The Oceans and Global Warming - Victim or Savior ?

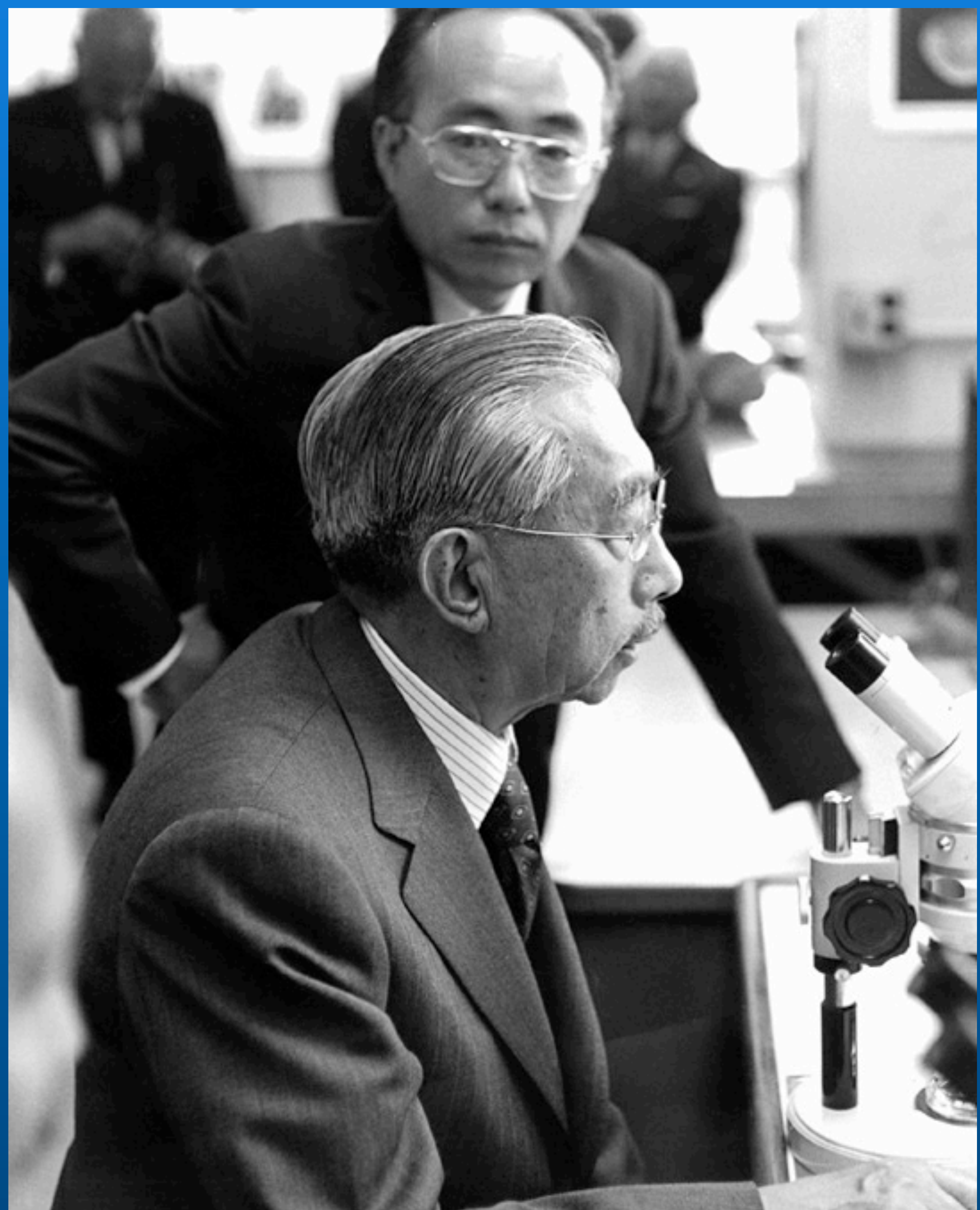
Kevin M. Ulmer, Ph.D.

16 & 19 March 2013

Outline

- Thanks and Disclosures

Sus Honjo - "*The* Giant"



Teacher, mentor, shipmate, colleague, friend...

Visionary scientist, tool maker, global thinker, humanitarian, entrepreneur...

Outline

- Thanks and Disclosures
- Anthropogenic Global Warming & Climate Change - An Overview
- *“The Tragedy of the Commons”* - Who’s Responsible?
- *“The Prisoner’s Dilemma”* - The Struggle for Global Cooperation
- *“On Civil Disobedience”* - Every Scientist’s Personal Dilemma
- Carbon “Seaquestration” - Buying Time?
- Get Involved - Take Action! - “What can I do?”

Anthropogenic Global Warming & Climate Change - An Overview

- The Carboniferous Period in Instantaneous Reverse
- *An Inconvenient Truth* - The Global Wake-Up Call
- *Storms of My Grandchildren* - The Book <u>Everyone</u> Should Read
- *Global Warming*'s *Terrifying New Math* - Three simple numbers that add up to global catastrophe - and that make clear who the real enemy is
- *Chasing Ice* - The “Extreme Ice Survey” movie
- Climate Update - March 2013

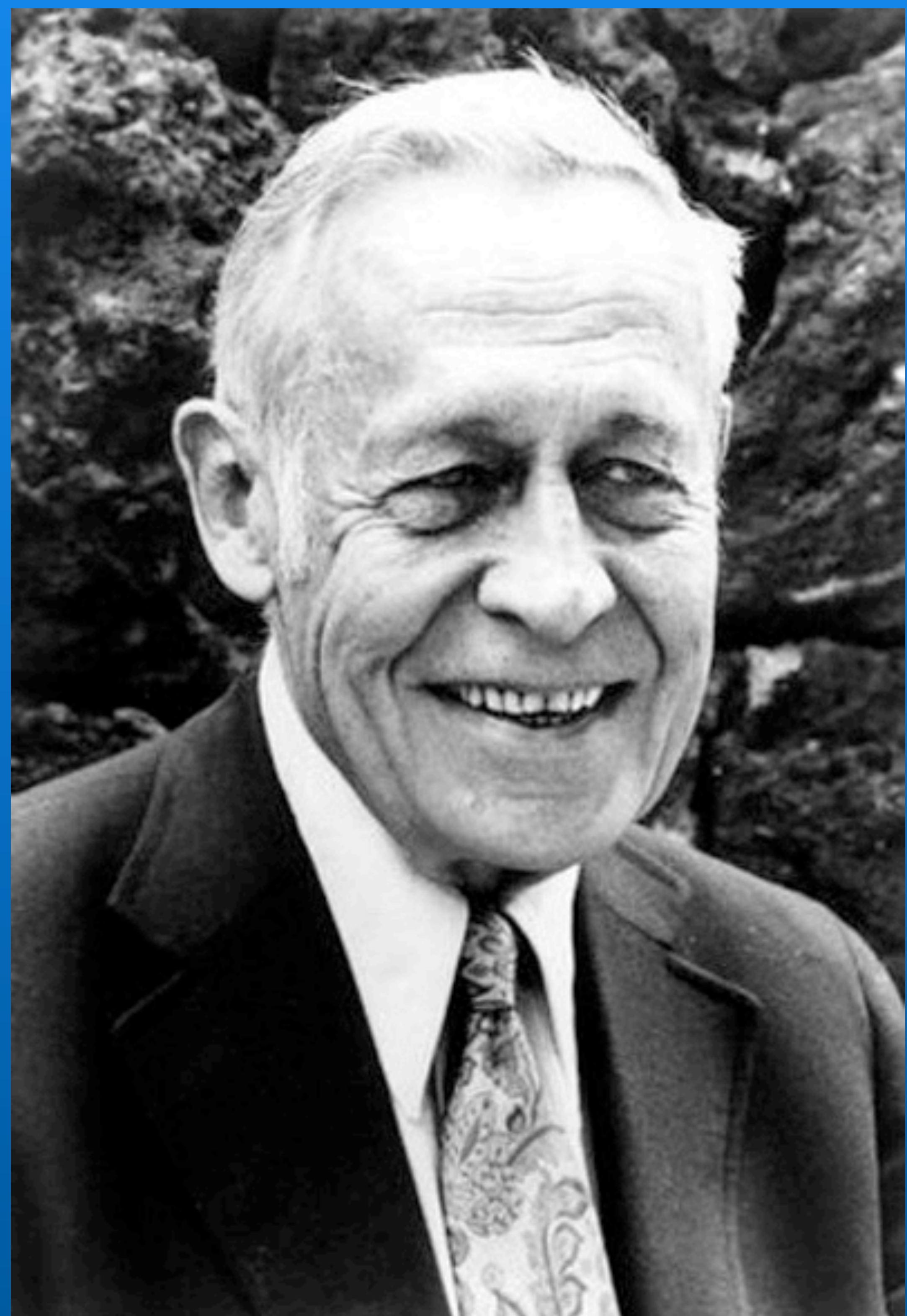
The Carboniferous Period in Instantaneous Reverse

- The Carboniferous was the geologic period between 360 and 300 million years ago during which most of Earth's coal deposits were formed
- Beginning with the Industrial Revolution in ~1760, the world started burning this coal, and later oil and gas, converting them back into atmospheric CO_2 where it all started
- The Problem: Deposition took 60+ million years, but the burning only 250 years...
- We have instantaneously returned all that CO_2 to the atmosphere!


GLOBAL WARMING
NUCLEAR POWER
THE CHRISTIAN SCIENCE MONITOR
Bennett

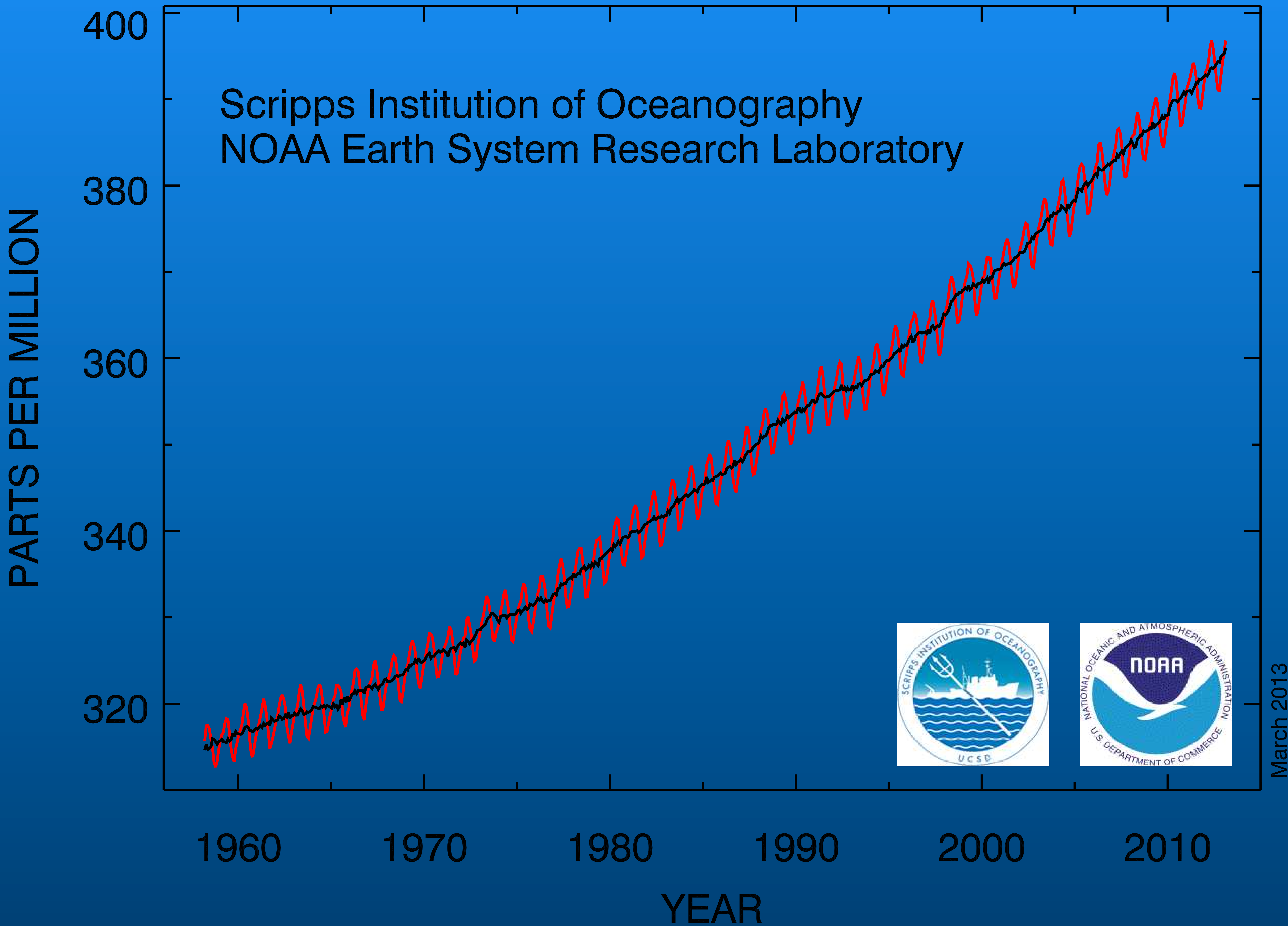
The Carboniferous Period in Instantaneous Reverse

- Why does all that extra CO_2 matter?
- CO_2 is a "greenhouse" gas
- CO_2 absorbs incoming solar energy and warms the atmosphere
- CO_2 also dissolves in the oceans, lowering the pH and making it more acidic
- Which then dissolves the shells of many marine organisms



Roger Revelle

Atmospheric CO_2 at Mauna Loa Observatory




by far the most terrifying film
you will ever see.
an inconvenient truth
A GLOBAL WARNING
now playing in select theaters
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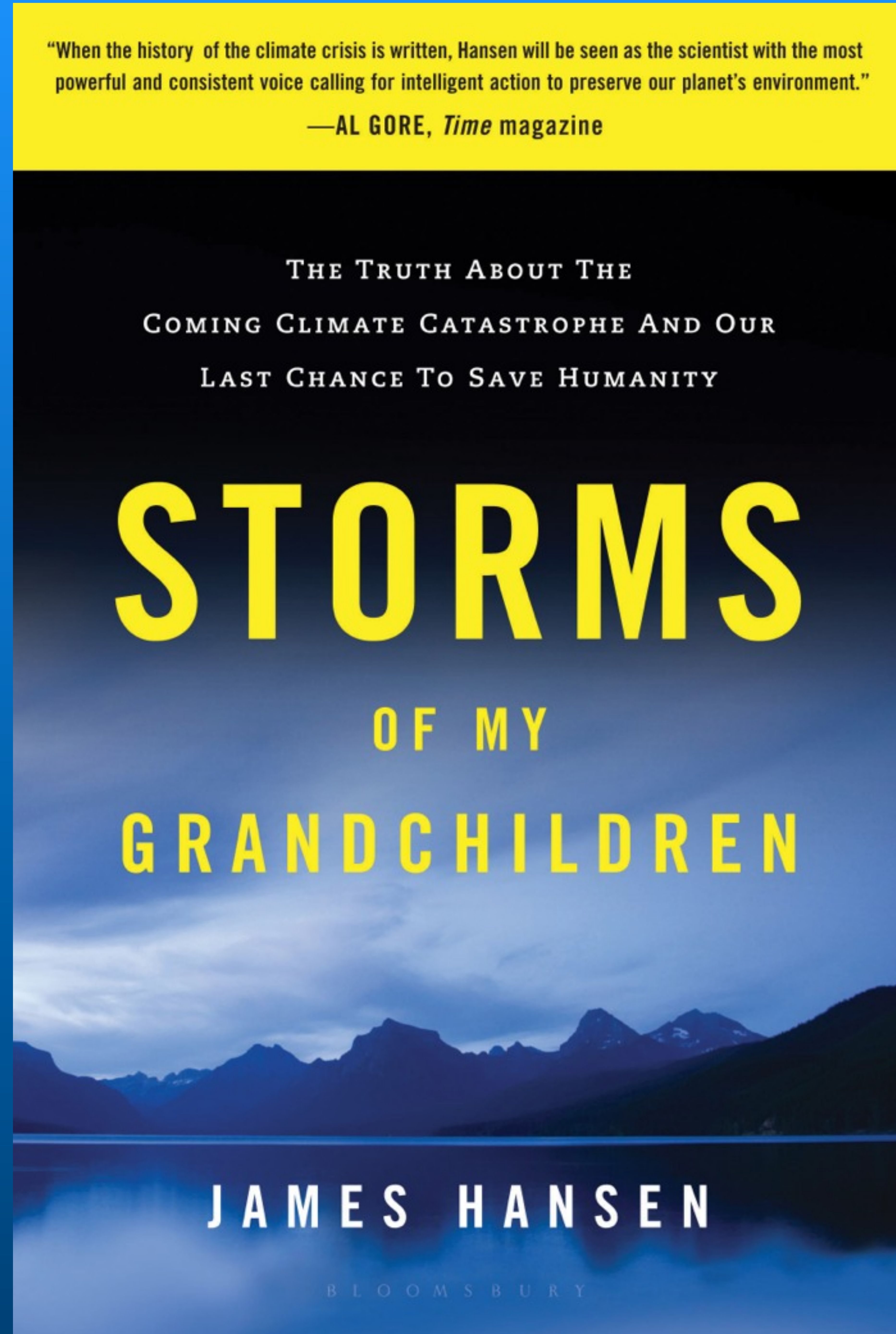
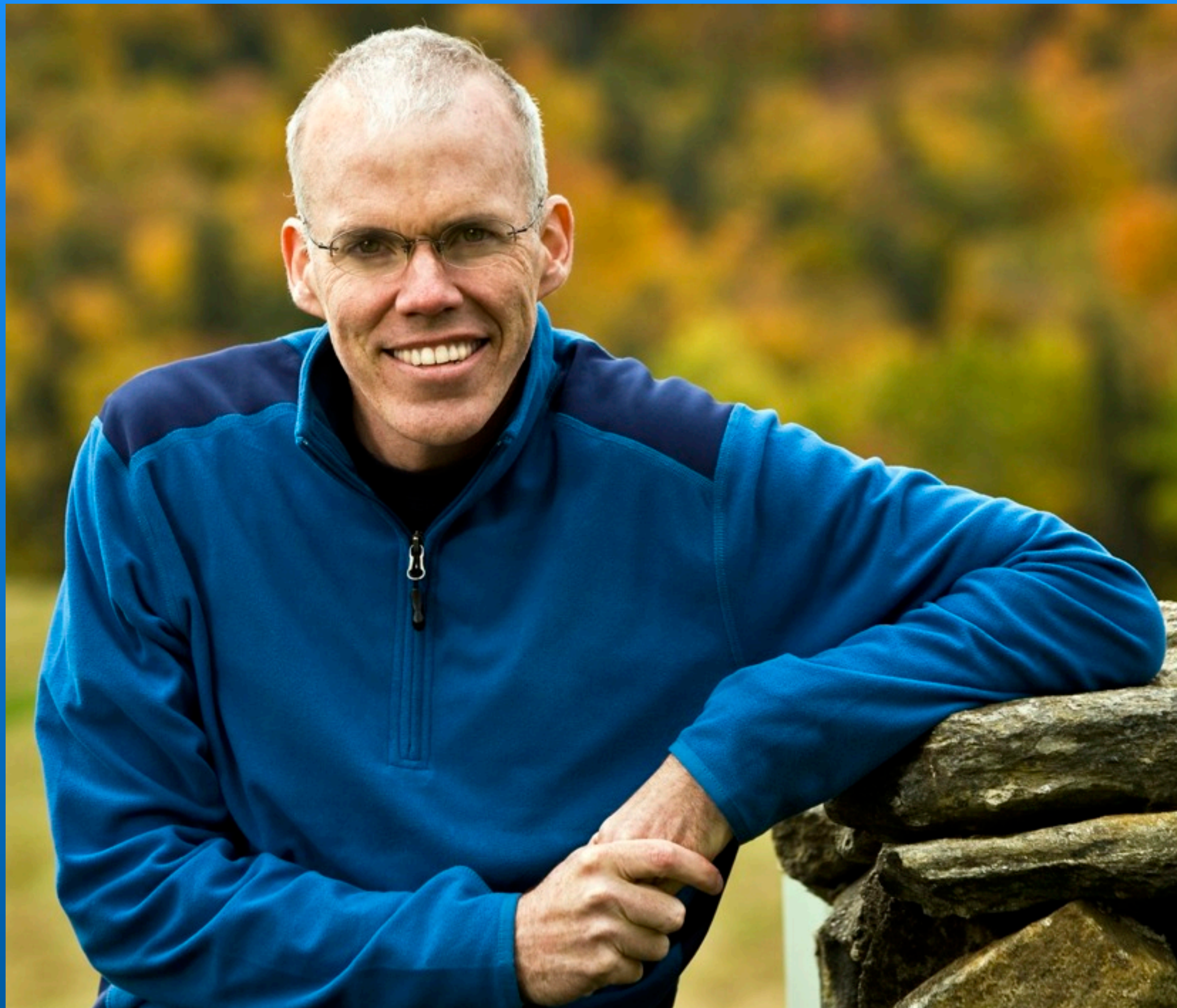
An Inconvenient Truth

A Global Wake-Up Call - but not without controversy

James E. Hansen
Columbia University
NASA Goddard Institute for Space Studies





Bill McKibben

350.org

Global Warming's Terrifying New Math - Three simple numbers that add up to global catastrophe - and that make clear who the real enemy is

JULY 19, 2012

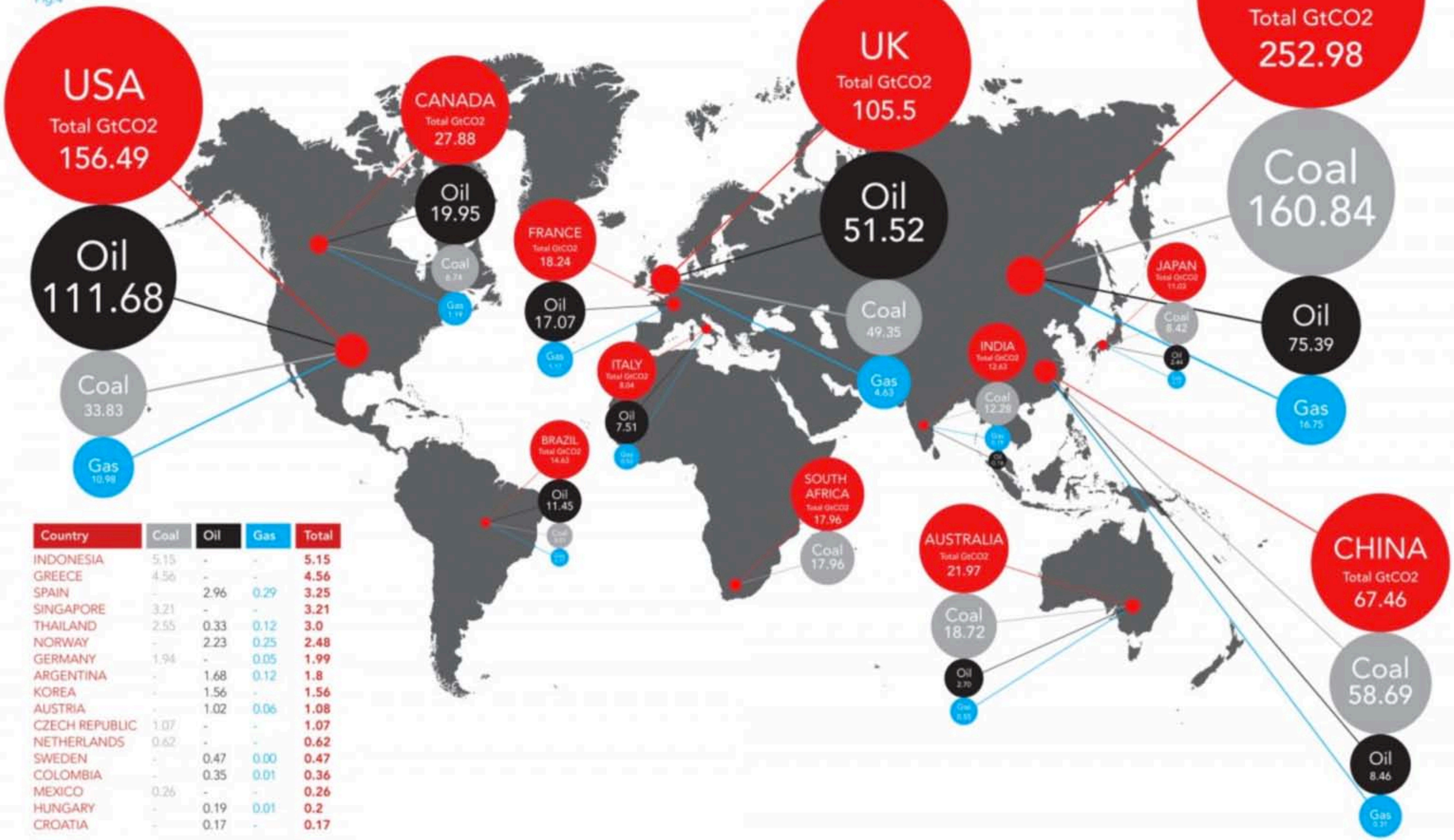
Rolling Stone

Global Warming's Terrifying New Math

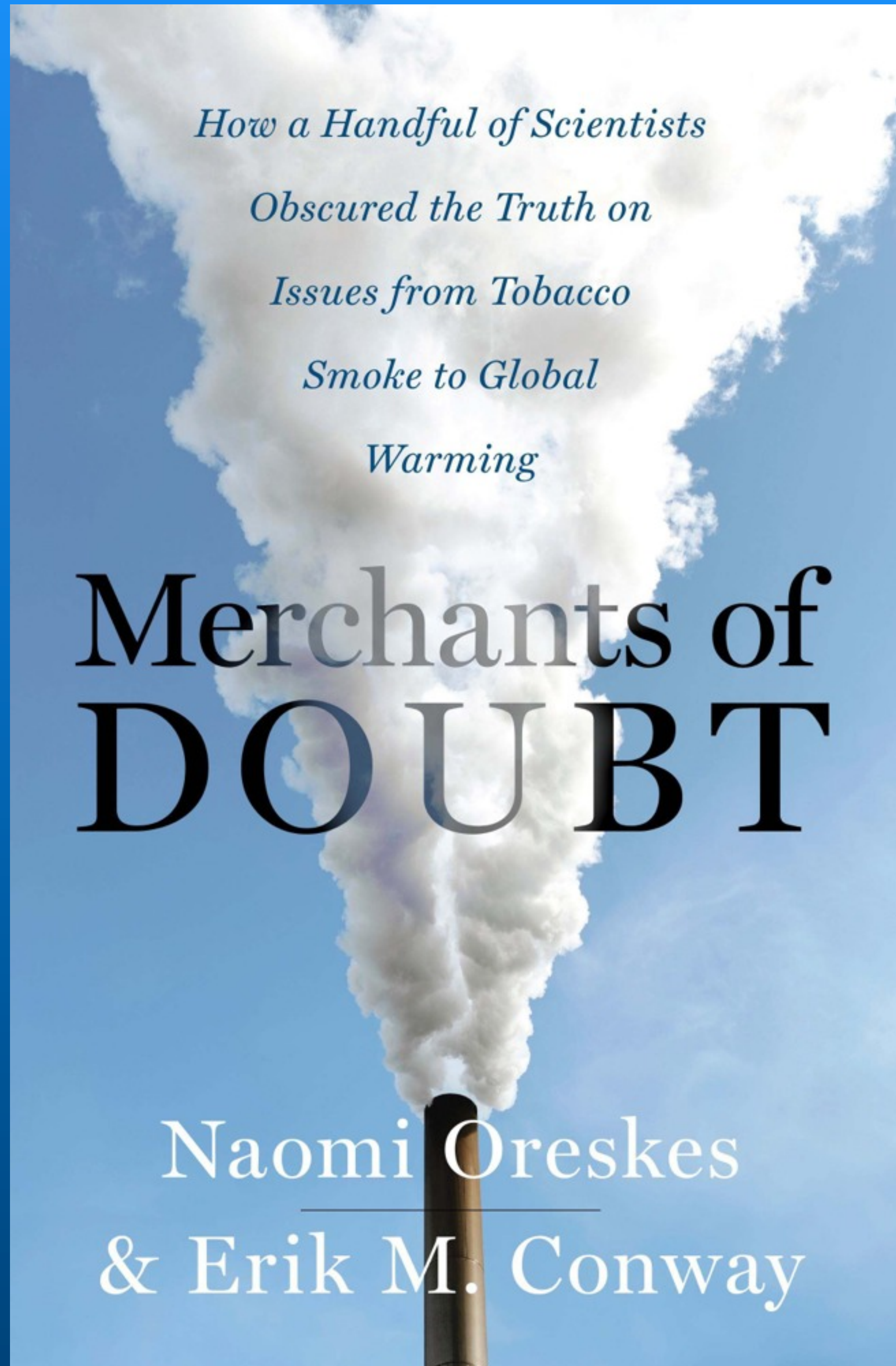
- 2°C - the amount that average global temperature can rise without catastrophic changes in climate (it has already risen by 0.8°C)
- 565 Gigatons - the estimated amount of additional CO_2 that the world can release to the atmosphere by mid-century and still remain below the 2°C limit
- 2,795 Gigatons - amount of *known* coal, oil and gas reserves (5X the allowable 2°C limit!)
- Conclusion: We must leave the bulk of these reserves in the ground and *never* burn them!
- Problem: Those fossil fuel reserves are valued at *$27 trillion!*

Distribution of fossil fuel reserves between stock exchanges

Fig.4



Country	Coal	Oil	Gas	Total
INDONESIA	5.15	-	-	5.15
GREECE	4.56	-	-	4.56
SPAIN	-	2.96	0.29	3.25
SINGAPORE	3.21	-	-	3.21
THAILAND	2.55	0.33	0.12	3.0
NORWAY	-	2.23	0.25	2.48
GERMANY	1.94	-	0.05	1.99
ARGENTINA	-	1.68	0.12	1.8
KOREA	-	1.56	-	1.56
AUSTRIA	-	1.02	0.06	1.08
CZECH REPUBLIC	1.07	-	-	1.07
NETHERLANDS	0.62	-	-	0.62
SWEDEN	-	0.47	0.00	0.47
COLOMBIA	-	0.35	0.01	0.36
MEXICO	0.26	-	-	0.26
HUNGARY	-	0.19	0.01	0.2
CROATIA	-	0.17	-	0.17


How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming
Merchants of DOUBT
Naomi Oreskes
& Erik M. Conway

G Model
JGEC-1043; No. of Pages 11

ARTICLE IN PRESS

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Climate change prediction: Erring on the side of least drama?

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[b] *History and Science Studies, University of California, San Diego, United States*
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A R T I C L E I N F O

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Scientific norms
Scientific assessment
Erring on the side of least drama

A B S T R A C T

Over the past two decades, skeptics of the reality and significance of anthropogenic climate change have frequently accused climate scientists of "alarmism": of over-interpreting or overreacting to evidence of human impacts on the climate system. However, the available evidence suggests that scientists have in fact been conservative in their projections of the impacts of climate change. In particular, we discuss recent studies showing that at least some of the key attributes of global warming from increased atmospheric greenhouse gases have been under-predicted, particularly in IPCC assessments of the physical science, by Working Group I. We also note the less frequent manifestation of over-prediction of key characteristics of climate in such assessments. We suggest, therefore, that scientists are biased not toward alarmism but rather the reverse: toward cautious estimates, where we define caution as erring on the side of less rather than more alarming predictions. We call this tendency "erring on the side of least drama (ESLD)." We explore some cases of ESLD at work, including predictions of Arctic ozone depletion and the possible disintegration of the West Antarctic ice sheet, and suggest some possible causes of this directional bias, including adherence to the scientific norms of restraint, objectivity, skepticism, rationality, dispassion, and moderation. We conclude with suggestions for further work to identify and explore ESLD.

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REPORTS 8 MARCH 2013 VOL 339 SCIENCE

A Reconstruction of Regional and Global Temperature for the Past 11,300 Years

Shaun A. Marcott,[1] Jeremy D. Shakun,[2] Peter U. Clark,[1] Alan C. Mix[1]

Surface temperature reconstructions of the past 1500 years suggest that recent warming is unprecedented in that time. Here we provide a broader perspective by reconstructing regional and global temperature anomalies for the past 11,300 years from 73 globally distributed records. Early Holocene (10,000 to 5000 years ago) warmth is followed by ~0.7°C cooling through the middle to late Holocene (<5000 years ago), culminating in the coolest temperatures of the Holocene during the Little Ice Age, about 200 years ago. This cooling is largely associated with ~2°C change in the North Atlantic. Current global temperatures of the past decade have not yet exceeded peak interglacial values but are warmer than during ~75% of the Holocene temperature history. Intergovernmental Panel on Climate Change model projections for 2100 exceed the full distribution of Holocene temperature under all plausible greenhouse gas emission scenarios.

PENNSTATE
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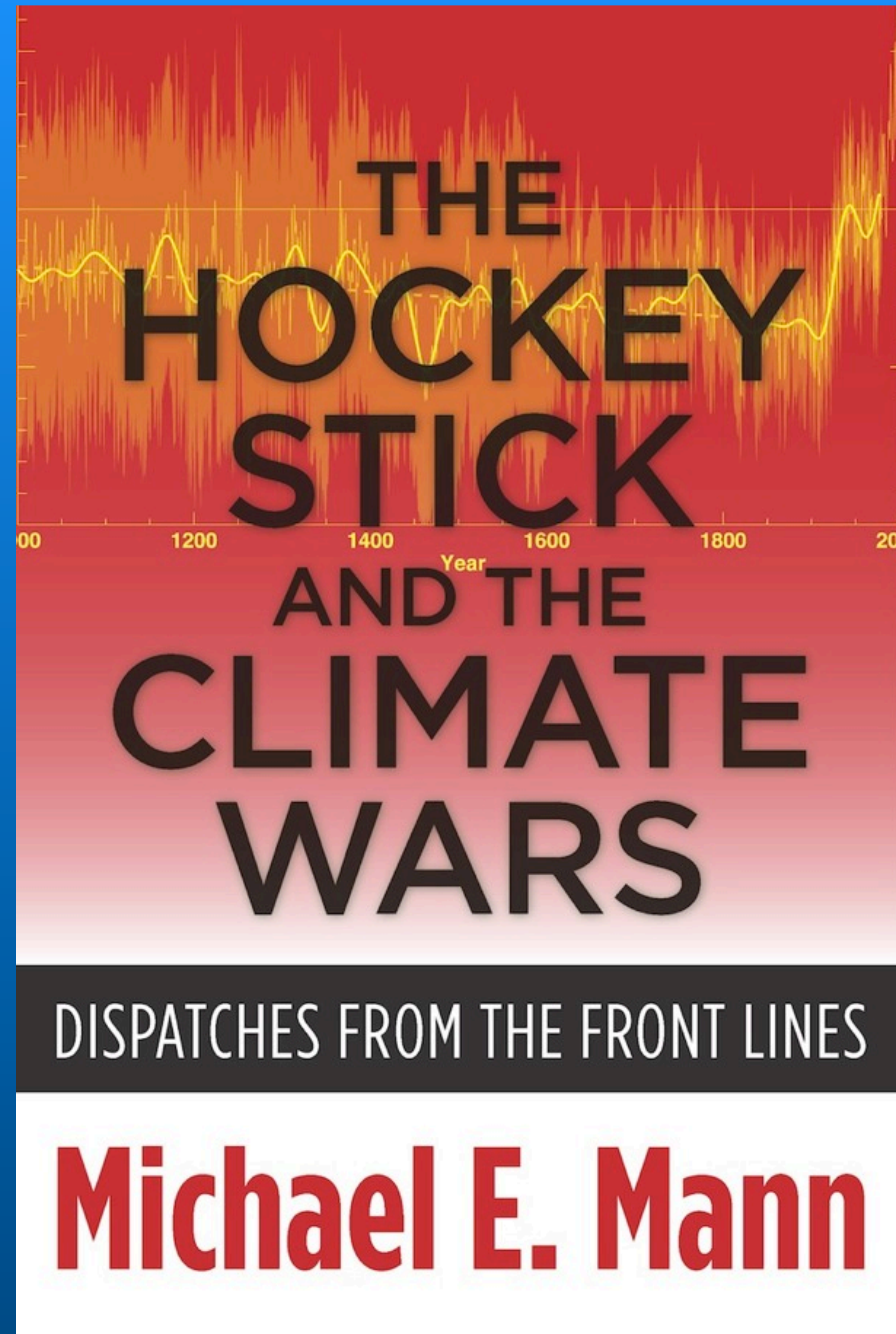

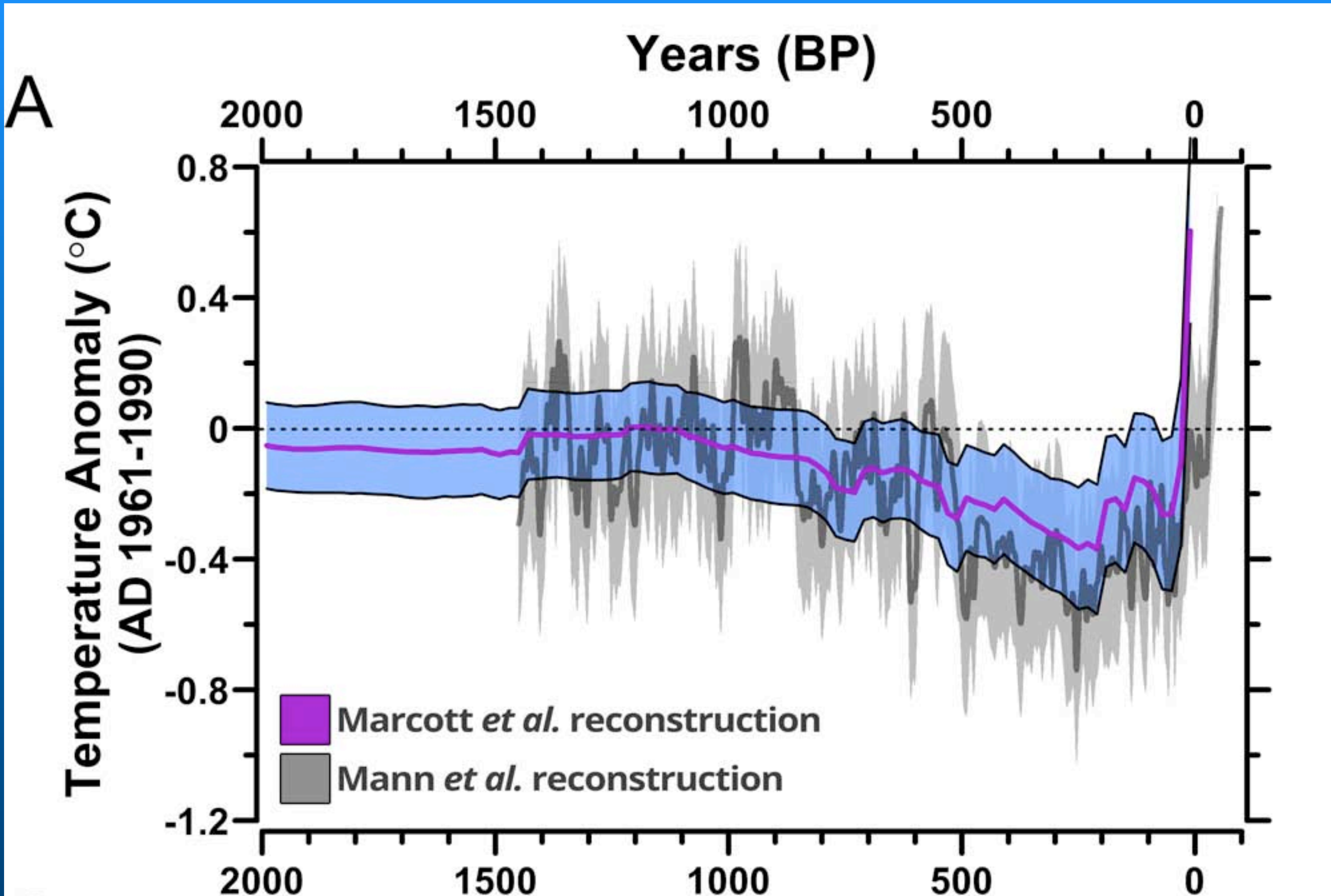
A
Years (BP)
2000
1500
1000
500
0
0.8
0.4
0
-0.4
-0.8
-1.2
Temperature Anomaly (°C)
(AD 1961-1990)
Marcott et al. reconstruction
Mann et al. reconstruction

Jiangxi province, China, 2009.

AFTER KYOTO

In this special issue, Nature *examines the end of the 1997 Kyoto climate treaty — and the path ahead.*

NEWS FEATURE

HOT AIR

BY QUIRIN SCHIERMEIER

Commitments made under the Kyoto climate treaty expire at the end of 2012, but emissions are rising faster than ever.

agreed to limit their emissions, something that they had objected to doing before the developed world acted. By the time the Kyoto Protocol came into force in February 2005, the United States had pulled out. The remaining signatories — 37 developed nations and economies in transition — pledged to reduce their greenhouse-gas emissions from 1990 levels by an average of 4.2% in the period from 2008 to 2012.

As that window closes, the countries that stuck with the treaty can claim some success. Overall, they met their target with room to spare, cutting their collective emissions by around 16%. But most of those cuts came with little or no effort, because of the collapse of greenhouse-gas

ESSMENT AGENCY/EC JOINT RES. CENTRE

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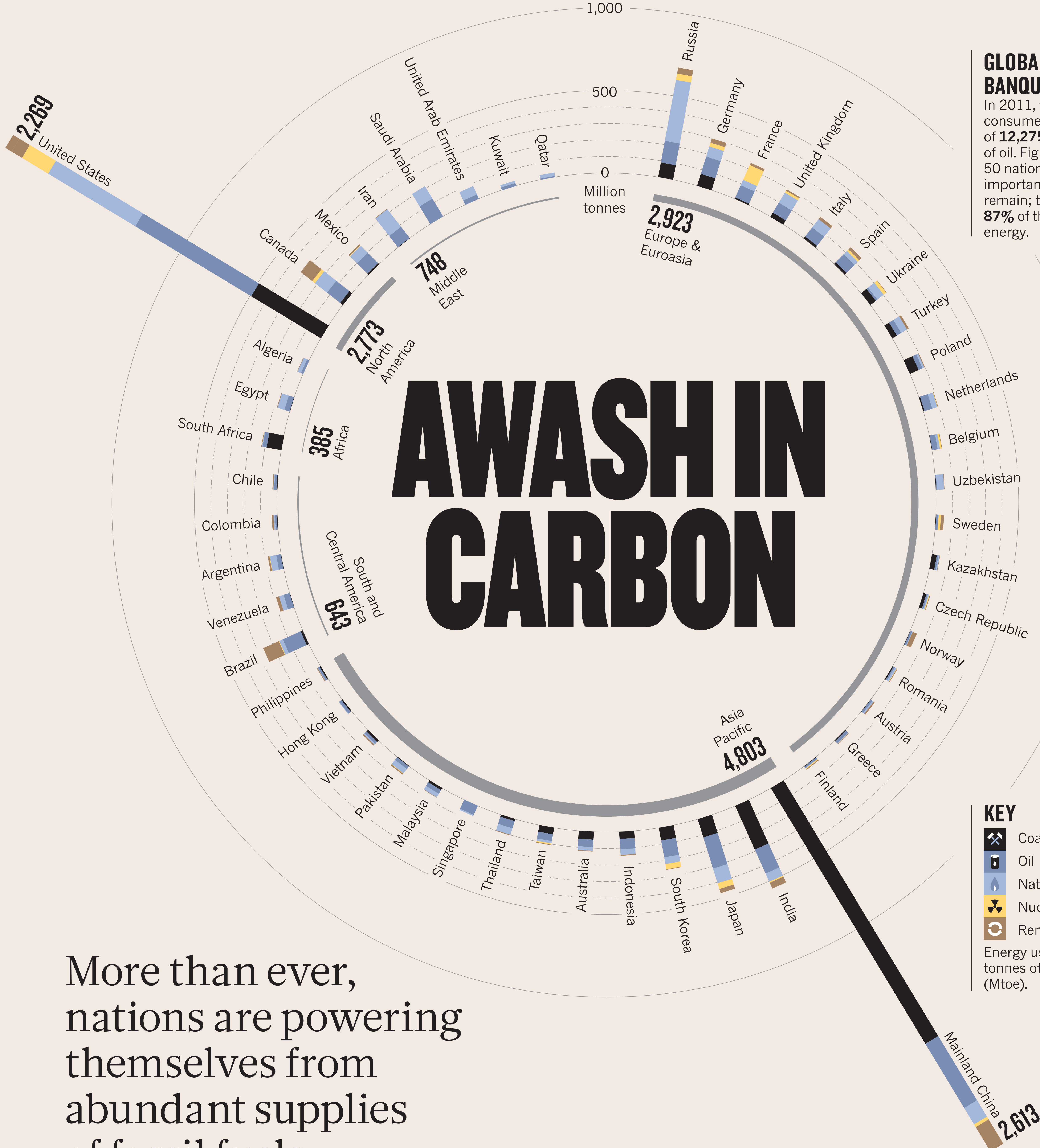
AWASH IN CARBON



GLOBAL ENERGY BANQUET

In 2011, the globe consumed the equivalent of **12,275 million tonnes** of oil. Figures for the top 50 nations show how important fossil fuels remain; they supplied **87%** of the world's energy.

SOURCE: BP STATISTICAL REVIEW OF WORLD ENERGY 2012

KEY

- Coal
- Oil
- Natural gas
- Nuclear
- Renewables

Energy use in million tonnes of oil equivalent (Mtoe).

More than ever, nations are powering themselves from abundant supplies of fossil fuels.

Taichung Power Plant - Taiwan

- 10 units @ 550MW each
- 12 million ton/yr bituminous coal
- 2.5 million ton/yr sub-bituminous coal
- World's largest CO_2 producer


JOHN GUILLEMIN/BLOOMBERG VIA GETTY

The Belchatow power station in Poland is Europe's largest coal-burning plant, but plans to capture carbon dioxide from it are in limbo.

CLIMATE

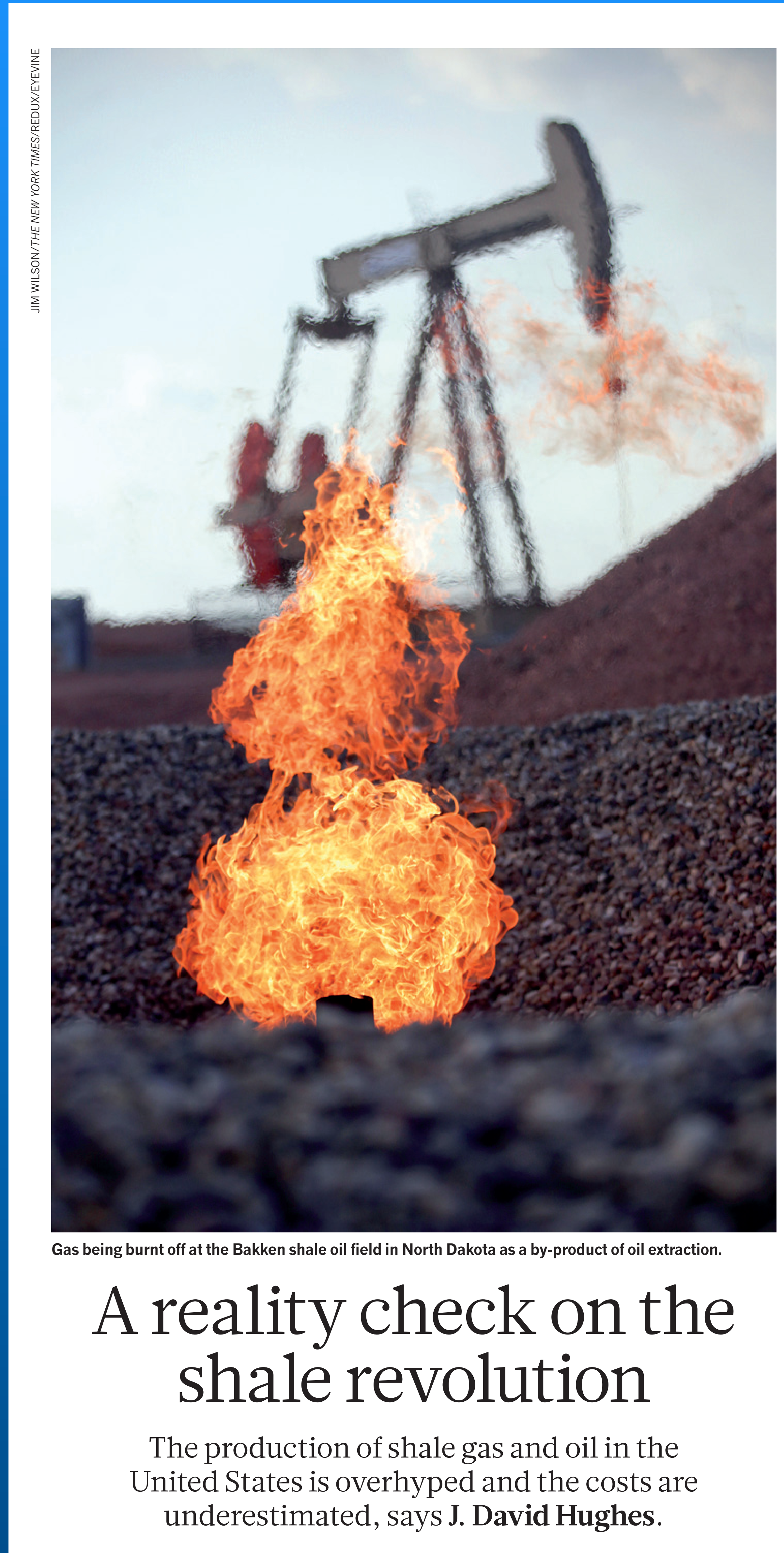
Europe's untamed carbon

Funding and politics hobble CCS technology, seen as the best hope for cleaning up coal.

Around 80% of China's electricity generation is coal-fired.

The Kyoto approach has failed

Abandon coal, price carbon consumption and look to new technologies for a lasting solution to global emissions, argues **Dieter Helm**.


JIM WILSON/THE NEW YORK TIMES/REDUX/EYEVINE

Gas being burnt off at the Bakken shale oil field in North Dakota as a by-product of oil extraction.

A reality check on the shale revolution

The production of shale gas and oil in the United States is overhyped and the costs are underestimated, says **J. David Hughes**.

21 FEBRUARY 2013 | VOL 494 | NATURE | 307

Mountaintop Removal - Appalachia

Keystone Pipeline - Alberta Tar Sands

CLIMATE CHANGE

All in the timing

How influential are the various factors involved in curbing global warming? A study finds that the timing of emissions reduction has the largest impact on the probability of limiting temperature increases to 2 °C. **See Letter p.79**

STEVE HATFIELD-DODDS

Climate science sometimes seems to have overtaken economics as the most dismal science. But a study by Rogelj *et al.* on page 79 of this issue[1] might just change that. The authors quantify the importance of five 'uncertainties' that are thought to influence the chance of limiting global temperatures to different levels, using a suite of models to generate around 500 scenario variations. They find that the timing of international action to limit emissions has by far the largest impact. Furthermore, the models show that the impact of timing is highly nonlinear, and that delaying emissions limits by only five years, from 2020 to 2025, would dramatically cut the likelihood of limiting warming to 2 °C. The findings should help to make risks and consequences more transparent, and thereby support better-informed economic and political decisions.

The five major uncertainties assessed by Rogelj and colleagues were the following: the responsiveness of the physical climate system to cumulative emissions; the deployment of energy- and land-based emission-reduction technologies; the global demand for energy (which includes combined uncertainties about population, income growth and energy efficiency); the global carbon price that the international community is willing to impose; and the timing of substantive action to limit emissions (phased in from 2010). The analysis covers limiting the temperature in 2100 to 1.5, 2, 2.5 and 3 °C above pre-industrial levels, with a focus on 2 °C.

These scenario comparisons revealed timing of global action to be the uncertainty with the greatest effect. For example, the authors find that bringing forward global action on emissions from 2020 to 2015 would improve the chance of limiting temperatures to 2 °C from 56% to 60%, all else being equal. To put this another way, achieving the same 60% chance of success with action starting in 2020 would require a 2020 carbon price of around US$150 per tonne of carbon dioxide equivalent (CO_2e) — more than double the $60 per tonne CO_2e required if action begins in 2015. However, delaying emissions limits from 2020 to 2025 would bring the chance of success down to 34%, and the authors found no scenario in which a feasible increase in carbon price or improvements in energy technology could make up for these five years of delay.

Geophysical uncertainties are the next most

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CLIMATE CHANGE

The Closing Door of Climate Targets

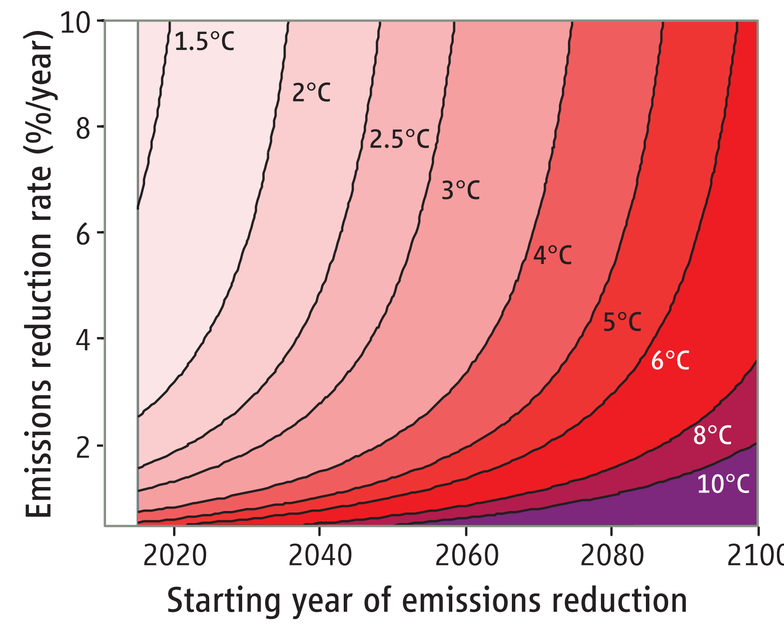
The linear relationship between cumulative carbon emissions and global climate warming implies that as mitigation is delayed, climate targets become unachievable.

Thomas F. Stocker

Robust evidence from a range of climate–carbon cycle models shows that the maximum warming relative to pre-industrial times caused by the emissions of carbon dioxide is nearly proportional to the total amount of emitted anthropogenic carbon (*1*, *2*). This proportionality is a reasonable approximation for simulations covering many emissions scenarios for the time frame 1750 to 2500 (*1*). This linear relationship is remarkable given the different complexities of the models and the wide range of emissions scenarios considered. It has direct implications for the possibility of achieving internationally agreed climate targets such as those mentioned in the Copenhagen Accord and the Cancun Agreements (*3*, *4*). Here I explain some of the implications of the linear relationship between peak warming and total cumulative carbon emissions.

The considerations presented here are based on the assumption of a generic set of carbon dioxide emissions scenarios that reasonably approximate what is presently observed and what needs to be done to limit warming below a specific global mean temperature increase. In these idealized and illustrative emissions scenarios (see the Box), emissions follow an exponential increase with a constant rate until a given year, after which the emissions decrease exponentially at a constant rate. The scenarios delineate the boundaries for any discussion and decision process for global measures limiting anthropogenic climate change.

Results from a large number of Earth system model simulations suggest that peak warming, ΔT, and cumulative CO_2 emissions, C_∞, are nearly linearly related via the parameter β, which is the peak response to cumulative emissions (see Eq. 3 in the Box).



Contours of peak warming. Contours of peak CO_2-induced warming (as given by Eq. 3 in the Box) as a function of the starting date of the GMS and the implemented reduction rate of emissions. Parameters are $C_0 = 530$ GtC, $E_0 = 9.3$ GtC per year, $\beta = 2°C\ (TtC)^{-1}$, and $r = 1.8\%$ per year. The later the GMS starts, the higher the required emissions reduction rate is for a given peak warming.

The value of β is estimated to be between 1.3° and 3.9°C per trillion metric tons of carbon (1 TtC = 10^{18} g carbon) (*1*). The uncertainty in β arises from the range of climate sensitivities and carbon cycle feedbacks in the models. More recent estimates of a closely related quantity, the transient climate response to cumulative emissions, take into account observational constraints and report 1.0° to 2.1°C $(TtC)^{-1}$ (*2*). However, this quantity is less useful here because warming can still continue when emissions stop. This warming is better captured by the peak response to cumulative emissions.

For a given β, the peak warming is determined by three quantities in these simple scenarios: the current rate of emissions increase, the starting time of the Global Mitigation Scheme (GMS), and the rate of emissions reduction realized by the GMS. The latter two depend on future choices and are therefore policy-relevant. As shown in the first figure, a delay in the start of the GMS results in a rapid increase in ΔT as a result of the continued exponential increase in emissions before the start of mitigation. Likewise, for a given starting date of mitigation, achieving a low climate target calls for very aggressive emission decreases. For example, under the present illustrative assumptions, keeping CO_2-induced global warming below 2°C would require emissions reductions of almost 3.2% per year from 2020 onward; this is more than

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Monday, March 11, 13

LETTER

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Probabilistic cost estimates for climate change mitigation

Joeri Rogelj[1,2], David L. McCollum[2], Andy Reisinger[3], Malte Meinshausen[4,5] & Keywan Riahi[2,6]

For more than a decade, the target of keeping global warming below 2 °C has been a key focus of the international climate debate[1]. In response, the scientific community has published a number of scenario studies that estimate the costs of achieving such a target[2–5]. Producing these estimates remains a challenge, particularly because of relatively well known, but poorly quantified, uncertainties, and owing to limited integration of scientific knowledge across disciplines[6]. The integrated assessment community, on the one hand, has extensively assessed the influence of technological and socio-economic uncertainties on low-carbon scenarios and associated costs[2–4,7]. The climate modelling community, on the other hand, has spent years improving its understanding of the geophysical response of the Earth system to emissions of greenhouse gases[8–12]. This geophysical response remains a key uncertainty in the cost of mitigation scenarios but has been integrated with assessments of other uncertainties in only a rudimentary manner, that is, for equilibrium conditions[6,13]. Here we bridge this gap between the two research communities by generating distributions of the costs associated with limiting transient global temperature increase to below specific values, taking into account uncertainties in four factors: geophysical, technological, social and political. We find that political choices that delay mitigation have the largest effect on the cost–risk distribution, followed by geophysical uncertainties, social factors influencing future energy demand and, lastly, technological uncertainties surrounding the availability of greenhouse gas mitigation options. Our information on temperature risk and mitigation costs provides crucial information for policy-making, because it clarifies the relative importance of mitigation costs, energy demand and the timing of global action in reducing the risk of exceeding a global temperature increase of 2 °C, or other limits such as 3 °C or 1.5 °C, across a wide range of scenarios.

zero (<1%; Fig. 1c). However, imposing a carbon price of about US\$20 tCO_2e^{-1} in our model would increase the probability of staying below 2 °C to about 50%, and carbon prices of more than US\$40 tCO_2e^{-1} would achieve the 2 °C objective with a probability of more than 66% ('likely' by the definition of the Intergovernmental Panel on Climate Change[19]). Similar trends hold for other cost metrics (Supplementary Information). For example, a carbon price of US\$20–40 tCO_2e^{-1} translates in our model to cumulative discounted mitigation costs (2012–2100) of the order of 0.8–1.3% of gross world product (Supplementary Fig. 10).

A marked feature of the mitigation cost distribution (Fig. 2) is that the probability of global warming staying below 2 °C levels off at high carbon prices. This occurs because, beyond a given carbon price, nearly all mitigation options that can substantially influence emissions in the medium term have been deployed in our model. Higher carbon prices help further to reduce emissions later in the century, but only affect temperatures after peaking[20]. Hence, the probability of staying below 2 °C during the twenty-first century reaches an asymptote.

Geophysical uncertainties shed light on only one aspect of mitigation costs, however. To gain insight into how assumptions regarding technological and social uncertainties influence our cost distribution, we create a large set of sensitivity cases (Table 1), in which we vary some salient features of the scenarios, namely the availability and use of specific mitigation technologies; future social development and, by extension, global energy demand; and the international political context surrounding climate mitigation action, specifically delays in the implementation of a globally comprehensive mitigation response[7] (Supplementary Information). We note that population and economic growth do not vary in our scenarios; we therefore cannot assess their relative importance with our ensemble (Supplementary Information). Given its policy relevance[21], we focus most of our discussion on the

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THIS WEEK

EDITORIALS

HERITAGE The true value of cultural sites to science and beyond p.302

WORLD VIEW The climate needs protest and civil disobedience p.303

OPEN WIDE Oral bumps help alligators and crocodiles find food p.304

America's carbon compromise

As looming tax increases and budget cuts threaten to plunge the US economy back into recession, Congress should take a hard look at introducing a carbon tax as an important part of the solution.

~~Cap-and-Trade~~

~~Carbon Credits~~

Carbon Tax

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ZUMA/REX FEATURES

US President Barack Obama reinforced environment promises in his second inaugural address.

ENVIRONMENT

Obama rekindles climate hopes

President will use regulations to sidestep stalled Congress.

“The Tragedy of the Commons” - Who’s Responsible?

SCIENCE VOL. 162:13
DECEMBER 1968

Garrett Hardin
University of California
Santa Barbara

ARTICLE

The Tragedy of the Commons

Garrett Hardin

At the end of a thoughtful article on the future of nuclear war, Wiesner and York (*1*) concluded that: “Both sides in the arms race are . . . confronted by the dilemma of steadily increasing military power and steadily decreasing national security. *It is our considered professional judgment that this dilemma has no technical solution*. If the great powers continue to look for solutions in the area of science and technology only, the result will be to worsen the situation.”

I would like to focus your attention not on the subject of the article (national security in a nuclear world) but on the kind of conclusion they reached, namely that there is no technical solution to the problem. An implicit and almost universal assumption of discussions published in professional and semipopular scientific journals is that the

perfectly. Put another way, there is no “technical solution” to the problem. I can win only by giving a radical meaning to the word “win.” I can hit my opponent over the head; or I can drug him; or I can falsify the records. Every way in which I “win” involves, in some sense, an abandonment of the game, as we intuitively understand it. (I can also, of course, openly abandon the game—refuse to play it. This is what most adults do.)

The class of “No technical solution problems” has members. My thesis is that the “population problem,” as conventionally conceived, is a member of this class. How it is conventionally conceived needs some comment. It is fair to say that most people who anguish over the population problem are trying to find a way to avoid

for the greatest number” be realized?

No—for two reasons, each sufficient by itself. The first is a theoretical one. It is not mathematically possible to maximize for two (or more) variables at the same time. This was clearly stated by von Neumann and Morgenstern (*3*), but the principle is implicit in the theory of partial differential equations, dating back at least to D’Alembert (1717–1783).

The second reason springs directly from biological facts. To live, any organism must have a source of energy (for example, food). This energy is utilized for two purposes: mere maintenance and work. For man, maintenance of life requires about 1600 kilocalories a day (“maintenance calories”). Anything that he does over and above merely staying alive will be defined as work, and is supported by “work calories” which he takes in. Work calories are used not only for what we call work in common speech; they are also required for all forms of enjoyment, from swimming and automobile racing to playing music and writing poetry. If our goal is to maximize population it is obvious what we must do: We must make the work calories

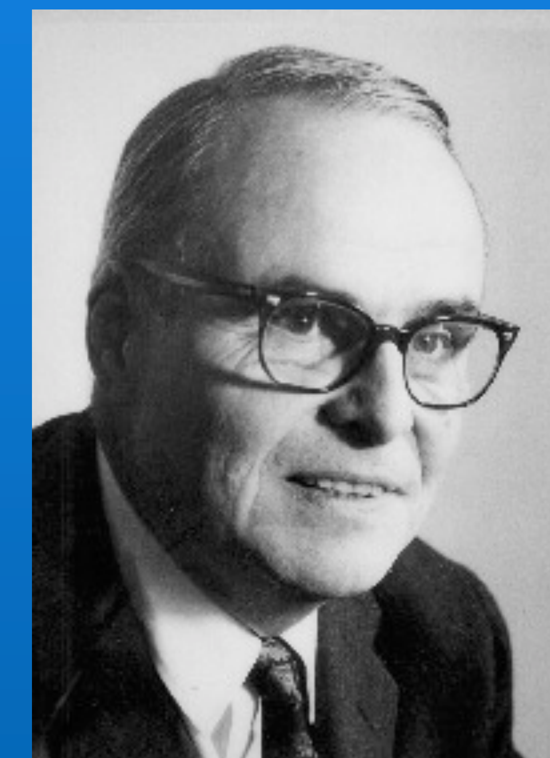
“The Prisoner’s Dilemma” - The Struggle for Global Cooperation

The Prisoner's Dilemma

Melvin Dresher

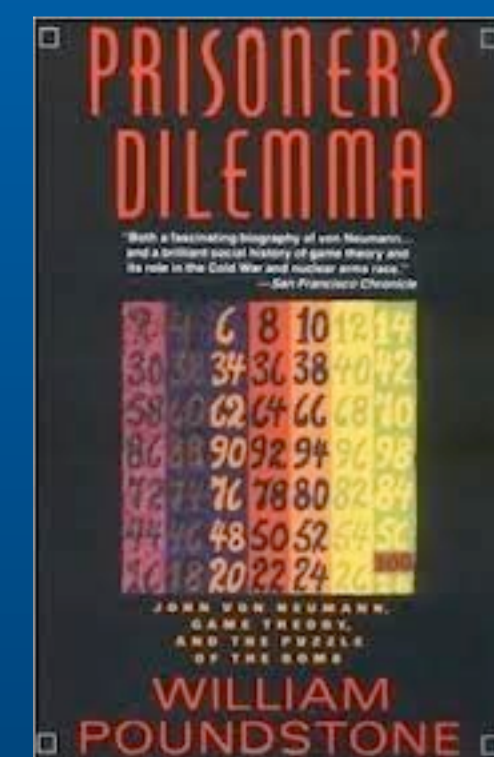
Merrill Flood

RAND CORPORATION



Albert Tucker

1950



new energy finance

The leading provider of clean energy financial research

White Paper

How to Save the Planet: Be Nice, Retaliatory, Forgiving & Clear

11 September 2007 | 7 pages

How to Save the Planet: Be Nice, Retaliatory, Forgiving & Clear

The Kyoto Protocol is due to expire in 2012. Conventional wisdom – especially among its fans – is that without agreement on a successor treaty the world will spiral into ever-increasing emissions and climate catastrophe will follow. New Energy Finance disagrees.

Summary

Analysis of climate change from a game-theoretical perspective reveals an Iterated Prisoner's Dilemma. As Robert Axelrod demonstrated in the Evolution of Cooperation (1985), such games are frequently characterised by the evolution of cooperative behaviour, independent of strong central authority. And indeed this is what we are already seeing in climate negotiations, with countries and regions increasingly committing to unilateral action.

The optimum strategy for an Iterated Prisoner's Dilemma is to be Nice, Retaliatory, Forgiving and Clear. This provides a framework for the evaluation of strategies to date, which shows that no country or region has so far adopted an optimal strategy. The US needs to start being Nice, Europe needs to learn to Retaliate, and the developing world needs to Forgive. All players bar Europe need to improve the Clarity with which they communicate their strategies.

The analysis also provides valuable insight into the optimal role of the UN. It should focus on its role as educator, coach and communications platform, rather than attempt to act as regulator and policeman. The UN should also find ways of breaking the negotiating process into smaller steps to encourage the emergence of sound national strategies.

For companies and investors, meanwhile, the lesson is that they should plan for a carbon-constrained future – irrespective of the outcome of upcoming negotiations.

Michael Liebreich

Table 1. Typical Prisoners Dilemma Payoff Table (Score in Years in Prison)

You keep silent (cooperate)	You score -1 Opponent scores -1	You score -10 Opponent scores 0
You confess (defect)	You score 0 Opponent scores -10	You score -5 Opponent scores -5
	Opponent keeps silent (cooperates)	**Opponent confesses (defects)**

If both parties remain silent (cooperate with each other), they each serve just one year in prison. If one tells on the other (defects) he or she goes free, while the other serves 10 years. If both tell on each other, they each serve five years. For a Prisoner's Dilemma to occur, the payoff for defecting must be higher than the payoff for mutual cooperation, which must in turn be higher than the payoff for mutual defection, which must be higher than the payoff for being the sucker.

Source: New Energy Finance, Various

Table 2. Simplified Climate Change Prisoners Dilemma Payoff Table (Score in Estimated % Loss of GDP per Capita)

You cut emissions (cooperate)	You score -1% to -21% Opponent scores -1.0% to -21%	You score -4% to -24% Opponent scores 0% to -20%
You refuse to act (defect)	You score 0% to -20% Opponent Scores -4.0% to -24%	You score 0% to -20% Opponent scores 0% to -20%
	Opponent cuts emissions (cooperates)	**Opponent refuses to act (defects)**

If all countries tackle emissions, the cost to the world economy is 1.0%, according to the Stern Review. If not, the cost is 5% to 20%. Any country that does not impose cuts when others do will experience a "freeloader's benefit", enjoying the advantage of limited climate change without the cost. Any country that imposes limits when its competitors do not incurs not just the cost of limiting its own emissions, but also a further cost in terms of reduced competitiveness – estimated here at an additional 3.0%. Clearly payoffs depend also on the behaviours of more than just these two players – hence the range of possible outcomes in each cell (see below under Theoretical Limitations). Of course if you and/or your opponent defect, you are more likely to end up near the top of the cost range, but the main point is that whatever your opponent does, you are likely to be better off not cutting emissions.

Source: Stern Review; New Energy Finance; Various

- Be Nice. Start by cooperating, and never be the first to defect. Otherwise you have no chance of getting into the zone where you both cooperate repeatedly and rack up the best outcome over time.

- Be Retaliatory. If the other player defects, inflict a cost on him or her which is at least as severe – otherwise you open yourself to exploitation.

- Be Forgiving. If your opponent mends his ways after defecting, restore cooperation as quickly as possible, so that you can both get back to scoring highly on each round.

- Be Clear. Since there is no way to beat the Nice, Retaliatory and Forgiving strategy, if your opponent knows you are following it, there is no incentive for him or her to seek advantage – it will only destroy his or her score as well as yours.

Climate negotiations under scientific uncertainty

Scott Barrett[a,b,c,1] and Astrid Dannenberg[a,d]

[a]Earth Institute and [b]School of International and Public Affairs, Columbia University, New York, NY 10027; [c]Princeton Institute for International and Regional Studies, Princeton University, Princeton, NJ 08544; and [d]Department of Economics, University of Gothenburg, 405 30 Gothenburg, Sweden

Edited* by Partha Sarathi Dasgupta, University of Cambridge, Cambridge, United Kingdom, and approved August 6, 2012 (received for review May 18, 2012)

How does uncertainty about "dangerous" climate change affect the prospects for international cooperation? Climate negotiations usually are depicted as a prisoners' dilemma game; collectively, countries are better off reducing their emissions, but self-interest impels them to keep on emitting. We provide experimental evidence, grounded in an analytical framework, showing that the fear of crossing a dangerous threshold can turn climate negotiations into a coordination game, making collective action to avoid a dangerous threshold virtually assured. These results are robust to uncertainty about the impact of crossing a threshold, but uncertainty about the location of the threshold turns the game back into a prisoners' dilemma, causing cooperation to collapse. Our research explains the paradox of why countries would agree to a collective goal, aimed at reducing the risk of catastrophe, but act as if they were blind to this risk.

which "there is a critical threshold between 350 and 550 p.p.m.v." (16). Our model can be interpreted as representing threshold uncertainty in this same way. Using the above reference values, our model suggests that countries can recognize that it is best to limit concentrations to 350 p.p.m.v. but still be compelled in this prisoners' dilemma to propose a higher target, to pledge less than is needed to meet this target, and then to contribute less than they pledged, with the consequence that concentrations ultimately exceed 550 p.p.m.v.

Although our paper was motivated by the climate problem, the participants in our experiment were not told of this motivation, making our results equally applicable to other situations in which collective action is needed to avoid a dangerous threshold. Examples range from the cascading effect of adding space debris beyond a critical level, rendering a key orbit unusable

www.pnas.org/cgi/doi/10.1073/pnas.1208417109

“On Civil Disobedience” - Every Scientist’s Personal Dilemma

- Henry David Thoreau (1817-1862)
  - American author, poet, philosopher, abolitionist, naturalist, tax resister, development critic, surveyor, historian, and leading transcendentalist
  - Pioneer of nature study
  - Lived in a one-room cabin on Walden Pond in Concord, Massachusetts for 2 years
  - Recorded flowering times, now used as evidence of global warming

OPEN ACCESS Freely available online

PLOS | ONE

Record-Breaking Early Flowering in the Eastern United States

Elizabeth R. Ellwood[1]*, Stanley A. Temple[2,3]*, Richard B. Primack[1]*, Nina L. Bradley[3]†, Charles C. Davis[4]*

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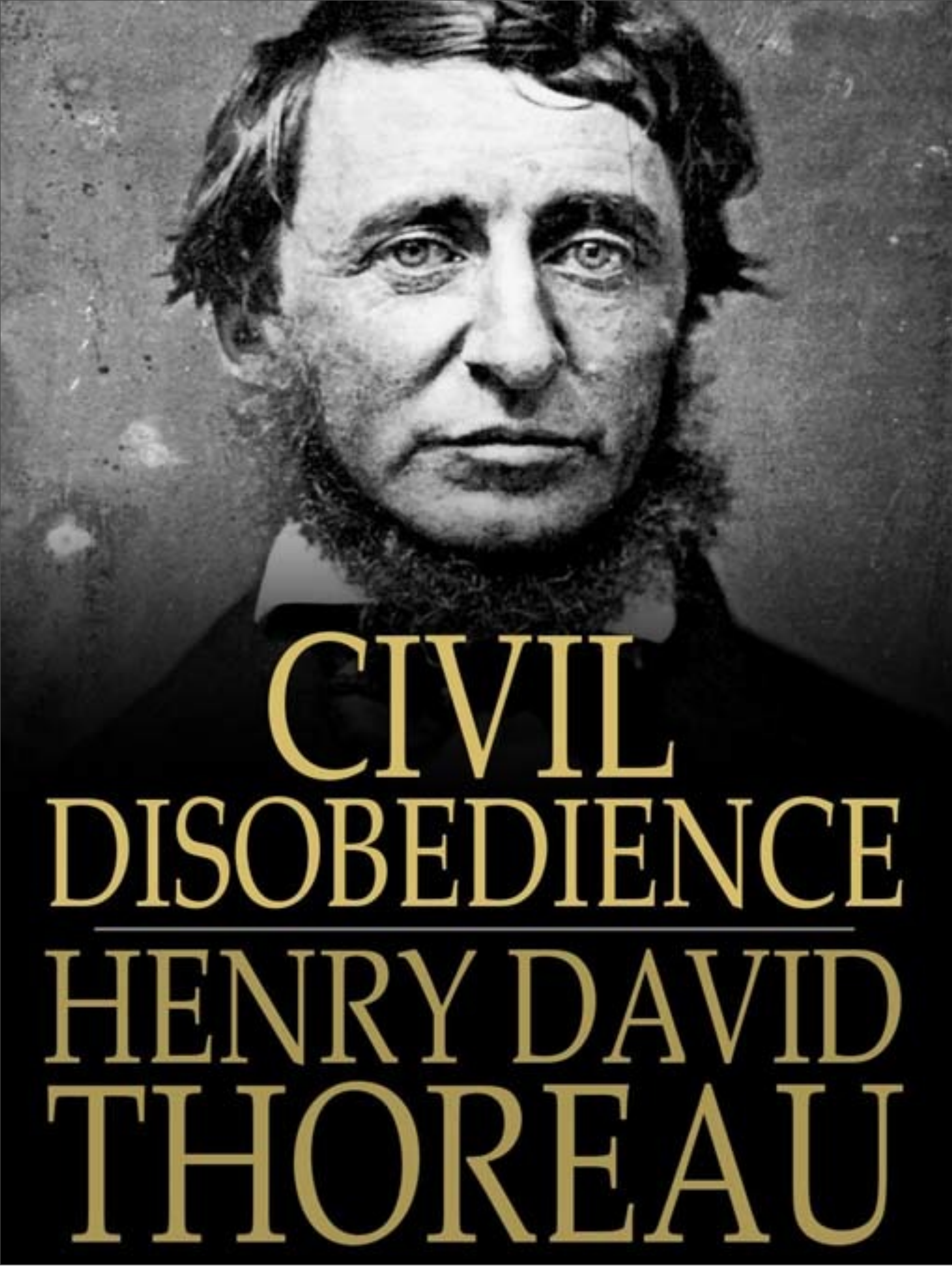
Abstract

Flowering times are well-documented indicators of the ecological effects of climate change and are linked to numerous ecosystem processes and trophic interactions. Dozens of studies have shown that flowering times for many spring-flowering plants have become earlier as a result of recent climate change, but it is uncertain if flowering times will continue to advance as temperatures rise. Here, we used long-term flowering records initiated by Henry David Thoreau in 1852 and Aldo Leopold in 1935 to investigate this question. Our analyses demonstrate that record-breaking spring temperatures in 2010 and 2012 in Massachusetts, USA, and 2012 in Wisconsin, USA, resulted in the earliest flowering times in recorded history for dozens of spring-flowering plants of the eastern United States. These dramatic advances in spring flowering were successfully predicted by historical relationships between flowering and spring temperature spanning up to 161 years of ecological change. These results demonstrate that numerous temperate plant species have yet to show obvious signs of physiological constraints on phenological advancement in the face of climate change.

January 16, 2013



"Unjust laws exist; shall we be content to obey them, or shall we endeavor to amend them, and obey them until we have succeeded, or shall we transgress them at once?"

"All men recognize the right of revolution; that is, the right to refuse allegiance to, and to resist, the government, when its tyranny or its inefficiency are great and unendurable."

WORLD VIEW *A personal take on events*

Be persuasive. Be brave. Be arrested (if necessary)

A resource crisis exacerbated by global warming is looming, argues financier **Jeremy Grantham**. *More scientists must speak out.*

I have yet to meet a climate scientist who does not believe that global warming is a worse problem than they thought a few years ago. The seriousness of this change is not appreciated by politicians and the public. The scientific world carefully measures the speed with which we approach the cliff and will, no doubt, carefully measure our rate of fall. But it is not doing enough to stop it. I am a specialist in investment bubbles, not climate science. But the effects of climate change can only exacerbate the ecological trouble I see reflected in the financial markets — soaring commodity prices and impending shortages.

My firm warned of vastly inflated Japanese equities in 1989 — the grandmother of all bubbles — US growth stocks in 2000 and everything risky in late 2007. The usual mix of investor wishful thinking and dangerous and cynical encouragement from industrial vested interests made these bubbles possible. Prices of global raw materials are now rising fast. This does not constitute a bubble, however, but is a genuine paradigm shift, perhaps the most important economic change since the Industrial Revolution. Simply, we are running out.

The price index of 33 important commodities declined by 70% over the 100 years up to 2002 — an enormous help to industrialized countries in getting rich. Only one commodity, oil, had been flat until 1972 and then, with the advent of the Organization of the Petroleum Exporting Countries, it began to rise. But since 2002, prices of almost all the other commodities, plus oil, tripled in six years; all without a world war and without much comment. Even if prices fell tomorrow by

fertilizer problem is seen also in the shocking lack of awareness on the part of governments and the public of the increasing damage to agriculture by climate change; for example, runs of extreme weather that have slashed grain harvests in the past few years. Recognition of the facts is delayed by the frankly brilliant propaganda and obfuscation delivered by energy interests that virtually own the US Congress. (It is not unlike the part played by the financial industry when investment bubbles start to form … but that, at least, is only money.) We need oil producers to leave 80% of proven reserves untapped to achieve a stable climate. As a former oil analyst, I can easily calculate oil companies' enthusiasm to leave 80% of their value in the ground — absolutely nil.

The damaging effects of climate change are accelerating. James Hansen of NASA has screamed warnings for 30 years. Although at first he was dismissed as a madman, almost all his early predictions, disturbingly, have proved conservative in relation to what has actually happened. In 2011, Hansen was arrested in Washington DC, alongside Gus Speth, the retired dean of Yale University's environmental school; Bill McKibben, one of the earliest and most passionate environmentalists to warn about global warming; and my daughter-in-law, all for protesting over a pipeline planned to carry Canadian bitumen to refineries in the United States, bitumen so thick it needs masses of water even to move it. From his seat in jail, Speth said that he had held some important positions in Washington, but none more important than this one.

President Barack Obama missed the chance

IT IS CRUCIAL THAT SCIENTISTS SOUND A MORE REALISTIC, MORE DESPERATE, NOTE ON GLOBAL WARMING.

Monday, March 11, 13

Stephen Gardiner
Department of Philosophy
University of Washington

SURVEY ARTICLE

Ethics and Global Climate Change*

Stephen M. Gardiner

Very few moral philosophers have written on climate change.[1] This is puzzling, for several reasons. First, many politicians and policy makers claim that climate change is not only the most serious environmental problem currently facing the world, but also one of the most important international problems per se.[2] Second, many of those working in other disciplines describe climate change as fundamentally an ethical issue.[3]

Ethics 114 (April 2004): 555–600


Glacier Watching Day 17

Carbon “Seaquestration” - Buying Time?

Carbon dioxide sequestration in deep-sea basalt

David S. Goldberg*, Taro Takahashi, and Angela L. Slagle

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Communicated by Wallace S. Broecker, Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY, May 7, 2008 (received for review April 3, 2008)

Developing a method for secure sequestration of anthropogenic carbon dioxide in geological formations is one of our most pressing global scientific problems. Injection into deep-sea basalt formations provides unique and significant advantages over other potential geological storage options, including (*i*) vast reservoir capacities sufficient to accommodate centuries-long U.S. production of fossil fuel CO_2 at locations within pipeline distances to populated areas and CO_2 sources along the U.S. west coast; (*ii*) sufficiently closed water-rock circulation pathways for the chemical reaction of CO_2 with basalt to produce stable and nontoxic (Ca^{2+}, Mg^{2+}, Fe^{2+})CO_3 infilling minerals, and (*iii*) significant risk reduction for post-injection leakage by geological, gravitational, and hydrate-trapping mechanisms. CO_2 sequestration in established sediment-covered basalt aquifers on the Juan de Fuca plate offer promising locations to securely accommodate more than a century of future U.S. emissions, warranting energized scientific research, technological assessment, and economic evaluation to establish a viable pilot injection program in the future.

climate change | ocean crust | climate mitigation | fossil fuel emissions | energy

In recent years, the debate over the most effective means to stabilize greenhouse gas concentrations in the atmosphere has

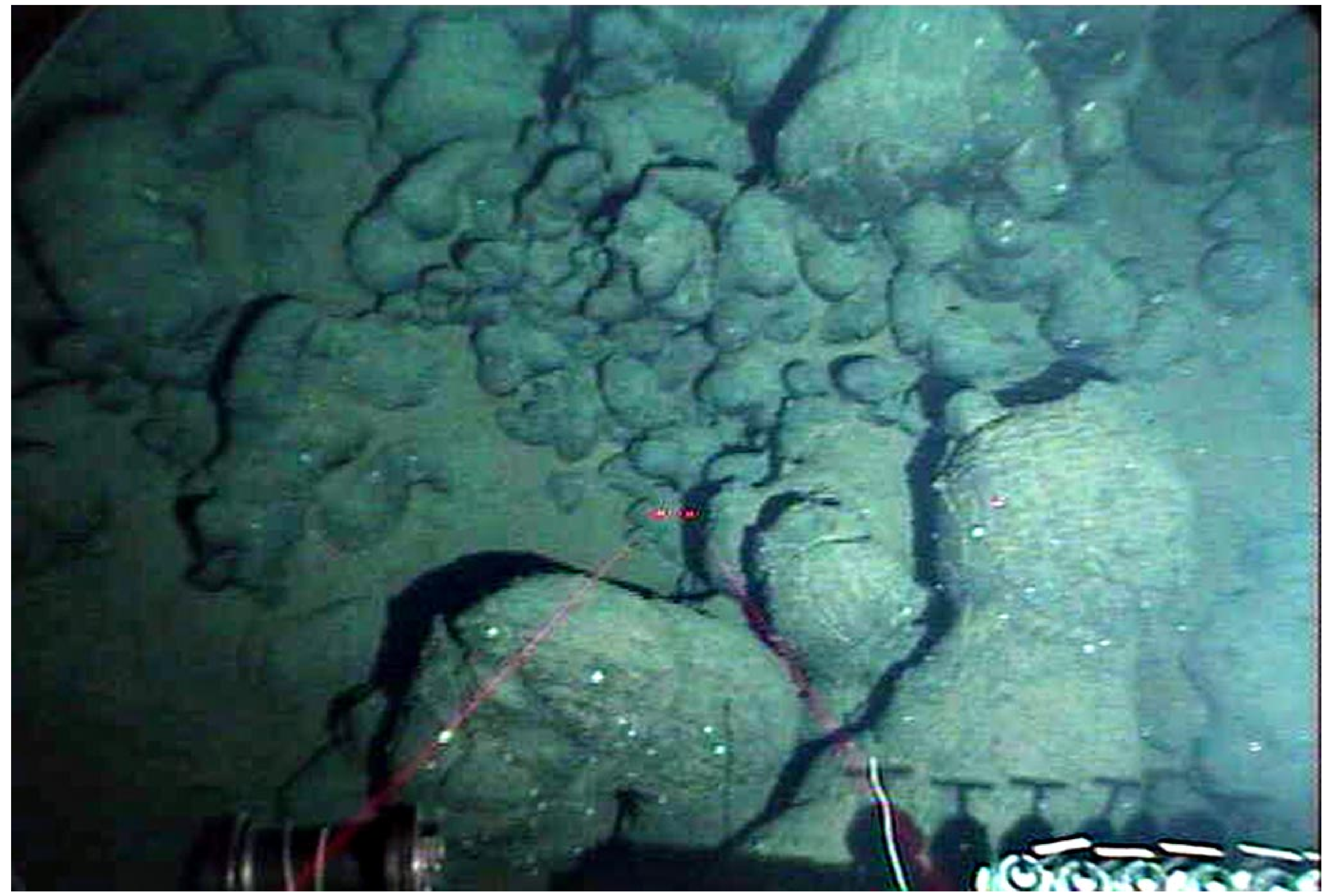

Fig. 1. Deep-sea basalt on the seafloor. Photograph of deep-sea pillow lavas emplaced on the ocean bottom near the Juan de Fuca ridge (data from cruise AT11-16, Alvin Dive 4045; http://4dgeo.whoi.edu). Rounded, intact pillow lavas transition to small cobbles and fragments across the area, forming large interpillow voids. Image scale is ≈1.5 m × 1 m (red laser points are 4 cm apart; water depth is ≈2,200 m).

Available online at www.sciencedirect.com
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Energy Procedia 1 (2009) 4961–4968
Energy Procedia
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GHGT-9

A case for deep-ocean CO_2 sequestration

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Abstract

Carbon sequestration (CO_2 disposal) may be only a temporary measure for bridging from the current situation in which carbon emissions to the atmosphere are unacceptably high and increasing, to a carbon-free economy, but it is a practical and immediate process that can be undertaken. Sequestration methods vary in effectiveness and cost, and each may have different opportunities, benefits, and drawbacks and periods of time over which the CO_2 is retarded from emitting into the atmosphere. Sequestration methods need to be tested on an appropriate scale as quickly as possible because carbon sequestration may help reverse the trend of increasing carbon emissions and remediate the atmosphere for a significant period of time.
Among proposed carbon sequestration technologies, temporary storage of CO_2 in the deep ocean may be the most practicable for many locations, and possibly the most energy efficient and cost-effective. In addition, an important added value benefit may be derived from deep ocean sequestration. A CO_2 hydrate industrial crystallization desalination/disposal process is particularly applicable to oceanic islands and coastal areas adjacent to narrow continental shelves where abyssal depths can be reached by the dense, dissolved CO_2-rich water gravity mass flows composed of processed water rejected from the desalination process.

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oceanic sequestration; CO_2; geoengineering, desalination, climate change

Energy Procedia 1 (2009) 4961–4968

NEWS IN FOCUS

GEOENGINEERING

Ocean-fertilization project off Canada sparks furore

Bid to boost salmon stocks relied on hotly debated science and dubious carbon credits.

BY JEFF TOLLEFSON

When a chartered fishing boat strewed 100 tonnes of iron sulphate into the ocean off western Canada last July, the goal was to supercharge the marine ecosystem. The iron was meant to fertilize plankton, boost salmon populations and sequester carbon. Whether the ocean responded as hoped is not clear, but the project has touched off an explosion on land, angering scientists, embarrassing a village of indigenous people and enraging opponents of geoengineering.

The first reports about the project, which appeared in British newspaper *The Guardian* on 15 October, presented it as a rogue geoengineering scheme — the largest in history — in "blatant violation" of international treaties. Critics suggested that Russ George, a US entrepreneur, had persuaded the Haida Nation village of Old Massett on the Queen Charlotte Islands to fund the project by promising that it would be possible to sell carbon credits for the carbon dioxide taken up by phytoplankton.

The reality was much more complex, and it underscores the combustible politics and uncertain science of geoengineering.

Contacted by *Nature*, George lashed out at the media and "radical environmentalists" for manufacturing a "racist" story about a maverick geoengineer taking advantage of naive natives. "This was their work and their project," he says. "It is not the result of them being too stupid to know better."

It is now clear that Old Massett, a fishing village of fewer than 1,000 people, embraced the project in hopes of restoring dwindling salmon runs by boosting phytoplankton and, in turn, the entire marine food web. Villagers voted in February 2011 to lend Can\$2.5 million (US\$2.5 million) to the Haida Salmon Restoration Corporation (HSRC) to fertilize the ocean, says John Disney, head of the Old Massett-based corporation and economic-development officer for the village. George, who previously headed Planktos, a firm based in San Francisco, California, that had sought to commercialize ocean fertilization using iron, signed on as chief scientist after the HSRC approached him, says Disney. The company planned to repay the village for its loan by selling carbon credits to companies seeking to offset their greenhouse-gas emissions, he adds.


HSRC

Workers on a Haida Salmon Restoration Corporation boat release iron sulphate into the Pacific Ocean.

"We created life where there wasn't life," says Disney, adding that the fertilization fed a phytoplankton bloom of some 10,000 square kilometres, which attracted fish, birds and whales (see 'Sowing controversy'). "The only difference between what we've done and what everybody else has done is that we've taken it up a notch."

In fact, the Old Massett scheme dumped five times more iron than previous fertilization experiments. And no scientists outside the project have seen data that might show whether it worked as advertised. "I'm not going to condemn it offhand, but this is just not the way to do this experiment," says Victor Smetacek, a marine biologist with the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany. "It's quite sophisticated science, and it would have been good if scientists had carried it out."

The project was also on uncertain legal grounds. Ocean fertilization is restricted by a voluntary international moratorium on geoengineering, as well as a treaty on ocean pollution. Both agreements include exemptions for research, and the treaty calls on national environment agencies to regulate experiments. Officials from Environment Canada say that the agency warned project leaders in May that ocean fertilization would require a permit.

"Environment Canada did not approve this non-scientific event," environment minister Peter Kent told Parliament on 18 October. "Enforcement officers are now investigating." The Canadian National Research Council gave nearly Can\$70,000 in funding to the HSRC, and the US National Oceanic and Atmospheric Administration provided 20 buoys to help to monitor water conditions. But officials at those agencies say they were never informed of the ocean-fertilization project, and they thought that the work involved salmon ecology.

Jason Blackstock, a geoengineering expert at the University of Oxford, UK, says that the situation highlights the grey area between geoengineering to alter global climate, and local actions with other goals such as boosting salmon stocks or seeding clouds for weather modification. "This has the potential to become a ubiquitous

SOWING CONTROVERSY
A company backed by a Canadian indigenous group has attempted to fertilize a region of the Pacific Ocean important for salmon stocks.

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Environmental Science & Technology

POLICY ANALYSIS

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Analysis and Status of Post-Combustion Carbon Dioxide Capture Technologies

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Electric Power Research Institute (EPRI), 3420 Hillview Avenue, Palo Alto, California 94304, United States

S *Supporting Information*

ABSTRACT: The Electric Power Research Institute (EPRI) undertook a multiyear effort to understand the landscape of postcombustion CO_2 capture technologies globally. In this paper we discuss several central issues facing CO_2 capture involving scale, energy, and overall status of development. We argue that the scale of CO_2 emissions is sufficiently large to place inherent limits on the types of capture processes that could be deployed broadly. We also discuss the minimum energy usage in terms of a parasitic load on a power plant. Finally, we present summary findings of the landscape of capture technologies using an index of technology readiness levels.

Environ. Sci. Technol. 2011, 45, 8624–8632

A Cheap and Easy Plan to Stop Global Warming

Intentionally engineering Earth's atmosphere to offset rising temperatures could be far more doable than you imagine, says David Keith. But is it a good idea?

By David Rotman on February 8, 2013

Why It Matters

The climate warming resulting from increased levels of carbon dioxide will last at least a thousand years. Geoengineering might be the only way to turn down Earth's thermostat.

Here is the plan. Customize several Gulfstream business jets with military engines and with equipment to produce and disperse fine droplets of sulfuric acid. Fly the jets up around 20 kilometers—significantly higher than the cruising altitude for a commercial jetliner but still well within their range. At that altitude in the tropics, the aircraft are in the lower stratosphere. The planes spray the sulfuric acid, carefully controlling the rate of its release. The sulfur combines with water vapor to form sulfate aerosols, fine particles less than a micrometer in diameter. These get swept upward by natural wind patterns and are dispersed over the globe, including the poles. Once spread across the stratosphere, the aerosols will reflect about 1 percent of the sunlight hitting Earth back into space. Increasing what scientists call the planet's albedo, or reflective power, will partially offset the warming effects caused by rising levels of greenhouse gases.

Research Articles

Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans

Richard A. Feely,[1,*] Christopher L. Sabine,[1] Kitack Lee,[2] Will Berelson,[3] Joanie Kleypas,[4] Victoria J. Fabry,[5] Frank J. Millero[6]

Rising atmospheric carbon dioxide (CO_2) concentrations over the past two centuries have led to greater CO_2 uptake by the oceans. This acidification process has changed the saturation state of the oceans with respect to calcium carbonate ($CaCO_3$) particles. Here we estimate the in situ $CaCO_3$ dissolution rates for the global oceans from total alkalinity and chlorofluorocarbon data, and we also discuss the future impacts of anthropogenic CO_2 on $CaCO_3$ shell–forming species. $CaCO_3$ dissolution rates, ranging from 0.003 to 1.2 micromoles per kilogram per year, are observed beginning near the aragonite saturation horizon. The total water column $CaCO_3$ dissolution rate for the global oceans is approximately 0.5 ± 0.2 petagrams of $CaCO_3$-C per year, which is approximately 45 to 65% of the export production of $CaCO_3$.

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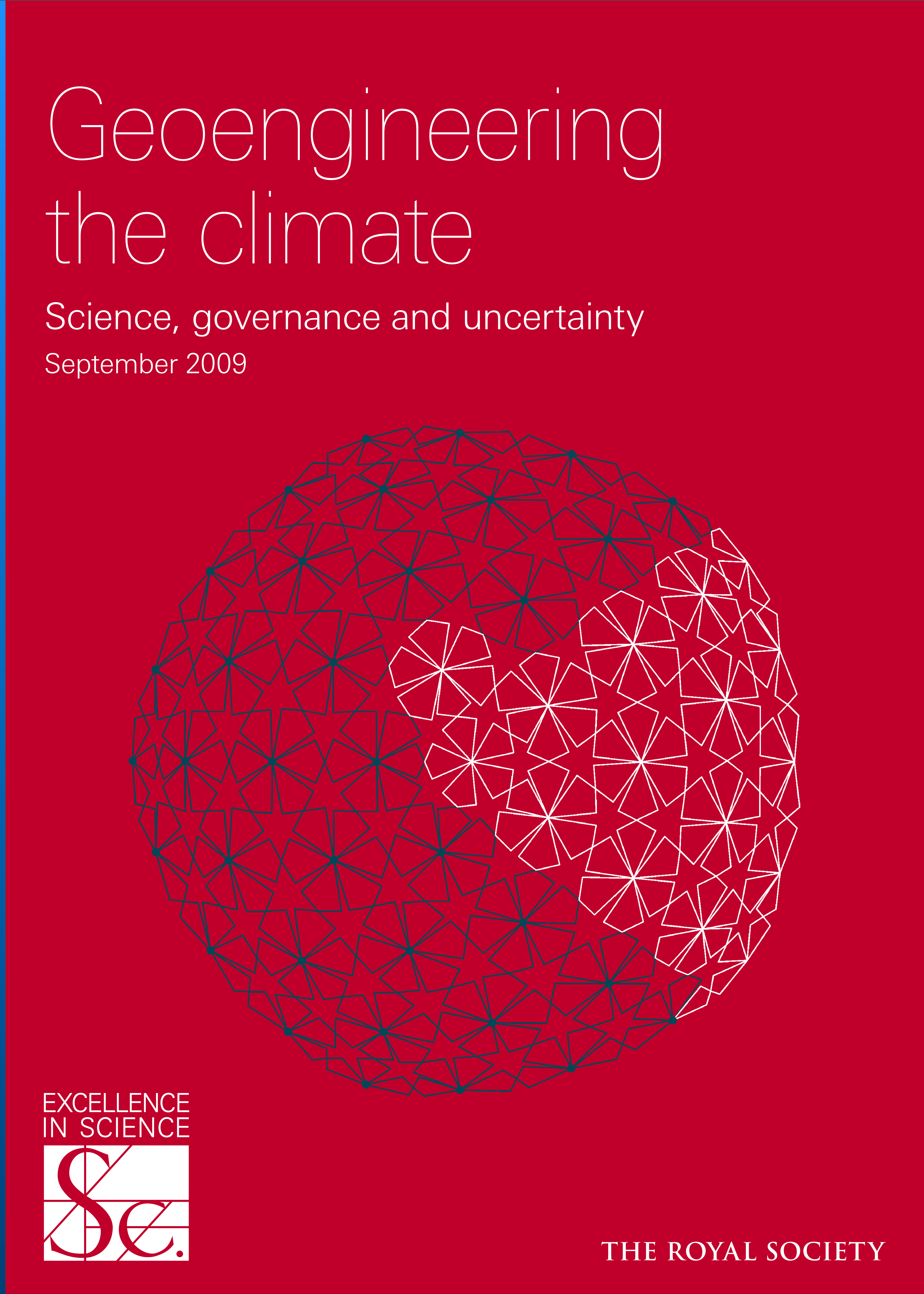


Geoengineering the climate

Science, governance and uncertainty

September 2009

EXCELLENCE IN SCIENCE

THE ROYAL SOCIETY

Monday, March 11, 13

The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques

Conference Report

Prepared by the

Asilomar Scientific Organizing Committee

November 2010

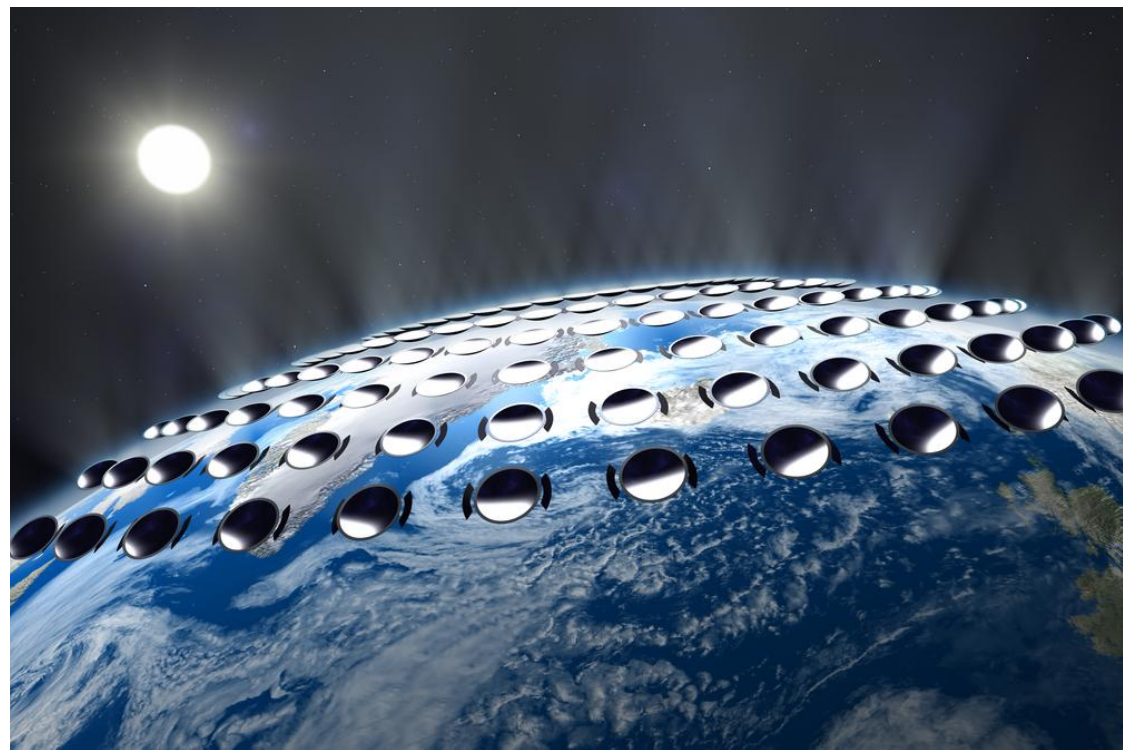
Climate Institute
Washington DC

NATURAL
ENVIRONMENT
RESEARCH COUNCIL

sciencewise
EXPERT RESOURCE CENTRE

FINAL REPORT
Prepared for the Natural Environment Research Council and Sciencewise-ERC

Evaluation of 'Experiment Earth?' Public Dialogue on Geoengineering



Experiment Earth?
Public Dialogue on Geoengineering

March 2011

Collingwood Environmental Planning Limited

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A New Iron Age, Or A Ferric Fantasy

by John H. Martin

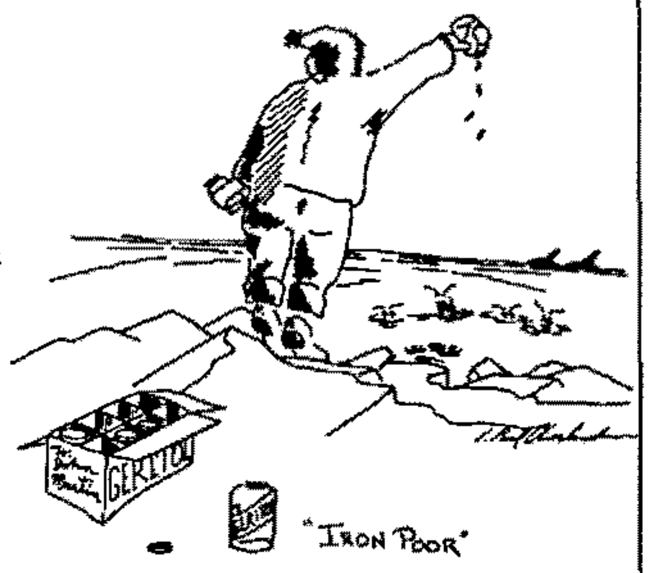

Illustration by E. Paul Oberlander

I first became interested in iron in the ocean at a U.S. JGOFS steering committee meeting in San Francisco during December 1986 at which Bruce Frost of the University of Washington gave an excellent briefing on the abundance of unused major nutrients in the offshore waters surrounding Antarctica.

Bruce outlined various hypotheses concerned with cold temperatures, low light levels, high grazing rates and the like. After his presentation I told him that I enjoyed his talk, but that the real reason for the nonutilization of major nutrients was Fe deficiency, after all.

Bruce smiled, covered his ears and said that it was too simple and he didn't want to hear about it. Jim McCarthy of Harvard University's Museum of Comparative Zoology joined us and soon said that he didn't want to hear about iron either. Naturally, this good-natured challenge made me all the more anxious to tell them about it. In order to do so, I had to quit bluffing and see if there really was any serious evidence for oceanic Fe deficiency.

After I returned to my office at Moss Landing Marine Laboratories, I started to go through the clutter on my desk. After some frantic digging, I found a top-quality Fe data set produced by my MLML associate Mike Gordon plus a reprint from Bob Duce, the famed atmospheric chemist from the University of Rhode Island.

Bob estimated that fallout of iron-rich atmospheric dust provided about 50% of the Fe needed by open-ocean phytoplankton. I plugged Mike Gordon's latest Fe numbers into Bob's formula, and the new estimate suggested that 95%, not 50%, of the phytoplankton's Fe requirement had to come from fallout from the atmosphere. It also suggested that the deep ocean water in the Pacific, once raised to the surface, was basically infertile because it didn't contain enough iron to allow the phytoplankton to make use of the available NO_3.

From my old days with Bob Duce in the IDOE (International Decade of Ocean Exploration) Pollutant Transfer Program, I recalled that the dust input into the Antarctic was very low. Looking for a more recent Antarctic estimate, I came across the French/Soviet Vostok ice core work of De Angelis and his colleagues, which showed that the present-day dust level was indeed very low. During the ice ages, however, it had been much higher.

My investigation led me onward to the scenario created by talented Princeton modelers Jorge Sarmiento and Robbie Toggweiler concerning atmospheric carbon dioxide, the biological pump and the use or nonuse of major nutrients in the Southern Ocean.

Then another French/Soviet team of glaciologists (Barnola et al.) published their CO_2 data from the Vostok ice core. When the Vostok Fe data were superimposed on the CO_2 data, the result was a striking inverse relationship. Mutterings increased from the growing numbers of Fe skeptics.

A desire to learn more about the Antarctic led me to a review of the expedition of the British research vessel *Discovery*. Those were the days (1925-27) when persons were persons and the scientists were gone for three years!

Sir Alister Hardy F.R.S. describes this monumental effort in writing, water color and fascinating detail in his book *Great Waters*. The British scientists went to the Antarctic to study the relationship between phytoplankton, krill and the whale fishery.

While reading the book through my iron-glazed eyes, I looked for evidence in support of the Fe hypothesis and noted the mention of great abundance of phytoplankton and krill, not to mention whales, on the shallow, iron-rich South Georgia whaling grounds. To my surprise and

(Cont. on page 11)

JGOFS-IGAC Cooperation Planned On Ocean/Atmosphere Interactions

Recognizing their common interest in understanding the biogeochemical exchanges between the atmosphere and the ocean, a working group of representatives of the Joint Global Ocean Flux Study (JGOFS), the International Global Atmospheric Chemistry (IGAC) program and the International Geosphere-Biosphere Programme (IGBP) got together in San Francisco last December to define overlapping areas of interest and look for ways to work together.

Peter Liss from IGBP served as chairman. Also attending were IGBP representatives Patrick Holligan and James McCarthy. JGOFS participants were Richard Gammon, Margaret Leinen and John Martin. Robert Charlson, Robert Duce and Joseph Prospero represented IGAC, and David Hurd attended from the National Science Foundation.

The meeting was held under the aegis of IGBP's Coordinating Panel 2. Both JGOFS and IGAC have been designated as IGBP core programs.

Participants agreed that certain important biogeochemical interactions require interdisciplinary investigation. JGOFS and IGAC are linked, the meeting report noted, by "the recognition that the living ocean strongly modifies the trace gas composition of the atmosphere and that, for climate prediction, experimental and modeling studies of this interaction are required, and further that atmospheric deposition can affect ocean productivity."

Among the scientific topics discussed was the issue of atmospheric inputs to the oceans. Discussion focused on three aspects of the problem: the effect of clouds and ozone on the quantity and quality of light at the ocean surface; the deposition of continental dust as a source of iron for open ocean phytoplankton, and the supply of nutrients such as nitrogen and ammonium to the surface waters in the form of aerosols.

Ocean inputs to the atmosphere formed the next topic. Workshop participants discussed the role of emissions of dimethylsulfide, a byproduct of algal metabolism, in the atmospheric sulfur budget, the formation of cloud condensation nuclei and the acid-base chemistry of rainwater. Also discussed were a

(Cont. on page 6)

"Give me half a tanker of iron, and I'll give you an ice age"

John H. Martin


“Give me half a tanker of iron, and I’ll give you an ice age”

The Iron Hypothesis

J. Phycol. **39,** 1145–1159 (2003)

THE ELEMENTAL COMPOSITION OF SOME MARINE PHYTOPLANKTON[1]

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Paul G. Falkowski

Environmental Biophysics and Molecular Ecology Program, Institute of Marine and Coastal Sciences, Rutgers University, New Jersey 08901, USA; and Department of Geology, Rutgers University, New Jersey 08901, USA

and

François M. M. Morel

Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA

We analyzed the cellular content of C, N, P, S, K, Mg, Ca, Sr, Fe, Mn, Zn, Cu, Co, Cd, and Mo in 15 marine eukaryotic phytoplankton species in culture representing the major marine phyla. All the organisms were grown under identical culture conditions, in a medium designed to allow rapid growth while minimizing precipitation of iron hydroxide. The cellular concentrations of all metals, phosphorus, and sulfur were determined by high-resolution inductively coupled plasma mass spectrometry (HR-ICPMS) and those of carbon and nitrogen by a carbon hydrogen nitrogen analyzer. Accuracy of the HR-ICPMS method was validated

results with published data suggests that the measured compositions reflect chiefly the intrinsic (i.e. genetically encoded) trace element physiology of the individual species. Published field data on the composition of the planktonic biomass fall within the range of laboratory values and are generally close to the approximate extended Redfield formula given by the average stoichiometry of our model species (excluding the hard parts):

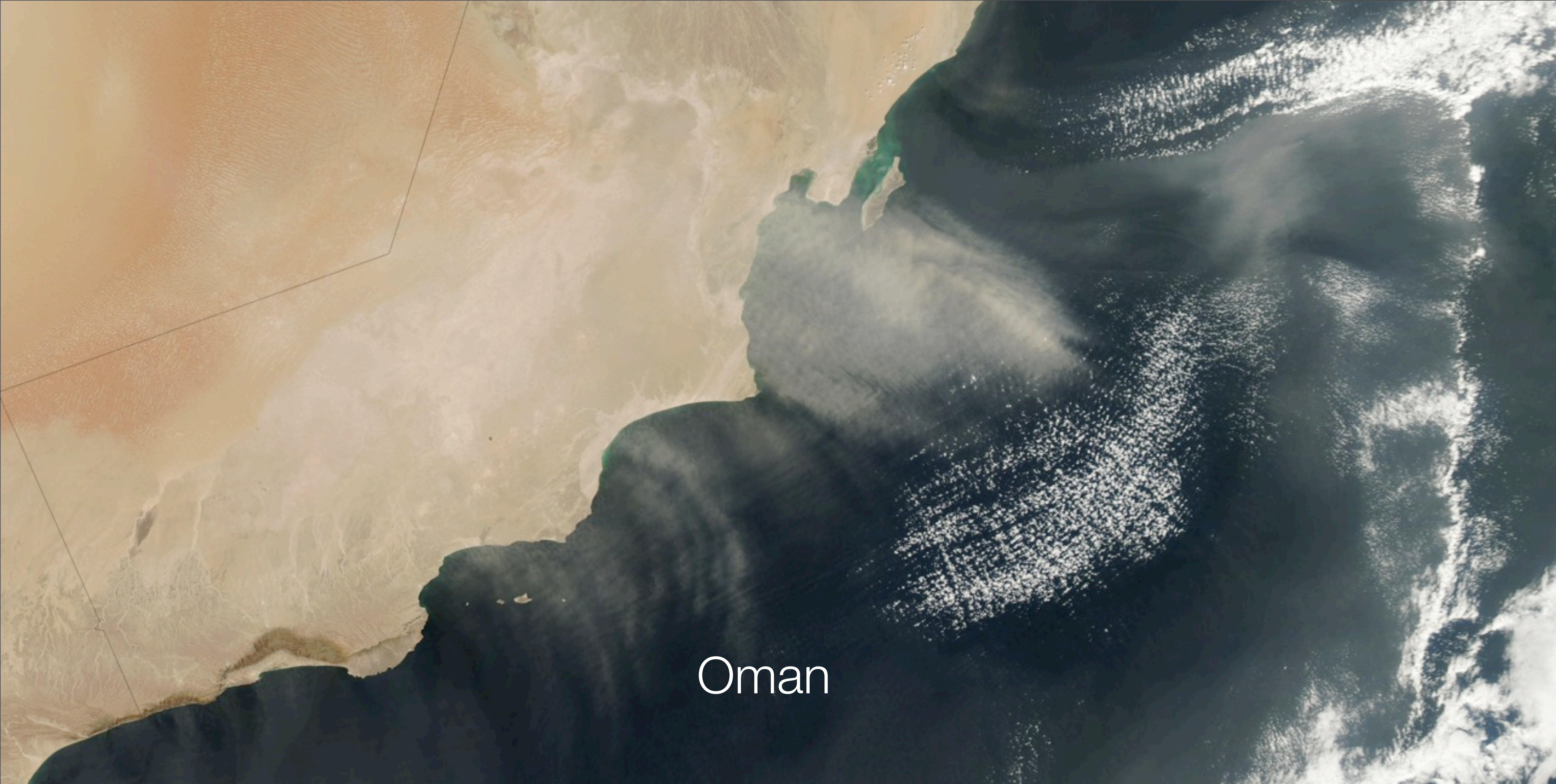
$$(C_{124}N_{16}P_{1}S_{1.3}K_{1.7}Mg_{0.56}Ca_{0.5})_{1000}Sr_{5.0}Fe_{7.5}Zn_{0.80}Cu_{0.38}Co_{0.19}Cd_{0.21}Mo_{0.03}$$

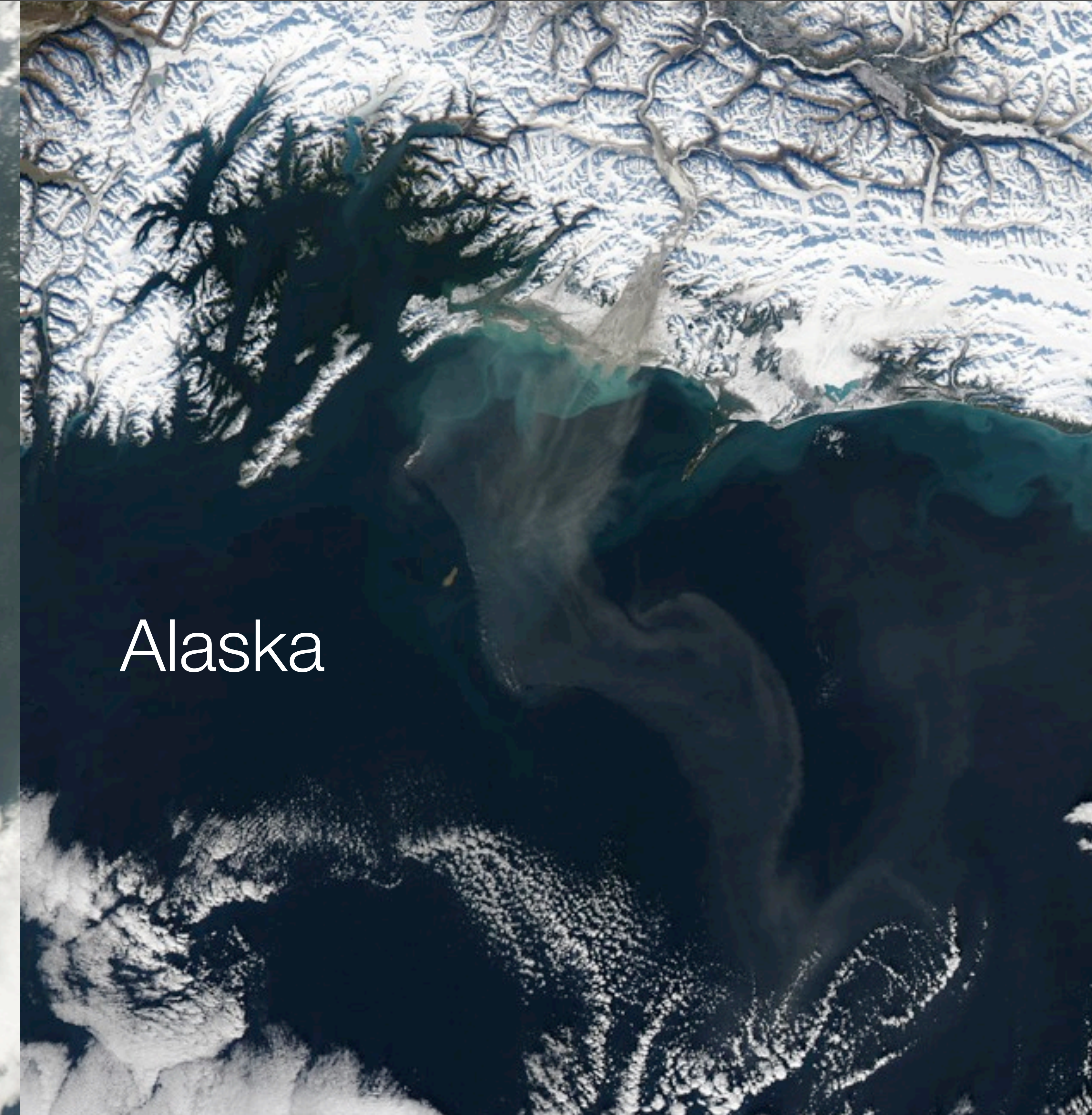
THE ELEMENTAL COMPOSITION OF SOME MARINE PHYTOPLANKTON

$$(C_{124}N_{16}P_{1}S_{1.3}K_{1.7}Mg_{0.56}Ca_{0.5})_{1000}$$

$$Sr_{5.0}Fe_{7.5}Zn_{0.80}Cu_{0.38}Co_{0.19}Cd_{0.21}Mo_{0.03}$$

$$C/Fe = 16{,}500:1$$


Oman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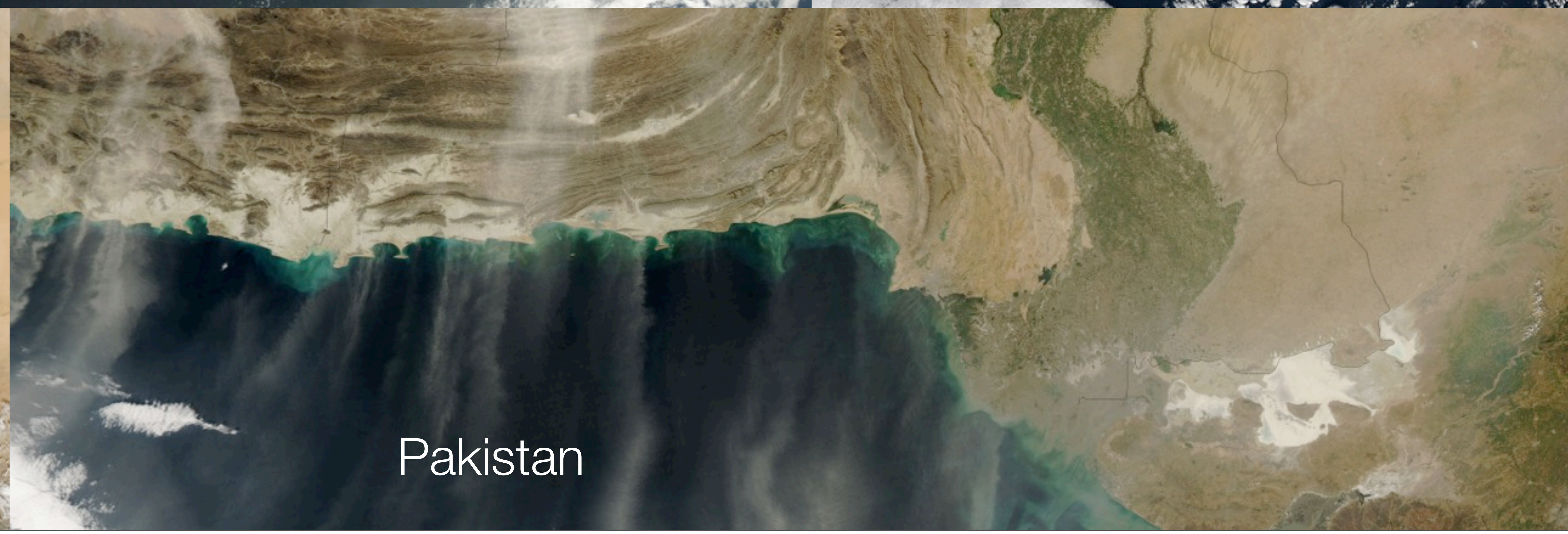
West Africa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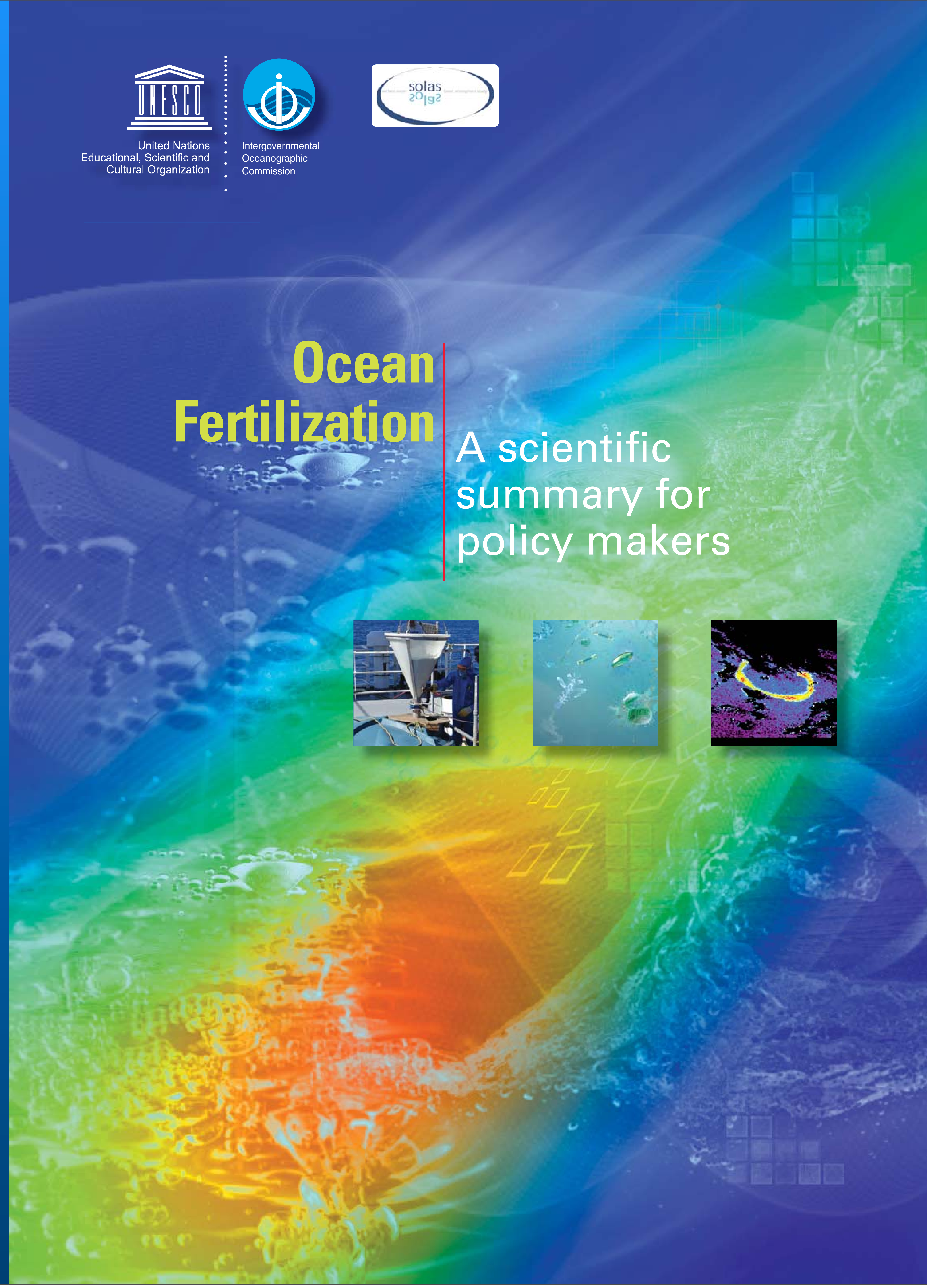
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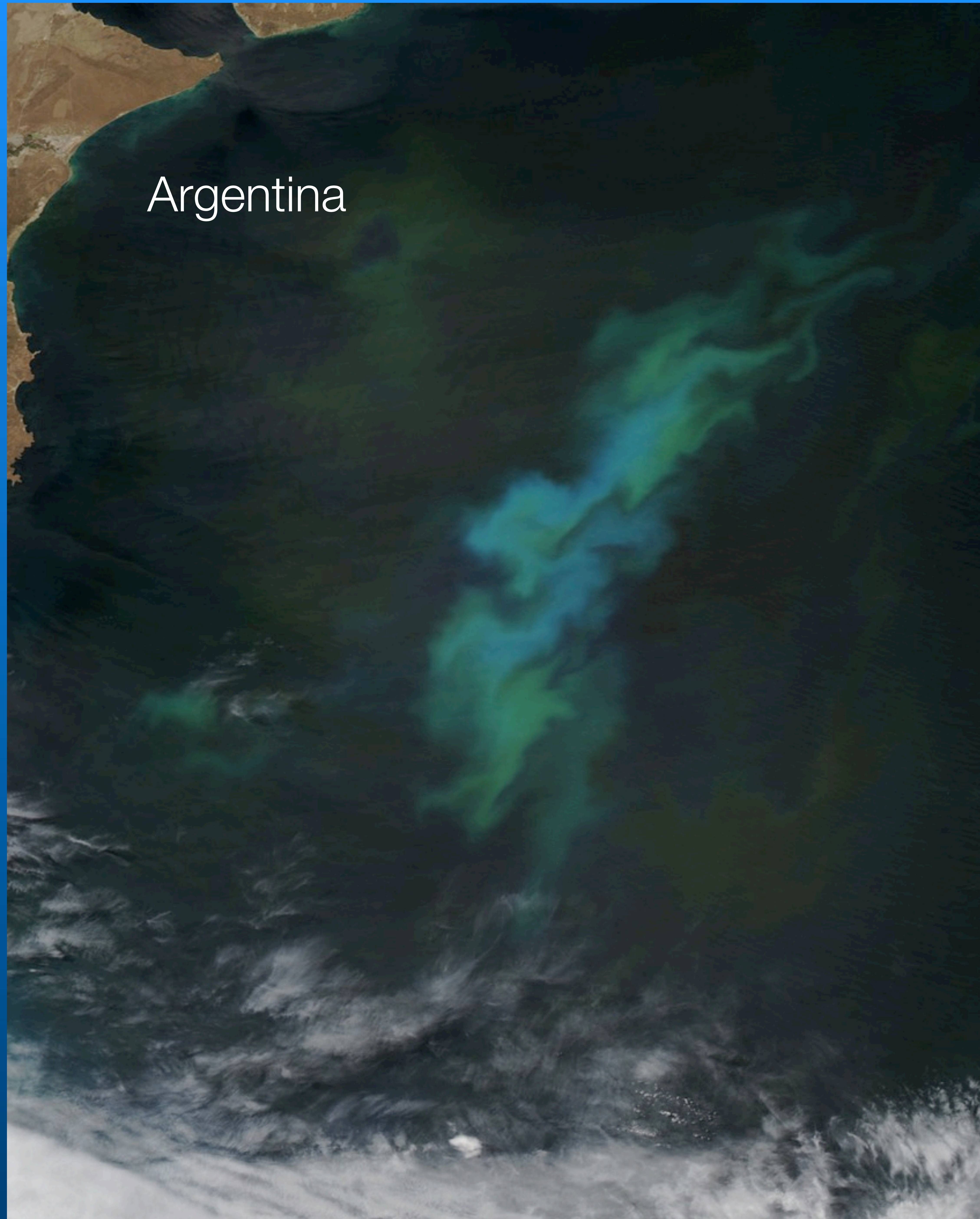
A scientific
summary for
policy makers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Ocean iron fertilization in the context of the Kyoto protocol and the post-Kyoto process

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A R T I C L E I N F O

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A B S T R A C T

Ocean iron fertilization is currently discussed as a potential measure to mitigate climate change by enhancing oceanic CO_2 uptake. Its mitigation potential is not yet well explored, and carbon offsets generated through iron fertilization activities could currently not be traded on regulated carbon markets. Still, commercial interests in ocean iron fertilization already exist, which underlines the need to investigate a possible regulatory framework for it. To this end, I first discuss important basic aspects of ocean iron fertilization, namely its scientific background, quantitative potential, side effects, and costs. In a second step, I review regulatory aspects connected to ocean iron fertilization, like its legal status and open access issues. Moreover, I analyze how the regulations for afforestation and reforestation activities within the framework of the Kyoto Clean Development Mechanism (CDM) could be applied to ocean iron fertilization. Main findings are that the quantitative potential of ocean iron fertilization is limited, that costs are higher than initially hoped, and that potential adverse side effects are severe. Moreover, the legal status of ocean iron fertilization is currently not well defined, open access might cause inefficiencies, and the CDM regulations could not be easily applied to ocean iron fertilization.

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ARTICLE

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Deep carbon export from a Southern Ocean iron-fertilized diatom bloom

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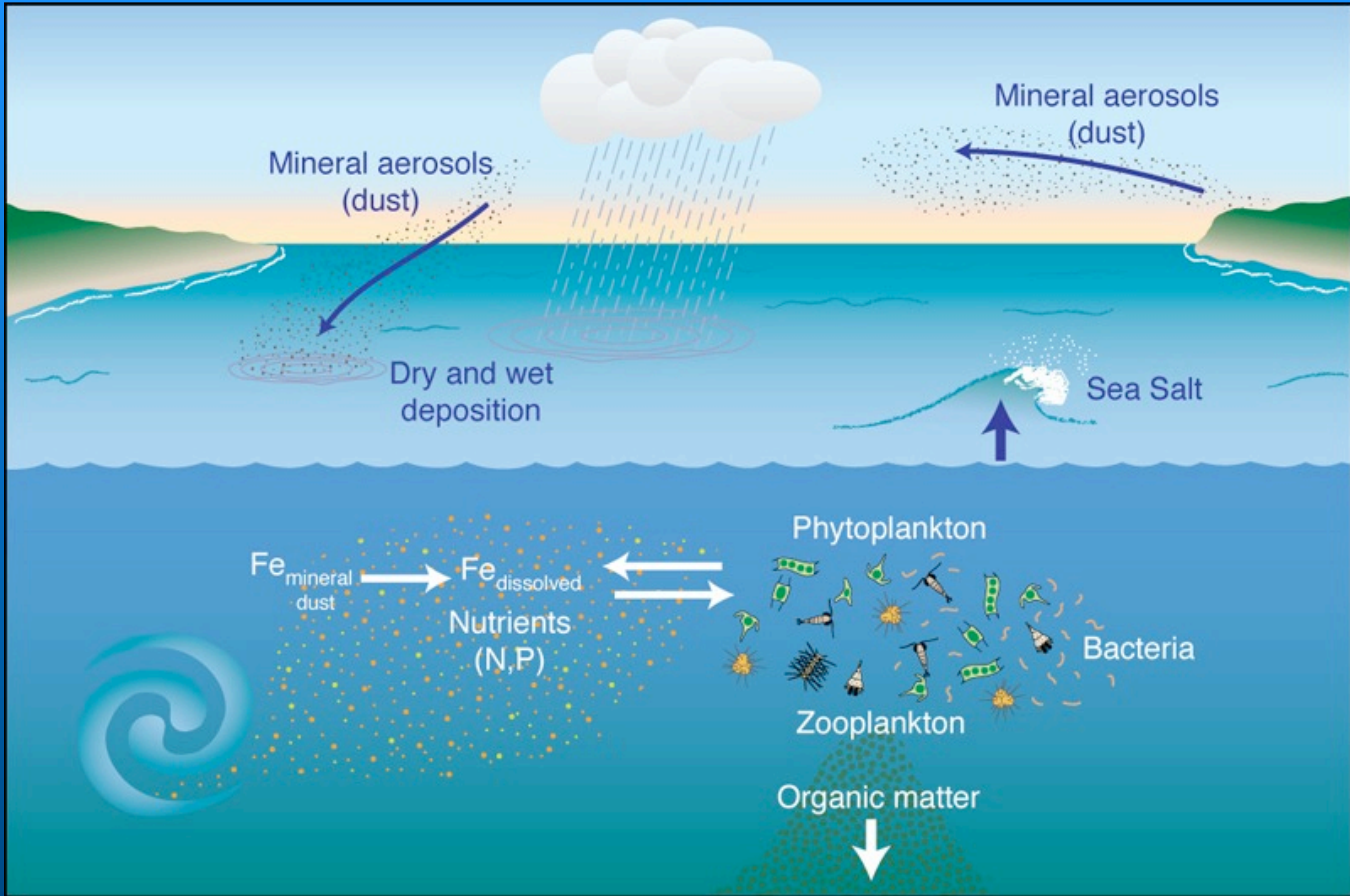
Fertilization of the ocean by adding iron compounds has induced diatom-dominated phytoplankton blooms accompanied by considerable carbon dioxide drawdown in the ocean surface layer. However, because the fate of bloom biomass could not be adequately resolved in these experiments, the timescales of carbon sequestration from the atmosphere are uncertain. Here we report the results of a five-week experiment carried out in the closed core of a vertically coherent, mesoscale eddy of the Antarctic Circumpolar Current, during which we tracked sinking particles from the surface to the deep-sea floor. A large diatom bloom peaked in the fourth week after fertilization. This was followed by mass mortality of several diatom species that formed rapidly sinking, mucilaginous aggregates of entangled cells and chains. Taken together, multiple lines of evidence—although each with important uncertainties—lead us to conclude that at least half the bloom biomass sank far below a depth of 1,000 metres and that a substantial portion is likely to have reached the sea floor. Thus, iron-fertilized diatom blooms may sequester carbon for timescales of centuries in ocean bottom water and for longer in the sediments.



http://www.whoi.edu/science/MCG/dept/facilities/sea_aer/maintextpg.html

NATURE . VOL 383 . 10 OCTOBER 1996

A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean

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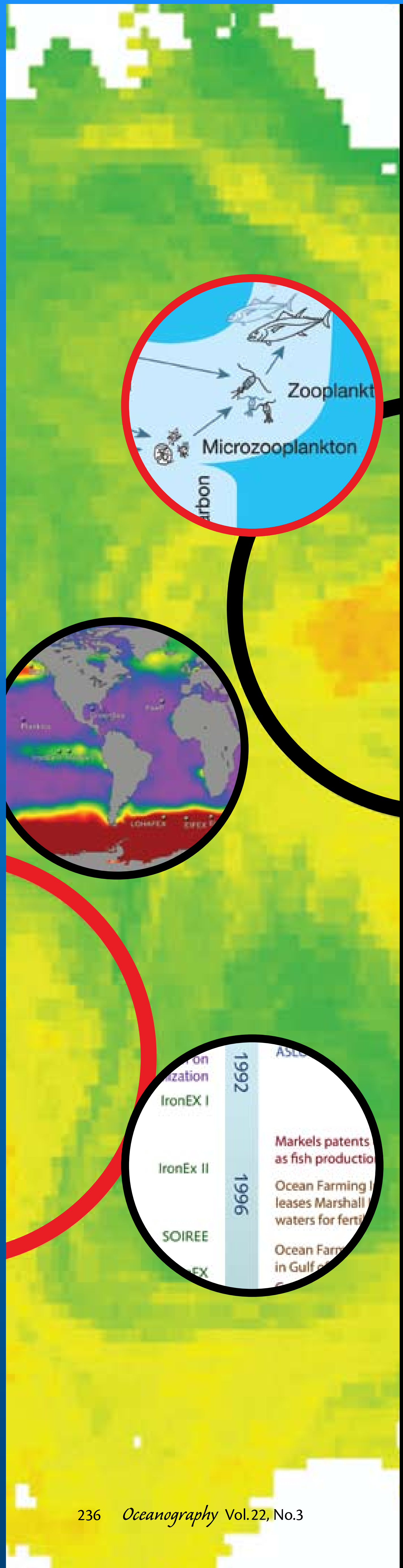
The seeding of an expanse of surface waters in the equatorial Pacific Ocean with low concentrations of dissolved iron triggered a massive phytoplankton bloom which consumed large quantities of carbon dioxide and nitrate that these microscopic plants cannot fully utilize under natural conditions. These and other observations provide unequivocal support for the hypothesis that phytoplankton growth in this oceanic region is limited by iron bioavailability.



Ocean Fertilization

Science, Policy, and Commerce

BY AARON L. STRONG, JOHN J. CULLEN,
AND SALLIE W. CHISHOLM

ABSTRACT. Over the past 20 years there has been growing interest in the concept of fertilizing the ocean with iron to abate global warming. This interest was catalyzed by basic scientific experiments showing that iron limits primary production in certain regions of the ocean. The approach—considered a form of "geoengineering"—is to induce phytoplankton blooms through iron addition, with the goal of producing organic particles that sink to the deep ocean, sequestering carbon from the atmosphere. With the controversy surrounding the most recent scientific iron fertilization experiment in the Southern Ocean (LOHAFEX) and the ongoing discussion about restrictions on large-scale iron fertilization activities by the London Convention, the debate about the potential use of iron fertilization for geoengineering has never been more public or more pronounced. To help inform this debate, we present a synoptic view of the two-decade history of iron fertilization, from scientific experiments to commercial enterprises designed to trade credits for ocean fertilization on a developing carbon market. Throughout these two decades there has been a repeated cycle: Scientific experiments are followed by media and commercial interest and this triggers calls for caution and the need for more experiments. Over the years, some scientists have repeatedly pointed out that the idea is both unproven and potentially ecologically disruptive, and models have consistently shown that at the limit, the approach could not substantially change the trajectory of global warming. Yet, interest and investment in ocean fertilization as a climate mitigation strategy have only grown and intensified, fueling media reports that have misconstrued scientific results, and conflated scientific experimentation with geoengineering. We suggest that it is time to break this two-decade cycle, and argue that we know enough about ocean fertilization to say that it should not be considered further as a means to mitigate climate change. But, ocean fertilization research should not be halted: if used appropriately and applied to testable hypotheses, it is a powerful research tool for understanding the responses of ocean ecosystems in the context of climate change.

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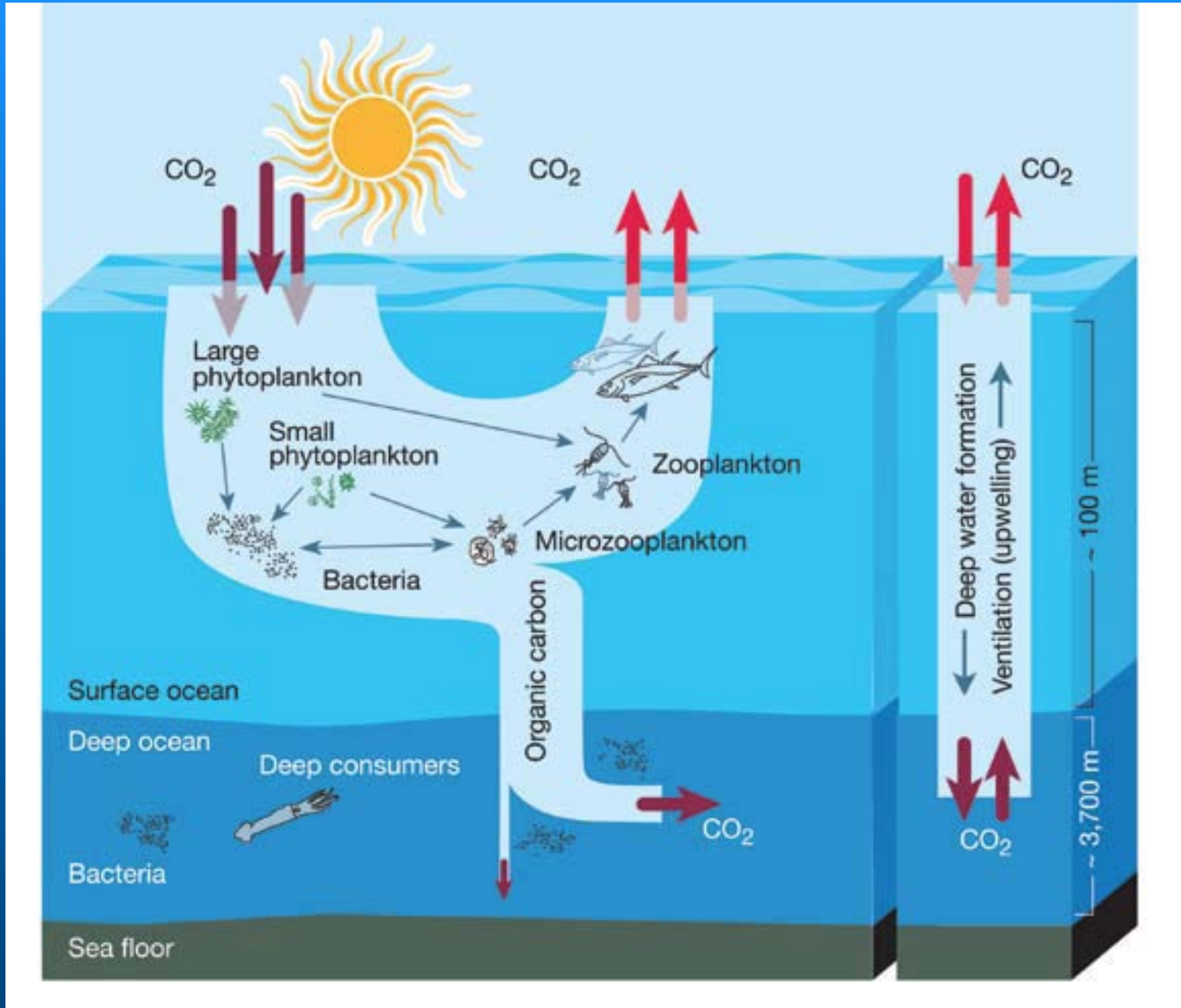


CO_2
CO_2
CO_2
Large phytoplankton
Small phytoplankton
Zooplankton
Microzooplankton
Bacteria
Organic carbon
Deep water formation
Ventilation (upwelling)
~ 100 m
Surface ocean
Deep ocean
Deep consumers
CO_2
CO_2
~ 3,700 m
Bacteria
Sea floor

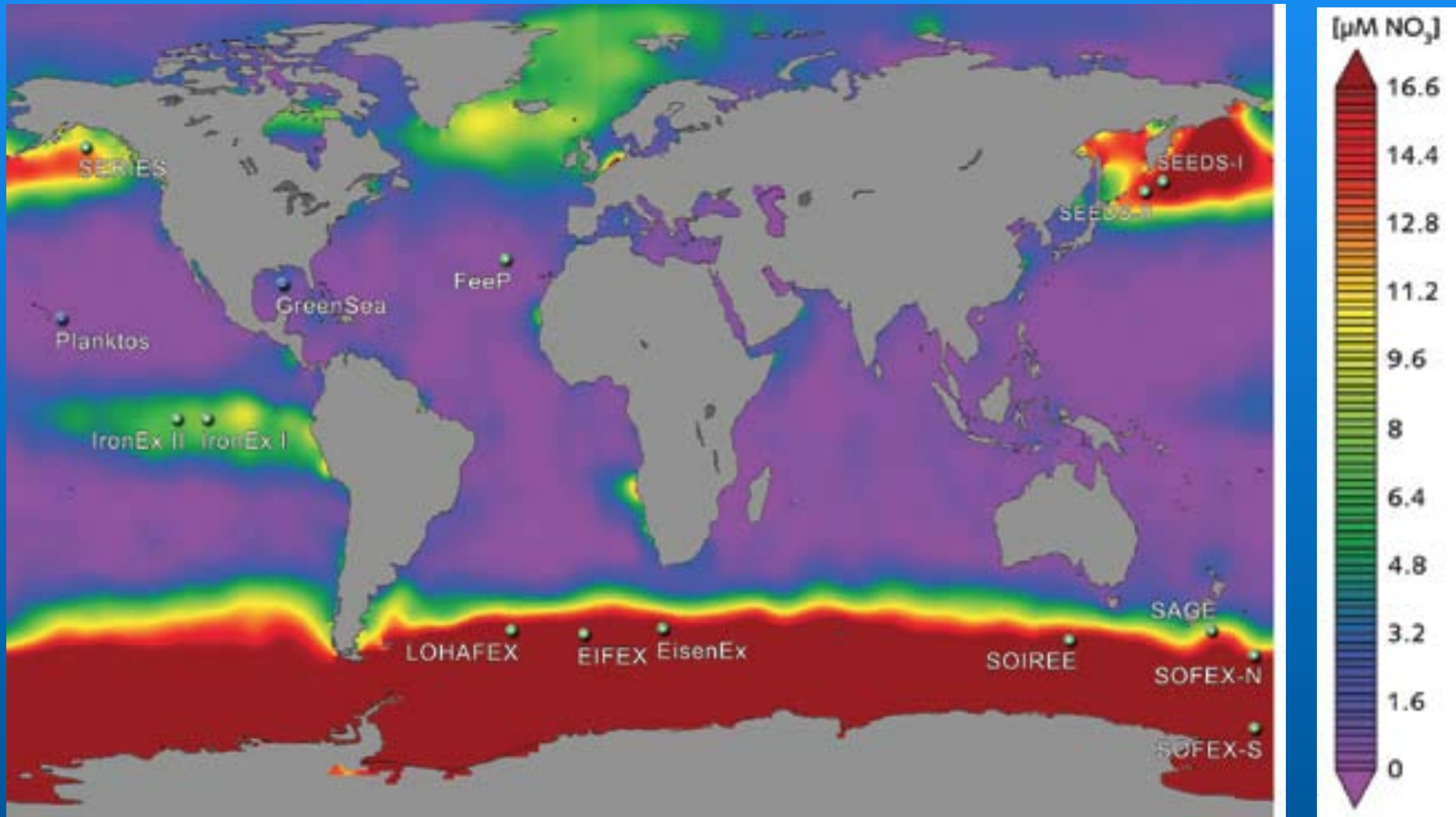


Figure 4. Locations of major artificial iron enrichment experiments, including the pilot demonstrations of GreenSea Venture and Planktos. Color heat map represents surface nitrate concentrations with warmer colors indicating higher concentrations, showing three major HNLC regions in the Southern Ocean, the eastern equatorial Pacific, and the subarctic Pacific. Data from National Virtual Ocean Data System, http://ferret.pmel.noaa.gov/NVODS/; analyzed nitrate data from the World Ocean Atlas 2005

Will Ocean Fertilization Work?

Ken O. Buesseler and Philip W. Boyd

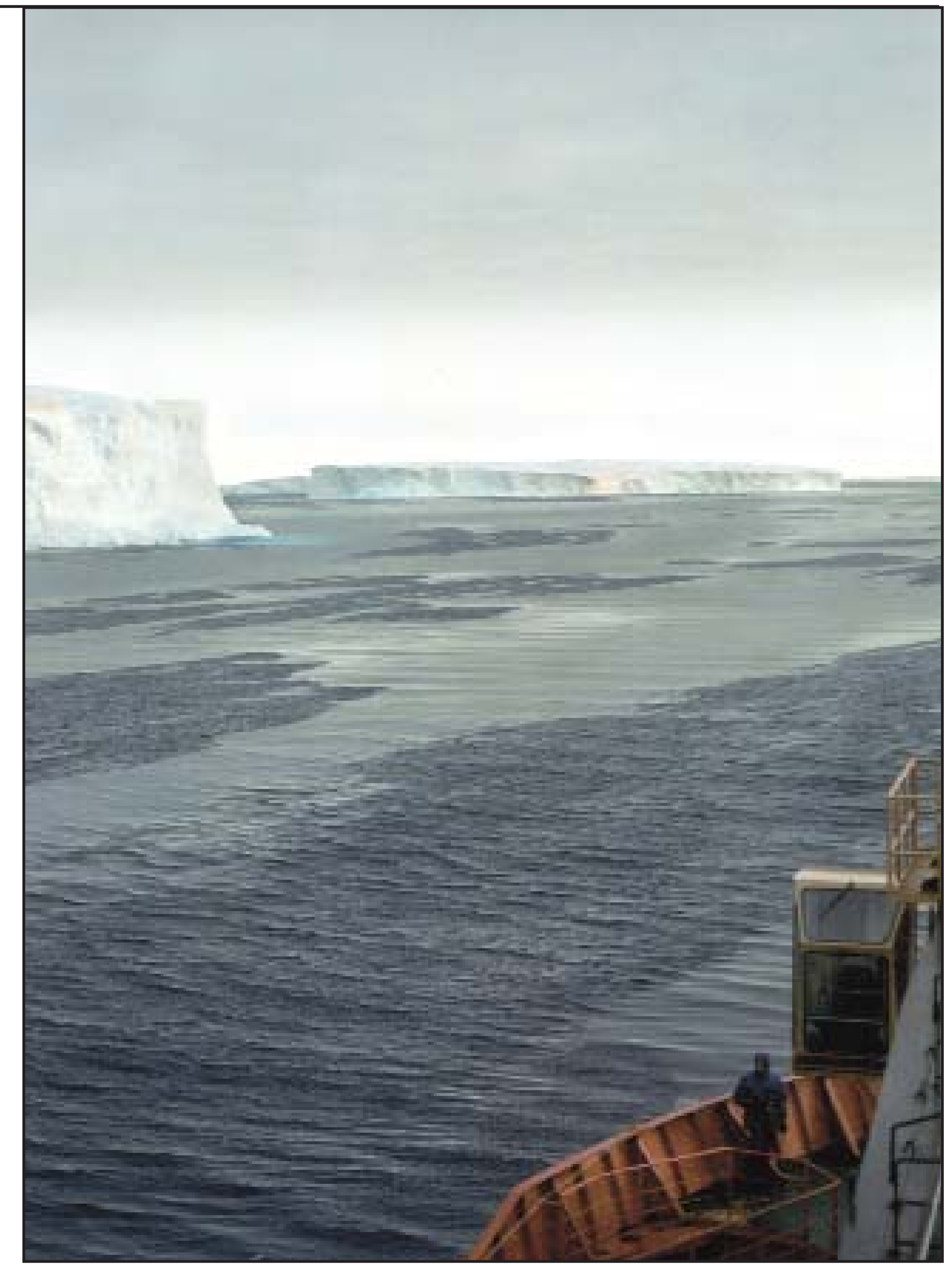
Iron fertilization of the ocean—a potential strategy to remove CO_2 from the atmosphere—has generated much debate among ocean and climate scientists (*1–4*). It is viewed as particularly attractive by geoengineers because the addition of relatively small amounts of iron to certain ocean regions may lead to a large increase in carbon sequestration at a relatively low financial cost.

To assess whether iron fertilization has potential as an effective sequestration strategy, we need to measure the ratio of iron added (Fe_{add}) to the amount of carbon sequestered (C_{seq}) (in the form of sinking particulate organic carbon, POC) to the deep ocean in field studies. We must then apply appropriate scaling factors to determine whether globally significant quantities of CO_2 can be removed from the atmosphere to the deep ocean in this way.

The Southern Ocean (see the figure) is the most important region for possible climate regulation by iron fertilization. In this high-nitrate low-chlorophyll (HNLC) region, large quantities of surface macronutrients return to the deep ocean via the flow of intermediate and deep waters. According to the "iron hypothesis" (*5*), adding iron to these nutrient-rich surface waters will increase phytoplankton biomass, resulting in increased uptake of CO_2 by the phytoplankton living in the surface ocean.

In the Southern Ocean, there have been three open-ocean iron-enrichment experiments: SOIREE (Southern Ocean Iron Enrichment Experiment) (*6*), EisenEx-1 [Eisen(=Iron) Experiment] (*7*), and SOFeX (Southern Ocean Iron Experiment) (*8*). All three produced notable increases in biomass and associated decreases in dissolved inorganic carbon and macronutrients. However, evidence of sinking particles carrying POC to the deep ocean was limited.

SOIREE (a 13-day experiment) and EisenEx-1 (21 days) showed no difference between particle fluxes in the fertilized and nonfertilized waters (*7*, *9–10*). During SOFeX (28 days), we observed in the fer-



Exploring the Southern Ocean. The research and supply vessel *Aurora Australis* heads into an iceberg field off Antarctica.

K. O. Buesseler is at Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. E-mail: kbuesseler@whoi.edu P. W. Boyd is at the Centre of Physical and Chemical Oceanography, National Institute for Water and Atmospheric Research, Department of Chemistry, University of Otago, Dunedin 9001, New Zealand. E-mail: p.boyd@niwa.co.nz

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Monday, March 11, 13

ENVIRONMENT

Ocean Iron Fertilization—Moving Forward in a Sea of Uncertainty

It is premature to sell carbon offsets from ocean iron fertilization unless research provides the scientific foundation to evaluate risks and benefits.

Ken O. Buesseler,[1]* Scott C. Doney,[1] David M. Karl,[2] Philip W. Boyd,[3] Ken Caldeira,[4] Fei Chai,[5] Kenneth H. Coale,[6] Hein J. W. de Baar,[7] Paul G. Falkowski,[8] Kenneth S. Johnson,[9] Richard S. Lampitt,[10] Anthony F. Michaels,[11] S. W. A. Naqvi,[12] Victor Smetacek,[13] Shigenobu Takeda,[14] Andrew J. Watson[15]

The consequences of global climate change are profound, and the scientific community has an obligation to assess the ramifications of policy options for reducing greenhouse gas emissions and enhancing CO_2 sinks in reservoirs other than the atmosphere (*1*, *2*).

Ocean iron fertilization (OIF), one of several ocean methods proposed for mitigating rising atmospheric CO_2, involves stimulating net phytoplankton growth by releasing iron to certain parts of the surface ocean. The international oceanographic community has studied OIF, including 12 major field programs with small-scale, purposeful releases of iron since 1993 (*3*, *4*). Although these experiments greatly improved our understanding of the role of iron in regulating ocean ecosystems and carbon dynamics, they were not designed to characterize OIF as a carbon mitigation strategy. The efficacy by which OIF sequesters atmospheric CO_2 to the deep sea remains poorly constrained, and we do not understand the intended and unintended biogeochemical and ecological impacts. Environmental perturbations from OIF are nonlocal and are spread over a large area by ocean circulation, which makes long-term verification and assessment very difficult. Modeling studies have addressed sequestration more directly and have suggested that OIF in areas of persistent high nutrients (so-called high-nutrient, low-chlorophyll areas) would be unlikely to sequester more than several hundred million tons of carbon per year. Thus, OIF could make only a partial contribution to mitigation of global CO_2 increases.

Despite these uncertainties in the science, private organizations are making plans to conduct larger-scale iron releases to generate carbon offsets. We are convinced that, as yet, there is no scientific basis for issuing such carbon credits for OIF. Adequate scientific information to enable a decision regarding whether credits should be issued could emerge from reducing uncertainties; this will only come through targeted research programs with the following specific attributes:

- Field studies on larger spatial and longer time scales, because ecological impacts and CO_2 mitigation are scale-dependent.
- Consideration of OIF in high- and low-nutrient regions to understand a wider range of processes that are affected by iron, such as nitrogen fixation and elemental stoichiometry.
- Detailed measurements in the subsurface ocean to verify the fate of fixed carbon, including remineralization length scales of carbon, iron, and associated elements.
- Broad assessment of ecological impacts from bacteria and biogeochemistry to fish, seabirds, and marine mammals.
- Characterization of changes to oxygen distributions, biophysical climate feedbacks, and cycling of non-CO_2 greenhouse gases, such as methane, nitrous oxide, and dimethylsulfide.
- Long-term monitoring and use of models to assess downstream effects beyond the study area and observation period.
- Improved modeling studies of the results and consequences of OIF, including higher spatial resolution, better ecosystem parameterization, inclusion of other greenhouse gases, and improved iron biogeochemistry.
- Analysis of the costs, benefits, and impacts of OIF relative to other climate and carbon mitigation schemes and to the impacts of global change if we take no action.

The organization of such experiments is as critical as the scientific design. The scope of the problem will require individual sponsors and partnerships of national science agencies, philanthropies, and commercial entities. Academic scientists need to be involved but must maintain independence. This can be accomplished by regulating experiments in a uniform manner under such international agreements as the London Convention, widely distributing science plans and results via open meetings and peer-reviewed journals, and requiring clear and explicit statements of conflicts of interest.

This group feels it is premature to sell carbon offsets from the first generation of commercial-scale OIF experiments unless there is better demonstration that OIF effectively removes CO_2, retains that carbon in the ocean for a quantifiable amount of time, and has acceptable and predictable environmental impacts. As with any human manipulation of the environment, OIF carries potential risks, as well as potential benefits; moving forward on OIF should only be done if society is willing to acknowledge explicitly that it will result in alteration of ocean ecosystems and that some of the consequences may be unforeseen. We are currently facing decisions on climate regulations, such as the post-Kyoto framework discussed in Bali, carbon cap-and-trade bills in the U.S. Congress, and consideration of OIF by the parties to the London Convention, and we feel that ocean biogeochemical research will help inform these important policy decisions.

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4. P. W. Boyd *et al.*, *Science* **315**, 612 (2007).

10.1126/science.1154305

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Monday, March 11, 13

Science
Corporate and Policy
Martin: "Give me half a tanker of iron, and I'll give you an ice age."
1988
US NRC workshop on global warming and phytoplankton
Washington Post covers OIF as potential "climate fix"
Martin's "iron hypothesis" papers published
ASLO Symposium on Iron Fertilization
ASLO issues resolution
1992
IronEX I
Markels patents OIF as fish production method
IronEx II
1996
Ocean Farming Inc. leases Marshall Islands waters for fertilization
SOIREE
Ocean Farming Inc. experiments in Gulf of Mexico
EisenEX
Carboncorp USA started
SEEDS-I
2000
DOE report on carbon sequestration cites OIF concerns
ASLO Workshop on Iron Fertilization
Carboncorp USA becomes Ocean Carbon Sciences Inc.
GreenSea Venture proposes 8,000 km² OIF "technology demonstration"
2002
SOFeX
SERIES
Planktos Foundation conducts OIF experiment in equatorial Pacific
EIFEX
SAGE
FeeP
SEEDS-II
CrozEX
KEOPS
2004
Living on Earth exposé on Planktos Foundation
Planktos Inc. purchased by Solar Energy Ltd.
Diatom Corp. gets marketing rights to Planktos Inc.'s OIF activities
2006
Climos Inc. founded
Leinen joins Climos
2007
Diatom Corp. becomes Planktos Corp.
Planktos plans 10,000-km² experiment
WHOI Iron Fertilization Workshop
London Convention (LC) Statement of Concern
2008
Planktos folds
UN Convention on Biological Diversity Moratorium
Papers on future of experiments
LC Resolution against OIF
2009
German Research Ministry suspends LOHAFEX for 2 weeks
LOHAFEX
Major international coverage of LOHAFEX suspension
LC Working Groups on OIF
2010
Planned Climos Southern Ocean Experiments
KEY
Science
Scientific iron fertilization experiment
Scientific meeting
Key scientific publication
Corporate and Policy
Private sector activities
Private sector experiment
Key press coverage
Legal decisions

Table 1. Summary of ocean iron enrichment experiments conducted between 1993 and 2009.
See also reviews by de Baar et al. (2005) and Boyd et al. (2007).

Experiment	Year	Location	Duration	Magnitude	Rationale/Hypothesis Tested	General Conclusions
IronEx I Martin et al., 1994	1993	Eastern equatorial Pacific Ocean	10 days	450 kg Fe 64 km^2	• Iron limitation of productivity in HNLC region	• Iron limits phytoplankton growth rate, but patch subducted; broader implications of OIF unclear
IronEx II Coale et al., 1996	1995	Eastern equatorial Pacific Ocean	17 days	450 kg Fe 72 km^2	• Iron limitation of productivity in HNLC region	• Iron definitively limits productivity in equatorial Pacific. Larger bloom than IronEx I
SOIREE Boyd et al., 2000	1999	Southern Ocean-Australia; South of Antarctic Polar Front (APF)	13 days	1740 kg Fe 50 km^2	• Iron limitation of productivity in Southern Ocean, south of the Antarctic Polar Front (APF) • Fate of carbon fixed in bloom	• Iron limits productivity in Southern Ocean • No downward carbon transport observed
EisenEx Smetacek, 2001; Assmy et al, 2007	2000	Southern Ocean-Africa; in APF zone	21 days	4 tonnes $FeSO_4$ 38.5 km^2	• Iron limitation of productivity in Southern Ocean, along APF • Simulate Fe dust deposition to test whether Fe dust contributed to lower atmospheric CO_2 concentrations during glacial periods	• Iron limits productivity in Southern Ocean • Fate of the bloom uncertain • Iron only affected certain species of phytoplankton
SEEDS-I Tsuda et al., 2005	2001	Subarctic Pacific-Northwest	13 days	350 kg Fe 80 km^2	• Iron limitation of productivity in HNLC of subarctic Pacific • Fate of carbon fixed in bloom	• Iron limits productivity in subarctic Pacific • Floristic shift to diatoms • Downward carbon export minimal
SOFeX-N SOFeX-S Coale et al., 2004; Buesseler et al., 2004	2002	Southern Ocean-New Zealand; north and south of APF	30 days	N: 1712 kg Fe 225 km^2 S: 1260 Kg Fe 225 km^2	• Does OIF increase flux of carbon to deep ocean? • Silicate influence and geographic variability of response	• Increase in POC export flux, but magnitude is small relative to natural blooms
SERIES Boyd et al., 2004	2002	Subarctic Pacific-Gulf of Alaska	25 days	490 kg Fe 77 km^2	• Fate of carbon fixed in iron-induced bloom • Efficiency of carbon export to deep ocean	• Majority of carbon remineralized • Inefficient transport of carbon below thermocline
EIFEX Hoffmann et al., 2006; Jacquet et al., 2008	2004	Southern Ocean-Atlantic	35 days	7 tonnes $FeSO_4$ 150 km^2	• Iron addition impacts on phytoplankton community structure • Carbon sequestration efficiency and remineralization rates	• Shift away from picophytoplankton • Majority of carbon fixed was not remineralized • Unpublished "massive carbon export" paper by Smetacek et al.
FeeP Rees et al., 2007; Karl and Letelier, 2008	2004	Sub-tropical Northeast Atlantic-LNLC	21 days	5 tonnes $FeSO_4$ (+20 t PO_4) 25 km^2	• Interaction between iron and phosphorus controls on biological activity in the subtropical North Atlantic	• Increased N-fixation activity was observed • No increase in primary productivity • Carbon export not measured
SAGE Law et al., 2006	2004	Southern Ocean-250 km from New Zealand	15 days	5.4 tonnes $FeSO_4$ 100 km^2	• Iron addition's influence on sea-air gas exchange • CO_2 drawdown and dimethylsulfide (DMS) production	• Doubling of chlorophyll *a* but no significant DMS production and no significant CO_2 drawdown (preliminary results)
SEEDS-II Tsuda et al., 2007	2004	Subarctic Pacific-Northwest	26 days	491 kg Fe 64 km^2	• Monitor ultimate fate of bloom and carbon for longer time period than SEEDS-I	• No diatom bloom response • Increased zooplankton grazing
LOHAFEX NIO Press Release, 2009	2009	Southern Ocean-Atlantic	40 days	10 tonnes $FeSO_4$ 300 km^2	• Ecological shifts and fate of sinking carbon	• Increased zooplankton grazing • Negligible carbon export (preliminary results)

“WE SUGGEST THAT IT IS TIME TO BREAK THIS TWO-DECADE CYCLE, AND ARGUE THAT WE KNOW ENOUGH ABOUT OCEAN FERTILIZATION TO SAY THAT IT SHOULD NOT BE CONSIDERED FURTHER AS A MEANS TO MITIGATE CLIMATE CHANGE.”

“BUT, OCEAN FERTILIZATION RESEARCH SHOULD NOT BE HALTED: IF USED APPROPRIATELY AND APPLIED TO TESTABLE HYPOTHESES, IT IS A POWERFUL RESEARCH TOOL FOR UNDERSTANDING THE RESPONSES OF OCEAN ECOSYSTEMS IN THE CONTEXT OF CLIMATE CHANGE.”

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Ocean iron fertilization: Why further research is needed

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Precautionary principle

ABSTRACT

Despite large uncertainties in the fertilization efficiency, natural iron fertilization studies and some of the purposeful iron enrichment studies have demonstrated that Southern Ocean iron fertilization can lead to a significant export of carbon from the sea surface to the ocean interior. From an economic perspective the potential of ocean iron fertilization (OIF) is far from negligible in relation to other abatement options. Comparing the range of cost estimates to the range of estimates for forestation projects they are in the same order of magnitude, but OIF could provide more carbon credits even if high discount rates are used to account for potential leakage and non-permanence. However, the uncertainty about undesired adverse effects of purposeful iron fertilization on marine ecosystems and biogeochemistry has led to attempts to ban commercial and, to some extent, scientific experiments aimed at a better understanding of the processes involved, effectively precluding further consideration of this mitigation option. As regards the perspective of public international law, the pertinent agreements dealing with the protection of the marine environment indicate that OIF is to be considered as lawful if and to the extent to which it represents legitimate scientific research. In this respect, the precautionary principle can be used to balance the risks arising out of scientific OIF activities for the marine environment with the potential advantages relevant to the objectives of the climate change regime. As scientific OIF experiments involve only comparatively small negative impacts within a limited marine area, further scientific research must be permitted to explore the carbon sequestration potential of OIF in order to either reject this concept or integrate it into the flexible mechanisms contained in the Kyoto Protocol.

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The Problems with Prior Efforts

- Too few in number
  - Only about a dozen experiments over 20 years
- Did not follow full bloom cycle
  - Limitation of human shipboard stationkeeping
- Measurements and observations were not comprehensive enough
  - Limitation of available sensors, samplers, profilers
  - Limit of human shipboard stationkeeping

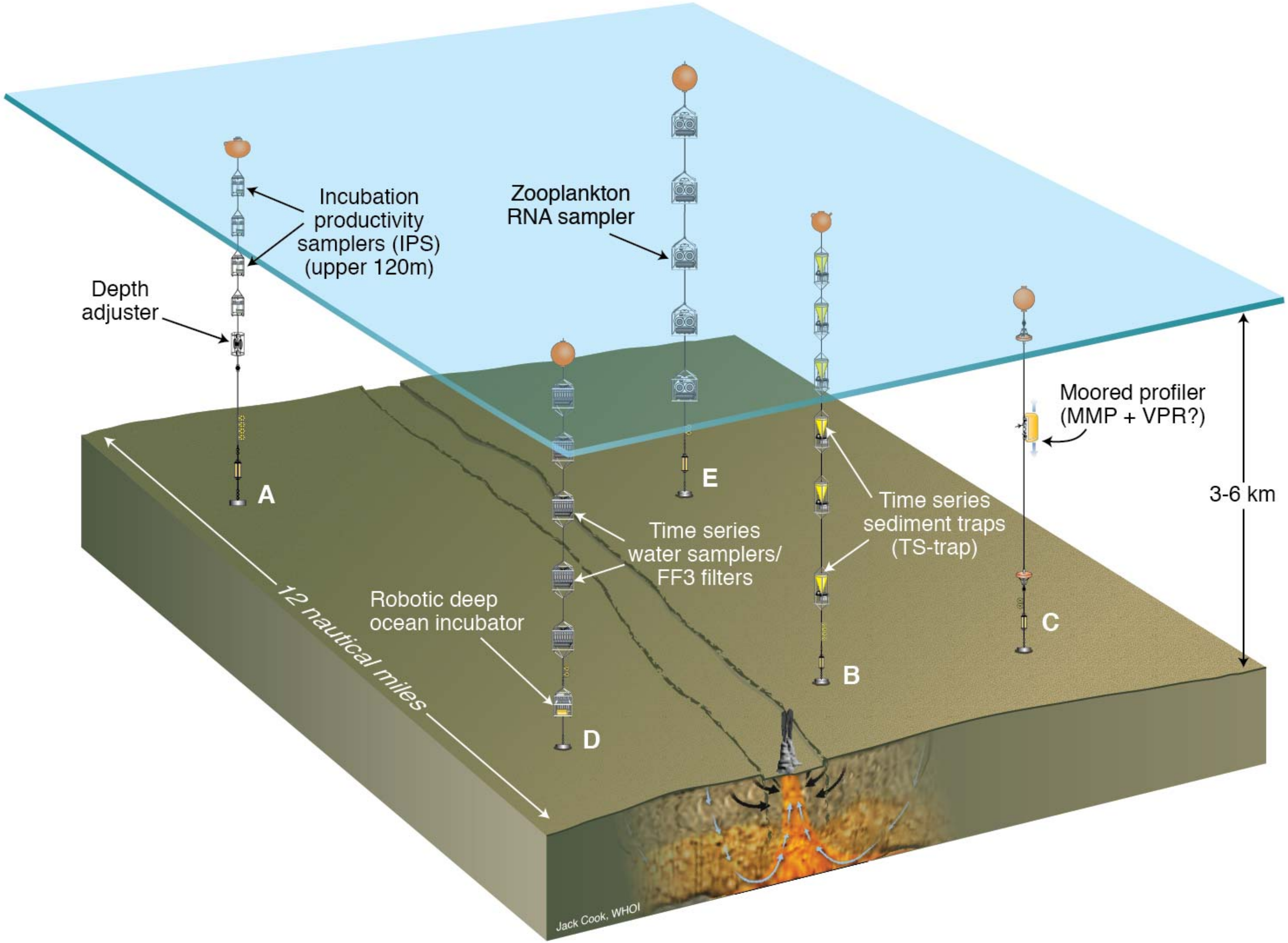
The Problems with Prior Efforts

- Limited use of remote sensing with ground truth calibration
- Did not report results quickly enough
  - e.g., EIFEX conducted in 2004, results reported in 2012


OIF Scientific Experiments
1993 IronEx-I 72 km²
1995 IronEx-II 64 km²
1999 SOIREE 50 km²
2000 EisenEx 38 km²
2001 SEEDS-I 72 km²
2002 SERIES 77 km²
2002 SOFeX-N 225 km²
2002 SOFeX-S 225 km²
2004 EIFEX 150 km²
2004 SEEDS-II 64 km²
2009 LOHAFEX 300 km²
Green Sea Venture Demonstrations
Spring 1998 Pilot Studies 9 km²
2001 Proposed Technology Demonstration (8,000 km²)
Planktos Demonstrations
Summer 2002 50 km swath of ocean
2007 Proposed Technology Demonstration (10,000 km²)
Proposed Climos Southern Ocean Experiment
Climos announced plans for an experiment that would be 200 x 200 km - 4 times the size of the largest square above.
Ocean Iron Fertilization for Geoengineering
According to modeling estimates, the entire Southern Ocean HNLC would have to be fertilized with enough iron to deplete surface macronutrients for decades, to sequester modest amounts of carbon compared to global carbon dioxide emissions. The size of the manipulation relative to those shown here would be ~55 full pages.

Future Fertilization Experiments

- Establish comprehensive baseline prior to fertilization
- Follow entire history of bloom throughout the water column and along the current path
- Tight integration with remote sensing
- Fleet of autonomous samplers and “mother ships”
- Data release within 24 hours - “Bermuda Agreement” - HGP
- Continuously refine and repeat


Incubation
productivity
samplers (IPS)
(upper 120m)
Zooplankton
RNA sampler
Depth
adjuster
Moored profiler
(MMP + VPR?)
A
E
3-6 km
Time series
sediment traps
(TS-trap)
Time series
water samplers/
FF3 filters
Robotic deep
ocean incubator
12 nautical miles
C
B
D
Jack Cook, WHOI


BLUEFIN
ROBOTICS
BLUEFIN
ROBOTICS

United Nations Convention on Biological Diversity (CBD)

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972 London Convention and 1996 London Protocol)

United Nations Convention on the Law of the Sea (UNCLOS)

Kiyomura, K.K. - $1.76 million!

つきじ喜代村
すしざんまい
SUSHIZANMAI

222 kg Pacific Bluefin Tuna - January 2013

“Farming” the Sea

- In the deep ocean, we are still only “hunter gatherers”
- Despite the lack of fences, we need to learn how to replenish our rapidly diminishing seafood stocks
- It starts at the bottom of the food chain with the same phytoplankton that fix, and potentially “seaquester” CO_2
- What’s the right “fertilizer” and how do we best apply it?

Haida Salmon Restoration Corporation

copepod
herring
seabird
tuna
whale
everything

Get Involved - Take Action!

What can *I* do?

For Addison & Courtland