Dahlem Workshop on Earth System Analysis for Sustainability (2003)



Environment-Information Ladder

Co-Evolution of Information Processing and Environmental Complexification



Pseudo-Time

E6

E5

E4

E3

E2

E1

I6

I5

I4

I3

I2

I1

Evolution

Coevolution

Forcing

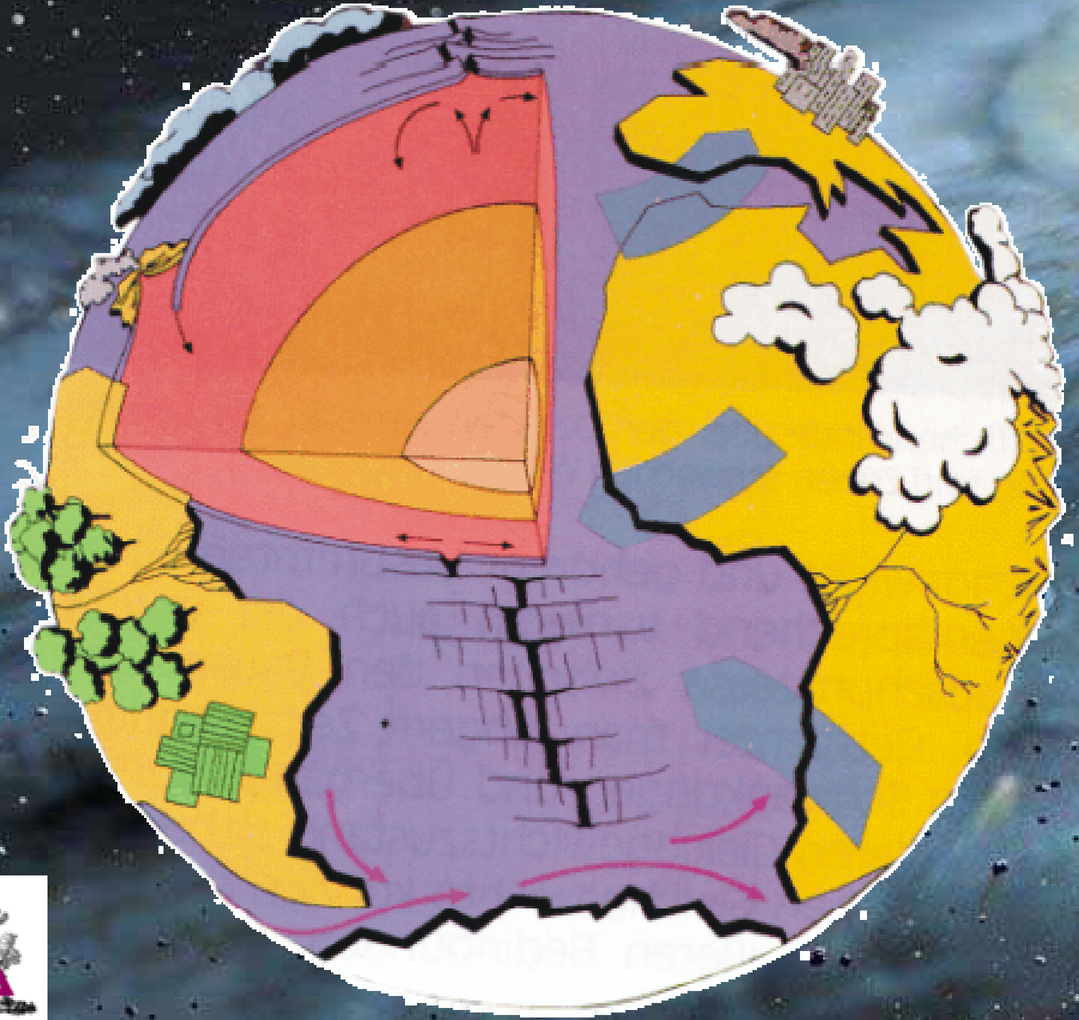
Degree of Complexity

Environmental Make-up

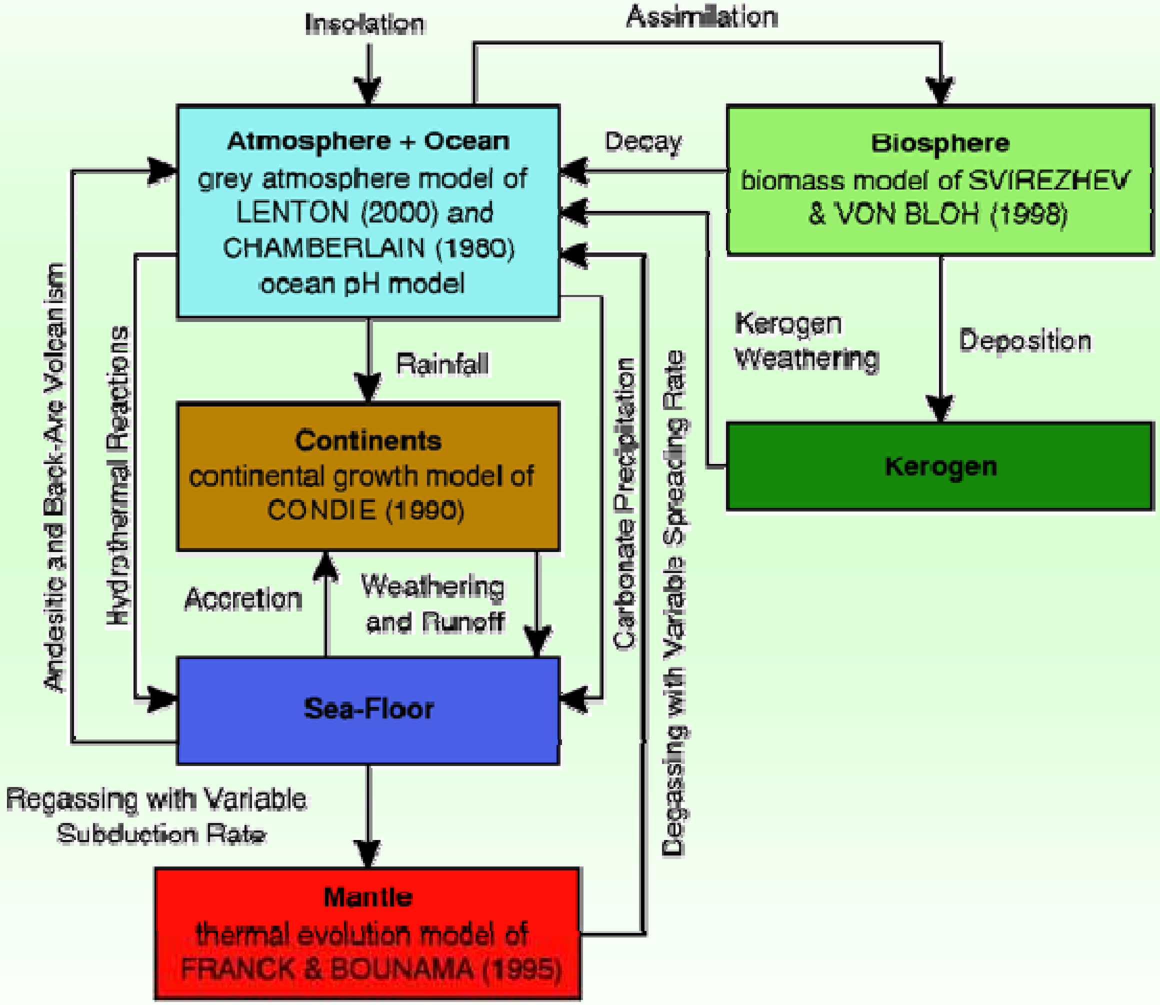
Informational Organization

Lenton, Schellnhuber & Szathmáry (2004): *Nature*, forthcoming

EARTH SYSTEM MODELLING

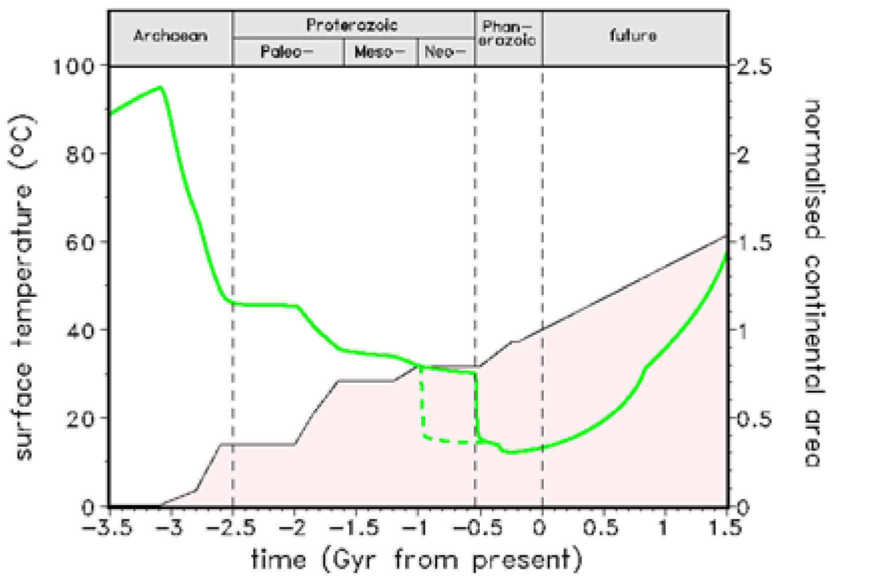


MODEL DESCRIPTION

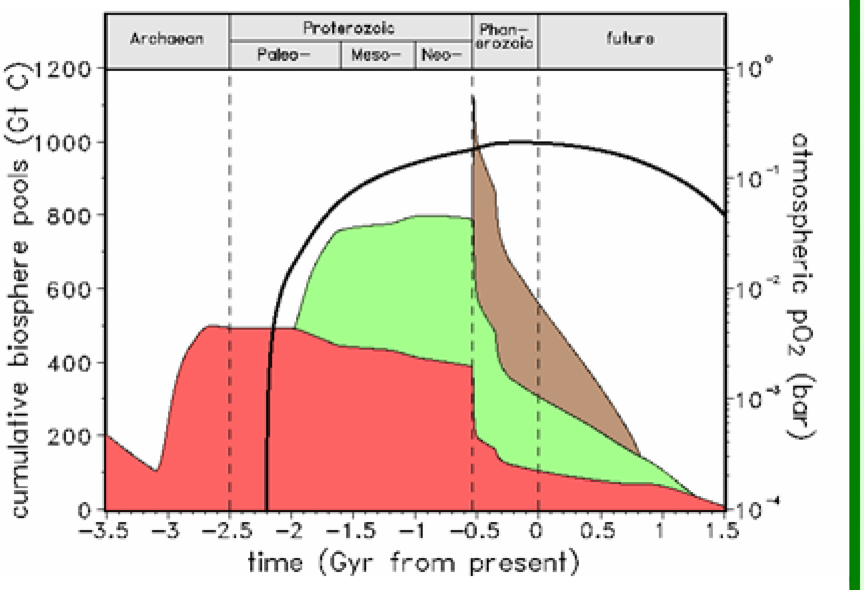


Franck et al. (2002): *Tellus* **54B** 325.

MODEL RESULTS



Evolution of global surface temperature.

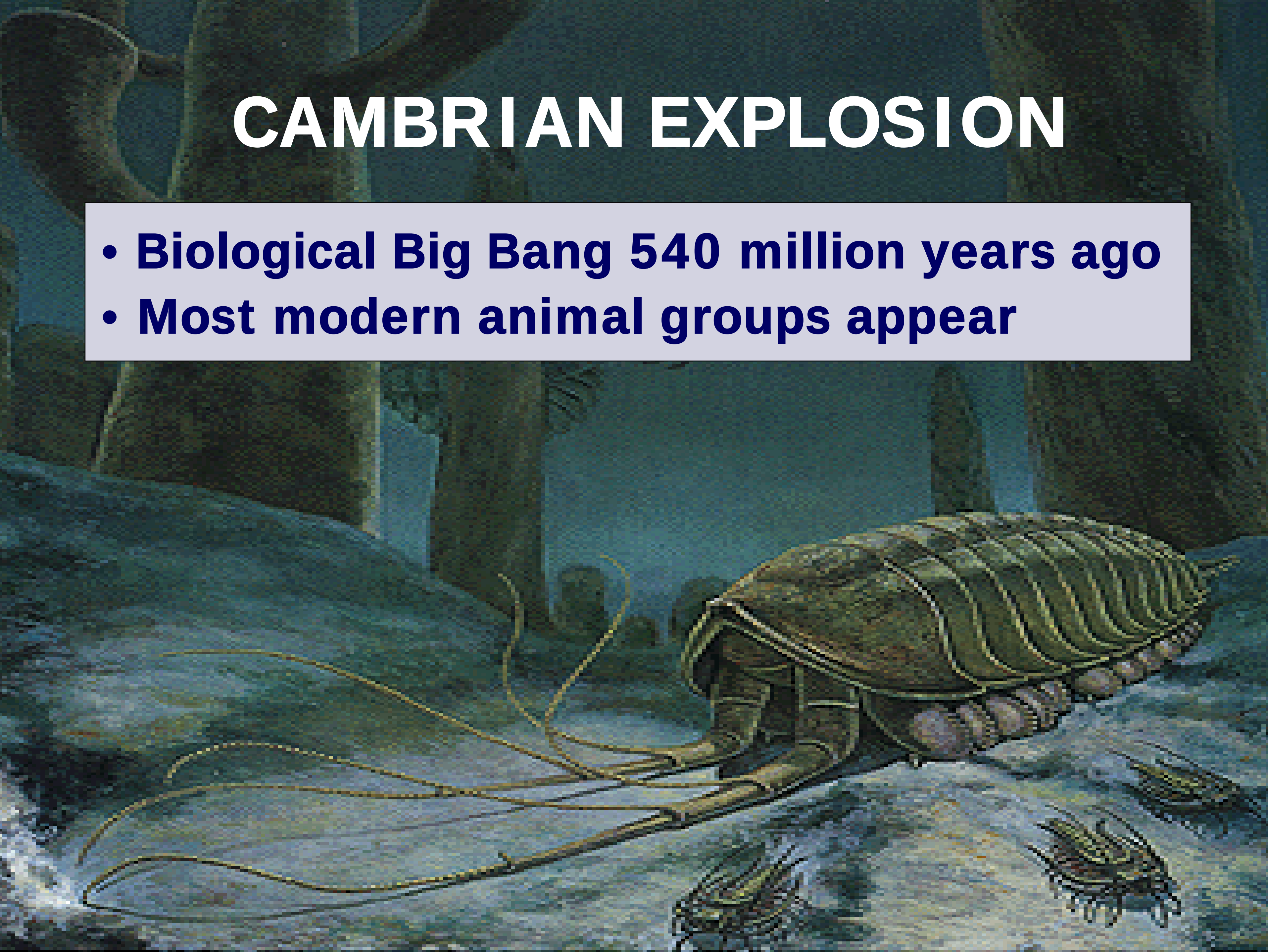


Evolution of the cumulative biosphere pools for prokaryotes, eukaryotes, and complex multicellular life.

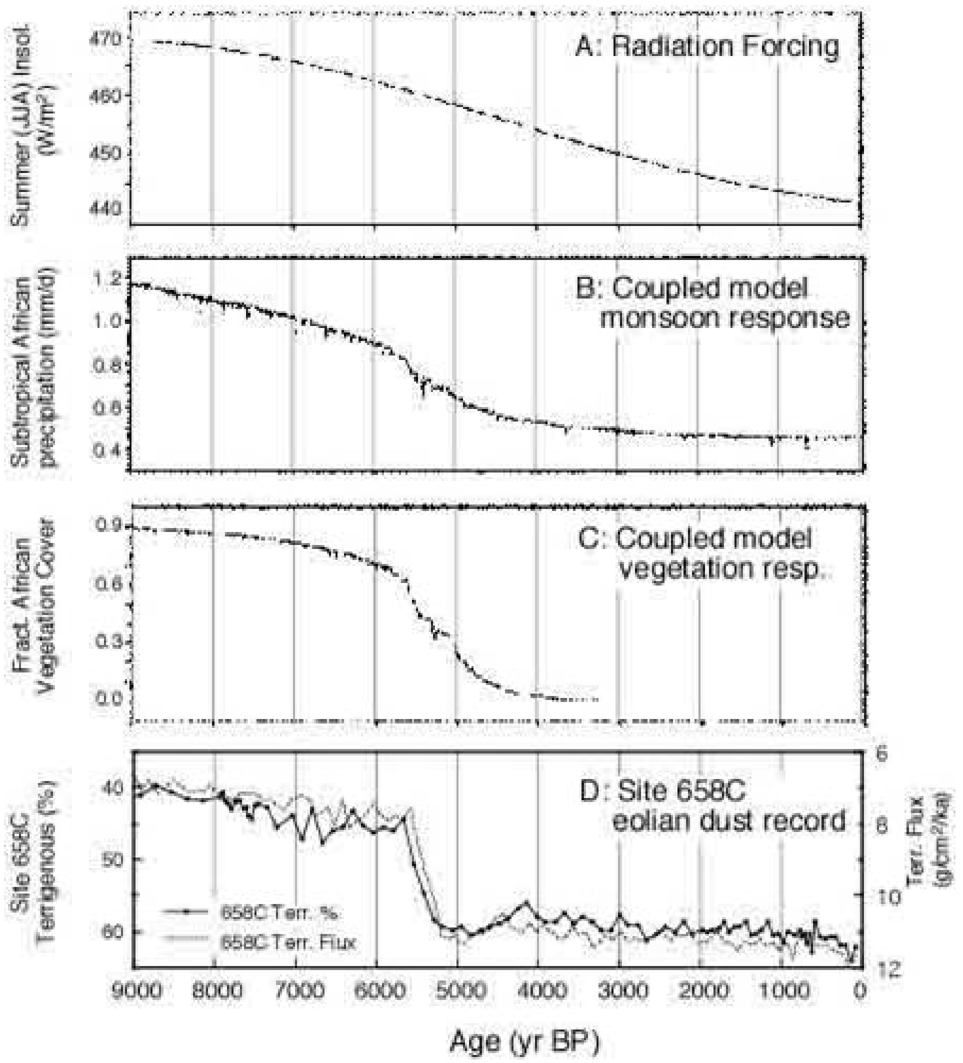
von Bloh, Bounama & Franck (2003):
Geophys. Res. Lett. **30** (18) 1963

CAMBRIAN EXPLOSION

- Biological Big Bang 540 million years ago
- Most modern animal groups appear



Mid-Holocene Saharan desertification



- Non-linear change in a single equilibrium
- Followed by the rise of “hydraulic societies” in Egypt, Mesopotamia…
- A tipping point in human systems linked to a tipping point in vegetation-climate?

De Menocal, P. J. *et al.* (2000). Quaternary Science Reviews 19: 347-361.

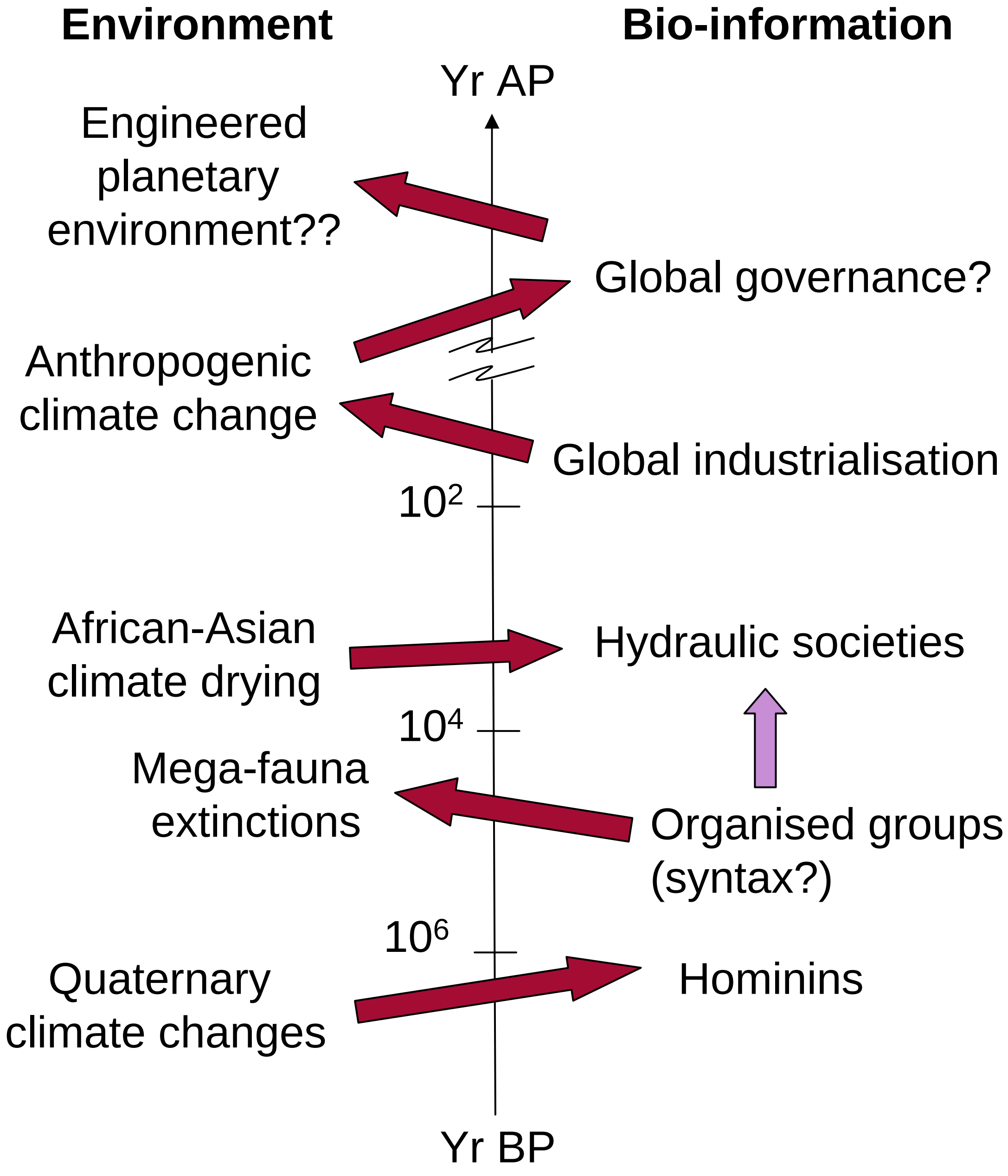
Human co-evolution

Civilisations collapse!

Read Jared Diamond

Tipping points:

- Food production
- Freshwater
- Displacement
- Disease
- Economy
- Technology
- Governance



Environment

Bio-information

Yr AP

Engineered planetary environment??

Global governance?

Anthropogenic climate change

Global industrialisation

10^2

African-Asian climate drying

Hydraulic societies

10^4

Mega-fauna extinctions

Organised groups (syntax?)

10^6

Quaternary climate changes

Hominins

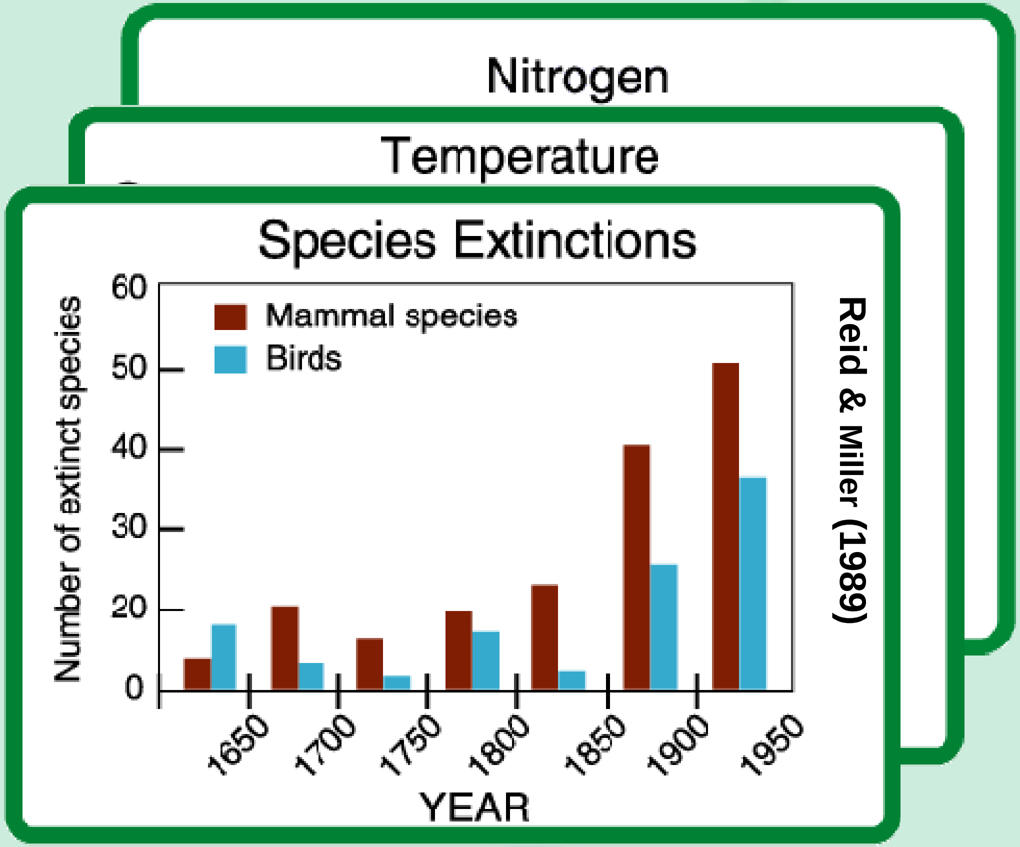
Yr BP

What is Global Change?

- Global-scale changes that affect the functioning of the Earth System
- Much more than climate change
- Socio-economic as well as biophysical

For example, changes in:

- Nitrogen fixation
- Temperature
- Biodiversity………..

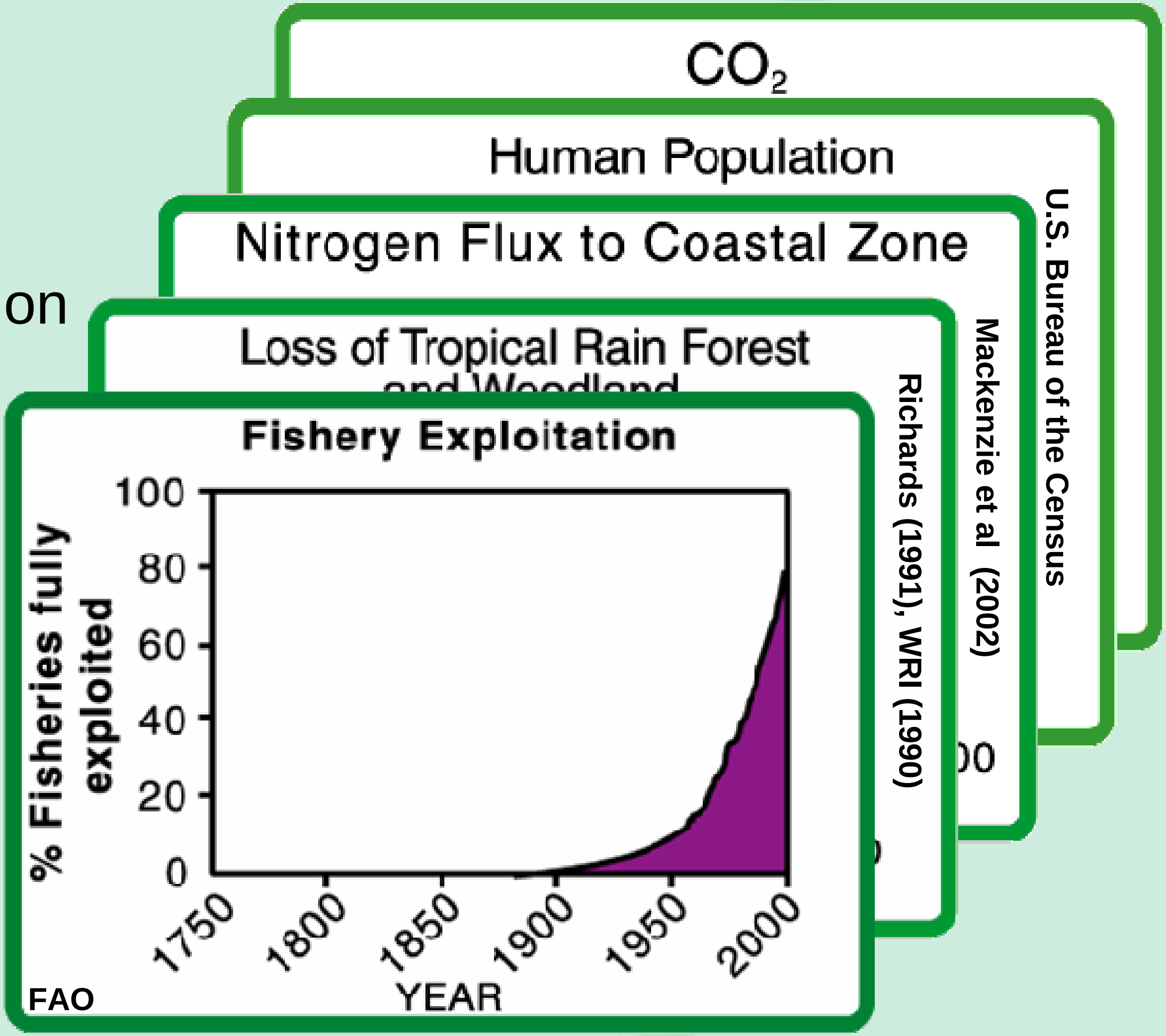


Reid & Miller (1989)

What is Global Change?

For example, changes in:

- Nitrogen fixation
- Temperature
- Biodiversity
- Atmosphere composition
- Population
- N in the coastal zone
- Forest cover
- Fisheries exploitation



CO_2

Human Population

U.S. Bureau of the Census

Nitrogen Flux to Coastal Zone

Mackenzie et al (2002)

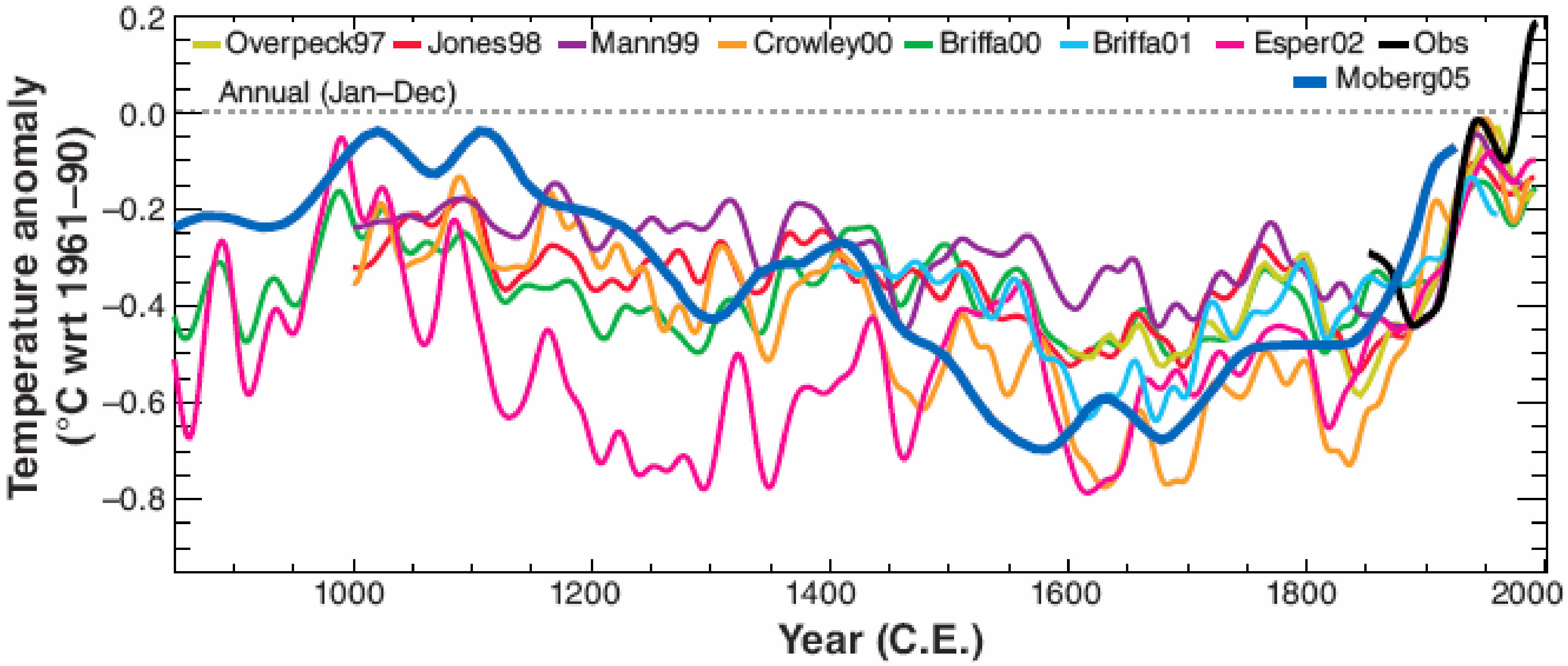
Loss of Tropical Rain Forest and Woodland

Richards (1991), WRI (1990)

Fishery Exploitation

FAO

Temperature Since 850 AD



Still no equal. Temperature records recovered from tree rings and other proxies broadly agree that no time in the past millennium has been as warm as recent decades (black).

***Science*, 10 February 2005**

Earth System Science Partnership

DIVERSITAS, IGBP, IHDP, WCRP

- an integrated study of the Earth System,
- the changes occurring to the System, and
- the implications for global sustainability.

Food Provision

Food demands are changing:

- How will global environmental change (GEC) affect food **provision** and **vulnerability**?
- How might societies and producers **adapt** their food systems to cope with GEC?
- What would be the environmental and socioeconomic **consequences** of such adaptations?

Carbon Cycle

- **Patterns and variability:** what are the geographical and temporal patterns of carbon sources and sinks?

- **Processes, controls and interactions:** what are the controls and feedback mechanisms - natural and anthropogenic - that determine the dynamics of the carbon cycle on scales of years to millennia?

- **Management of the carbon cycle:** what are the future dynamics of the carbon-climate system and what are the points of intervention and windows of opportunity for managing this system?

Global Water System Project

Water Resources

- What are the **relative magnitudes of changes** in the global water system (GWS) due to human activities and environmental factors?
- What are the social and Earth System **feedbacks** of human-driven change to the global water system?
- To what extent is the GWS **resilient** and **adaptable** to global change?

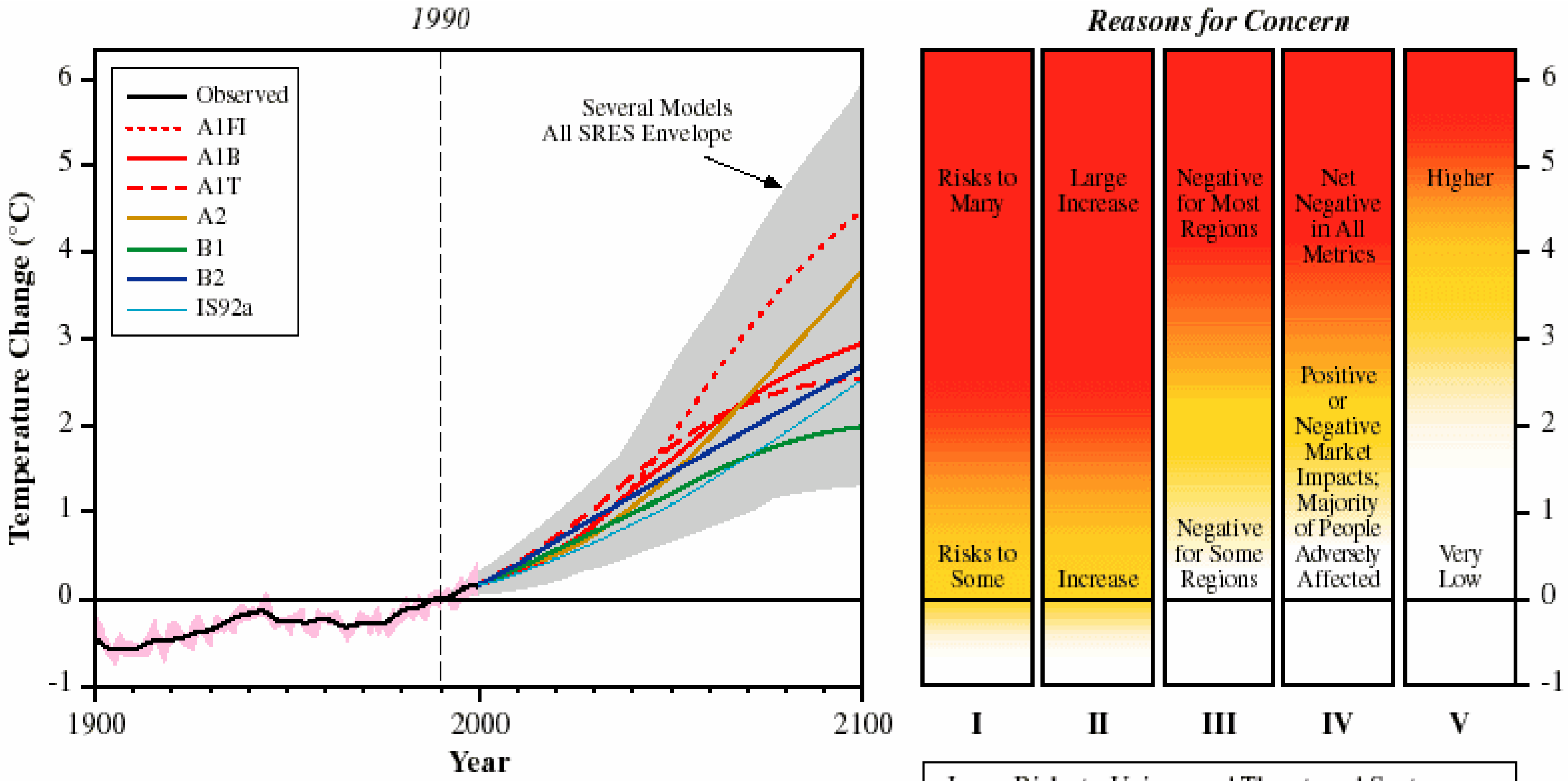
Human Health

Under Development

Project Goals:

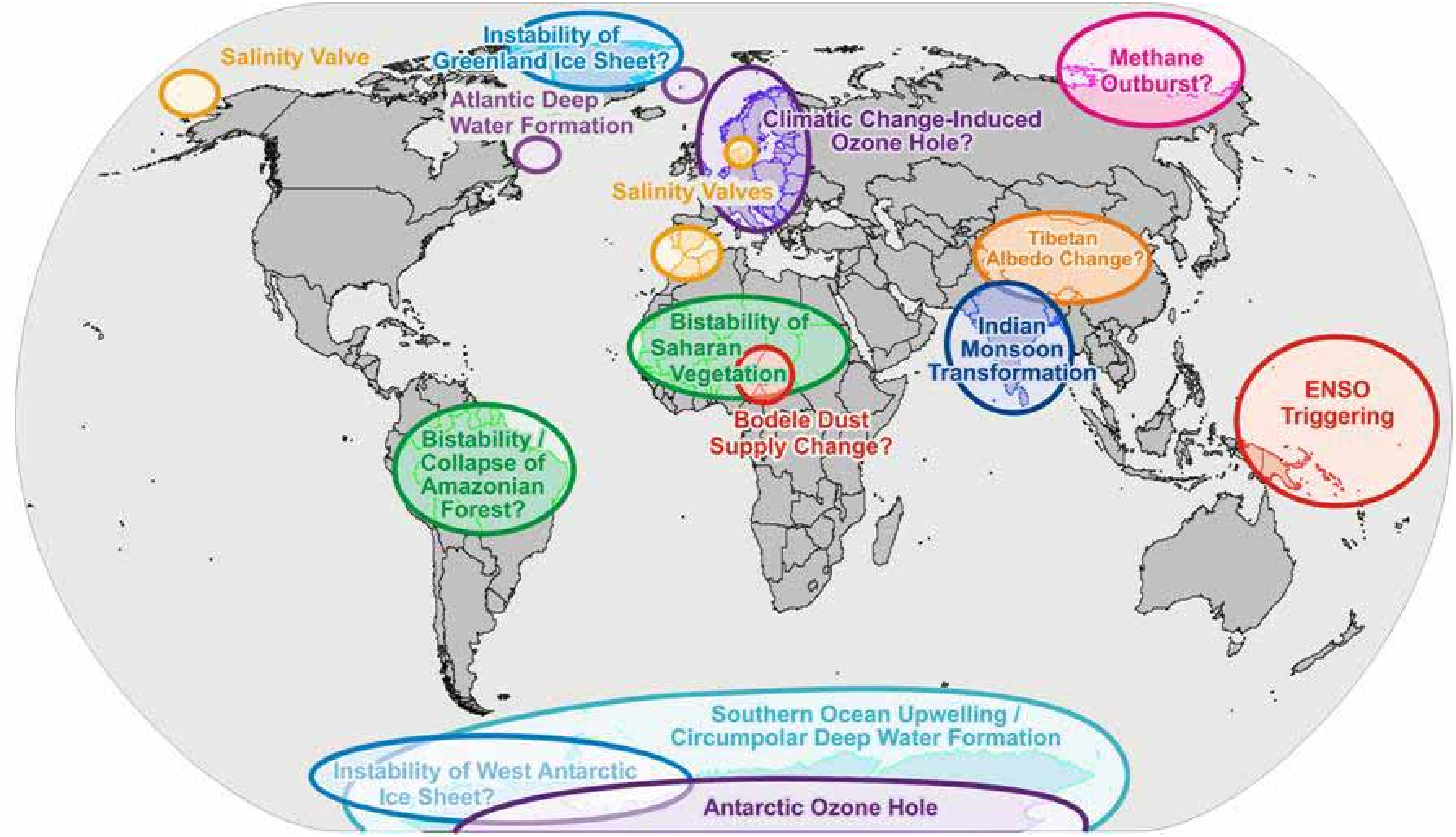
- To determine the past, current, and future health impacts of global environmental change.

- To enrich the policy discussion about mitigation and adaption from a human health perspective.

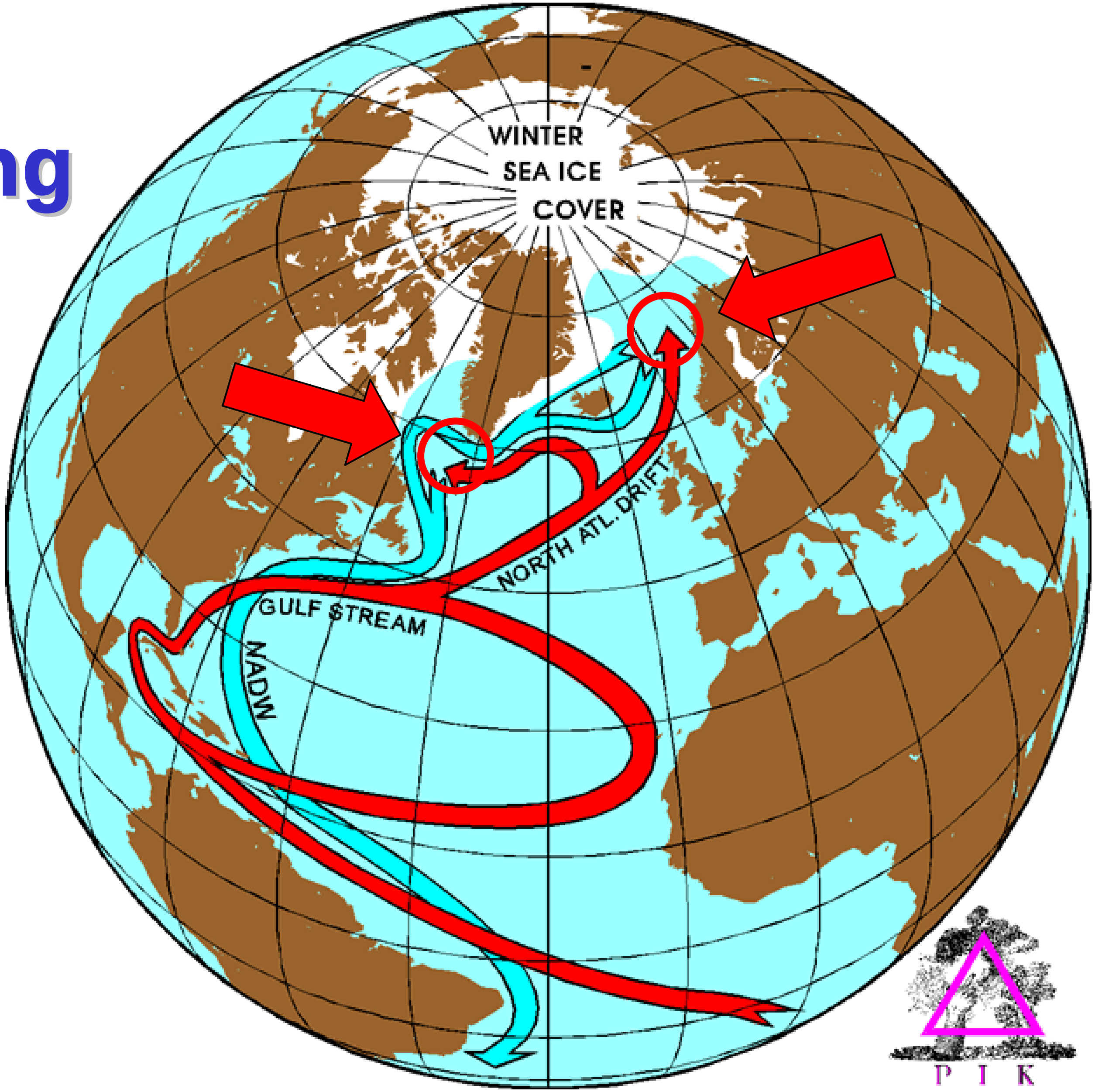


I	Risks to Unique and Threatened Systems
II	Risks from Extreme Climate Events
III	Distribution of Impacts
IV	Aggregate Impacts
V	Risks from Future Large-Scale Discontinuities

Earth System Achilles Heels

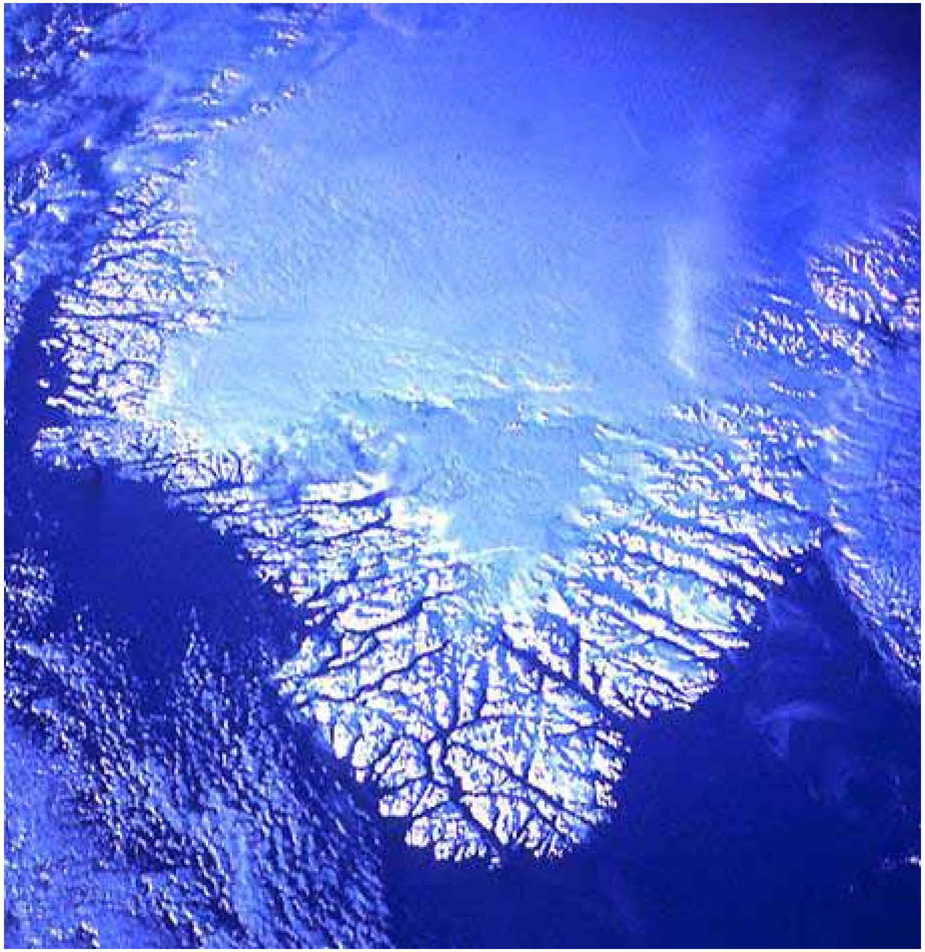


Europe's Free Heating System



P I K

West Antarctic Ice Sheet



Greenland Ice Sheet

PIK

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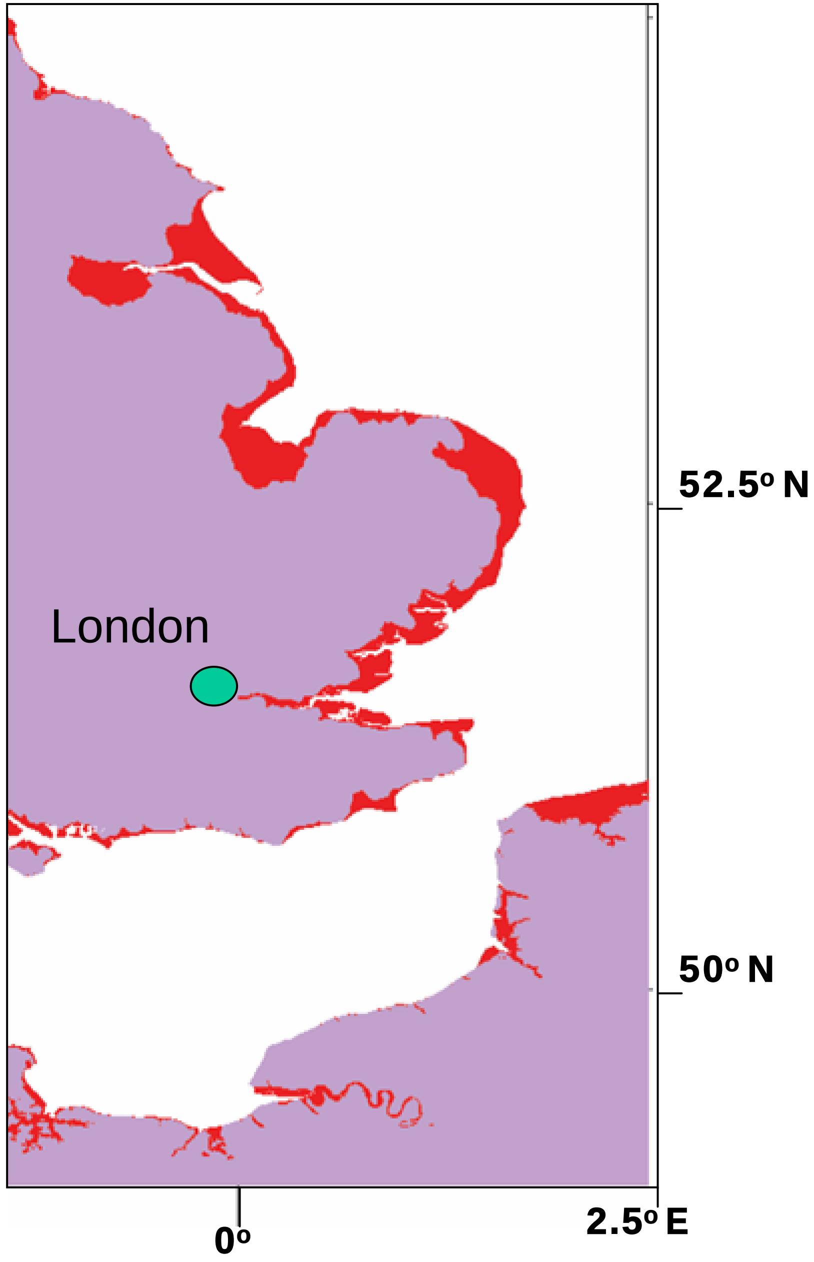
The coastline of south-eastern UK, assuming **6m of sea level rise** in the wake of **Greenland Ice Sheet melting**



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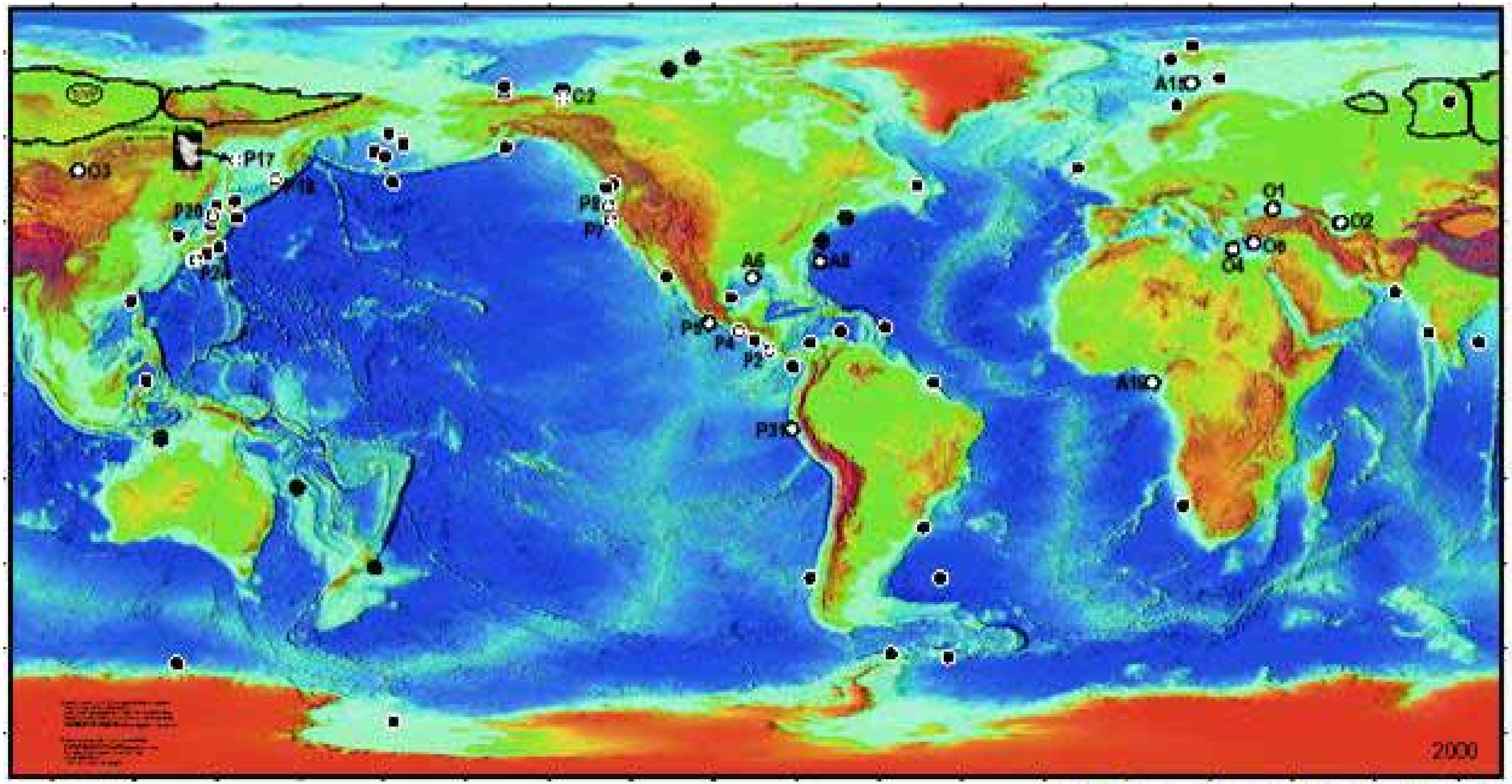
for Climate Change Research

A Global Inventory of Natural Gas Hydrate Occurrence

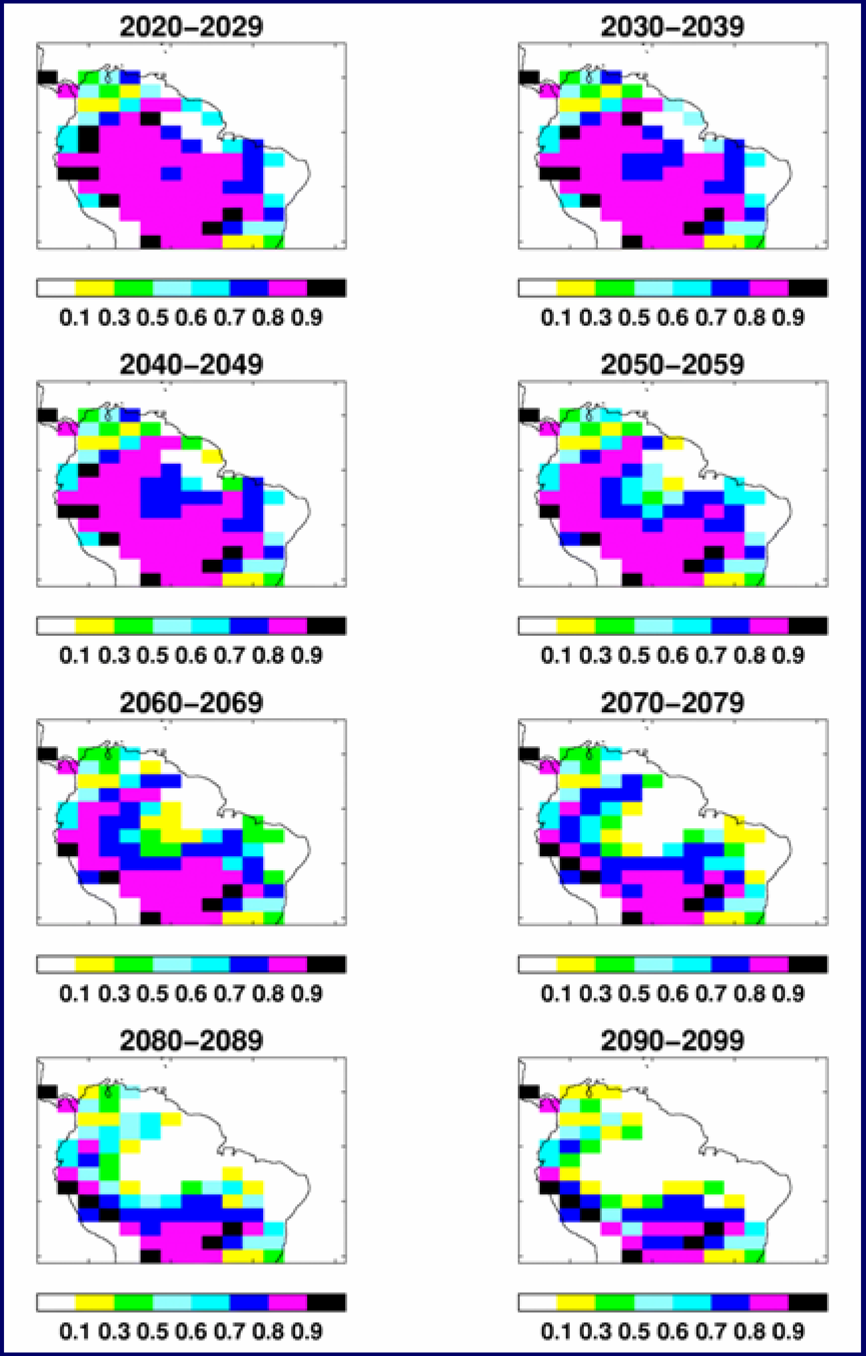


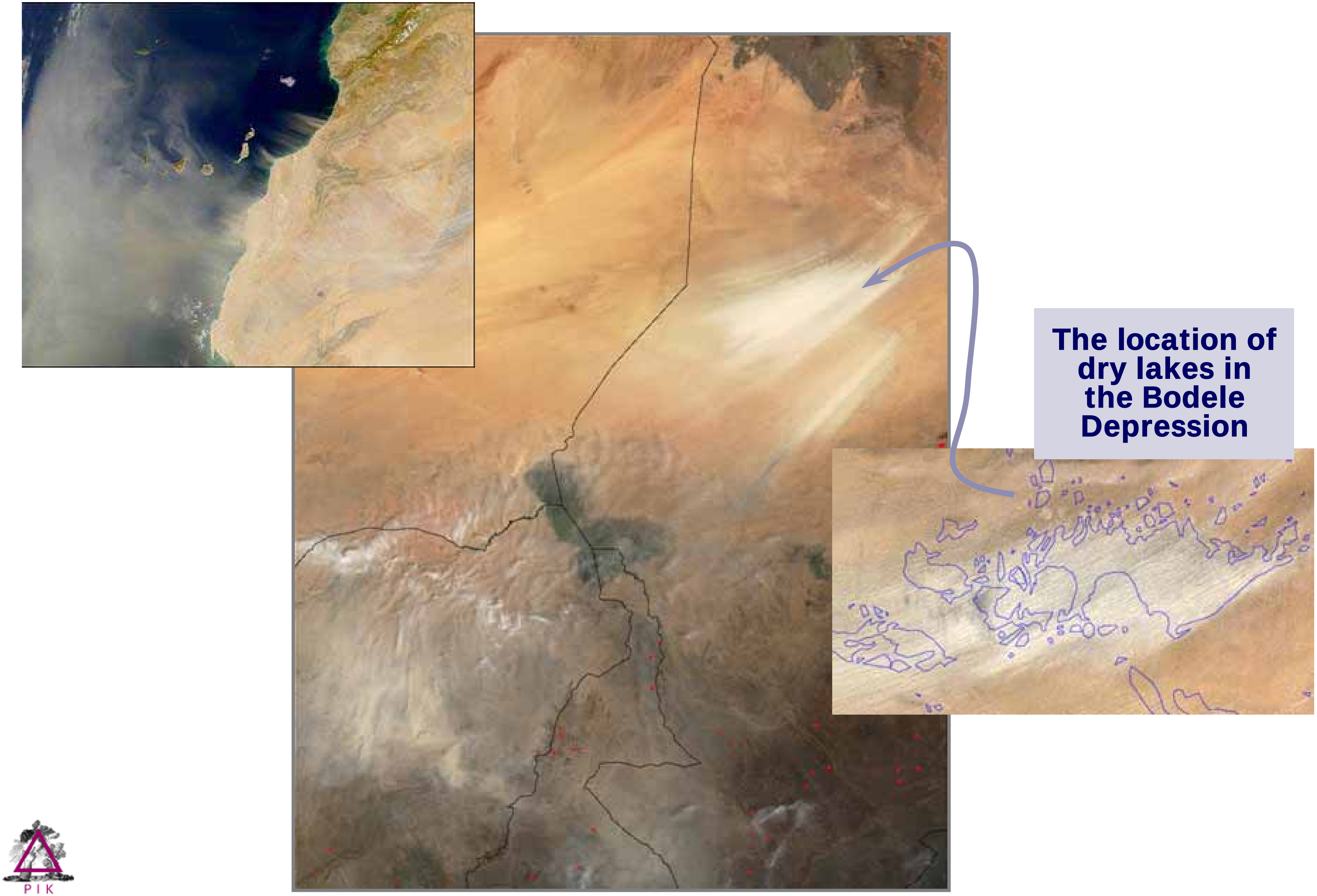
Keith A. Kvenvolden and Thomas D. Lorenson

USGS, 2001. More information: http://walrus.wr.usgs.gov/globalhydrate/

Tibetan Plateau

Broadleaf tree cover (gridbox fraction) in coupled climate-carbon cycle simulation





The location of dry lakes in the Bodele Depression

Dust Storm - Bodele Depression, Chad

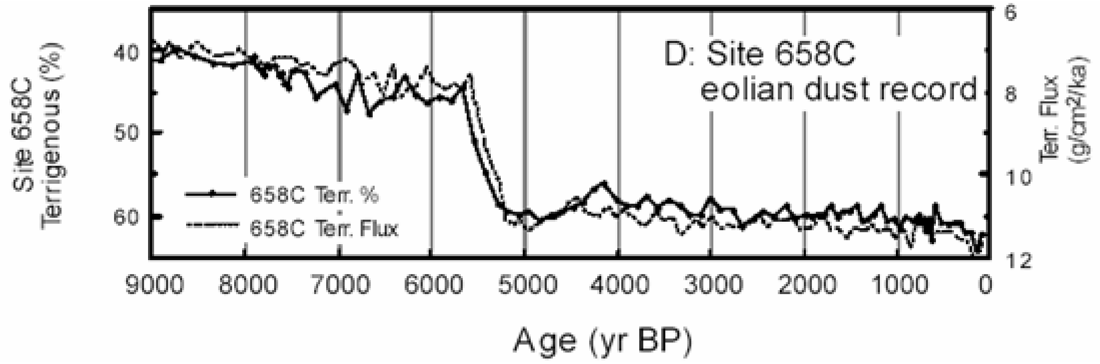
Thanks to Joseph M. Prospero
RSMAS, Univ. of Miami

PIK

Tyndall°Centre
for Climate Change Research

Will Greenhouse Green the Sahara?

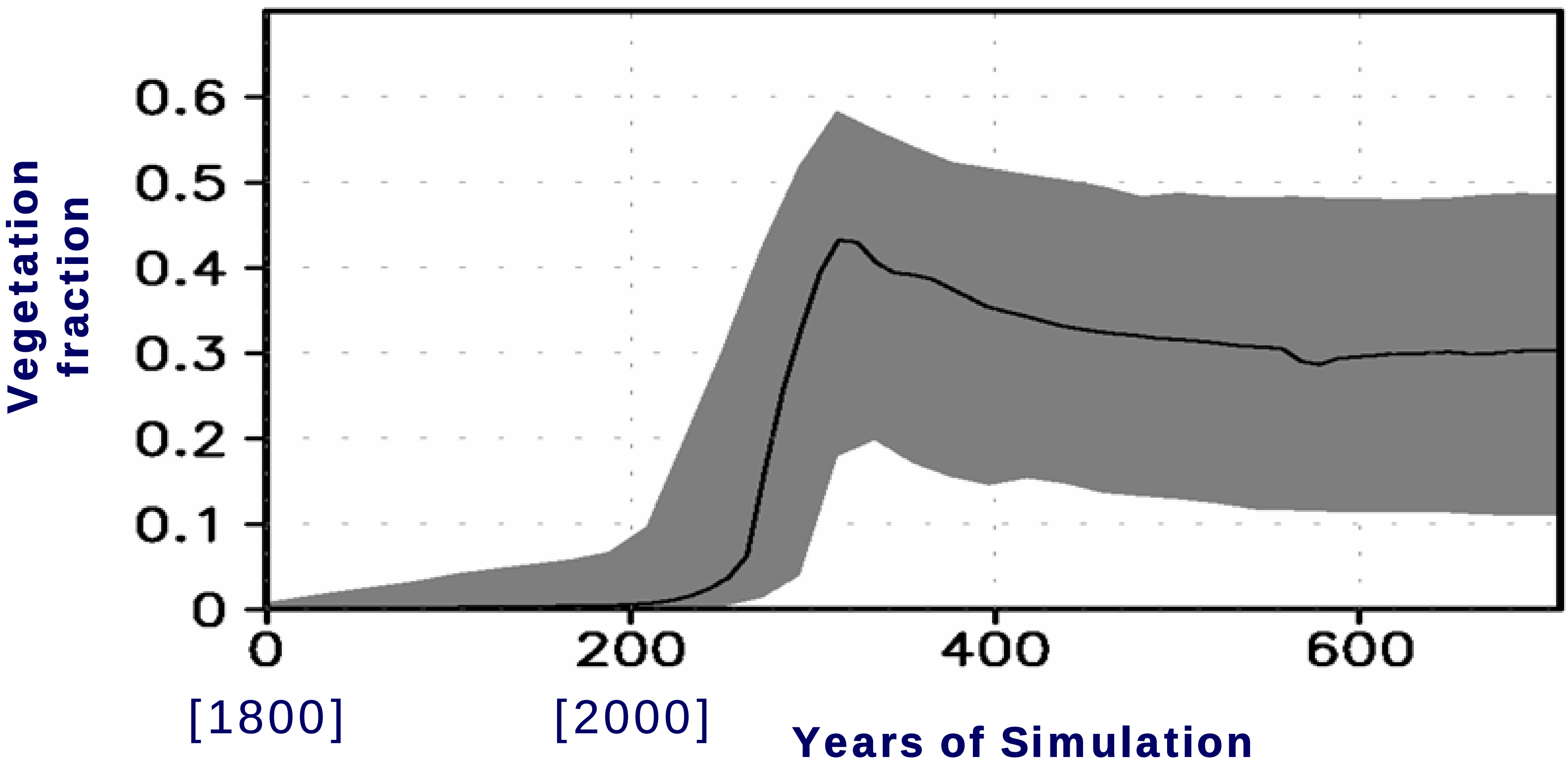
(N. Petit-Maire, 1990)



deMenocal et al., 2000

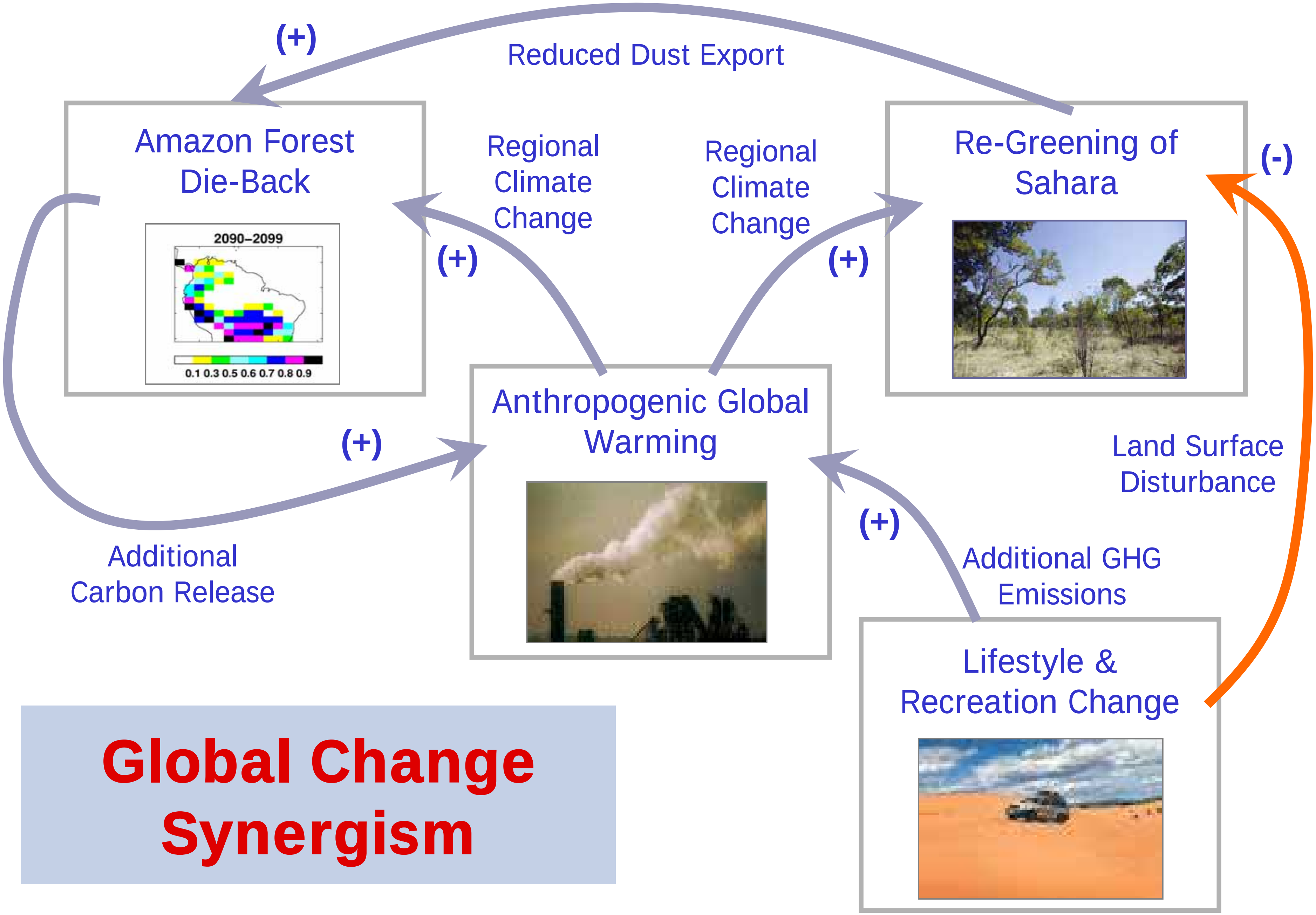
Changes in Potential Vegetation Cover in the Sahara

Transient CO_2 scenario (1%, 1000 ppm)



Claussen et al., 2003

Global Change Synergism



Amazon Forest Die-Back

Re-Greening of Sahara

Anthropogenic Global Warming

Lifestyle & Recreation Change

(+) Reduced Dust Export

Regional Climate Change (+)

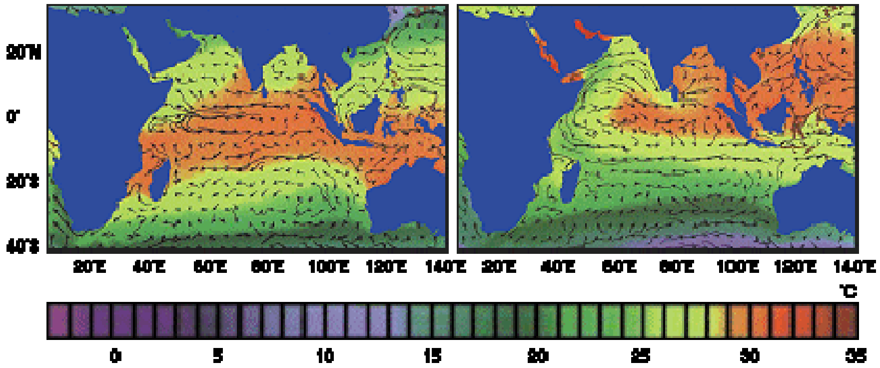
Regional Climate Change (+)

(+) Additional Carbon Release

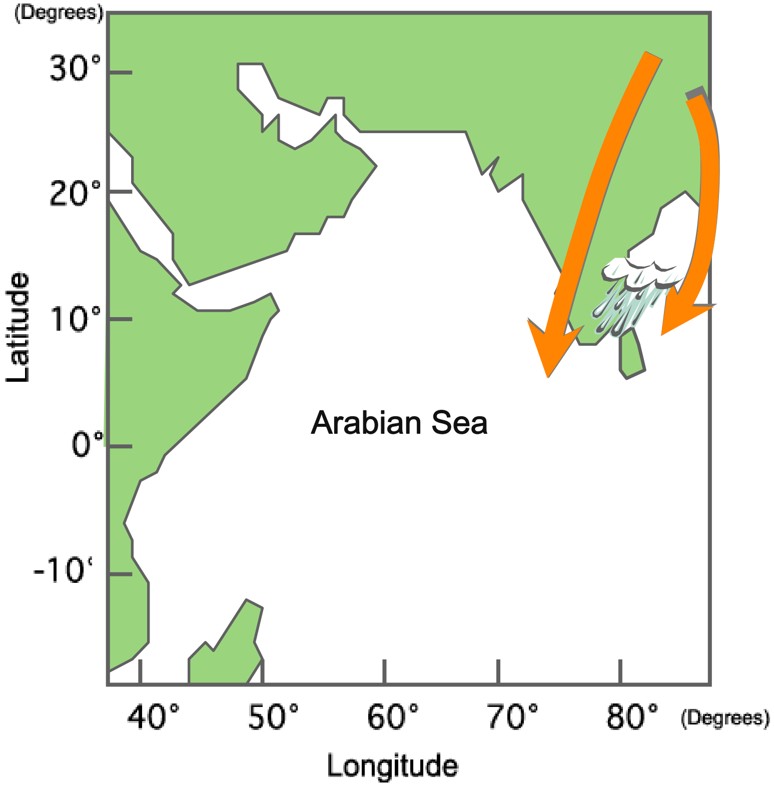
(+) Additional GHG Emissions

(-) Land Surface Disturbance

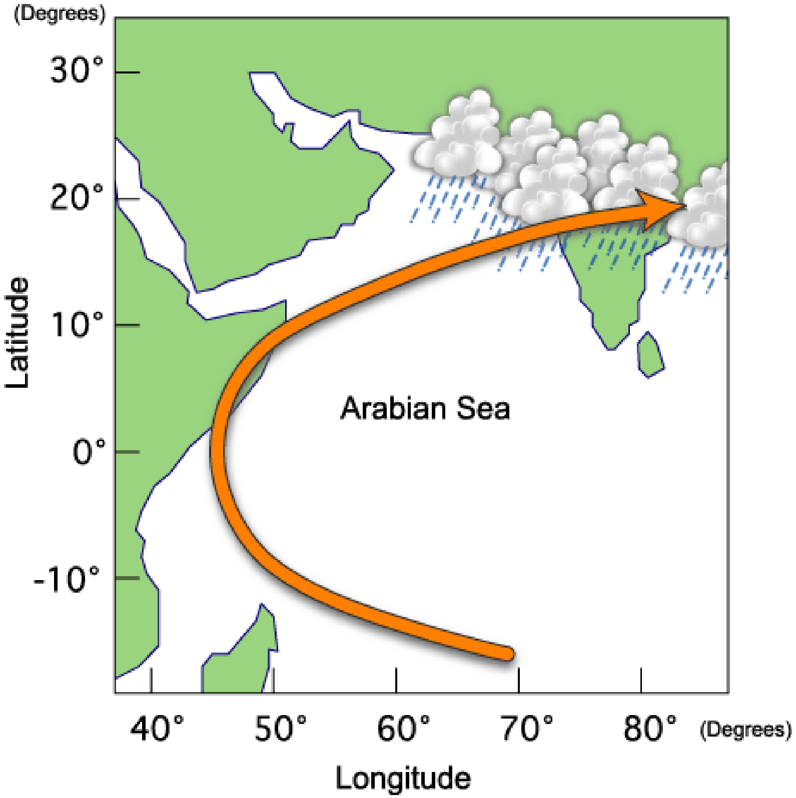
Image: WJ Schmitz, WHOI



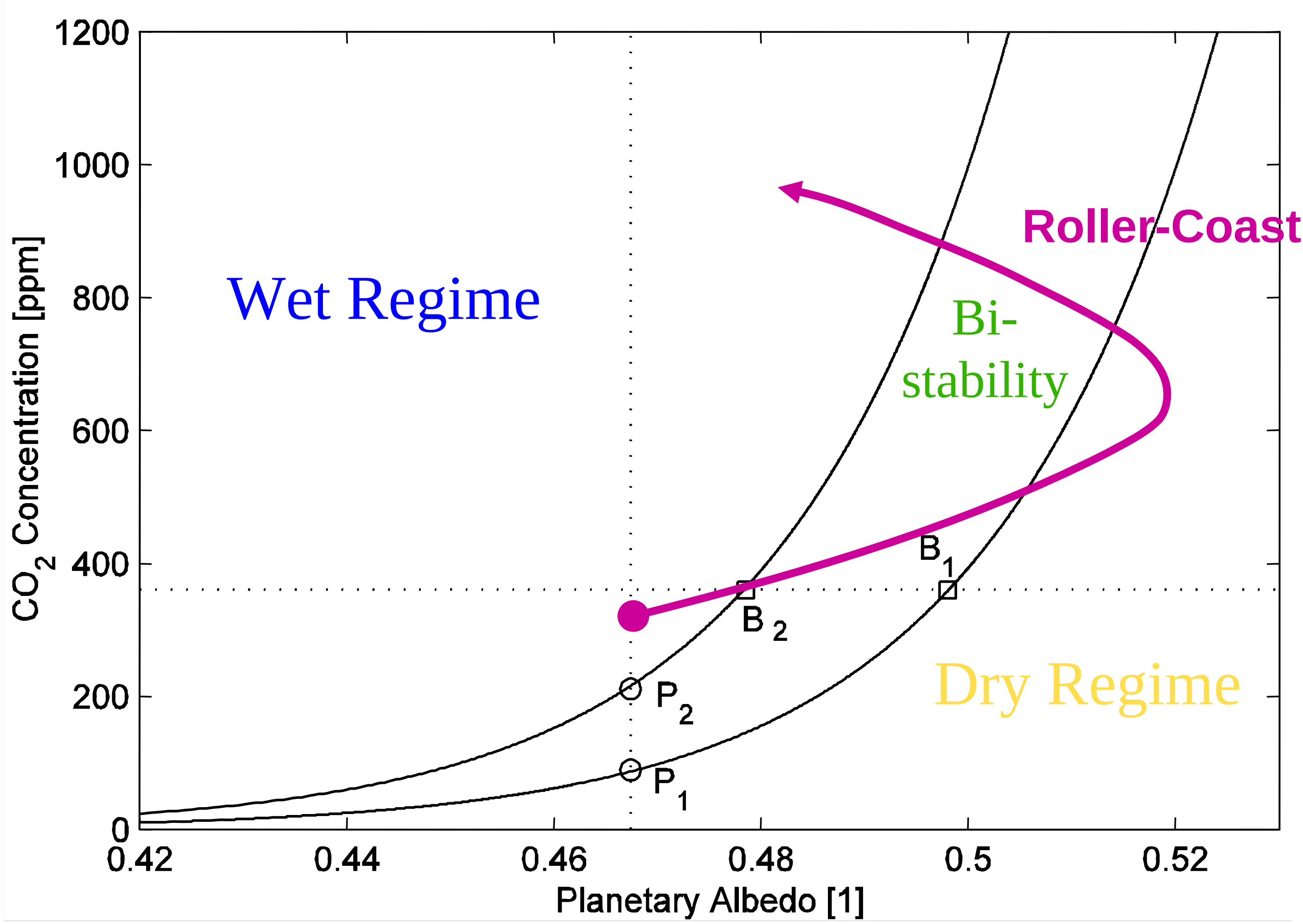
Northeasterly Winter Monsoon



Southwesterly Summer Monsoon



Worst Case Scenario for Monsoon Development



Zickfeld et al. 2005, GRL 32, 15707 (see also Ball 2005, Nature, August 15th)

The Telegraph
calcutta, india

Thursday, August 18, 2005

Man’s murder of monsoon

· German climate researchers issue India warning

G.S. MUDUR


DANGER LURKS

A schoolboy guides his sister through a flooded Calcutta street after monsoon rains. AFP

- Steady increase in aerosols* or loss of forest cover may cause sudden monsoon breakdown
- It will mean consistently weak rainfall over several years
- Aerosols tend to reduce monsoon rain
- Greenhouse gases tend to increase rain
- Monsoon might also display sudden downs and ups
- Increased air pollution may weaken monsoon
- But if pollution is reduced, greenhouse gas effects will abruptly intensify monsoon

** Aerosols are airborne particles spewed by burning coal and firewood*

New Delhi, Aug. 17: Increasing air pollution and loss of forest cover in South Asia may trigger a sudden breakdown of the Indian monsoon and sharply reduce rainfall in the subcontinent within decades, climate scientists said.

Researchers at Germany’s Potsdam Institute for Climate Impact Research who set out to explore the stability of the summer monsoon over India have particularly vulnerable to human influences.

“The stage seems to be set for a man-made reduction of the Indian summer monsoon,” climate physicist Kirsten Zickfeld and her colleagues said in a paper published in the latest issue of the journal, *Geophysical Research Letters*.

The scientists have shown that tiny particles called aerosols, spewed into the atmosphere during the burning of coal and firewood, reduce monsoon rainfall, while rising greenhouse gases such as carbon dioxide tend to increase rainfall.

A steady rise in aerosols will reduce the amount of sunlight striking land and lower land temperatures. This will decrease the supply of moisture-laden from the sea and lower rainfall. Shrinking forest cover will also have the same effect.

“When these effects exceed a critical threshold, the monsoon could experience a sudden breakdown,” Zeckfeld told The Telegraph in a telephone inte “We’d then see a very weak monsoon consistently over many years,” she said.

“This is something we should be concerned about,” said Sourendra Bhattacharya, a climate scientist at the Physical Research Laboratory in Ahmedabad.

Climate records have revealed that the Indian monsoon has undergone abrupt changes over the past 8,000 years. “There have been some dramatic ups and downs in the monsoon,” said Bhattacharya who specialises in ancient climate studies.

“While those ancient changes in rainfall were driven by natural phenomena, we’re now anticipating changes influenced by human activities,” he said.

Zeckfeld said her study could not quantify the reduction in the rainfall, nor predict when exactly the breakdown of the monsoon might occur.

But with rising aerosol levels, it could happen over the next few decades, she said.

f India adopts new technologies to reduce its aerosol emissions, Zeckfeld said, the monsoon may display a “roller-coaster” behaviour. After a suppression over the next decades, as aerosol-reduction policies begin to take effect and economic growth drives up carbon dioxide emissions, the monsoon may abruptly intensify and re-establish the “wet-monsoon” regime within a few years.

It might be hard for India to have the monsoon doing really weird things — reducing and then abruptly increasing,” she said. The study has also cautioned that India might find it a challenge to adapt to such a roller-coaster scenario.

This is not the first study to signal the danger that aerosols pose to the monsoon. A study by climate scientist Murari Lal, formerly at the Indian Institute of Technology, New Delhi, in 1995 was the first to show that aerosols can weaken rainfall.

Bhattacharya said the impact of aerosols would depend on what type they were. Some aerosols such as soot absorb sunlight and will tend to increase rainfall, while sulphur-containing particles will reflect sunlight and tend to reduce rainfall.

We might also have a scenario where the effects of aerosols and greenhouse gases cancel each other out,” Bhattacharya said.

Monsoon Chaos?

Physically based Lorenz-type model for the Indian summer monsoon:

$$C_s \frac{\partial T_s}{\partial t} = -LE - H + F_{\downarrow}^{S}(1 - A_S) - F_{\uparrow}^{T} + F_{\downarrow}^{T}$$

$$C_A \frac{\partial T_A}{\partial t} = H - F_{\downarrow}^{S}(1 - A_S) + F_{\uparrow}^{T} - F_{\downarrow}^{T} + F_{\downarrow}^{S,H}(1 - A_{SY}) - F_{\uparrow}^{T,H} + LP + A_T$$

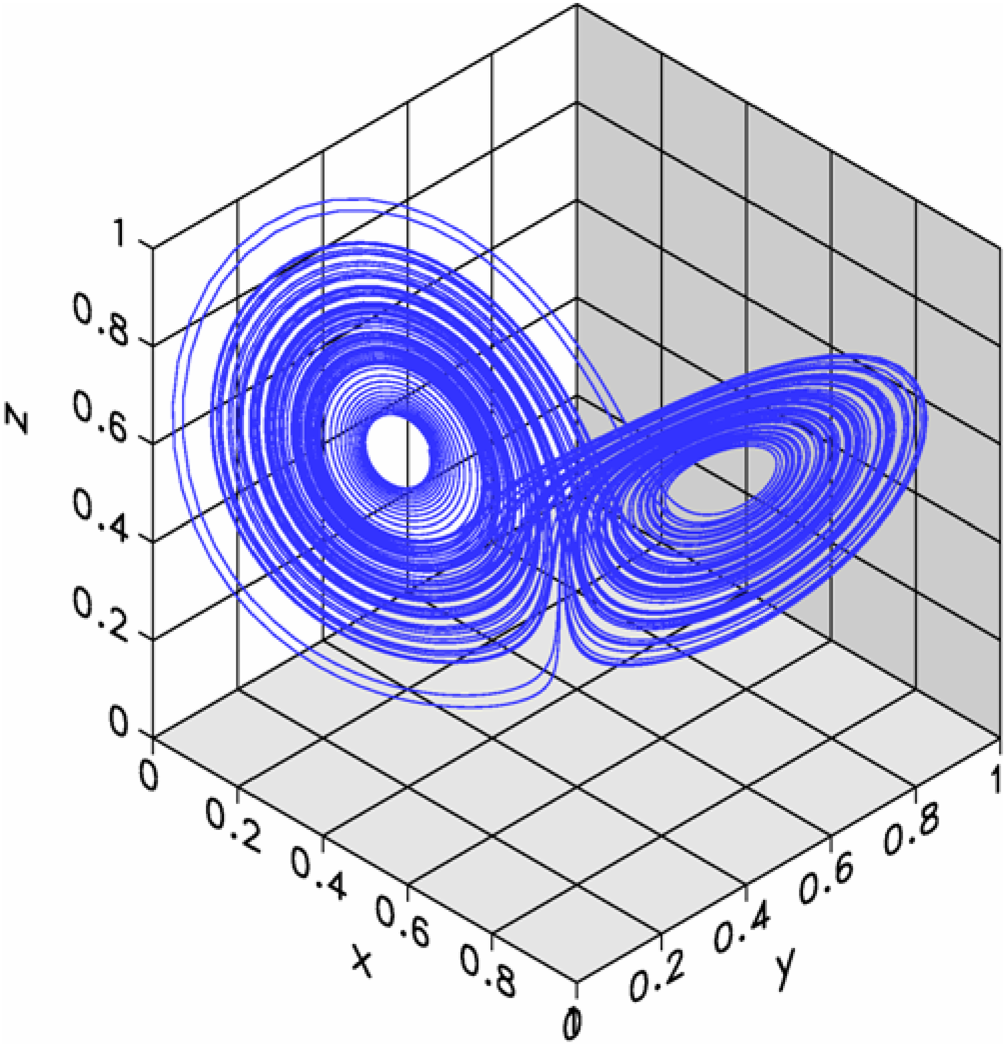
$$\frac{\partial W_2}{\partial t} = \frac{f_1}{f_2} \frac{W_1 - W_2}{\tau}$$

$$C_q \frac{\partial q_V}{\partial t} = E - P + A_V$$

$$\frac{\partial W_1}{\partial t} = \frac{P - E - R}{f_1} + \frac{W_2 - W_1}{\tau}$$

T_s: surface temperature
T_A: near-the-surface atmosphere temperature
q_v: near-the-surface specific humidity
$W_{1,2}$: wetness of the upper and the lower soil layer
E: evaporation
P: precipitation
H: sensible heat flux from the surface

Lorenz Attractor



$$\dot{X} = -\sigma X + \sigma Y$$

$$\dot{Y} = -aXZ + rX - cY$$

$$\dot{Z} = dXY - bZ,$$

where

$$X = \frac{W_2'}{W_0}; Y = \frac{W_1'}{W_0}; Z = \frac{q_V'}{q_{V,0}}$$

Parameter Settings

$\sigma = 10$

$a, c, d = 1$

$b = 8/3$

$r = 28$

One view of climate change

“I believe that climate change is the most important long-term issue we face as a global community. It is an issue that will require sustained action over the coming decades. A sound understanding of the science must be the basis for this action.”

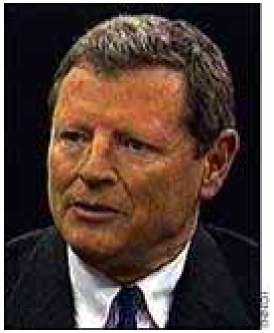
Tony Blair, UK Prime Minister

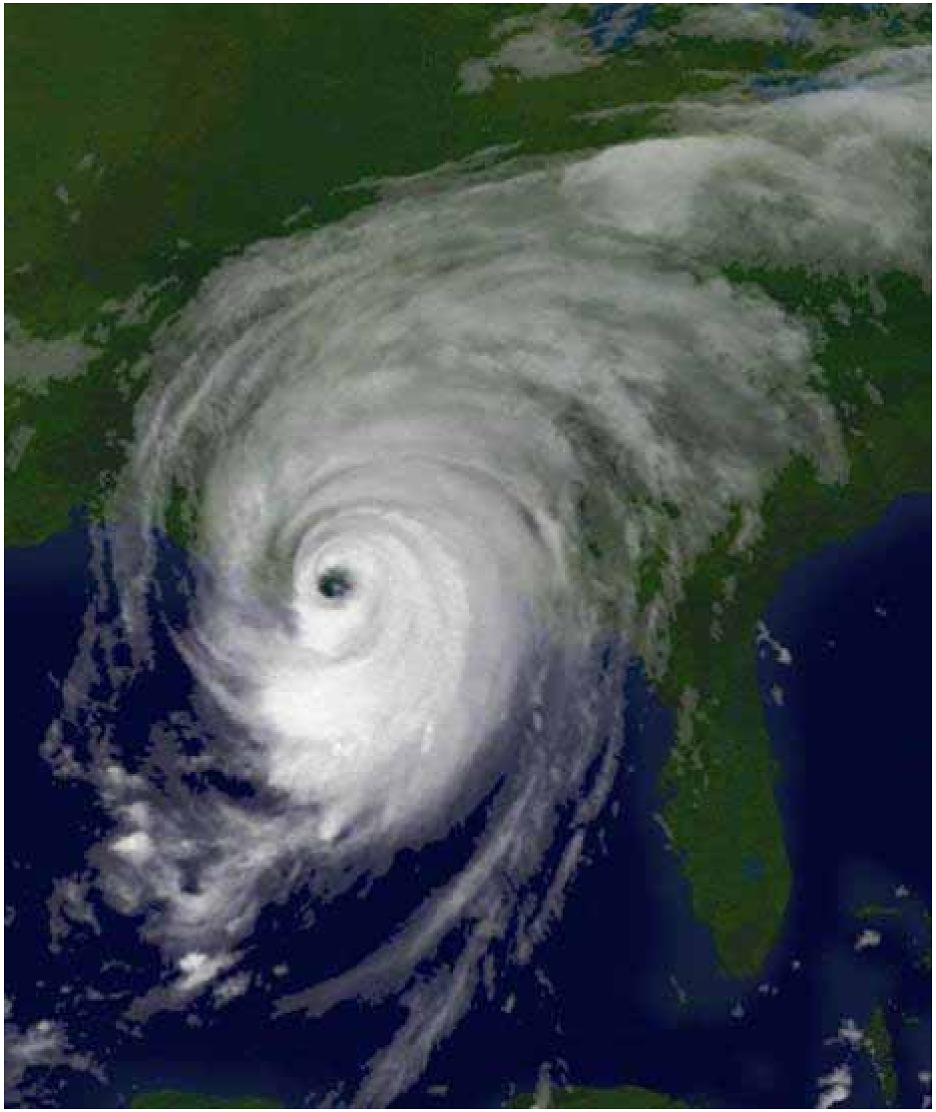
3 Nov 2004

....and another

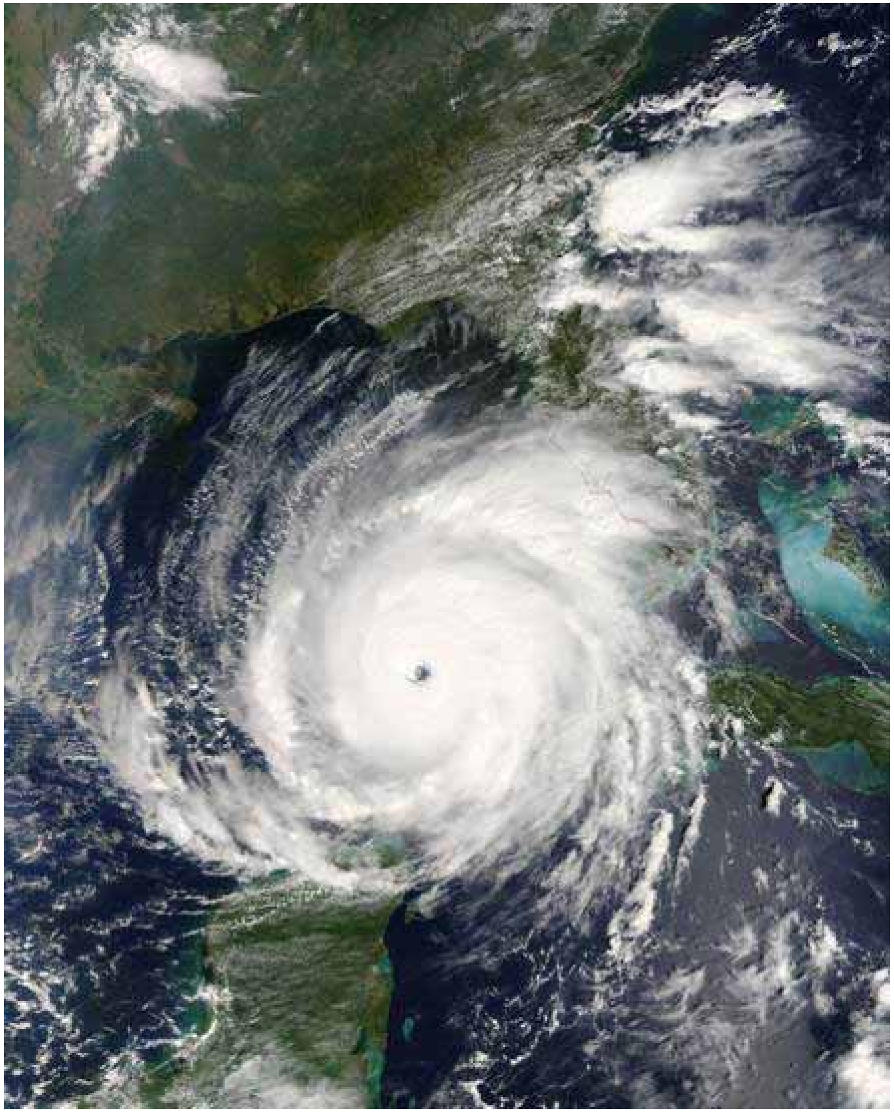
> “Much of the debate over global warming is predicated on fear, rather than science. I called the threat of catastrophic global warming the greatest hoax ever perpetrated on the American people.”

James M. Inhofe, US Senator &
Chairman of Environment and Public Works Committee
4 Jan 2005





Hurrican Katrina



Hurrican Rita

Consolidated Results:

Schellnhuber et al. (Eds.)

„Avoiding Dangerous Climate Change“

CUP, forthcoming

AVOIDING DANGEROUS CLIMATE CHANGE
1-3 February 2005 Met Office, Exeter, UK

International Symposium on Stabilisation of Greenhouse Gases

Met Office, Exeter
United Kingdom

1 – 3 February 2005

Abstracts of Symposium Papers

Scientific Steeering Committe

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John Ashton, E3G, UK
Zhou Dadi, Beijing Energy Efficiency Centre, China
Luiz Gylvan Meira Filho, University of São Paulo, Brazil
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Martin Parry, Hadley Centre, Met Office, UK
John Schellnhuber, Tyndall Centre for Climatic Research, UK
K S Yap, Malaysian Meteorological Service, Malaysia
Robert Watson, World Bank, USA
Tom Wigley, National Centre for Atmospheric Research, Colorado

This event is sponsored by the UK Department of Environment, Food and Rural Affairs (DEFRA)

Tyndall°Centre
for Climate Change Research

The
Cambridge-MIT
Institute

Tyndall Centre & Cambridge-MIT Institute Symposium

MACRO-ENGINEERING OPTIONS FOR CLIMATE CHANGE MANAGEMENT & MITIGATION

Isaac Newton Institute, Cambridge, England, 7-9 January 2004

Final Draft Programme (18 December 2003)

Wednesday 7 January

1530 **Registration opens (at INI)**
1600 **Tea/Coffee**
1630 **Informal discussions, preparatory briefings etc**
1800 **Close**

1930 **Ice-breaker Reception** (Dept. of Earth Sciences, Downing Street)
Welcome by Professor Sir David King, (Chief Scientific Adviser, UK Government)

Thursday 8 January

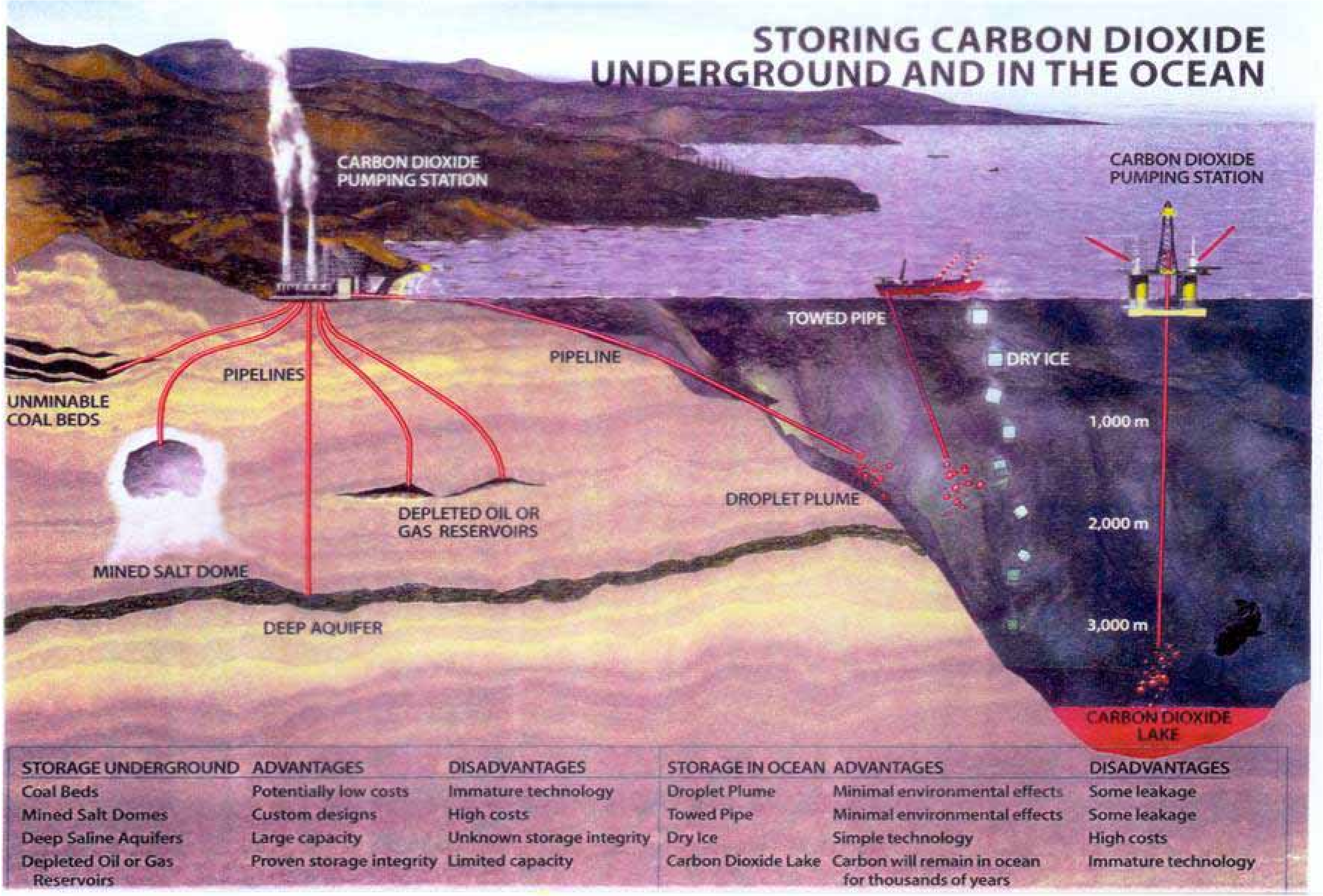
0900 **Symposium Opens** (Harry Elderfield)
0910 **Introductory Remarks**
- Tyndall Centre (John Schellnhuber)
- Cambridge-MIT Institute (Ed Boyle)

0920 **Informal overview** (Jim Lovelock)
0945 **Background & Introduction to the Symposium** (John Shepherd)
1000 **Keynote paper**: **Geo-engineering & climate: An Overview** (David Keith)
Plenary Discussion (Scope, process, etc)
1100 **Coffee/Tea**

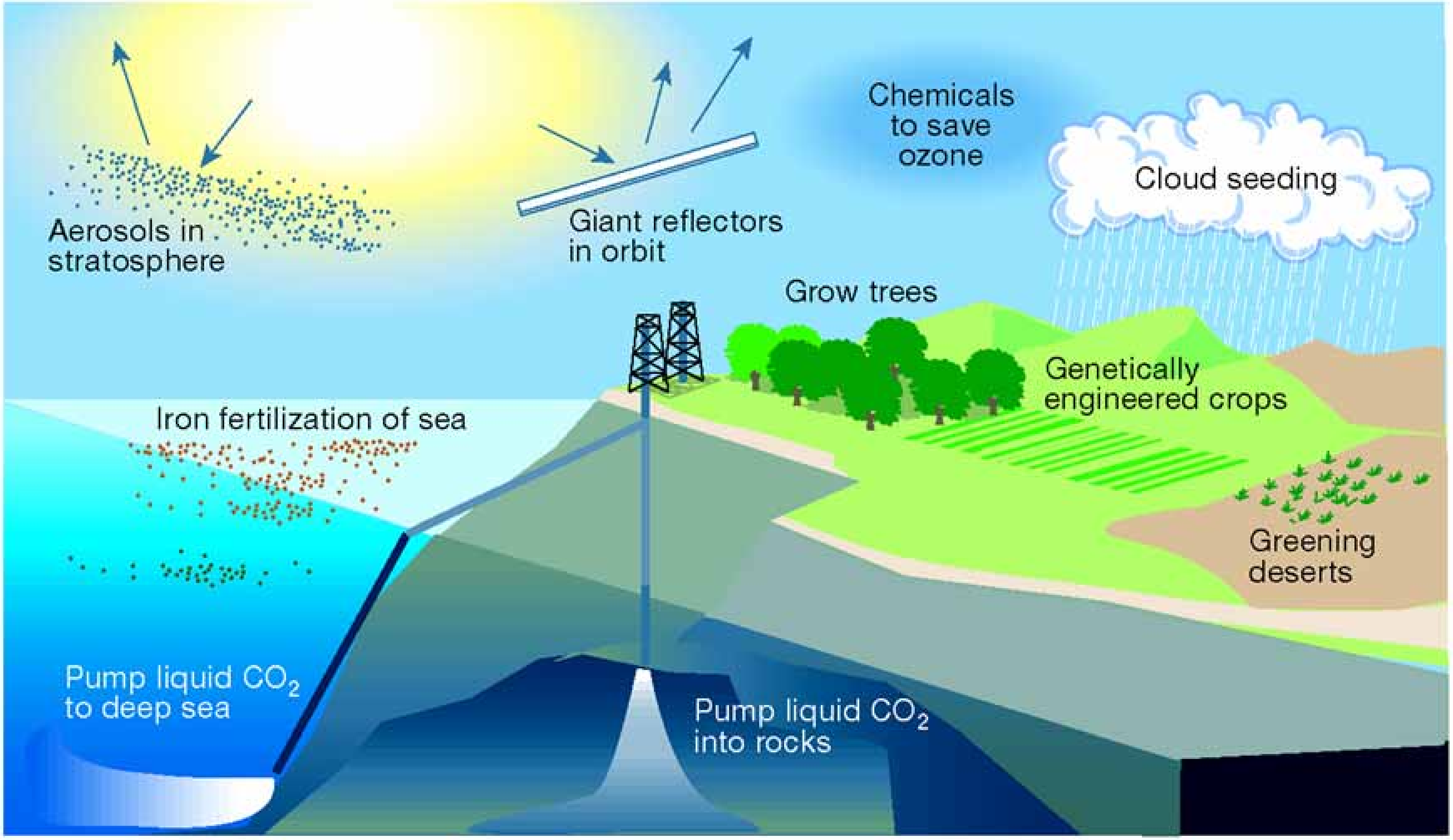
Session 1a: CO_2 Capture & Storage : "Current" Sequestration options
(Chair: Ed Boyle)
1130 **Geological Sequestration** (Julio Friedmann)
1200 **Ocean Disposal** (Ken Caldeira)
1230 **Land carbon sinks** (Victor Brovkin)
1300 **Lunch**

Session 1b: CO_2 Capture & Storage: potential & future options
(Chair: John Shepherd)
1400 **Ocean fertilisation** (Victor Smetacek)
1430 **Atmospheric scrubbing** (Klaus Lackner)
1500 **Discussion**
1530 **Tea/Coffee**

Carbon Management



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES	STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology	Droplet Plume	Minimal environmental effects	Some leakage
Mined Salt Domes	Custom designs	High costs	Towed Pipe	Minimal environmental effects	Some leakage
Deep Saline Aquifers	Large capacity	Unknown storage integrity	Dry Ice	Simple technology	High costs
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity	Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology



Macro-Engineering Options

Practical Geoengineering Options to Prevent Abrupt and Long-Term Climate Change

Alvia Gaskill, President
Environmental Reference Materials, Inc.
Research Triangle Park, N.C.
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Consultant
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reese@adeptscience.com
356-2137-1223

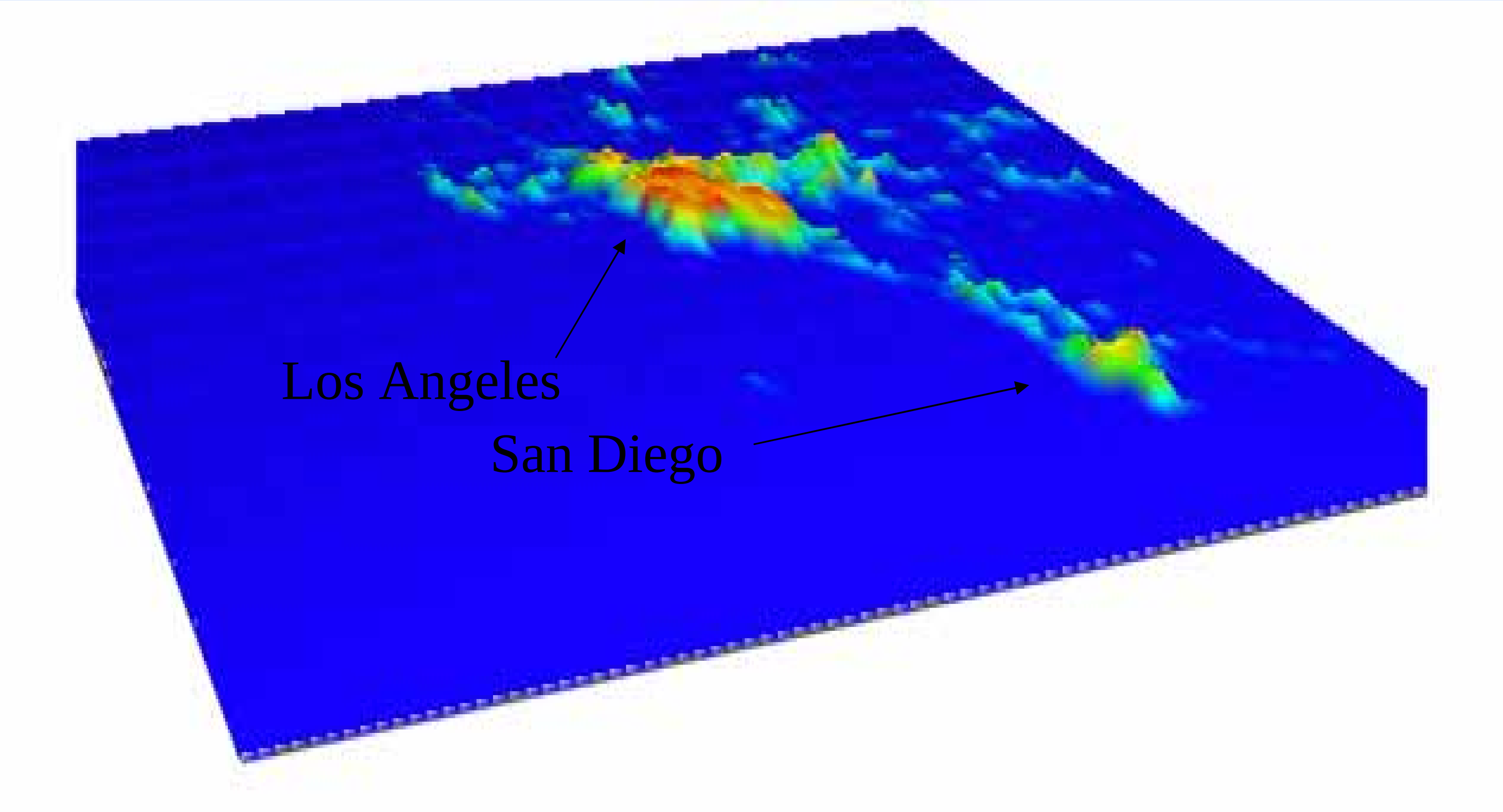
Presented to:

U.S. Climate Change Technology Program
U.S. Department of Energy
Washington, D.C.

June 16, 2004

Our Conclusion

- GHG emissions will **NOT** be reduced in time to prevent a climate catastrophe!



Albedo modification potential for Southern California

Example: urban albedo increase 5km cells: 1291>0, 625>0.01, 456>0.02, 256>0.05, 143>0.10, 40>0.15, 17>0.16

Candidates for Albedo Enhancement

- Las Vegas, NV
- Phoenix, AZ
- Covering 5-20 square miles outside each city may cool off the cities themselves.
- This can be done much sooner than the whitening of urban surfaces and large scale tree planting which may take decades to complete.

GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 14, PAGES 2141-2144, JULY 15, 2000

Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change

Bala Govindasamy and Ken Caldeira

Climate and Carbon Cycle Group, Lawrence Livermore National Laboratory, Livermore, California, USA

Abstract. To counteract anthropogenic climate change, several schemes have been proposed to diminish solar radiation incident on Earth's surface. These geoengineering schemes could reverse global annual mean warming; however, it is unclear to what extent they would mitigate regional and seasonal climate change, because radiative forcing from greenhouse gases such as CO_2 differs from that of sunlight. No previous study has directly addressed this issue. In the NCAR CCM3 atmospheric general circulation model, we reduced the solar luminosity to balance the increased radiative forcing from doubling atmospheric CO_2. Our results indicate that geoengineering schemes could markedly diminish regional and seasonal climate change from increased atmospheric CO_2, despite differences in radiative forcing patterns. Nevertheless, geoengineering schemes could prove environmentally risky.

Introduction

Several schemes have been proposed to counteract the warming influence of increasing atmospheric CO_2 content via intentional manipulation of Earth's radiation balance [*Budyko*, 1977; *Early*, 1989; *NAS*, 1992; *Watson et al.*, 1995; *Flannery et al.*, 1997; *Teller et al.*, 1997]. Proposed "geoengineering" schemes typically involve placing reflectors or scatterers in the stratosphere or in orbit between the Earth and Sun, diminishing the amount of solar radiation incident on the Earth. However, the radiative forcing from increased atmospheric carbon dioxide [*Kiehl and Briegleb*, 1993] differs markedly (Plate 1) from that of a change in effective solar luminosity [*List*, 1951]. Carbon dioxide traps heat in both day and night over the entire globe, whereas diminished solar radiation would be experienced exclusively in daytime, and on the annual mean most strongly at the equator, and seasonally in the high-latitude summers. One might expect [*Schneider*, 1996], therefore, that a geoengineered CO_2-laden world would have less of a diurnal cycle, less of a seasonal cycle, and less of an equator-to-pole temperature gradient than in an undisturbed climate.

Paper number 1999GL006086.
0094-8276/00/1999GL006086$05.00

The Model and Experiments

We investigated these issues using the standard configuration of the Community Climate Model (CCM3), with a simple slab ocean and thermodynamic sea-ice model, developed at the National Center for Atmospheric Research [*Kiehl et al.*, 1996]. We performed three model simulations: (i) "Control" or pre-industrial, with a CO_2 content of 280 ppm and a solar "constant" of 1367 W m^{-2}; (ii) "Doubled CO_2", with doubled atmospheric CO_2 content (560 ppm), but the same solar constant as the Control simulation; and (iii) "Geoengineered", with doubled atmospheric CO_2 content and the solar constant reduced by 1.8% to approximately offset the radiative forcing from a CO_2 doubling (4.17 W m^{-2}). This reduction in incident solar radiation could be effected through the placement of reflecting or scattering devices between the Earth and Sun [*Early*, 1989; *Flannery et al.*, 1997; *Teller et al.*, 1997]. The resulting net change in radiative forcing generally would be an order of magnitude smaller than that associated with Milankovitch cycles [*Imbrie et al.*, 1984].

For the experiments presented here, the model was run for 40 years; climate statistics were calculated for the last 15 years. We assessed the statistical significance of the difference in the means between the test (Doubled-CO_2 or Geoengineered) and Control simulations at each model-grid point using the Student-t test [*Press et al.*, 1989], corrected for the influence of serial correlation [*Zwiers and Storch*, 1995].

Results

In the Doubled-CO_2 simulation, the planet warms 1.75 K, leading to reduced sea-ice volume and increased precipitation (Table 1). The 1.8% reduction in solar luminosity cools the Earth 1.88 K from its doubled-CO_2 state. We estimate that a shielding of ~1.7% of incident solar radiation would more exactly compensate the effect of a CO_2 doubling in this model.

The warming in the Doubled-CO_2 climate (Plate 2) is statistically significant at the 5% level over 97.4% of the globe, and is most pronounced in high latitudes. In sharp contrast, the Geoengineered simulation shows relatively little surface temperature change. There are significant differences (at the 5% level) in annual mean temperature between the Geoengineered and Control

Figure 1 **Some geoengineering projects, such as this plan for the irrigation of the Sahara by creating a 'second Nile' to refill Lake Chad, have become part of geoengineering folklore. (Reproduced from ref. 3.)**

Cost Benefit Equation for Climate Policy Implemented through Mitigation (M) and Adaptation (A)

$$B(M,A) = AD(M,A) - C_1(M) - C_2(A)$$

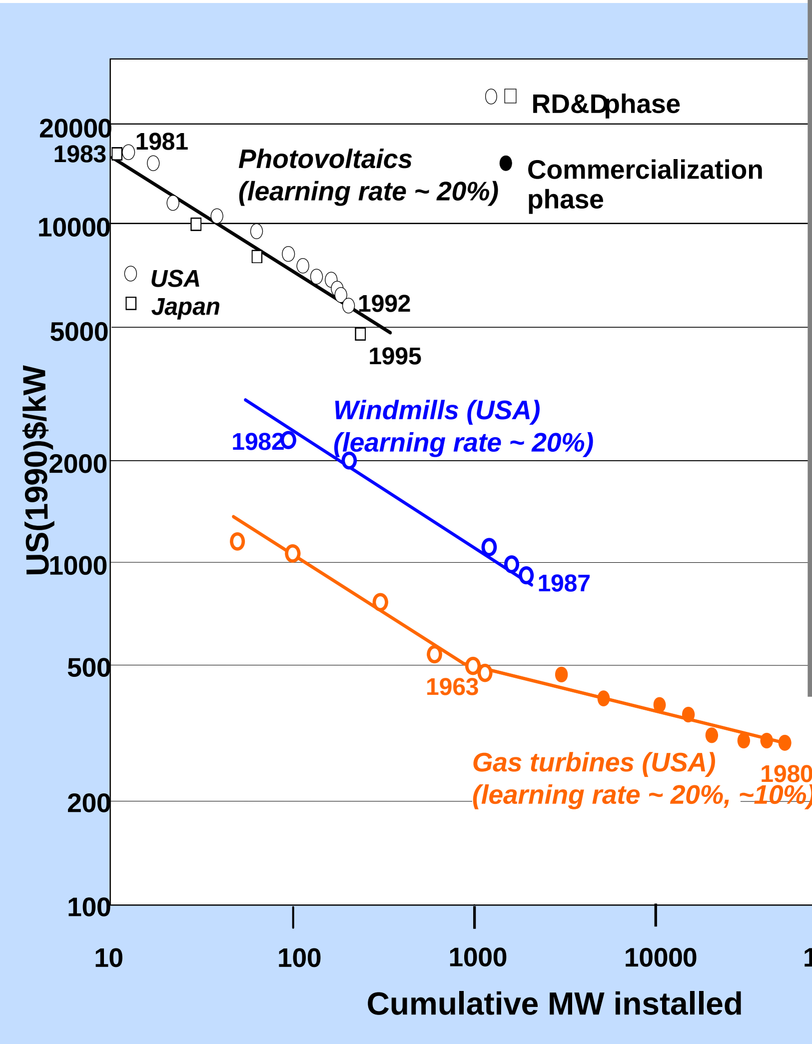
$B(M,A)$	$AD(M,A)$	$C_1(M)$	$C_2(A)$
Net Benefits	**Avoided Damages**	**Mitigation Costs**	**Adaptation Costs**

Claims:

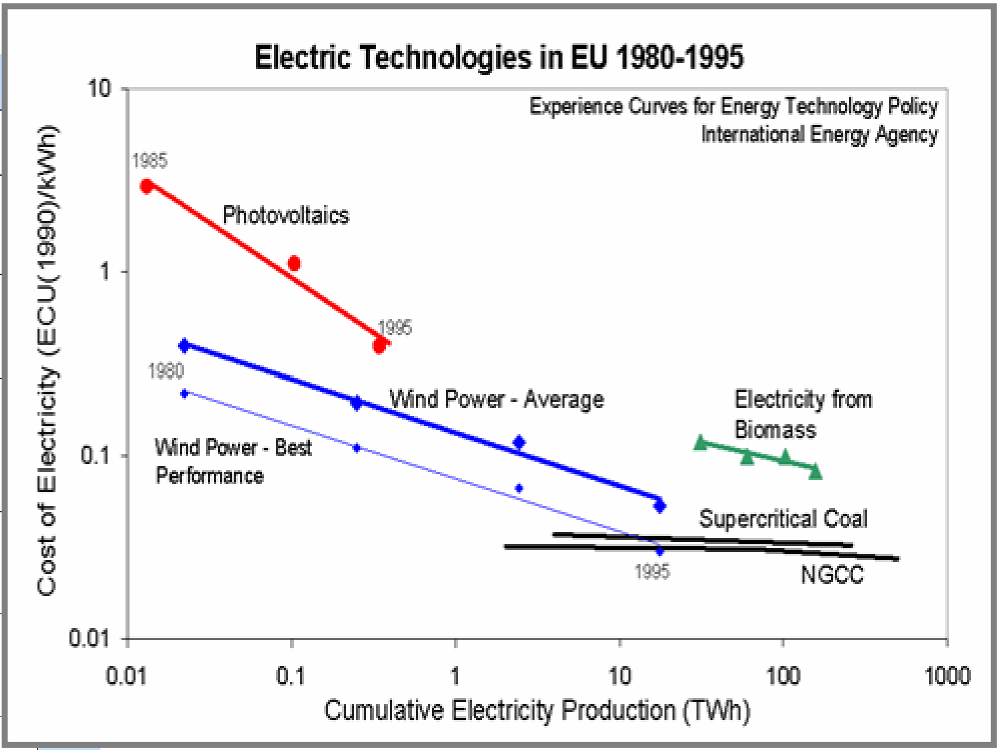
1. $$\frac{\delta AD(M,A)}{\delta M} \gg \frac{\delta AD(M,A)}{\delta A}$$

2. $C_1(M) \lesssim$ **1% Global GDP**

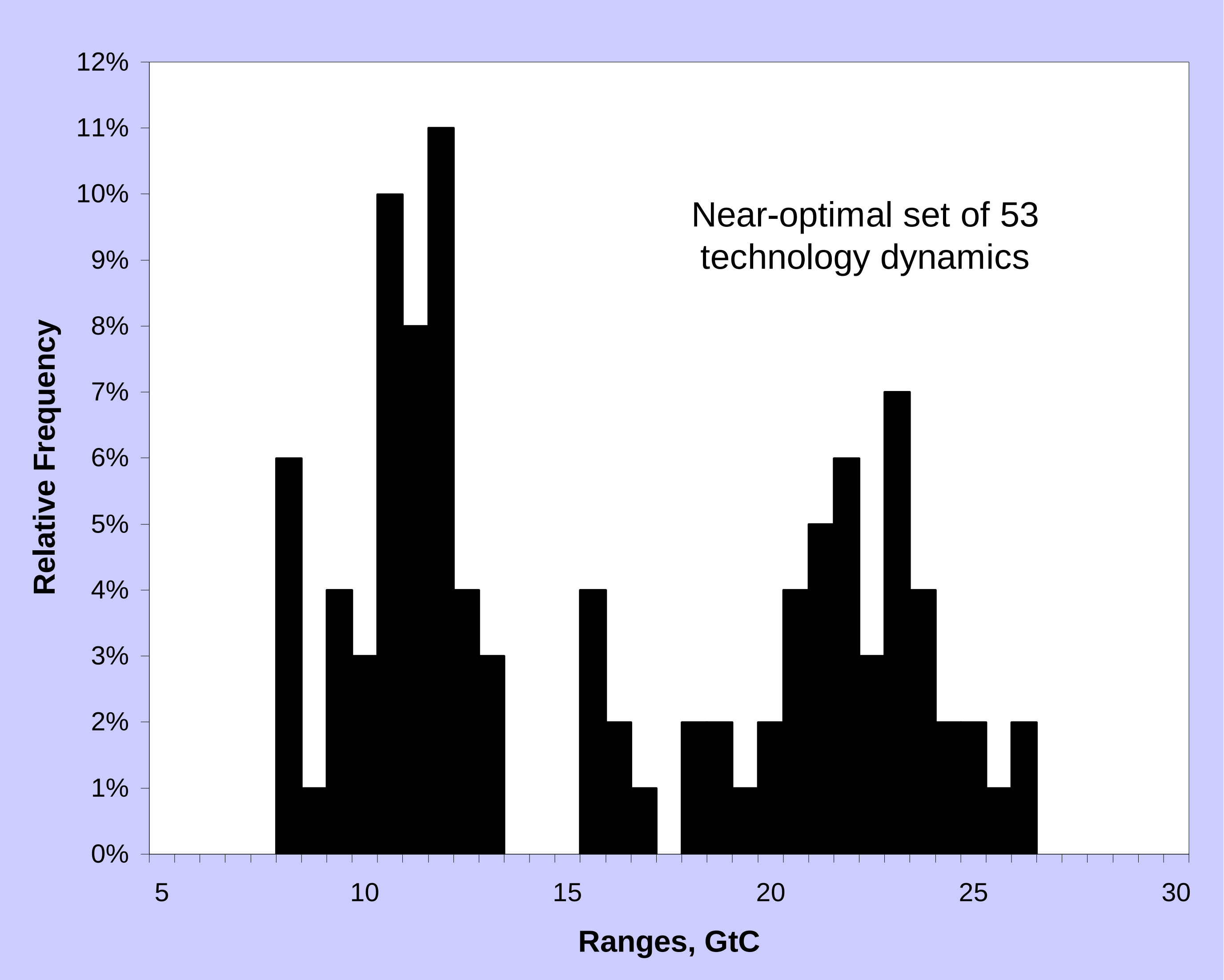
Learning Curves



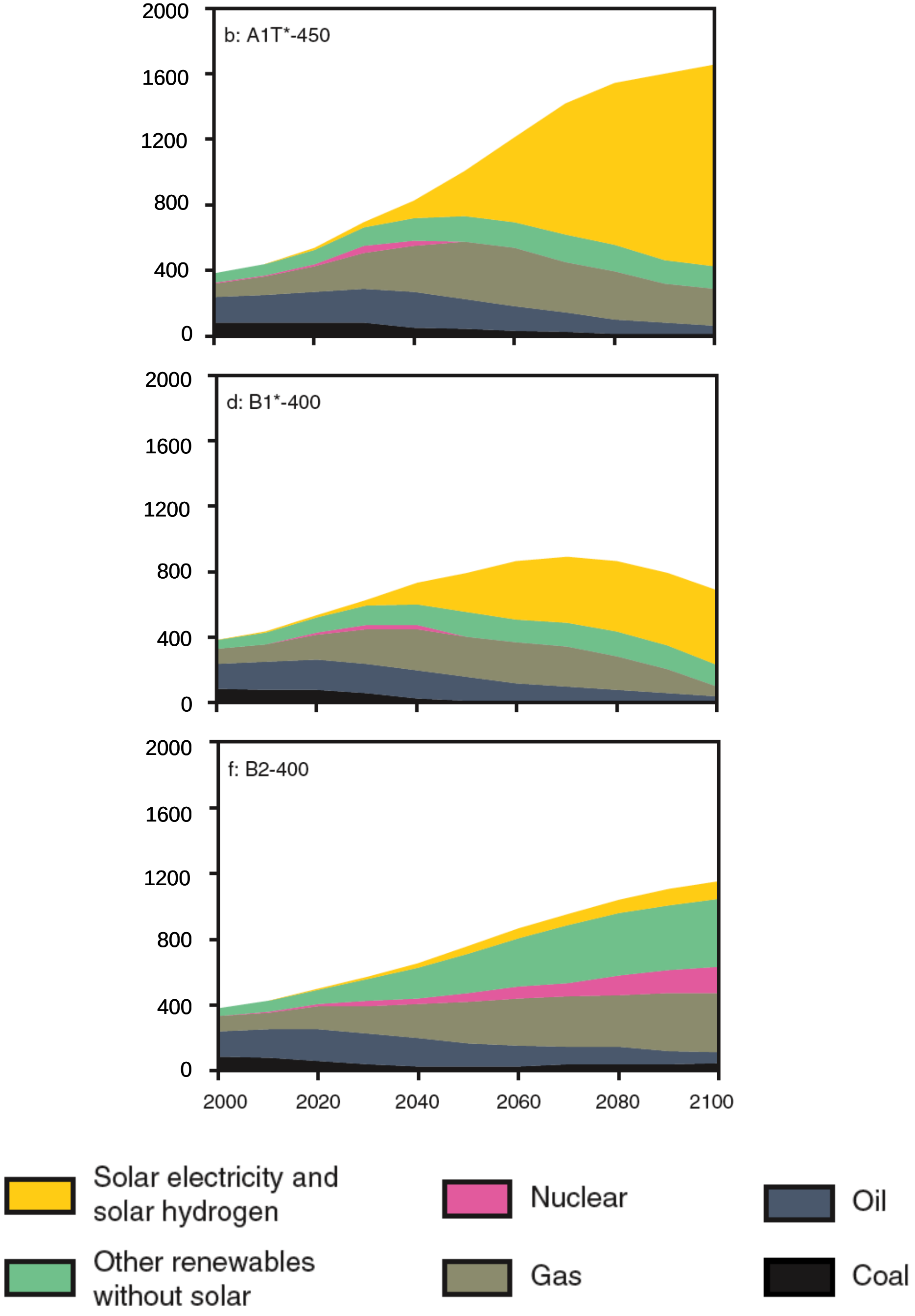
Nakicenovic et al. IIASA 1998

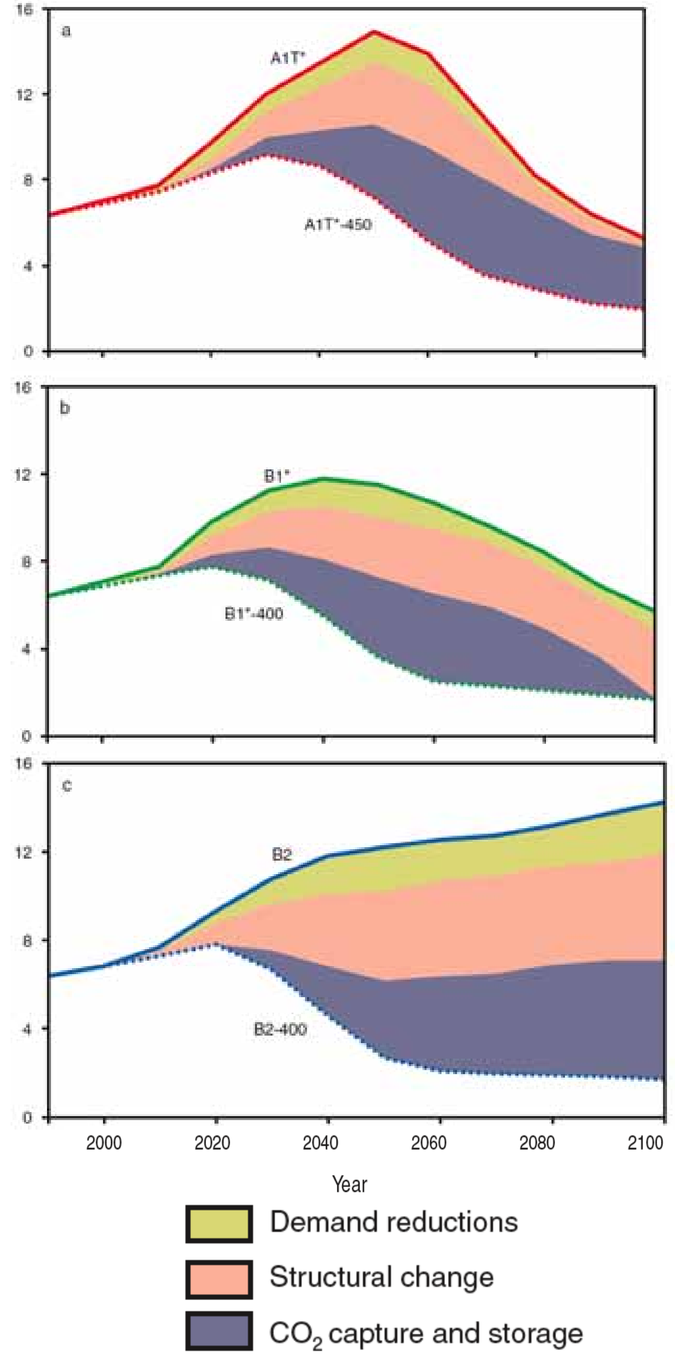


IEA (2000): Experience Curves for Energy Technology Policy; p. 21

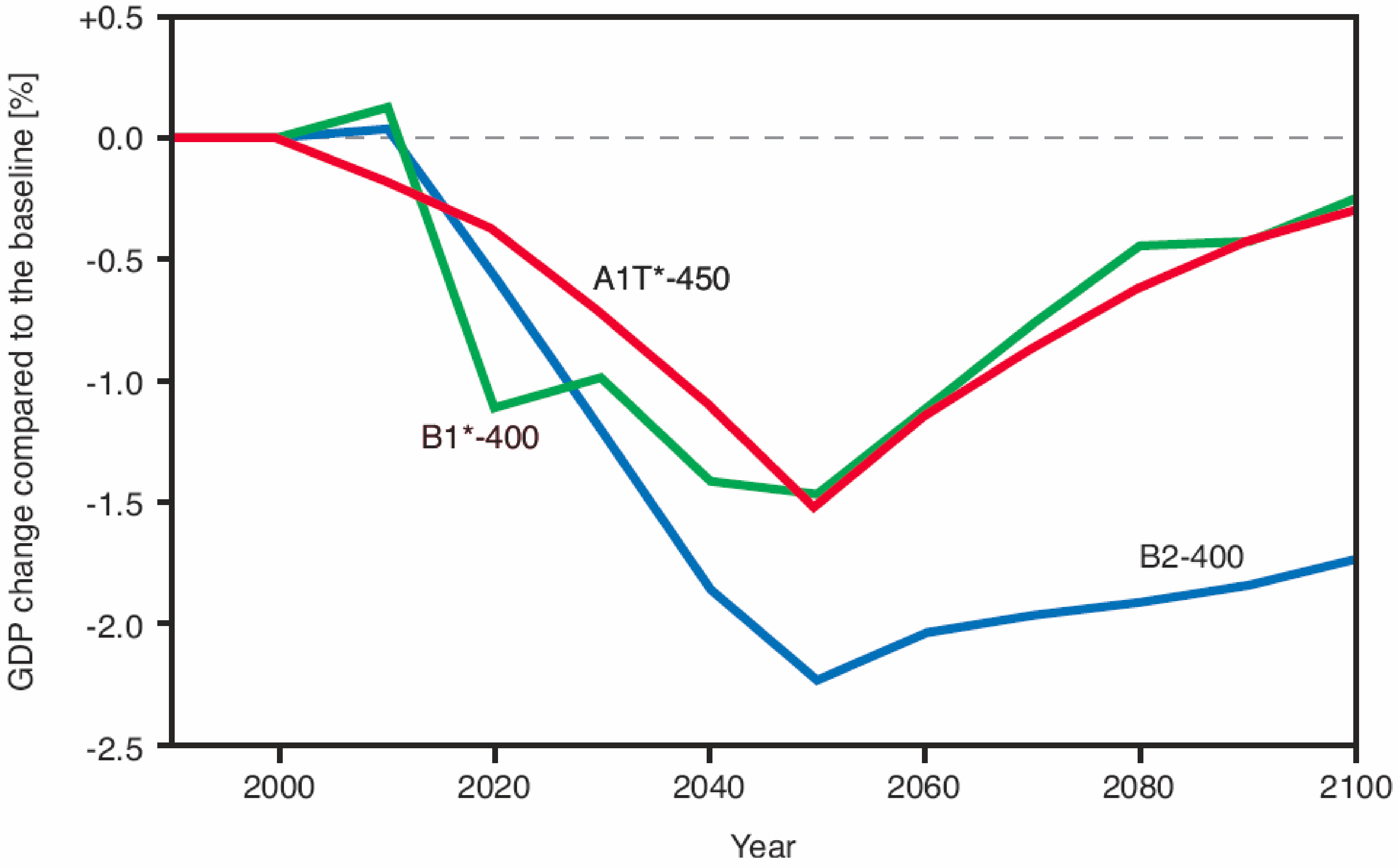


Based on Gritsevkyi & Nakicenovic, IIASA 2000


b: A1T*-450
d: B1*-400
f: B2-400
2000
1600
1200
800
400
0
2000
2020
2040
2060
2080
2100
Solar electricity and solar hydrogen
Other renewables without solar
Nuclear
Gas
Oil
Coal


a
A1T*
A1T*-450
b
B1*
B1*-400
c
B2
B2-400
16
12
8
4
0
2000
2020
2040
2060
2080
2100
Year
Demand reductions
Structural change
CO2 capture and storage

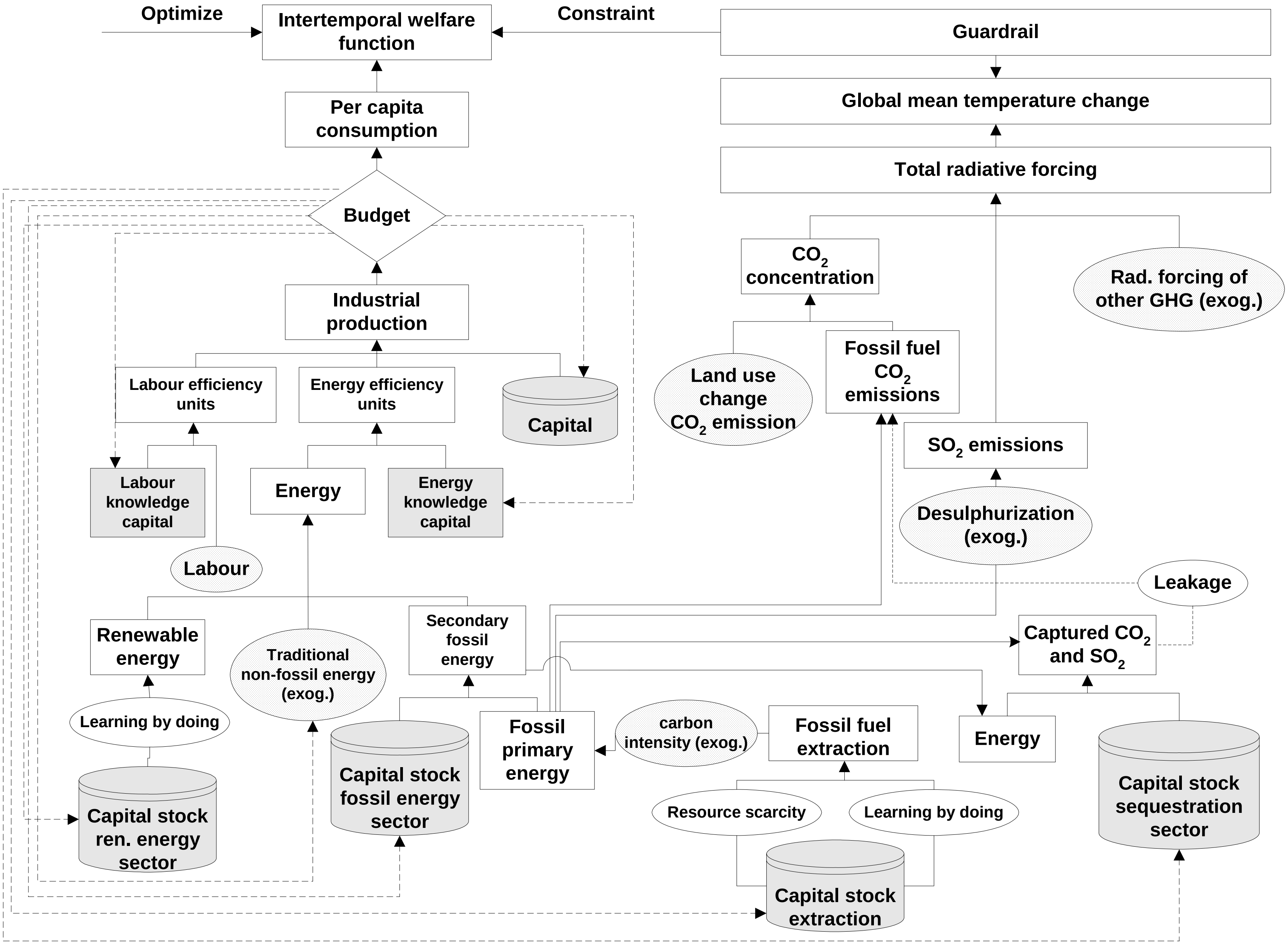
Relative losses of global GDP
as a consequence of Climate Change mitigation measures



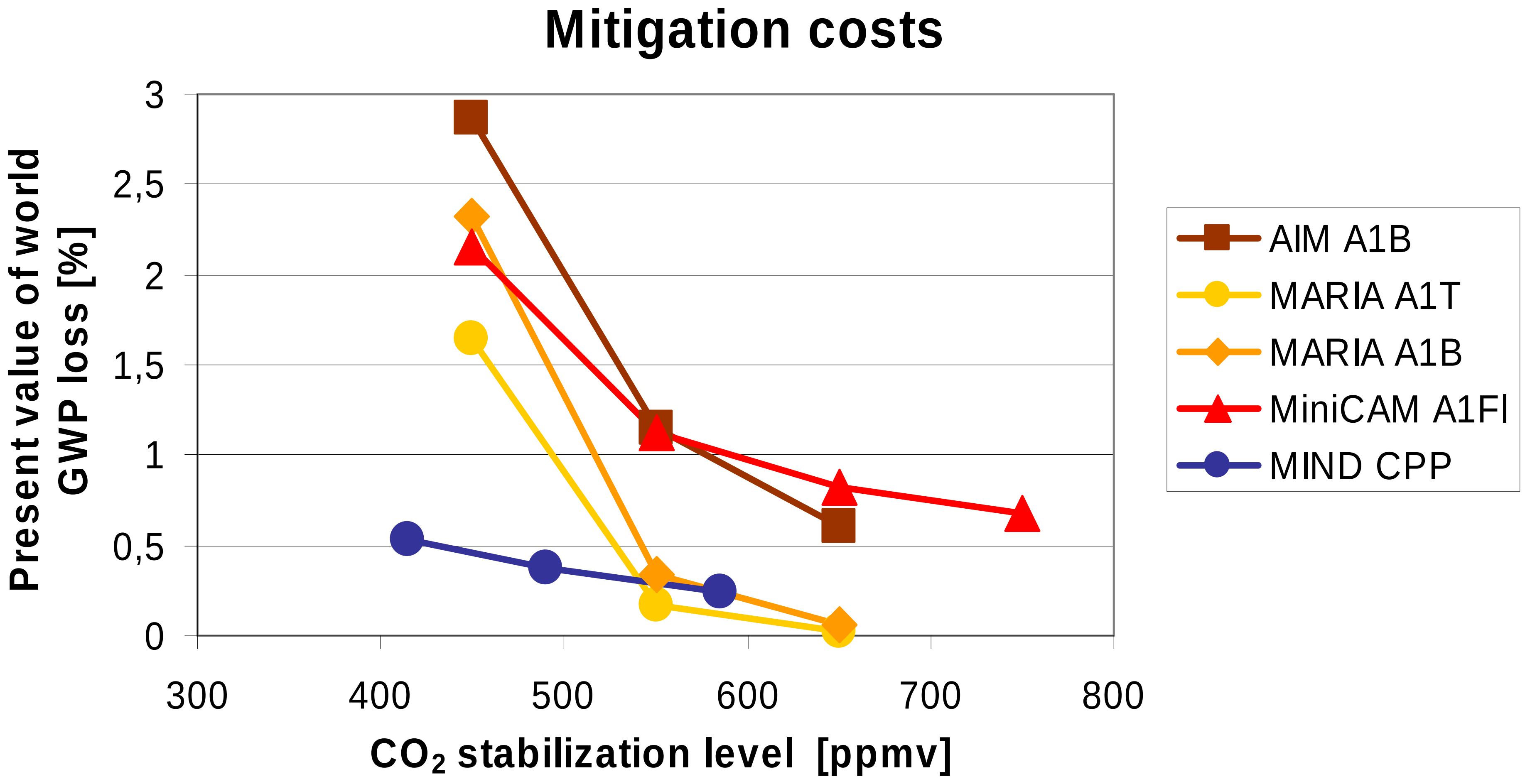
The Model MIND

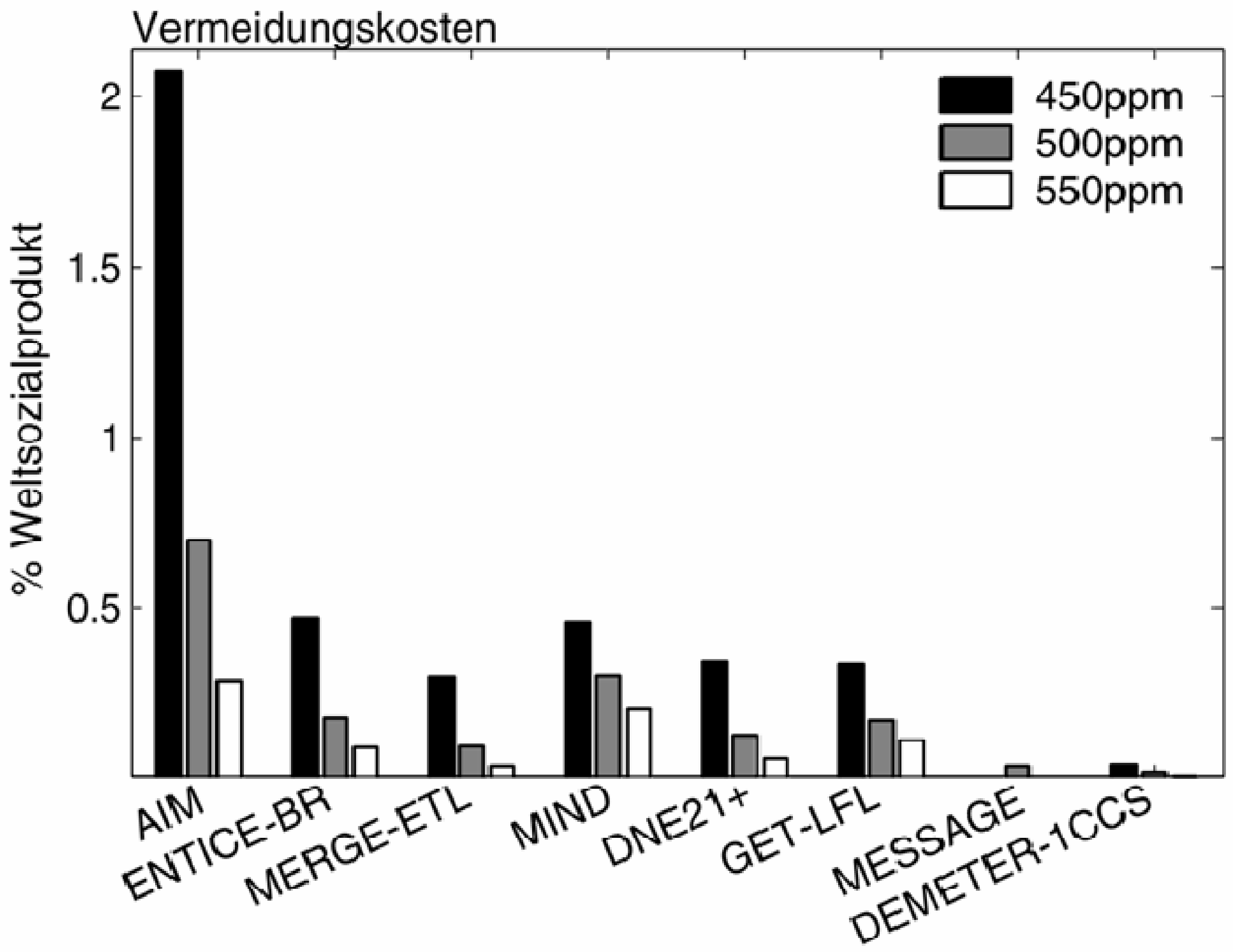
Technological change is driven by investment decisions

- Learning-by-doing in the energy sectors
- Assessment of Mitigation Options
  - Energy efficiency
  - Renewable energy sources
  - Carbon Capturing and Sequestration


Optimize
Intertemporal welfare function
Constraint
Guardrail
Global mean temperature change
Total radiative forcing
Per capita consumption
Budget
Industrial production
CO_2 concentration
Rad. forcing of other GHG (exog.)
Labour efficiency units
Energy efficiency units
Capital
Land use change CO_2 emission
Fossil fuel CO_2 emissions
SO_2 emissions
Labour knowledge capital
Energy
Energy knowledge capital
Desulphurization (exog.)
Labour
Leakage
Renewable energy
Traditional non-fossil energy (exog.)
Secondary fossil energy
Captured CO_2 and SO_2
Learning by doing
Fossil primary energy
carbon intensity (exog.)
Fossil fuel extraction
Energy
Capital stock fossil energy sector
Capital stock ren. energy sector
Resource scarcity
Learning by doing
Capital stock sequestration sector
Capital stock extraction

Costs of Reducing Climate Change

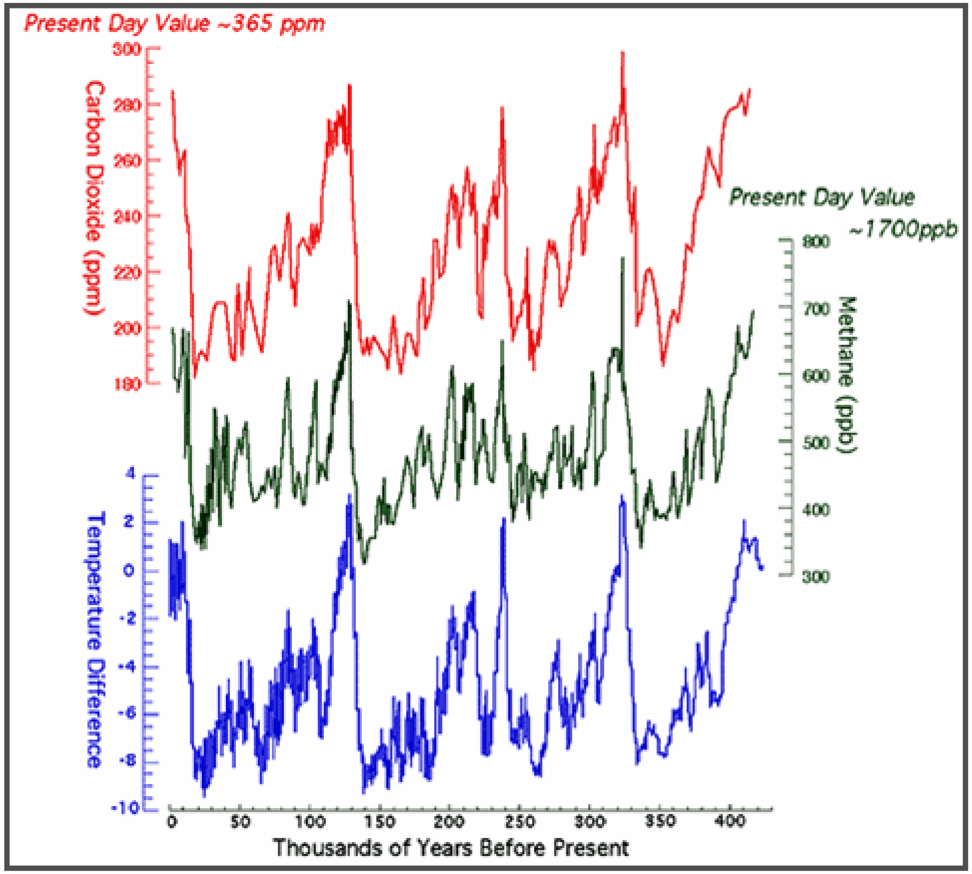


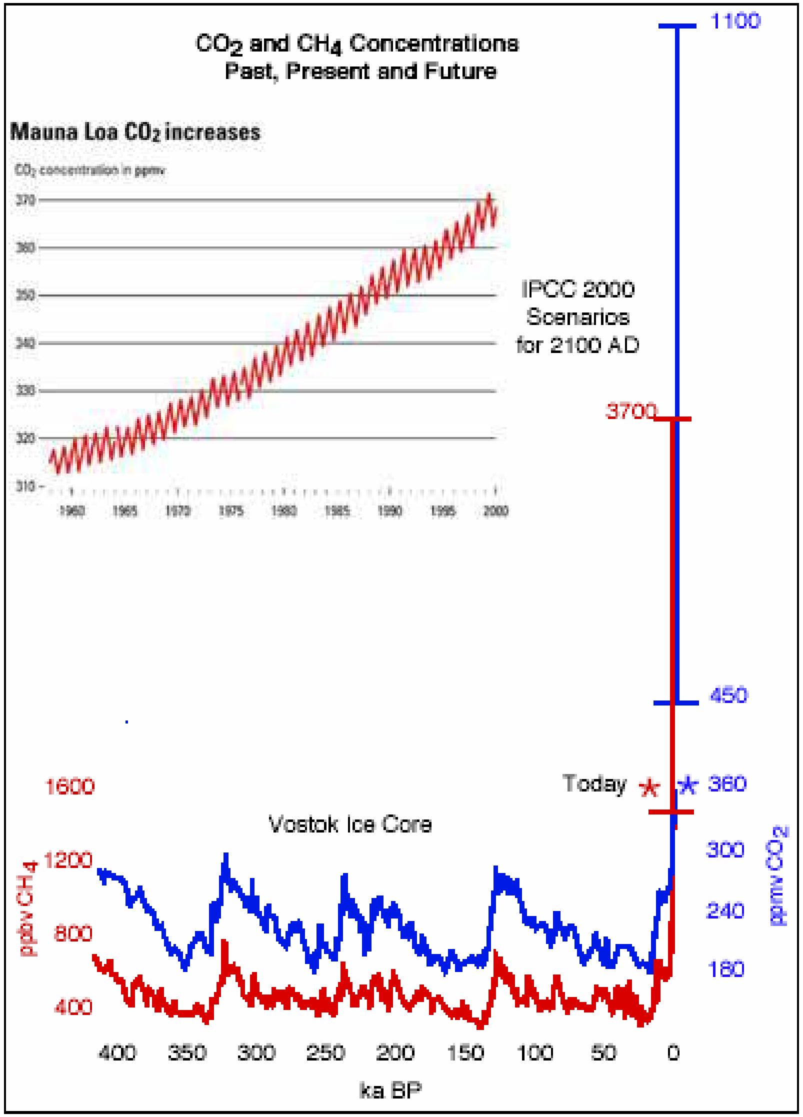


IMPC-Kostenvergleich für DO2-Stabilisierung bei 450, 500 bzw. 550 ppm. Erfaßt sind nur Modelle, die in vergleichbarer Weise geeignet sind, den technischen Fortschritt darzustellen.

Human Impact on Atmosphere

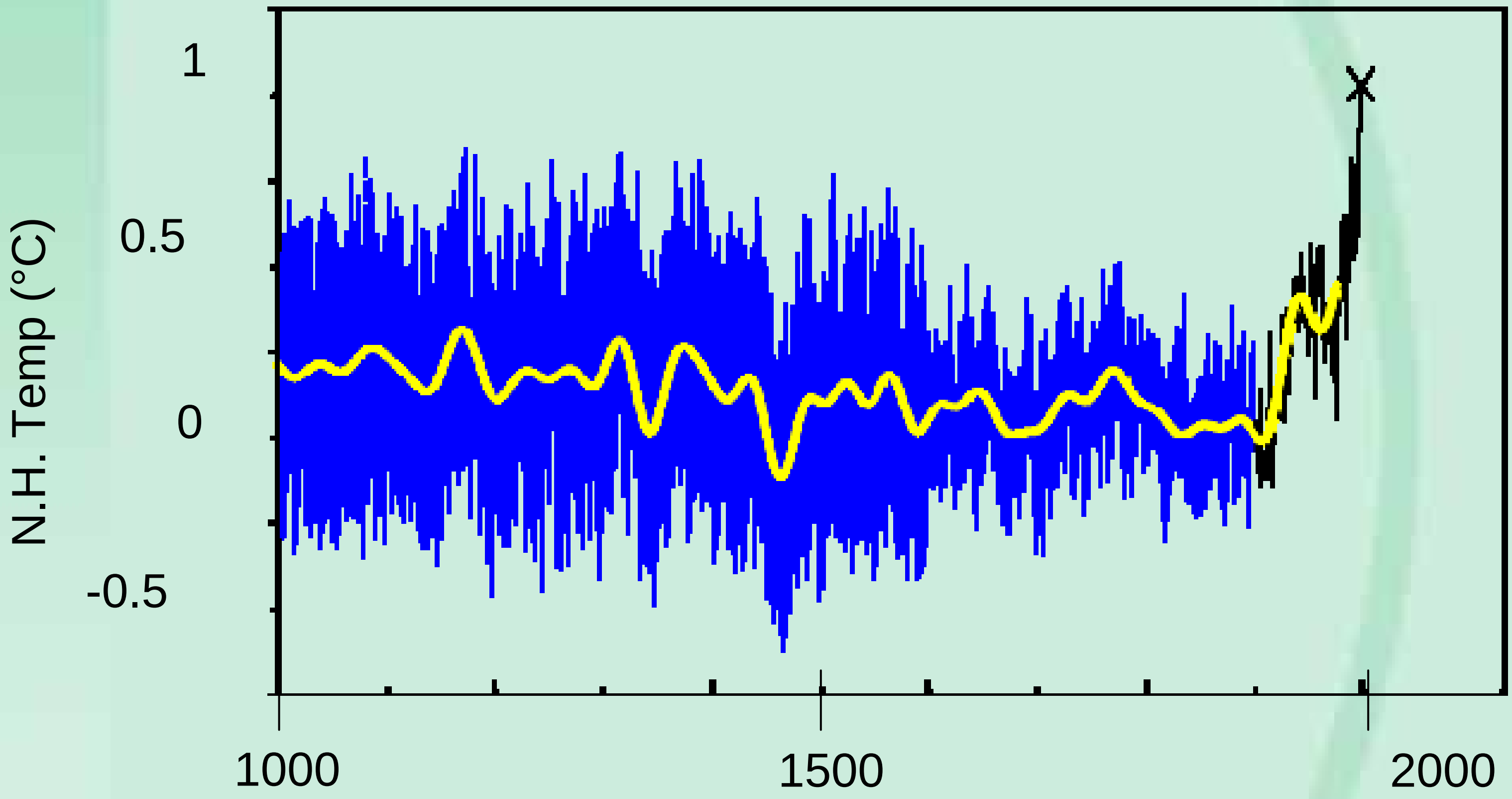
Vostok Ice Core – the record of the last 420,000 years





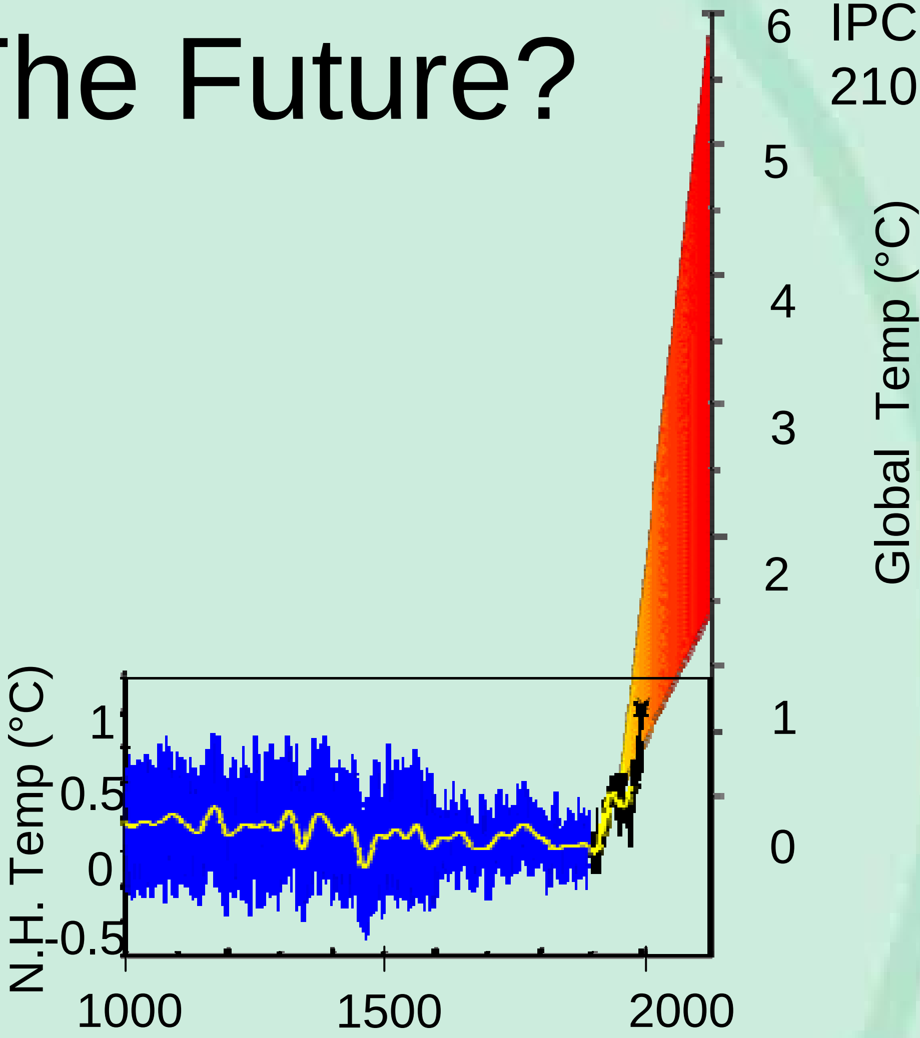
Images from WDCP/IPCC

The Future?



Mann et al (1999) and IPCC 2000

The Future?



IPCC Projections
2100 AD

Mann et al (1999) and IPCC 2000