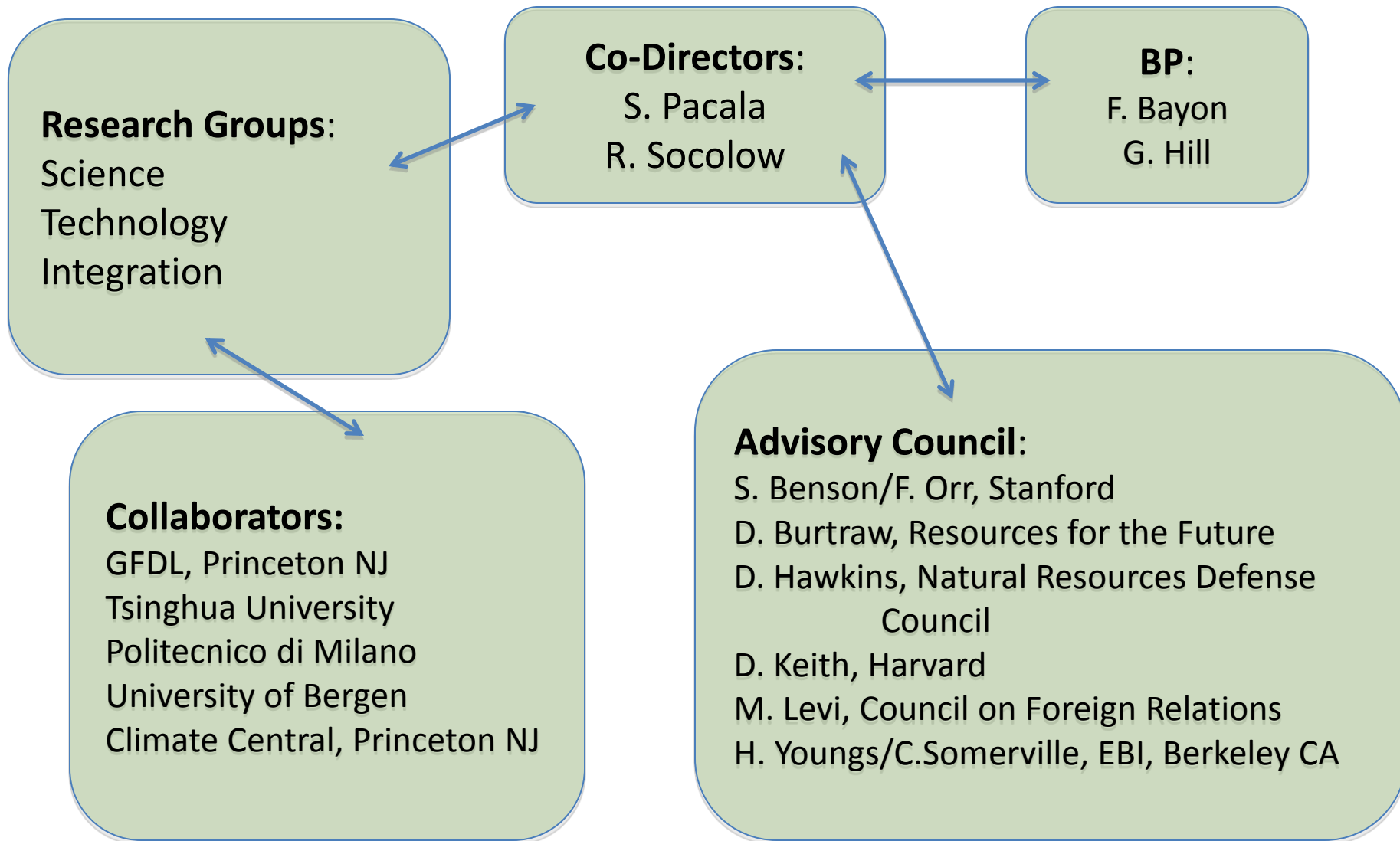


Introduction to CMI-13:

The thirteen annual meeting of
the Carbon Mitigation Initiative

Steve Pacala and Rob Socolow
April 15, 2014

CMI Structure



CMI Mission Statement

The mission of CMI is to lead the way to a compelling and sustainable solution of the carbon and climate change problem. By combining the unique and complementary strengths of the CMI parties – a premier academic institution and an influential global company – CMI participants seek to attain a novel synergy across fundamental science, technology development, and business principles that accelerates the pace from discovery, through proof of concept, to scalable solution.

CMI's Carbon Commitment

CMI will remain a “steward” of the climate change problem, so that when attention is refocused, the CMI partners will be ready.

Agenda and goals: today

Agenda item	Why included?
This talk	Introduce/reintroduce CMI Provide highlights from 2013 Provide context for renewed CMI, 2014-2020
Sarmiento	New CMI results in ocean and terrestrial carbon science
Stone and Phillips	New independent report on geothermal energy, a dispatchable non-carbon resource (Stone, co-author)
Celia and Kang	Risk analyses for below-ground CO ₂ and CH ₄
Deep dive #1: Ramaswamy, Delworth, Knutson (GFDL)	Update on climate science: “certainty,” simulation tools, evaluation of extreme events
BP Review	Report on BP evolution and reengagement
Flannery	30-year perspective on climate change, the oil industry, and university-industry partnerships

Agenda and goals: tomorrow

Agenda item	Why included?
Meggers	New faculty: energy-efficient buildings revisited
Steingart	New faculty: battery research frontier
Advisory committee	Independent perspectives on CMI
Deep dive #2: Hawkins, Burtraw, Levi (advisory committee)	The Washington carbon scene in the key year ahead for activism in the executive branch

Read our Annual Report



Current Roster

≈ 20 professor-level investigators

≈ 70 post-docs, graduate students, support staff

Posters

Carbon Science Group:

Monika Barcikowska: “Changes in tropical cyclone activity over the western North Pacific”

Sarah Batterman: “Can nitrogen feedback save the tropical carbon sink?”

Paul Gauthier: " Oxygen photosynthesis and respiration in leaves"

Jennifer Levy-Varon: "Carbon consequences of a nitrogen fixation feedback"

Nathan Serota: “Carbon impacts of anthropogenic aerosol transitions”

Sam Rabin: "Regional patterns of cropland and pasture burning”

Alan Southworth: “Leaf respiration and forest carbon budgets”

Jodi Young: “Primary production in cold water: Understanding the mechanisms and effects of global change”

Low-Carbon Energy Group:

Eric Larson: “Energy systems analysis toward net-negative-carbon transportation”

Fluids & Energy Group:

Zhong Zheng: “Flow regimes for fluid injection into a porous medium”

Policy and Integration Group:

Joseph Majkut: “Resolving uncertainty in the social cost of carbon”

“Best-Paper Prize,” 2013

LETTERS

PUBLISHED ONLINE: 24 NOVEMBER 2013 | DOI:10.1038/NCLIMATE2060

nature
climate change

Continued global warming after CO₂ emissions stoppage

Thomas Lukas Frölicher^{1,2★}, Michael Winton³ and Jorge Louis Sarmiento²

LETTER

Nature, October 10, 2013

doi:10.1038/nature12525

Key role of symbiotic dinitrogen fixation in tropical forest secondary succession

Sarah A. Batterman¹, Lars O. Hedin¹, Michiel van Breugel², Johannes Ransijn^{3,4}, Dylan J. Craven^{5†} & Jefferson S. Hall²

New book: *Paleoclimate*, by Michael Bender

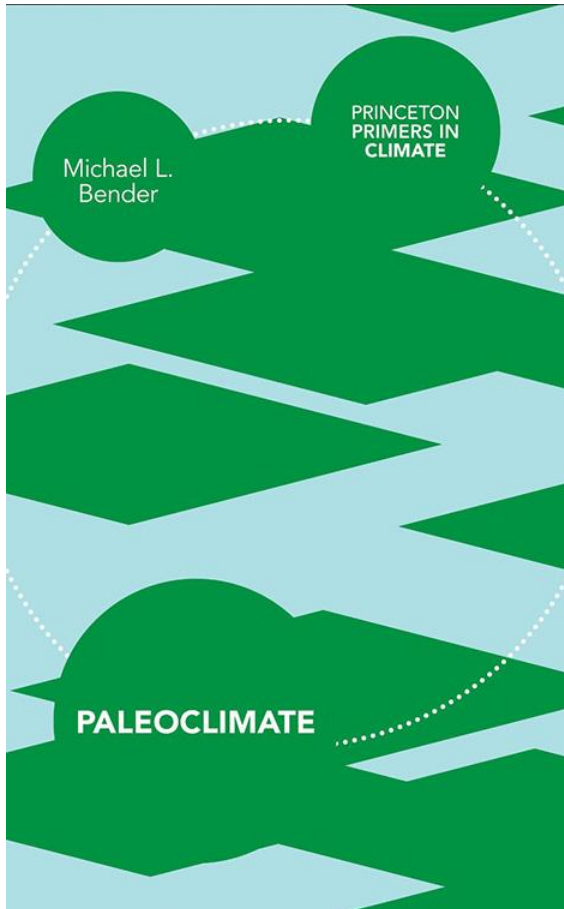


Table of Contents:

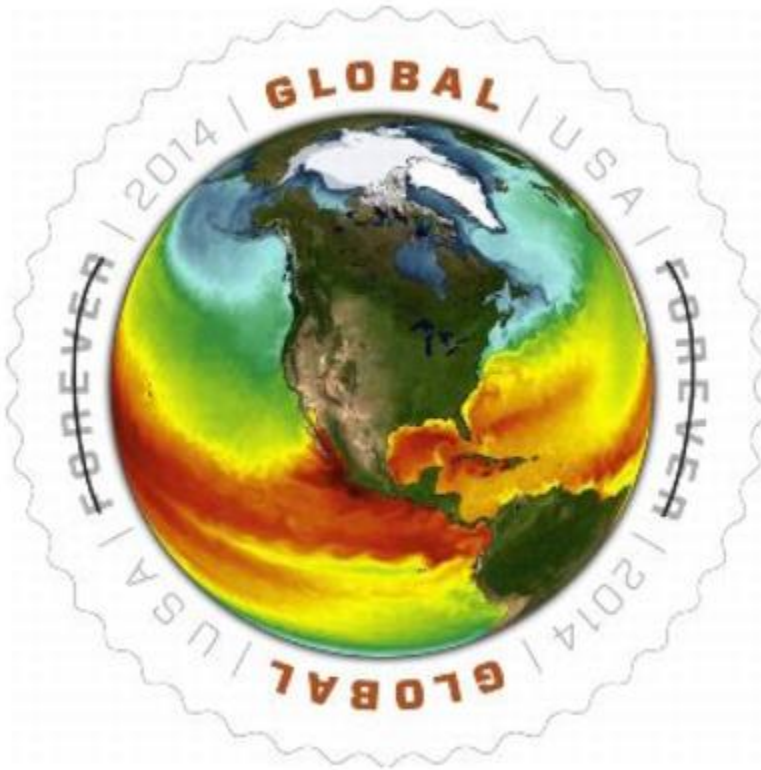
List of Boxes vi

Preface vii

Acknowledgments xiii

1. Earth's Climate System 1
 2. The Faint Young Sun 24
 3. Precambrian Glaciations 38
 4. Regulation of the Earth System and Global Temperature 54
 5. The Late Paleozoic Ice Ages 73
 6. Equable Climates of the Mesozoic and Paleogene 97
 7. The Paleocene-Eocene Thermal Maximum 125
 8. The Long Cooling of the Cenozoic 144
 9. The Origin of Northern Hemisphere Glaciation and the Pleistocene Ice Ages 172
 10. Rapid Climate Change during the Last Glacial Period 235
 11. The Holocene 264
 12. Anthropogenic Global Warming in the Context of Paleoclimate 287
- Glossary* 295
- Index* 303

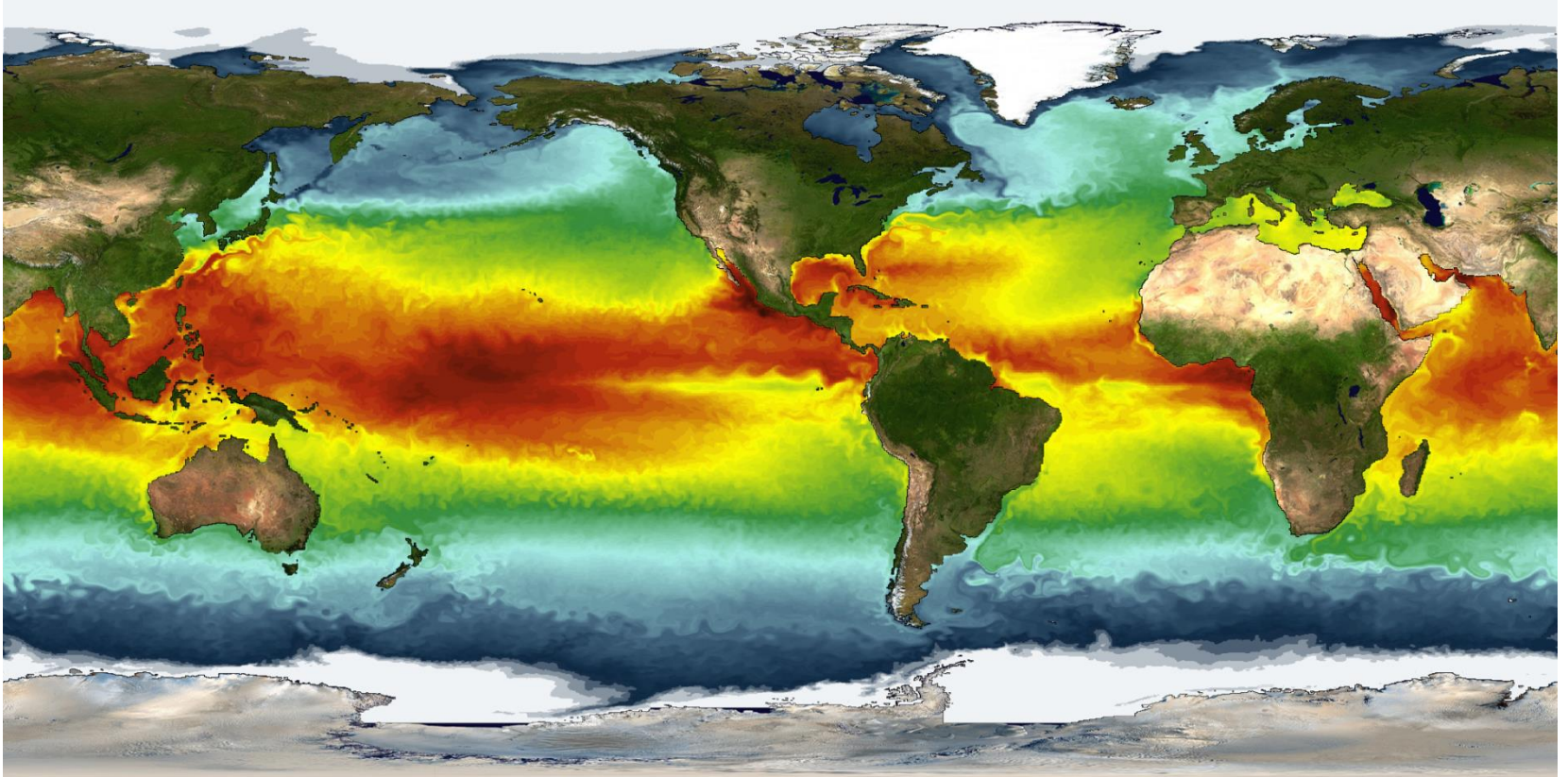
The 2014 Earth Day stamp



Ocean surface temperature on a single day, simulated in a GFDL high-resolution climate model typical of conditions in the 1990s. Warmest are red, coolest are dark blue. Swirls in the ocean represent the effects of time-varying currents and meanderings. The band of yellow leaving the coast of North America by New Jersey represents part of the Gulf Stream.

Value of stamp: \$1.15 now, but valid for an international letter “forever.”

The original GFDL image



History

CMI began in 2000, at a time when John Browne sensed that the world might pass through a discontinuity and begin to take climate change seriously. He wanted BP to develop a comfortable relationship with a thought center that would advance climate science and analyze low-carbon technology. The following few years were indeed characterized by greatly increased interest and concern: serious initiatives in carbon trading and subsidies for low-carbon energy – including CO₂ capture and storage (CCS). Princeton and BP were leaders in this effort in our respective domains.

The extension of CMI from 2015 to 2020 is now under review at BP.

Much has changed and is changing

Low-carbon energy is arriving unevenly: wind, solar, and vehicle fuel efficiency are being realized at a one-wedge pace, while hydrogen power, CCS, and nuclear power are faltering. Low-carbon technology is being dramatically affected by the arrival of shale gas and oil.

Less recognized, in climate science new modeling capability will enable more forceful statements about near-term effects of climate change. This is likely to increase the sense of urgency in public discussion. The international conversation, now truly global, will be transformed.

As it has done since its inception, CMI will adjust its focus and structure so as to be a leader as this transition occurs.

This is a time of paradox

What happens when an irresistible force meets an immovable object?

The irresistible force: Fossil fuels, as vital as ever.

The immovable object: Climate change, which looms ominously.

Confronting the paradox, rather than wishing it away, animates CMI.

The premise of CMI is that, at some unknown pace but conceivably soon, the world will become seriously engaged with climate change.

“Virtual certainty,” IPCC 2013

“It is virtually certain that internal variability alone cannot account for the observed global warming since 1951.”

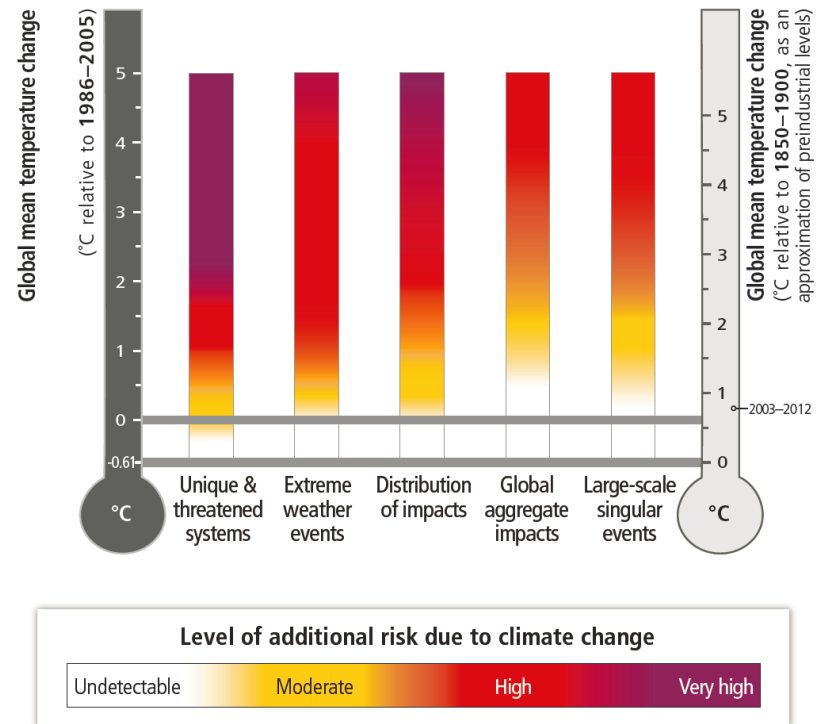
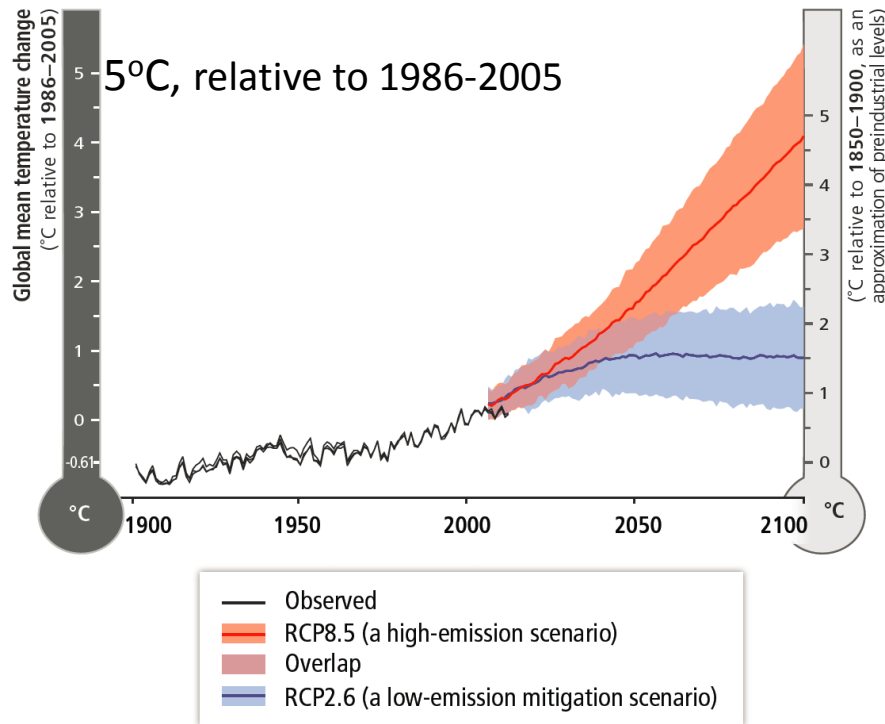
“The observed global-scale warming since 1951 is large compared to climate model estimates of internal variability on 60-year time scales... The spatial pattern of observed warming differs from those associated with internal variability. The model-based simulations of internal variability are assessed to be adequate to make this assessment.” {9.5.3, 10.3.1, 10.7.5, Table 10.1}

“It is virtually certain that human influence has warmed the global climate system.”

“Anthropogenic influence has been identified in changes in temperature near the surface of the Earth, in the atmosphere and in the oceans, as well as changes in the cryosphere, the water cycle and some extremes. There is strong evidence that excludes solar forcing, volcanoes and internal variability as the strongest drivers of warming since 1950.” {10.9.2, Table 10.1}

No such certainty existed when CMI began.

Impacts are increasingly well understood



“Burning Embers” is back!

Source: IPCC, 2014. *Summary for Policymakers*, Working Group 2, Fifth Assessment Report

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO		
	YES		

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. 5°C.
	YES	Environmentalists, nuclear advocates are often here. 2°C.	OUR WORKING ASSUMPTIONS. 3°C, tough job.

The paradox will be resolved, but no one knows when

There is something eerily familiar about the situation in 2014, as we look ahead to the work we will do together between now and 2020. Again, the public's attention is elsewhere, the fossil energy industry is complacent, and carbon policy has little priority .

This time, however, there is broad recognition that the lull is temporary. The earlier period sensitized everyone to carbon's threat to climate, which makes it credible that the second response, when it comes, will be more forceful.

Keeping an eye to windward

Investors in the fossil energy industries, more than any other stakeholders, want to keep an eye out to windward and to receive the earliest possible warning of transformative knowledge that could stimulate new policy formation.

Risks of climate change for BP

The climate problem has the potential to disrupt BP's core business in at least three ways:

1. Effective climate policies can emerge that discourage fossil fuel consumption, that impose environmental performance standards on production processes, and that subsidize or otherwise promote efficiency and low carbon energy.
2. Climate-motivated research can create disruptive new energy technology.
3. The consequences of climate change can directly disrupt BP's investments in energy production infrastructure and supply chains.

BP supports CMI to help manage risks

1. CMI sharpens its corporate perspective on climate change. It provides BP with strategic understanding of the potential physical, biological and human systems impacts.
2. BP benefits when CMI disseminates sound information that supports effective public policy discussions.
3. [Ellen Williams] BP leverages a much larger effort. Princeton has extensive funding for a wide variety of projects in related areas. CMI leaders survey all this and help develop best connections for BP. By funding specific projects within broader areas, BP gains benefits from the overall breadth of program, especially because the integration work draws on the totality, not just the parts BP directly supports.

Structure of the new program

We now have a three-group structure for CMI:

Science

Technology

Integration

We will discuss then in reverse order.

Integration

CMI integration will continue to aim for the accessibility, distillation, and balance that were hallmarks of the wedges work (*Science*, August 2004). Among the areas of interest are:

- cumulative-emission budgets
- the carbon costs of intermittent renewable energy
- mitigation and adaptation

Cumulative-emission targets

The world's fourth try at framing a global climate target:

1. Emission rate at some future date
2. Concentration never to be exceeded
3. Surface temperature never to be exceeded
4. Cumulative emissions from now on (IPCC, Sept. 2013)

Fossil fuels are so abundant that, for *any* cumulative-emissions target, even a weak one, *attractive* fossil fuel will be left in the ground.

CCS expands the budget.

Ambiguities: Is land-use change included? Are methane and other greenhouse gases included (CO_2 vs. $\text{CO}_{2\text{eq}}$)?

“Emissions budgets” mean choices

Beyond counting carbon atoms, the budget concept leads inexorably to choices:

When?

Whose?

Used where?

For what purpose?

Which fossil fuels?

Better options someday?

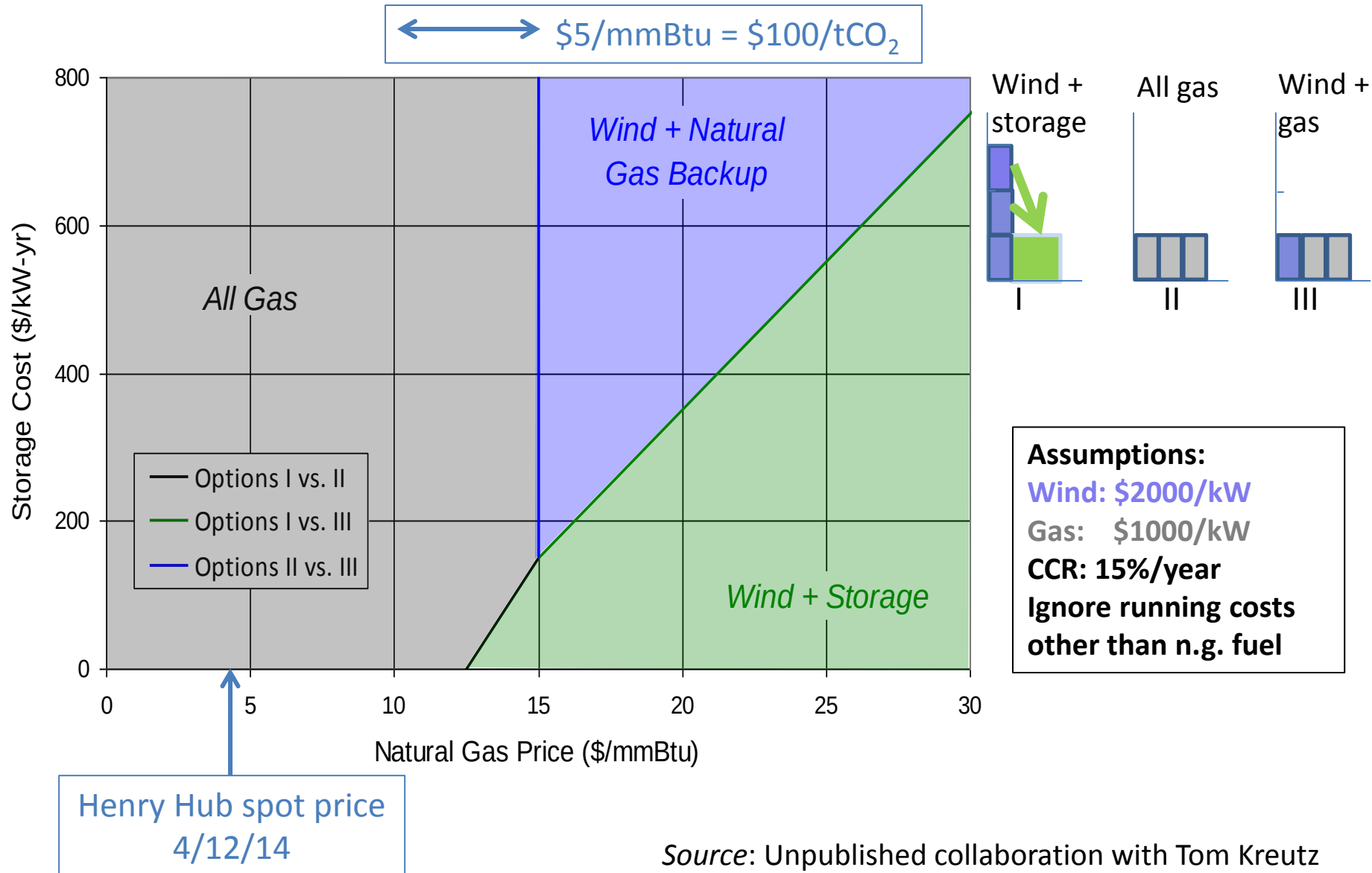
Geopolitical stability

“Fairness”

Who judges?

Those with the highest H/C ratio?

How low-carbon are wind and solar?



Mitigation and adaptation

CMI will address some of the intersections of mitigation and adaptation. Exactly how we address adaptation is under discussion.

[Ellen Williams] The reason for heightened global interest in adaptation is pragmatic: the impacts of recent extreme events have been framed by decision makers in the context of the climate change.

Some integration products from CMI

The Pacala-Socolow “wedges” paper (*Science*)

The “one billion high emitters” paper (Chakravarty et al., *PNAS*)

A sustainability-based classification of biomass feedstocks (Tilman et al., *Science*)

The fateful choice between nuclear power and climate change (Socolow and Glaser, *Daedalus*)

CO₂ capture from air (Socolow and Desmond, *APS*)

Ocean iron fertilization to remove atmospheric CO₂ (Sarmiento group)

Sea-level rise: science and risk communication (Oppenheimer)

Monitoring of compliance with international agreements (Pacala, NRC)

Technology

A unified Technology Group will investigate opportunities for low-carbon energy. Current research areas:

- The carbon footprints of CCS and natural gas. A smaller footprint requires environmentally sound management of brine, process water, methane, and CO₂. *[Celia's talk this morning.]*
- Conversion of biomass to power, fuels, chemicals, and heat – with and without CCS and with and without fossil fuel co-conversion.
- Systematic underestimation of the costs of construction of billion-dollar-scale, first-of-a-kind energy demonstration projects.

A new biofuels project via GCEP (Stanford)

There is co-funding for CMI's biofuels work, thanks to a three-year GCEP (Stanford) award. The GCEP grant also funds an upstream effort by David Tilman's Lab at U. Minnesota.

The CMI component will compare thermochemical and biochemical energy conversion. Collaboration with the Energy Biosciences Institute is being developed.

Land for biomass to address climate



Stock



Flow

Four carbon-related demands on land compete with traditional demand, at the scale of hundreds of millions of hectares:

- Biofuel to address oil and carbon, displacing fossil fuels
- Biopower without CCS, displacing fossil fuels
- Biopower with CCS (BECCS), scrubbing the atmosphere
- Biocarbon build-up (in forests, soils), scrubbing the atmosphere

Food, oil and carbon have made the world's land into a single system

A change in land use in one part of the world has knock-on effects on land use everywhere else.

With regard to carbon policy, if climate change is what matters most, a single price will apply to biocarbon and fossil carbon – with profound consequences.

We are exploring CMI contributions.

Why are cost estimates for billion-dollar demos systematically low?

Construction costs for first-of-a-kind demonstration projects are systematically underestimated – not just by academics like ourselves but by government agencies and private contractors.

Will governments and capital markets shy away from supporting *any* large first-of-a-kind energy projects?

We are collaborating with Michael Desmond (BP) and Chris Greig (University of Queensland). Greig is the former head of Zero-Gen, a CCS demonstration project that he personally canceled as “true” costs became manifest.

Gorgon, Australia

Investors **Chevron** (operator), Shell & Exxon Mobil

Sanctioned 2009

Scope 3 x 5 Mtpa LNG Trains;

CCS – 3.5 Mtpa CO₂ (saline aquifer)



Project KPI	Concept (2003)	PFS (2007)	Sanctioned (Post FEED) (2009)	Current Forecast / Actual
Capital Cost	\$11 Billion	\$23 Billion	\$37 Billion	\$52 Billion
Start-up			H1 2014	H1 2015
Throughput	10 Mtpa?	10 Mtpa	15 Mtpa	

Source: Chris Greig, talk at Princeton, Feb 10, 2014

ZeroGen, Australia

Investors ZeroGen (operator), State Government, Australian Coal Association, Mitsubishi

Sanctioned **CANCELLED 2011**

Scope 400 MWe IGCC,
up to 90% CCS (saline aquifer)



Project KPI	Concept (2007)	Scoping (2008)	PreFEED (2010)	Current Forecast / Actual
Capital Cost	\$3.1 Billion	\$4.2 Billion	\$6.93 Billion	
Start-up		Q4 2014	Q4 2015	CANCELLED
Throughput	430 MW	420 MW	390 MW	

Source: Chris Greig, talk at Princeton, Feb 10, 2014

Duke Edwardsport, Indiana

Investors **Duke Energy** (operator), DOE

Sanctioned **2009**

Scope **618 MWe IGCC (No CCS)**



Project KPI	PreFEED? (2007) Sanctioned	Mid- Construction FEED? (2009)	Current Forecast / Actual
Capital Cost	\$1.9 Billion	\$2.3 Billion	3.7 Billion
Start-up		Q1 2013	Q3 2013
Throughput	618 MW	618 MW	

Source: Chris Greig, talk at Princeton, Feb 10, 2014

Southern Co. Kemper, Mississippi

IGCC with CCS

Investors **Southern Company** (operator), DOE

Sanctioned **2010**

Scope 580 MWe IGCC,
lignite, transport gasifier,
65% CCS (EOR)

Princeton field trip, Feb 2014



Project KPI	PreFEED (2010)	FEED (2010) Sanctioned	Mid- Construct (2012)	Current Forecast / Actual
Capital Cost	\$2.4 Billion	\$2.9 Billion	\$3.25 Billion	5.0 Billion
Start-up		Q1 2014	Q2 2014	Q4 2014
Throughput	618 MW	618 MW		

Source: Chris Greig, talk at Princeton, Feb 10, 2014

Excuses and reality (adapted from Greig)

Project proponents blamed:

- Labor issues
- Exchange rates
- Burdensome regulation
- Unseasonal weather
- Contracting strategy

A more honest appraisal:

- Zeal – A determination to see the project built prevails over risk assessment
- Excessive optimism – Reluctance to do a full risk assessment
- Counterproductive incentives

Must mega-projects invariably blow-out?

Science

1. Natural sinks and sources.

The most powerful mitigating factor is carbon uptake by plants and oceans.

2. Earth System Models.

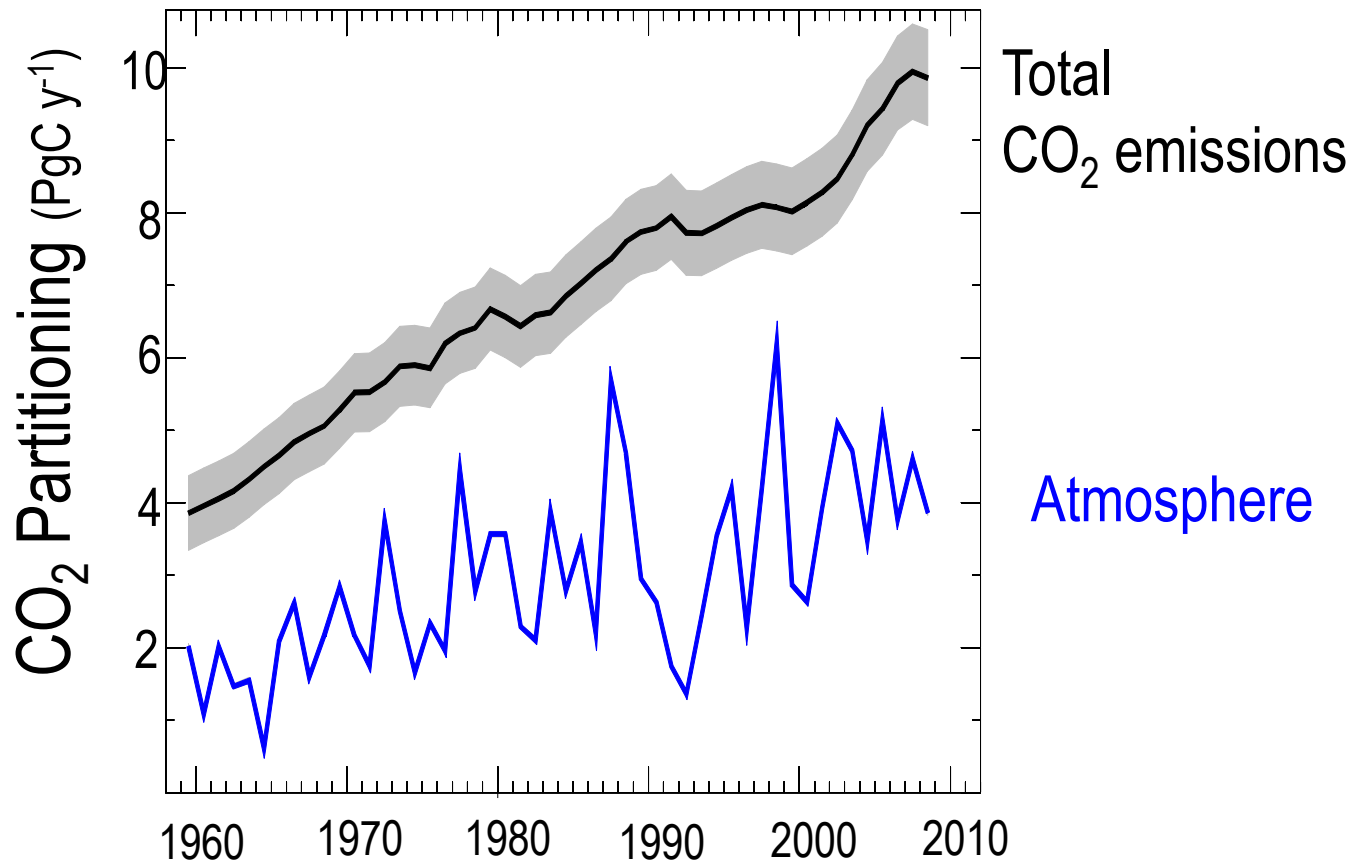
Understanding feedback between climate and anthropogenic GHG's and aerosols.

3. Climate Variability and Extremes.

Predicting and managing risk.

Expanded participation of GFDL.

Evolution of the fraction of total emissions that remain in the atmosphere



Fate of Anthropogenic CO₂ Emissions

(2000-2008)

1.4 PgC y⁻¹



7.7 PgC y⁻¹ +



4.1 PgC y⁻¹

45%



3.0 PgC y⁻¹

29%



26%

2.3 PgC y⁻¹



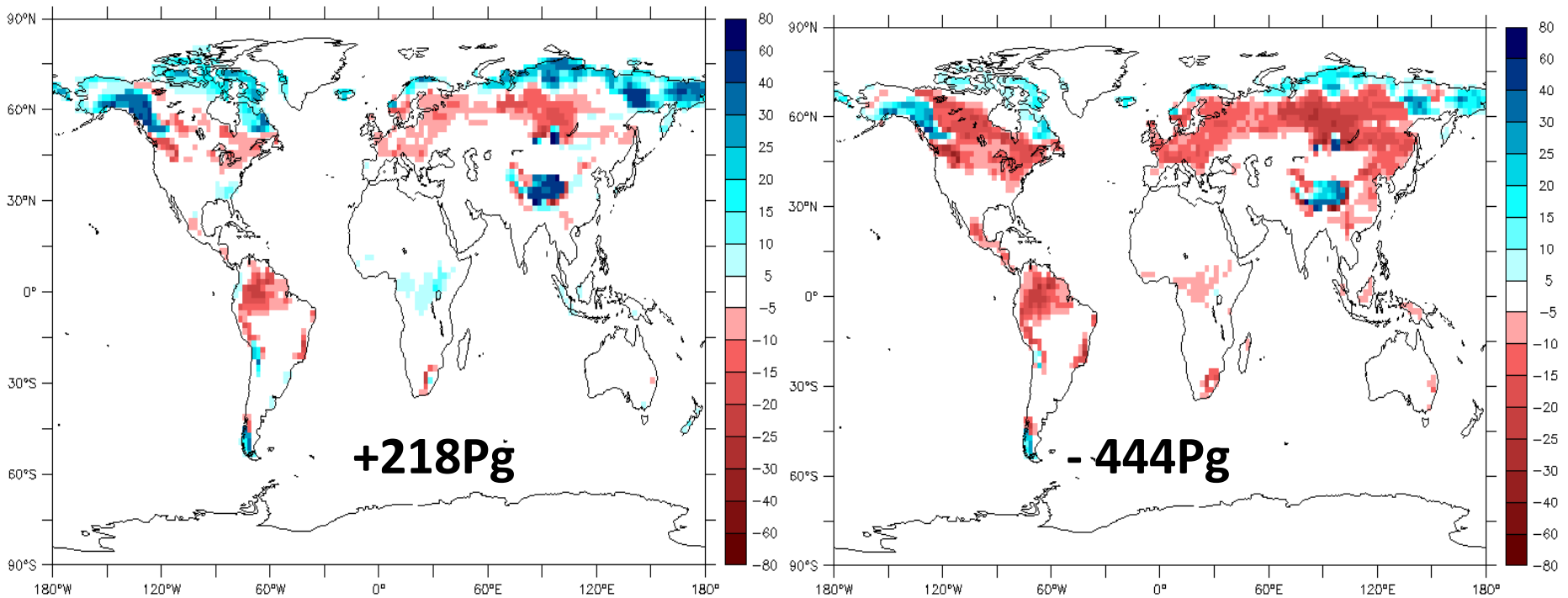
Historical benefit from sinks

The historical sink from CO₂ fertilization of terrestrial vegetation has reduced the current atmospheric CO₂ concentration by 80 ppmv and the mean global temperature by 0.4°C.

The size of this benefit has been masked partly by offsetting sources such as warming-induced loss of undecomposed organic matter.

Source: Shevliakova et al., PNAS 2013:

Catastrophe from a global failure of the terrestrial carbon sink at ~550 ppmv. GFDL ESM2G-LM3V.



CO₂ Fertilization Sink Persists

CO₂ Fertilization Sink Stops

If the CO₂ fertilization sink fails:

CO₂ from More
than a Trillion
Tons of Heated
Peat Enters the
Atmosphere

~2050

2012

1995

850

800

750

550

500

450

400

350

300

- Deglaciation and Loss of Coastal Cities
- Mass Extinction
- Deep Sea Circulation Stops
- Tropical Famine

• Parts per Million in the Atmosphere

Science

1. Natural sinks and sources.

The most powerful mitigating factor is carbon uptake by plants and oceans.

2. Earth System Models.

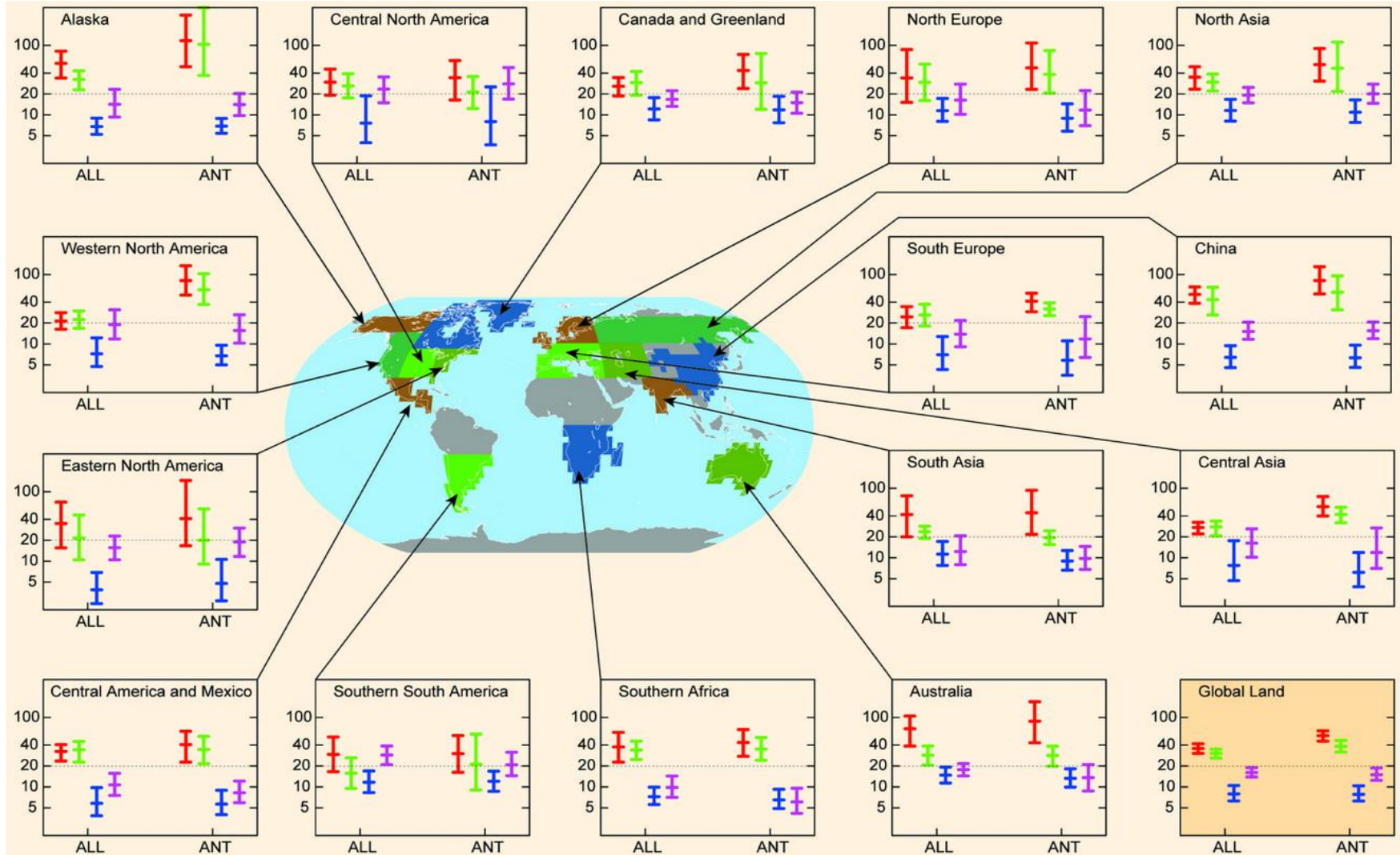
Understanding feedback between climate and anthropogenic GHG's and aerosols.

3. Climate Variability and Extremes.

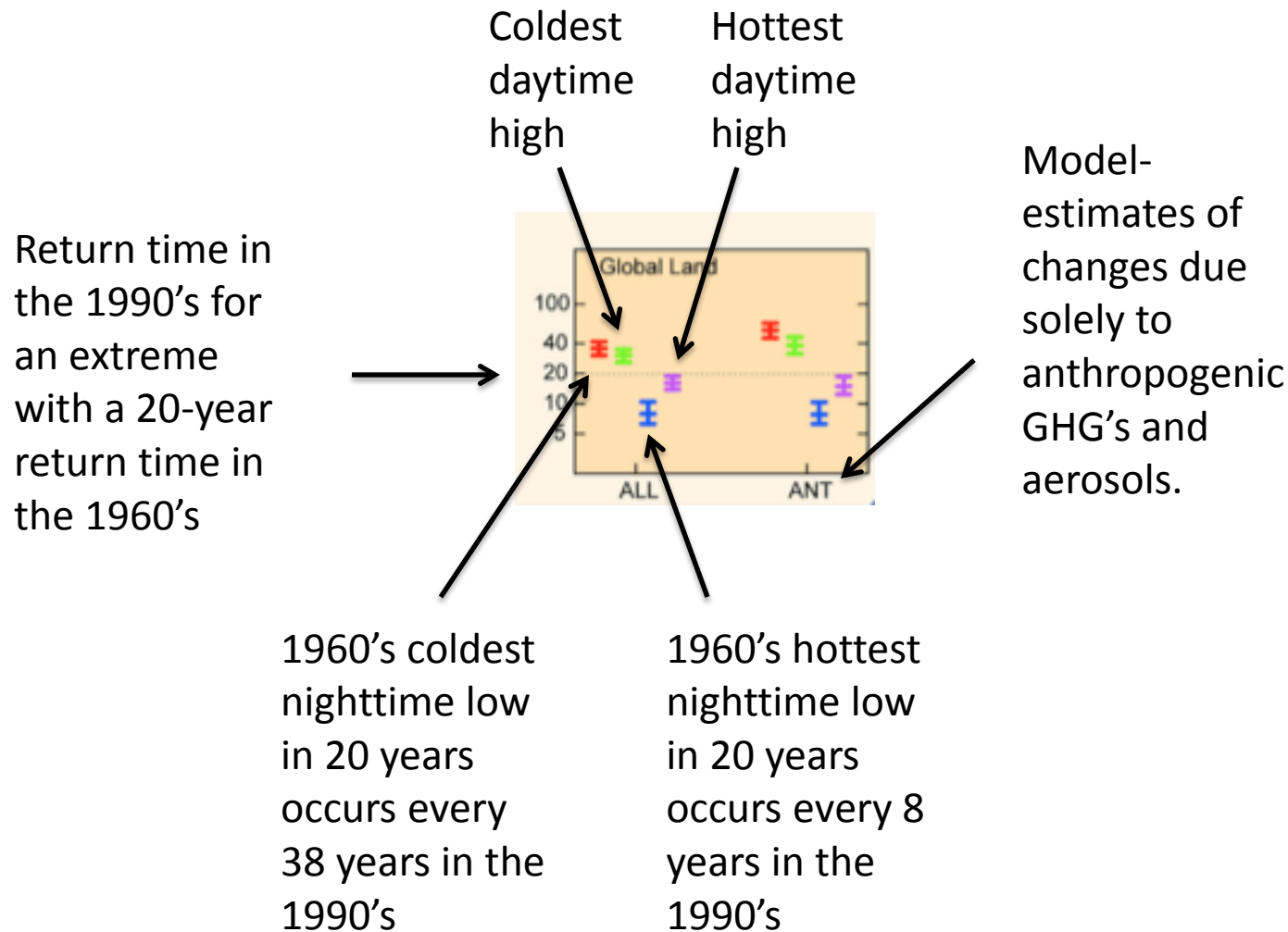
Predicting and managing risk.

Expanded participation of GFDL.

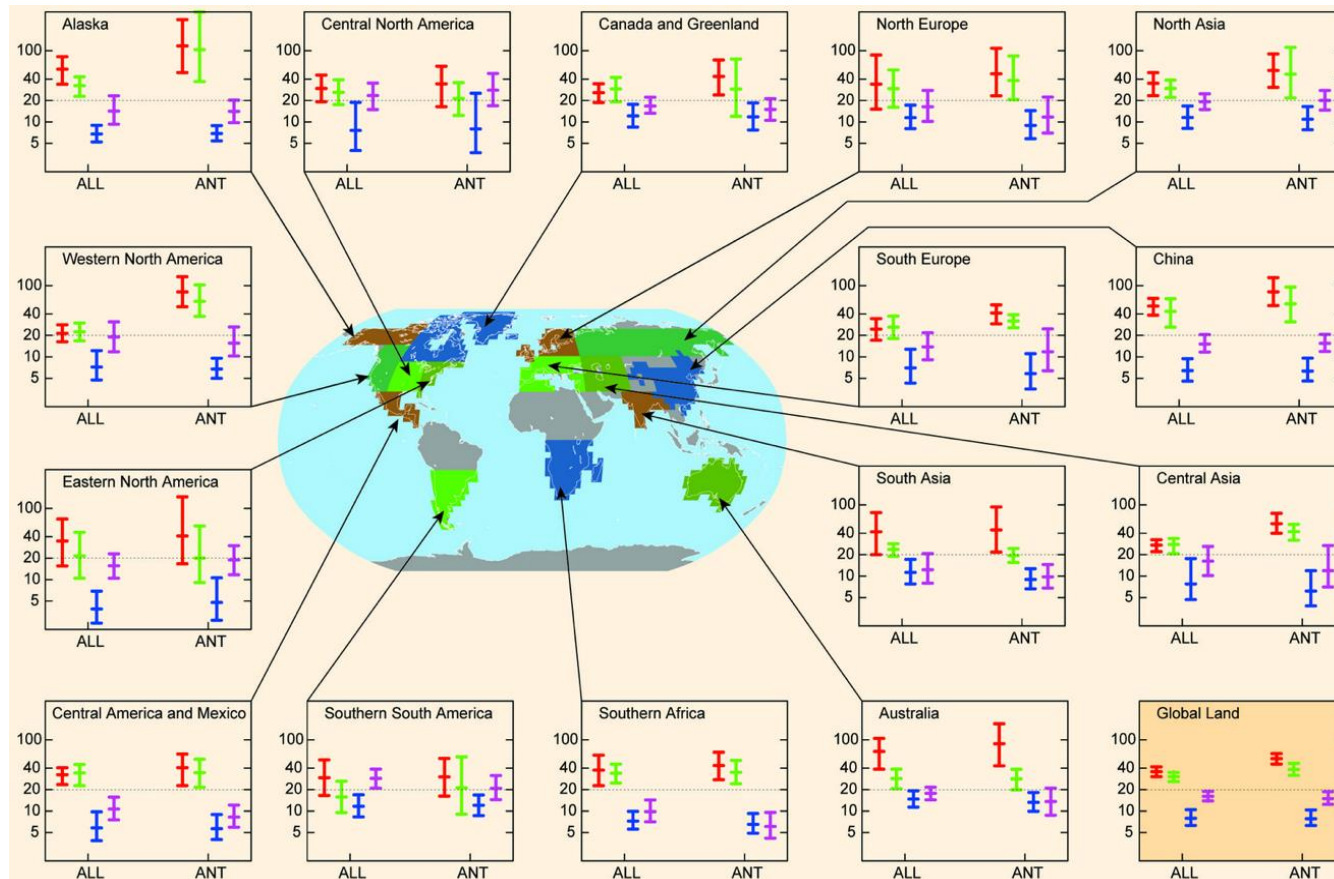
Climate Variability and Extremes



IPCC SREX on Extremes and AR5



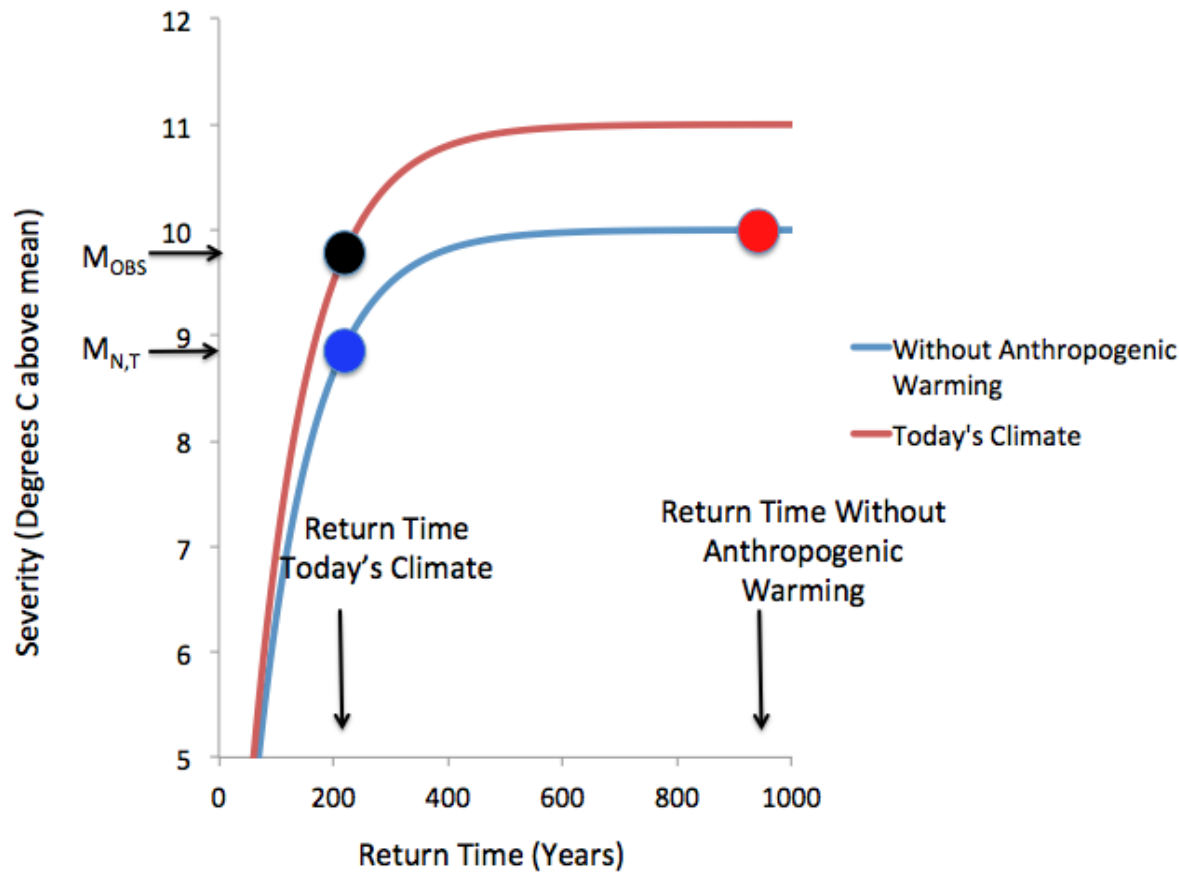
20-year extremes of heat and cold have changed rapidly on every continent. Source: IPCC SREX and AR5 2013.



And some of the the rarest and most extreme events have changed even more.

Some examples, published in 2013, of changes in the chance of severe extreme events because of anthropogenic climate change.

1. 10-fold increase in frequency for a heat waves like the 2010 Moscow or 2003 European events.
2. 20X increase for a 2011 Texas drought.
3. 10X decreased the probability of a UK winter as cold as the 2009/2010.
4. 4X increase for a failure of the annual rains like that in 2011 in East Africa.
5. No change for the probability of a UK winter as wet as this year's.



Why frequencies of some rare extremes increase faster than those of mild extremes as the climate changes.

The Variability Project is centered in GFDL. The postdocs all work there with GFDL scientists who are directly involved in the work.

Postdoctoral fellows and current projects:

- Dr. Massimo Bollassina, January 1, 2013 - August 15, 2013.
 - response of the South Asian monsoon to aerosol forcing.
 - recipient of the 2013 James R. Holton Junior Scientist Award and the WMO's Norbert Gerbier MUMM International award for best original scientific paper.
- Dr. Monika Barcikowska, August 1, 2013 – present.
 - Detection, estimation and prediction of frequencies in extreme precipitation. Cause of ongoing temperature hiatus..
- Dr. Dan Li, November 2013 –present.
 - Extremes in mega-cities.
- Recruiting a new postdoc to explore dust-aerosols and extreme drought.

Goals for current funding:

New global estimates and predictions for risk of extreme precipitation.

New global estimates and predictions for risk of extreme heat.

New global estimates and predictions for city-generated weather (e.g. heat waves).

New global analysis of drought risk.

Possible BP-Imperial-Princeton University China project with Ralf Toumi.

Agenda and goals: today

Agenda item	Why included?
This talk	Introduce/reintroduce CMI Provide highlights from 2013, including the climate variability project Provide context for renewed CMI, 2014-2020
Sarmiento	New CMI results in ocean and terrestrial carbon science
Stone and Phillips	New independent report on geothermal energy, a dispatchable non-carbon resource (Stone, co-author)
Celia and Kang	Risk analyses for below-ground CO ₂ and CH ₄
Deep dive #1: Ramaswamy, Delworth, Knutson (GFDL)	Update on climate science: “certainty,” simulation tools, evaluation of extreme events
BP Review	Report on BP evolution and reengagement
Flannery	30-year perspective on climate change, the oil industry, and university-industry partnerships