Global Change

International Geosphere-Biosphere Programme
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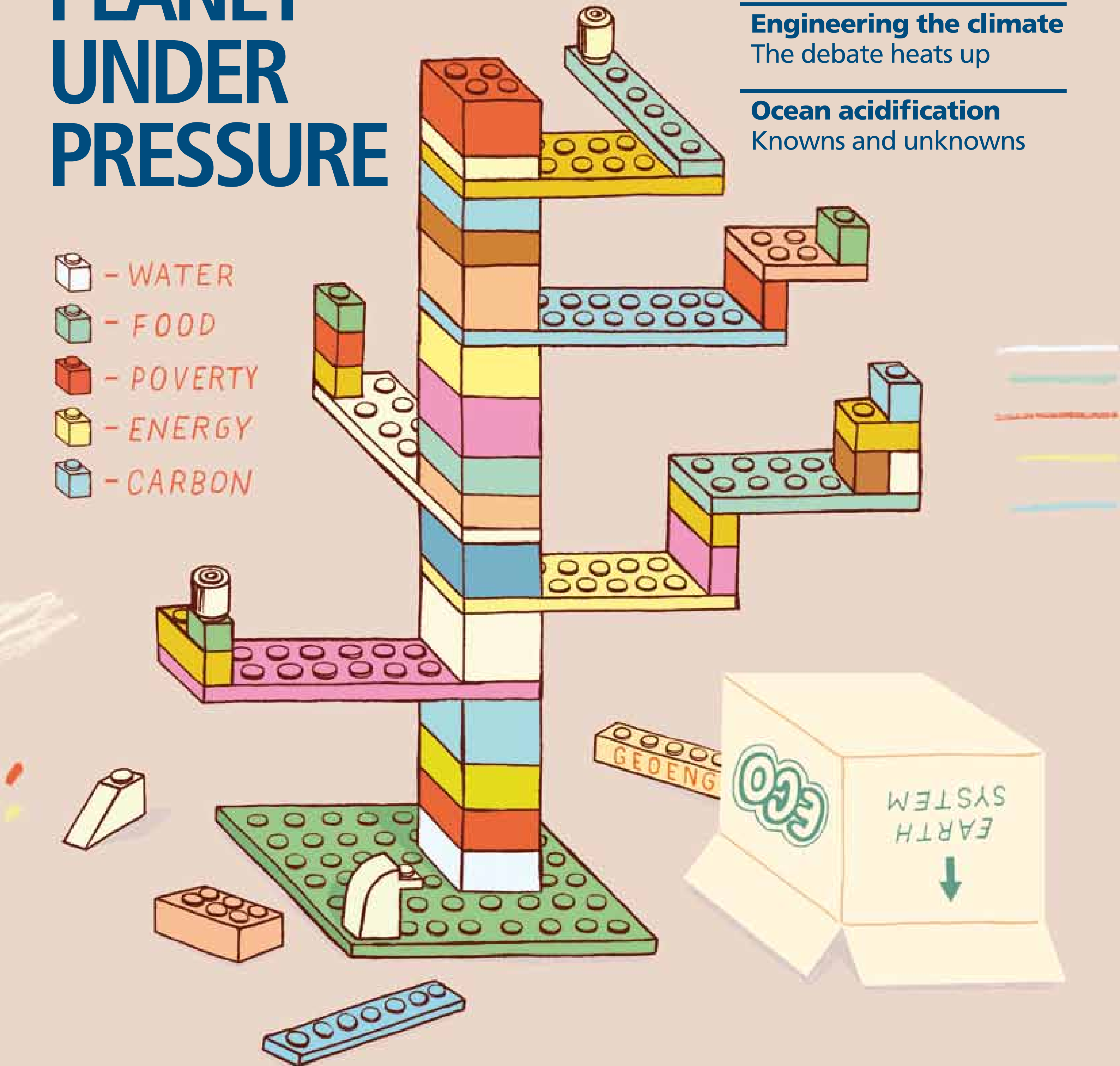
Peak phosphorus
Controversial estimates

Engineering the climate
The debate heats up

Ocean acidification
Knowns and unknowns

PLANET UNDER PRESSURE



GLOBAL IGBP CHANGE International Geosphere-Biosphere Programme

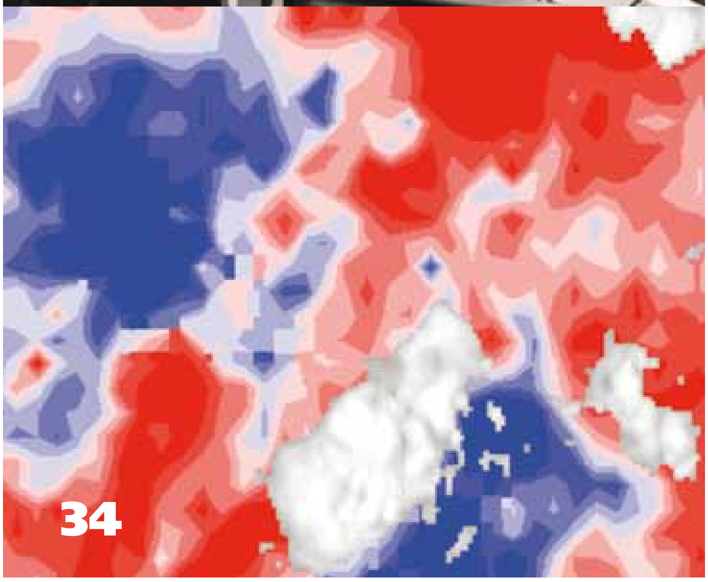
www.igbp.net
Earth-system science for a sustainable planet

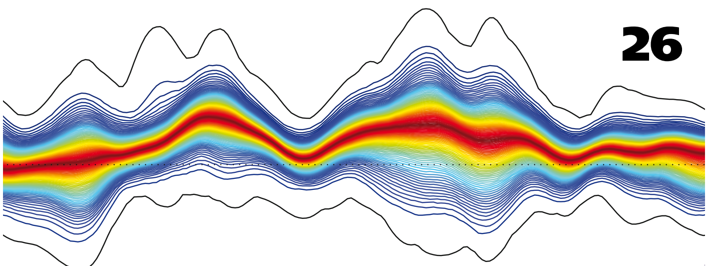
ICSU International Council for Science

Contents

Cover image

Previous attempts to push society onto a sustainable pathway have struggled to deliver. Several ongoing and planned initiatives seek to make a difference by taking a fresh approach. The cover depicts the artist's representation of the creative process associated with this approach.





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Sybil Seitzinger, Executive Director, IGBP

The landscape of global-change research is in flux (see page 7). Top funders are calling on the international research programmes to refocus efforts to deliver knowledge that supports action and adaptation to regional environmental change. The International Council for Science – IGBP's sponsor – is challenging the four global-environmental-change programmes to better integrate social-science research and provide policy-relevant knowledge in the service of global sustainability.

At the same time, other actors are beginning to explore new ways of achieving sustainability. The Global Sustainability Panel, recently set up by UN Secretary-General Ban Ki-moon, is an attempt to bring a holistic approach to bear on issues such as climate change, food and water security, and development.

Meanwhile, the four programmes and their partnership are preparing for an ambitious conference to be held in London in 2012 (see back cover). What differentiates this conference from others is the emphasis on a truly transdisciplinary approach and the desire to engage a broad community – scientists, funding agencies, policymakers, industry, non-governmental organisations and communications professionals – to find creative solutions to the most pressing global-change issues. There is a commitment to strive for 40 percent participation from the developing world.

Another distinguishing feature of the conference is the role that pre- and post-conference workshops will play. This reflects the belief that the diverse communities participating in a conference of this nature will need test beds to explore avenues for constructive collaboration. Outcomes of the workshops and the conference are expected to feed into several processes and events. These include the 2012 Earth Summit in Rio and the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change). And as Janos Pasztor (Ban Ki-moon's Chief Climate Advisor) suggests in an interview on page 10, the preparatory process for the conference could also guide the Global Sustainability Panel's deliberations.

Ambitions bring along several challenges too. An important one is to achieve an appropriate regional and gender balance. It is encouraging that the recently constituted scientific organising committee for the 2012 conference consists of a diverse set of women and men, representing a broad community. Another, perhaps tougher challenge, is to balance the reality of entrenched disciplinary boundaries and differing agendas with the desire for a transdisciplinary approach and a shared agenda.

The first test will be in London later this month, when the organising committee meets to decide on the preparatory process and themes to help shape the conference. There are good reasons to be optimistic about the results.

> "What differentiates this conference from others is the emphasis on a truly transdisciplinary approach.

New IGBP vision published

IGBP IS UPDATING its strategic vision. The new draft vision, now online, states that the role of IGBP is to "provide essential scientific leadership and knowledge of the Earth system to help guide society onto a sustainable pathway during rapid global change". The ten-year vision has been developed by a small team led by the IGBP secretariat, IGBP's senior decision-making bodies and former IGBP chair Guy Brasseur. It has three key components: understanding our planet, understanding the pressure it is under and "transformation in an era of rapid global change". The vision refocuses on and re-emphasises some of the questions the IGBP research community has been addressing. For example, how are Earth's ecosystem processes, society and biogeochemical cycles linked, and how will they behave in the future? What and where are the boundaries, tipping elements and thresholds in the Earth system? How are Earth's marine, terrestrial, atmospheric and cryospheric systems linked? More emphasis will be placed on the planet under pressure. New research questions include: how is human activity affecting Earth's biogeochemical cycles? And, how are Earth-system changes affecting society? Providing useful information to society will feature prominently.

EMISSIONS: BEYOND THE USUAL SUSPECTS

A KEY UNCERTAINTY in climate-change research is how life on land will react to higher levels of atmospheric carbon dioxide. Will trees grow bigger and faster, soaking up some of the excess carbon and eventually cooling the climate? Or will life decay rapidly emitting more carbon and leading to warming?

A recent review, published in *Nature Geoscience*, suggests that with elevated atmospheric carbon dioxide levels, we can anticipate additional greenhouse-gas emissions from soils, forests and wetlands, leading to more warming.

The terrestrial biosphere – life on land – is a key regulator of climate and atmospheric chemistry. Climate change will lead to increases in CO_2 and methane emissions from wetlands, nitrous oxides from soils, volatile organic compounds from forests, plus more trace-gas emissions and soot from fires. Some of these processes are reasonably well understood. But others have been largely ignored until recently.

The review finds that the combined estimated warming from feedbacks associated with terrestrial carbon, nitrogen and atmospheric-chemistry interactions could potentially be large enough to offset a significant proportion of the cooling due to additional plant growth stimulated by CO_2. The researchers conclude that while carbon cycle-climate interactions are a major focus of modelling work, other biogeochemistry feedbacks could be at least equally important for future climate change.

But the scientists caution that the uncertainty levels are still high. Lead author Almut Arneth from Lund University, Sweden, said, "There are large uncertainties associated in these feedbacks, especially in how changes in one biogeochemical cycle will affect other cycles."

Policymakers need to know when the uncertainties will start becoming certainties. At least enough to be included in, for example, the Intergovernmental Panel on Climate Change's assessment of global radiative forcing. "Ask us again in five years," says Arneth.

Arneth is part of the Scientific Steering Committee of the IGBP project Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS).

Arneth A *et al.* (2010) *Nature Geoscience* 3: 525-532.

IGBP DIARY

2011

March

1-3. IGBP International Project Officers meeting. Bern, Switzerland.

15-17. SOLAS Scientific Steering Committee meeting. Tsukuba, Japan.

22-24. DIVERSITAS Scientific Committee meeting. Paris, France.

28 March-1 April. IGBP Scientific Committee meeting. Washington, DC, USA.

April

4-8. WCRP Joint Scientific Committee meeting. Exeter, UK.

11-13. IMBER Scientific Steering Committee meeting. Marseille, France.

May

9-11. GLP Scientific Steering Committee meeting. Maryland, USA.

23-27. ESSP Scientific Committee meeting. Wageningen, Netherlands.

July

29-30. PAGES Scientific Steering Committee meeting. Bern, Switzerland.

September

8-10. LOICZ Scientific Steering Committee meeting. Yantai, China.

8-15. Young LOICZ Forum. Yantai, China.

12-15. LOICZ Open Science Conference. Yantai, China.

18-23. iLEAPS Open Science Conference. Garmisch-Partenkirchen, Germany.

October

24-28. WCRP Open Science Conference. Denver, Colorado, USA.

26-28. ICSU General Assembly, Italy.

TERRESTRIAL CARBON BUDGET REFINED

RESEARCHERS have announced that each year global vegetation draws down 123 billion tonnes of carbon from the atmosphere. The most accurate measurement to date of the carbon exchange between atmosphere and land was made possible by a global network of over 250 measuring stations.

The result will help improve climate models because the terrestrial carbon balance is a major area of uncertainty. The research supports outputs from process-oriented models that estimate terrestrial carbon movement as a function of environmental conditions.

The highest gross carbon uptake in terrestrial ecosystems is found in tropical forests – over a third (34 percent) of the carbon dioxide (CO_2) uptake from the atmosphere. Savannahs cover twice the area but account for about one quarter (26 percent) of the global CO_2 uptake.

The researchers used FLUXNET, a global network of observation towers. The towers measure how CO_2, water vapour and energy move between the atmosphere and the main ecosystems on land: temperate, tropical and boreal forests, crops, grasslands, chaparral, wetlands and tundra.

The research team, from 18 institutes, also discovered that rainfall plays a more significant role than previously thought in determining the amount of carbon captured by plants during photosynthesis. Precipitation rates were found to have considerable influence in more than 40 percent of vegetated regions, and in half of all croplands. This has important implications for global food production.

The reason rainfall is crucial is down to plants' response to soil moisture. Low rainfall leads to dry soils. In such conditions, root-water uptake cannot keep up with transpiration and plants close the small holes on the surface of leaves (stomata) to prevent drying out. But this reduces the amount of CO_2 the plants take up because this gas, in addition to water, is exchanged through stomata.

Lead author Christian Beer, from the Max Planck Institute for Biogeochemistry in Germany, said: "We reached a milestone with this paper by using plenty of data from FLUXNET in addition to remote sensing and climate reanalysis."

"With our estimation of global gross primary production (GPP), we can do two things – compare our results with Earth system process models and further analyse the correlation between GPP and climate," he added.

Reseachers associated with IGBP's iLEAPS project contributed to this work.

Beer C *et al.* (2010) *Science* 329: 834-838.

Ocean acidification symposium announced

THE THIRD symposium on The Ocean in a High-CO_2 World will be held in Monterey, California, September 24-27 2012. The symposium aims to attract more than 300 of the world's leading scientists to discuss the impacts of ocean acidification on marine organisms, ecosystems, and biogeochemical cycles. It will also cover socio-economic consequences of ocean acidification, including policy and management implications. The symposium is sponsored by the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

Humboldt medal for Nobre

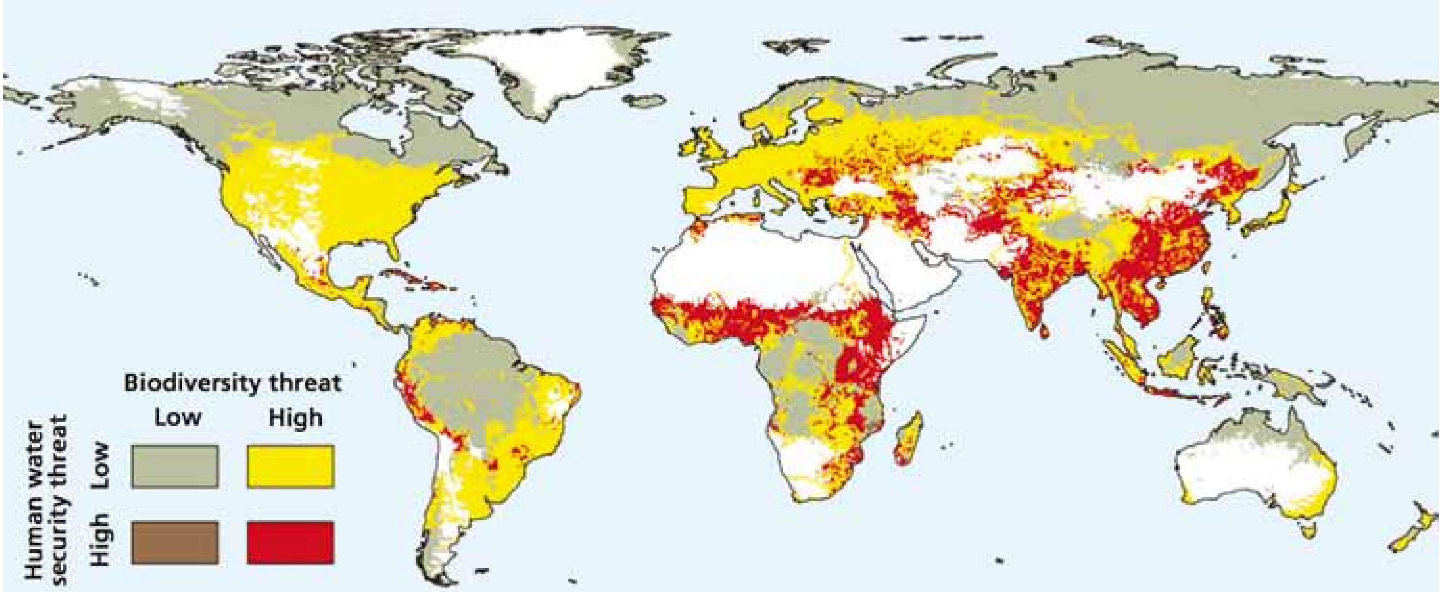
IGBP CHAIR Carlos Nobre is the recipient of this year's Alexander von Humboldt Medal, awarded by the European Geosciences Union (EGU). According to the EGU, the medal has been awarded to Prof. Nobre for his outstanding work on biosphere-atmosphere interactions, with particular emphasis on the Amazonian forests and their role in Earth's climate system. The medal is reserved for scientists from developing countries, particularly from Latin America and Africa, who have achieved exceptional international standing in the geosciences, and planetary and space sciences.

New IGBP website launching soon

BY THE END of 2010, IGBP will relaunch its website. The new website will aggregate news from across the IGBP research community more effectively. It will make more use of imagery, multimedia tools and new digital technology. The site will be easier to navigate and provide more background information on global change. IGBP intends to work with data visualisation experts to make our data more accessible. www.igbp.net

Global change conference update

A MAJOR international conference, Planet Under Pressure, organised by the four global-environmental-change programmes and their partnership, will be held in London 26-29 March 2012. Elinor Ostrom (winner of the 2009 Nobel Prize in economics), Lidia Brito (UNESCO's Director of Science Policy and Sustainable Development) and Mark Stafford Smith (Science Director of the Climate Adaptation Flagship of CSIRO) will lead the scientific organising committee. www.planetunderpressure2012.net/



GLOBAL WATER INSECURITY ANALYSED IN MAJOR STUDY

THE WATER security of around five billion people – 80 percent of the human population – is threatened, according to research published in the journal *Nature*.

Scientists associated with the Global Water Systems Project have created a global database of rivers pinpointing risks to human water security and biodiversity. They took 23 parameters affecting river health including, for example, water diverted to cropland, livestock density, nitrogen enrichment, pesticide levels, sediment deposits, damming and invasive species.

By combining these parameters, the scientists, led by Charles Vörösmarty and Peter McIntyre, produced a set of global maps showing areas at high risk.

Densely populated regions face the highest risk to their water security. "A strikingly small fraction of the world's rivers remain unaffected by humans," the authors report.

Countries facing the highest joint threats to water supply and biodiversity are in the developing world: China, India, Peru, sub-Saharan Africa, parts of Central Europe and Central Asia.

Rich nations – Europe, Australia and North America – have avoided threats to water security by expensive engineering projects: building dams and treatment plants, managing rivers and erecting barriers to allow crops on flood plains. But these technical fixes have reduced biodiversity. The authors note that with instant access to clean water, people in these countries have largely ignored the growing threats to biodiversity.

The authors argue these technological solutions are often unnecessary. Vörösmarty told the Reuters press agency: "If your concern is flooding you might wish to preserve flood plains and wetlands in low-lying areas as they absorb the shock of floods."

Now decision-makers are caught in a dilemma. Societies in poorer countries face the highest risk to their water security. If they adopt the same solutions as rich nations it will be costly, further harm ecosystems they depend upon and fail to deal with the underlying cause.

The paper says, "The decision to construct large-scale dams is a prime example of how development pressure is often at odds with biodiversity conservation."

It adds that human water security must be established in the developing world "while preserving biodiversity". This will be an additional financial burden if these countries follow practices in Europe and North America. But another route is open: "integrated water resource management that expressly balances the needs of humans and nature".

Vörösmarty and colleagues conclude, "Although our results offer *prima facie* evidence that society has failed to institute this principle broadly, there are promising, cost-effective approaches to preserve and rehabilitate ecosystems. Engineers, for instance, can rework dam operation rules to maintain economic benefits while simultaneously conveying adaptive environmental flows for biodiversity.

"Protecting catchments reduces costs for drinking water treatment, whereas preserving river flood plains sustains valuable flood protection and rural livelihoods. Such options offer developing nations the opportunity to avoid the high environmental, economic and social costs that heavily engineered water development systems have produced elsewhere."

The authors are not expecting a quick fix, arguing that if climate negotiations are any guide, "a generational timeframe may be necessary to stimulate sufficient political willpower to address the global river health challenge."

Meanwhile, the majority of people on the planet and countless freshwater species remain living on the edge.

Vörösmarty *et al.* *Nature* 467: 555–561, doi:10.1038/nature09440. www.riverthreat.net

ICSU CALLS FOR "UNPRECEDENTED DECADE OF RESEARCH"

Global-change programmes may shift focus to global sustainability research.

THE INTERNATIONAL Council for Science (ICSU) is calling for its four global-change programmes to rally around "an unprecedented decade of research" to provide the science to put society onto a sustainable pathway.

ICSU wants the four programmes, including IGBP, to switch focus to policy-relevant research relating to global sustainability. This is the outcome of ICSU's lengthy "visioning process" now led by Johan Rockström from the Stockholm Resilience Centre.

The new vision is split into five grand challenges. The first is to build coordinated global and regional monitoring systems. The second, better prediction. The third, how do we avoid or cope with "massive cascading environmental shocks"? The fourth, what economic systems and institutional systems will contribute most to global sustainability? And finally, the fifth challenge asks what are the technological, social and political innovations needed to transform society?

But the first challenge for ICSU and the global-change programmes, including IGBP, is to work out how to reorganise existing international research to achieve these new goals.

Rockström and the rest of the task team meet early 2011 to decide the next move.

Arguably the biggest hurdle will be finding funding agencies to stump up the cash in an age of austerity. But in a separate initiative, some of the world's leading funding agencies of environmental science have met to agree a focus for future funding: "regional environmental change: human action and adaptation".

The proposal from funders in the USA, UK, Japan, Germany, France, Canada and Australia calls for better dialogue between funding agencies and ICSU's global-change programmes.

This new scheme, called the Belmont Challenge because it was first proposed at a meeting in Belmont, Maryland, USA, has outlined the most urgent global environmental challenges: coastal zones, water, sustainable economies and the most vulnerable societies.

The Belmont group of funders commissioned ICSU to produce a report, "What does it take to meet the Belmont Challenge?" The report, led by former IGBP chair Guy Brasseur, states that regional and decadal prediction, advanced observing systems and more inclusion of social sciences are needed urgently.

www.icsu-visioning.org

http://www.icsu.org/2_resourcecentre/ICSU_Belmont_report/

FOOD FOR THOUGHT

INCREASED carbon dioxide concentrations could lead to higher yields of most crops by the middle of the century, according to a recent review. Moreover, crops will consume less water in such an environment. This may offset to an extent the negative consequences of climate change, for example the anticipated increases in ozone and decreases in rainfall.

The review was one of a series published by the UK Royal Society that sought to explore whether and how we can feed nine billion people in the year 2050. Some of the reviews investigated factors that could shape future demand and the potential pitfalls in meeting that demand, whereas others sought to explore the links with economics and implications for human health.

As summarised by Charles Godfray and colleagues in the introduction to the special issue, the challenges are many and include limited availability of fertile land, climate variability and the socio-economic consequences of increasing urbanisation. For example, industry and urban regions are expected to compete with agriculture for water, and expanding farmland might come at the expense of forests and wetlands.

At the same time, the anticipated stabilisation of population and demand, and the willingness to contemplate sustainable application of technology present real opportunities. And even climate change may bring unexpected benefits, as the review on the influence of increased carbon dioxide concentrations on crop yields shows.

Godfray and colleagues point out that the policy choices we make today will determine future food security. And they highlight the need for ongoing research – involving natural and social scientists, economists and policymakers – that will provide the knowledge to understand and cope with the challenges.

Philosophical Transactions of the Royal Society 365 (1554).

ASIA'S WATER FUTURES


© Istockphoto.com/Roberto Caucino

WATER AVAILABILITY in the Indus and Brahmaputra river basins is likely to be affected substantially by climate change, thereby threatening the food security of populations in these basins, a recent study suggests. Basins of Asian rivers such as the Ganges and Yangtze will be less affected, whereas the Yellow River basin might even benefit.

Many of the glaciers in the Himalaya and on the Tibetan Plateau are receding. Glaciers and melting snow supply some water to rivers that originate in this region, but how critical is this meltwater to each basin?

To quantify this, the study's lead author – Walter Immerzeel of FutureWater, the Netherlands – and colleagues turned to satellite data. They found that meltwater is indeed an important contributor to the total discharge of the Indus and Brahmaputra rivers, whereas the Ganges, Yangtze and Yellow rivers get just a limited amount of their water from melting glaciers and snow.

The researchers used several model simulations to come up with predictions about how a changing climate – and the changes in glacier volume and rain/snow fall that would result – would affect water availability in upstream areas by the middle of the century. Upstream areas are important, the researchers point out, because they hold reservoirs that modulate water supply to more populated downstream regions.

The results suggest that the upstream supply of meltwater will decrease considerably for most rivers. But this will be compensated partially by the predicted increase in rainfall in upstream areas. As a result, the effects on the rivers will be less severe than predicted by the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change.

In fact, the Yellow River basin might actually benefit: simulations by the researchers show an increase in early spring precipitation for this river during the coming decades, which will help agriculture in the basin. Nevertheless, rivers such as the Indus and Brahmaputra, with large downstream populations, will experience substantial decreases in spring and summer discharges after the middle of the century. The study estimates that this could threaten the food security of 60 million people.

An important result of the study is the variability in the response of various rivers to climate change, which results from a complex range of variables. Plans aimed at adapting to the inevitable effects of climate change in this region would do well to bear this complexity in mind to achieve the most effective results.

Immerzeel W W, Van Beek L P H and Bierkens M F P (2010) *Science* 328: 1382-1385.

Call for international carbon office

SCIENTISTS from the Global Carbon Project have called for the creation of an international carbon office, to collect, analyse and provide information to help policymakers limit global warming to 2°C. Writing in *Current Opinions in Environmental Sustainability*, the scientists say that existing institutions are inadequate to provide a full accounting of the balance of greenhouse gases, including their sources and sinks.

At present, several organisations provide bits and pieces of information pertaining to greenhouse-gas cycles. However, no organisation has been mandated to pool such information together, either at the regional or global scale. As a result, there is no mechanism to determine, for example, whether the measures instituted to stabilise emissions are working. The Global Carbon Project attempts to synthesise relevant information on a yearly basis. But, say the scientists, it has neither the long-term mandate nor the resources to do a full accounting.

A new office would eventually provide advance warning of changes in the sources or sinks of carbon; this would help shape adequate policy responses.

Events

2010

December

13-17. AGU Fall Meeting. San Francisco, USA.

2011

January

9-11. Innovation and sustainability transitions in Asia. Kuala Lumpur, Malaysia.

February

13-18. ASLO Aquatic sciences meeting. San Juan, Puerto Rico.

March

27 March-1 April. Arctic Science Summit Week, Seoul, South Korea.

April

4-8. EGU annual meeting. Vienna, Austria.

June

14-18. 22nd Pacific Science Congress. Kuala Lumpur, Malaysia.

20-24. Ocean Acidification: Consequences for marine ecosystems and society, 7th EGU Alexander von Humboldt Conference. Penang, Malaysia.

July

20-27. 18th INQUA Congress. Bern, Switzerland.

August

14-19. Goldschmidt 2011. Prague, Czech Republic.

September

26-30. World Conference on Marine Biodiversity. Aberdeen, Scotland, United Kingdom.

November

2-4. Sixth International Symposium on Non-CO_2 Greenhouse Gases (NCGG-6): Science, Policy and Integration. Amsterdam, the Netherlands.

December

12-16. AGU Fall Meeting, San Francisco, USA.

New book on acidification

THE US National Academies Press has published a book entitled *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. The book, published by the US National Research Council, reviews the current state of knowledge of ocean acidification, explores gaps and identifies key findings. http://www.nap.edu/catalog.php?record_id=12904#description

Economic slowdown led to emissions fall in 2009

In 2009, emissions of carbon dioxide from fossil fuels dipped by over one percent, according to scientists from the Global Carbon Project. Writing in *Nature Geoscience*, the scientists attribute the fall to the global financial crisis that began in 2008.

Because modern economic growth relies on burning fossil fuels, carbon dioxide emissions tend to track the gross domestic product (GDP) of nations. A study published last year in the same journal predicted that as the global economy faltered, GDP would shrink and emissions would decrease by almost three percent. Just half of that expected decrease seems to have materialised. What happened?

Developed nations such as the US, UK and Germany did indeed emit lower quantities of carbon dioxide relative to 2008 levels. But the financial crisis did little to slow down the growth in emissions in China and India: these nations emitted more carbon dioxide in 2009 relative to 2008. As a result, the net reduction in emissions was less than anticipated.

The world still burned enough fossil fuel and produced enough cement to ensure that the emissions in 2009 were the second highest in history. And as economies rebound, 2010 emissions are likely to be about three percent higher relative to last year.

Interestingly, a combination of new data and modelling indicates that carbon dioxide emissions due to land-use change during the past decade were lower than in the 1990s. Recent reports of decreasing rates of deforestation in some parts of the world, coupled with forest regeneration in Eurasia, lend credence to this conclusion, although uncertainties remain quite high.

Friedlingstein P *et al.* (2010) *Nature Geoscience.*

FALLING GLOBAL PLANT GROWTH

BETWEEN 2000 and 2009 global plant growth on land – net primary productivity (NPP) – fell slightly. Widespread droughts are largely to blame. The fall reverses growth seen in previous decades (1982-1999). Reduced NPP could threaten global food and biofuel production.

Maosheng Zhao and Steve Running from the University of Montana's Numerical Terradynamic Simulation Group used satellite data and observation towers to piece together a picture of global productivity patterns. NPP fell in some regions and rose in others. It increased slightly over the northern hemisphere. Around 65 percent of vegetated land in this hemisphere saw a rise including large areas of North America, Western Europe, India, China and the Sahel region. But NPP decreased in Eastern Europe, Central Asia and high latitudes of West Asia.

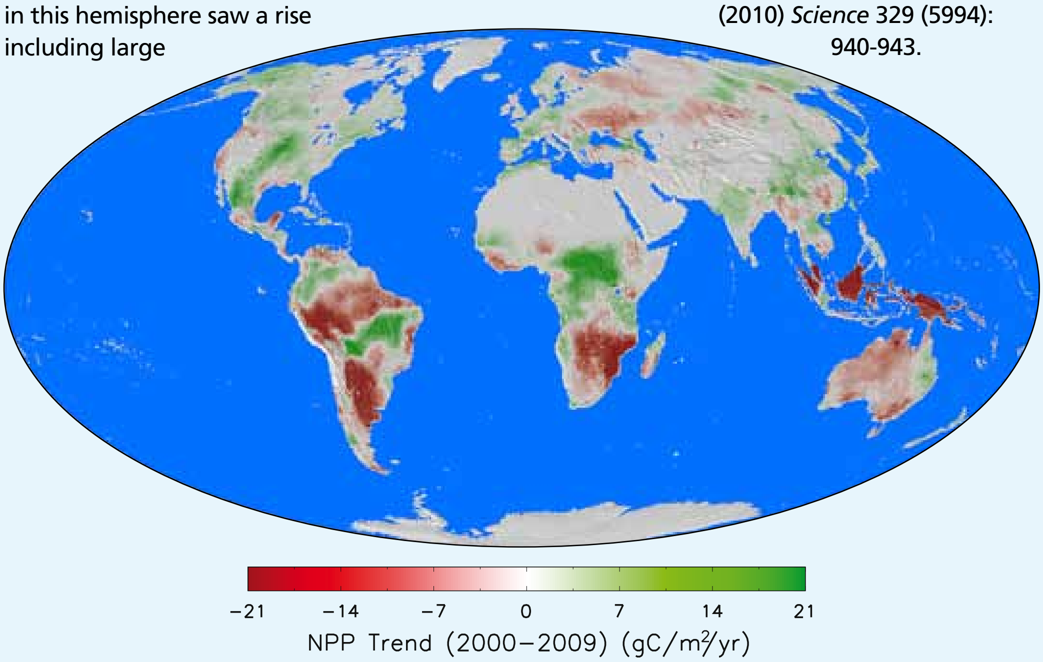
In northern high latitudes, warming lengthens the growing season promoting plant growth. Nitrogen deposition and fertilizer use also stimulated a rise in NPP in the northern hemisphere.

A different picture emerges in the southern hemisphere, which accounts for 41 percent of global NPP. Here, NPP reduced markedly, a fall that more than counteracted the northern hemisphere rise. In the south, 70 percent of vegetated lands saw a decrease in NPP including large parts of South America, Africa and Australia.

Severe regional droughts have become more frequent. For example, droughts reduced NPP in North America and China in 2000, in Europe in 2003, and in Australia from 2007 to 2009.

Plant productivity increased between 1982 and 1999, according to a 2003 study. Researchers at that time attributed that trend to a warmer climate and increased solar radiation. The new findings highlight the need to monitor NPP continuously to determine whether the trend is decadal variation or a long-term decline in the terrestrial carbon sink.

Zhao M and Running S (2010) *Science* 329 (5994): 940-943.



Steve Running

Global Net Primary Productivity (2000-2009). The Southern hemisphere suffers a significant decrease in productivity.

UN sustainable?

The United Nations has struggled to deliver on many environmental and developmental challenges. Time for new thinking, then, which is why UN Secretary-General Ban Ki-moon has set up the Global Sustainability Panel. But how can science contribute? **Owen Gaffney** discusses the panel with **Janos Pasztor**.

In August 2010, UN Secretary-General Ban Ki-moon announced, "We need a new blueprint for a more liveable, prosperous and sustainable future for all." With that, he launched the Global Sustainability Panel. The 21-strong panel (Box 1) will be co-chaired by South Africa's President Jacob Zuma and Finland's President Tarja Halonen, and is due to report back to the Secretary-General by the end of 2011, well in time to make an input into the 2012 UN Conference on Sustainable Development to be held in Rio de Janeiro. The secretariat supporting the panel will be directed by Mr Ban's Chief Climate Advisor Janos Pasztor.

Why have you set up the Global Sustainability Panel now?

The panel should have been set up some time ago to be honest. The idea came early last year, initially from the Stockholm Commission on Climate Change and Development report. The report asked the Secretary-General to set up a high-level panel of this nature to bring climate change into the development process. Around the same time many national governments decided to go ahead with the United Nations conference on Sustainable Development in Rio de Janeiro in 2012 (commonly referred to as Rio +20).

The panel took some time to put together. It was more or less ready at the end of last year and our plan was to launch in January right after Copenhagen. Then of course Copenhagen did not turn out how we wanted it, so the Secretary-General was very busy in the follow-up. This included setting up another high-level panel that became the advisory group on climate-change financing. This took away some of our energy. We are now ready. And we have to be ready. We are less than two years away from the Rio 2012 conference, and the panel is set to make an important contribution to it. Rio 2012 is not the only target we have but it is definitely an important target to aim for.

> **We are less than two years away from Rio 2012, and the panel is set to make an important contribution to it.**

The panel documents say the "panel will seek to explore approaches for building a low-carbon, green and resilient economy that can eradicate poverty." This is pretty much what was expected from the Rio Earth Summit in 1992. Why do you think this new panel can succeed where others have failed?

We have learned a lot since 1992 on the different aspects of the problem. We know more about both climate change and poverty eradication. I think that we still

Presidents Tarja Halonen (second from left) and Jacob Zuma (on the screen) are chairing the Global Sustainability Panel.

lack sufficient experience with how to connect the dots, how to bring together concepts like climate change and poverty eradication, climate change and food security, and climate change and access to water. Ultimately, if we do not solve climate change we will not solve food security; yet, we are still treating the two as separate issues. Agriculture is not just a key source of emissions but it is also a key area for adaptation and a more resilient development process. These things are inter-related. The international community, and for that matter national governments, have been unable to address these inter-linkages well enough. This is what our panel will be focusing on.

There is an expectation that a panel like this will try to solve everything in the world. This is not possible. We want to focus on climate change – not in the 'climate change' box but in the 'development' box. We must connect it to these drivers: poverty reduction, food security and access to water.

So it seems to me that the UN is seeking a more unified, holistic approach to these problems, not just conceptually, but structurally. This is reflected in the panel's terms of reference which state "we are reaching and increasingly overstepping planetary boundaries," a reference to Johan Rockström and colleagues' *Nature* paper published in 2009. I guess this indicates a strong desire by the UN to link the challenges?
Absolutely, absolutely. This is being done for a number of reasons. First, you cannot solve these problems separately. Second, international institutions – the UN and others – are fragmented. One of the key issues to be discussed in Rio de Janeiro in 2012 is precisely this: how do we improve this situation? How can we improve the linkages between institutions so we can have overarching comprehensive strategies and implementation of these strategies?

The planetary boundaries are linked not just between themselves but to other socio-economic goals and developmental targets.

We want to focus on climate change not in the climate change box but in the development box.

The planetary boundaries concept was only published in September 2009. Has it had an impact at the high level you are working at within the UN?
Not yet, but that is part of the reason why we have such a panel. These issues are on the table. The Rockström *et al.* paper is there. It is a very good paper. But it needs to be understood and picked up by the politicians, by the political discourse. We definitely hope that

through this panel, which consists of senior politicians of one type or another, those issues will become part of the political discourse.

The International Council for Science (ICSU) is discussing launching a major programme on global sustainability research. In 2011, there will be a Nobel Symposium on sustainability in Stockholm. And, in March 2012, in the run-up to the 2012 Rio conference, the global-change programmes hold a major conference in London on sustainability: Planet Under Pressure. Is there a mechanism for the scientific community to feed into your panel?

We will have a very intensive and open process to engage and seek inputs from the key actors in the world.

Not yet. But there will be. We have just started, literally. I have just hung up the phone on the first meeting with panel members and their advisors. Connecting over 20 places in the world is quite a challenge. The intention is definitely there to engage some of the key constituents, one of which is clearly the scientific community. Whether it will be through setting up working groups or engaging existing processes like ICSU and others on the business side and civic society side, we are not sure yet. We now have a number of thoughts on this. The secretariat will put together some ideas for the first meeting.

I can assure you that the scientific community is a key sector we will be working with. Maybe you have some thoughts on how to go about this? If you have a major meeting in March 2012, the preparatory process that will go into that meeting could be used as an input into the work of the high-level panel.

Box 1. The Global Sustainability Panel.

Co-chairs

Tarja Halonen
President of the Republic of Finland

Jacob Zuma
President of the Republic of South Africa (not in photograph)

Other members: (in alphabetical order)

H.H. Sheikh Abdallah Bin Zayid Al Nahayan, Minister of Foreign Affairs of the United Arab Emirates; **Hajiya Amina Az-Zubair,** Senior Special Assistant/Advisor to the President of Nigeria on MDGs; **Ali Babacan,** Deputy Prime Minister of Turkey; **James Laurence Balsillie,** Co-CEO, Research in Motion, and Chair of the Board, Centre for International Governance Innovation (CIGI), Canada; **Alexander Bedritsky,** Advisor to the President of the Russian Federation and Special Envoy for Climate, President of the World Meteorological Organization (WMO); **Gro Harlem Brundtland,** Former Prime Minister of Norway and former Chair of the World Commission on Environment and Development; **Micheline Calmy-Rey,** Minister for Foreign Affairs of Switzerland; **Julia Carabias,** Environmentalist and former Secretary of the Environment of Mexico; **Gunilla Carlsson,** Minister for International Development Cooperation of Sweden; **Luisa Dias Diogo,** Member of Parliament and former Prime Minister of Mozambique; **Han, Seung-soo,** Chairman of the Governing Board, Global Green Growth Institute (GGGI) and former Prime Minister of the Republic of Korea; **Yukio Hatoyama,** Member of the House of Representatives and former Prime Minister of Japan; **Connie Hedegaard,** EU Commissioner for Climate Action; **Cristina Narbona Ruiz,** Spanish Ambassador to the OECD and former Minister of Environment of Spain; **Jairam Ramesh,** Minister of Environment of India; **Susan E. Rice,** United States Permanent Representative to the UN and member of the United States President's Cabinet; **Kevin Rudd,** Member of Parliament and former Prime Minister of Australia; **David Thompson,** Prime Minister of Barbados; **Zheng, Guoguang,** Administrator, China Meteorological Administration.

Maybe, in a more practical way, we can exchange the agendas of the two panels. The scientific panel will have its own work programme and its own agenda. Our high-level panel is about to finalise its own agenda and programme based on its terms of reference. Maybe at a secretariat level we can see how we can put these agendas together and adjust the respective agendas in light of each other. And then have a group of scientists come to the panel and say "here, this is what the scientists think." I can envisage a number of different ways to make this work.

How were panel members selected?

The Secretary-General wanted to have a good number of top-level existing office-holders. He felt if you have too many ex-ministers and ex-presidents they will have nice ideas but their proposals may no longer be politically feasible or doable. We wanted a certain level of accountability. We can achieve this better by having current officials who have some understanding of these issues and who are struggling with them right now.

I think we have a very good list. I really look forward to working with them. The first phone call we had was fantastic. There is a real willingness to work and to engage. Broadly speaking, there is a shared feeling on how to go about this.

Given the panel is made up of people who are part of the system that is failing to deliver, how can you be sure the ideas generated will deliver? Is there enough out-of-the-box thinking?

This was confirmed by our initial teleconference a few moments ago. Not all the wisdom resides in the members of the panel. They are very good people, but they recognise they do not have all the answers. The conclusion to that is that we will have a very intensive and open process to engage and seek inputs from the key actors in the world so we do get rich inputs, new ideas and out-of-the-box thinking.

The UN was set up to stop wars. Is it really able to deal with planetary environmental issues and to effectively start managing some of Earth's biogeochemical cycles?

This is not a UN panel even though it was set up by the Secretary-General. It is not about the UN, it is about the world and the role of the UN in that world. Is the UN able to deal with the interconnected global issues like planetary boundaries combined with socio-economic objectives in the world? If it isn't, then it is no longer relevant. This will be the test that will demonstrate the extent to which the UN can be relevant in the 21st century: can we successfully rise to these challenges?

How did you choose the name, Global Sustainability Panel?

Initially, this was meant to be a high-level panel on climate change and development. But as we started looking at the broader context of development, it was felt that we had to do something much broader. Besides if you put climate change in the title, then no matter what else you put there it will be very much taken over by climate change, and we decided it was more important to look at the broader context. We could have called it "sustainable development" but "sustainability" is shorter and more encompassing.

Gordon Conway, former President of the Rockefeller Foundation and Chief Scientific Advisor to DFID, once said that the number one position on the planet, the Ban Ki-moon position, should not have the title "UN Secretary-General", but the title, "Planetary Ecologist". How close to this are we?

Closer than ever before, if I can put it that way. This Secretary-General has had these issues on his radar screen more than any of his predecessors. Of course, he does not have all the means at his disposal to simply deliver on all these issues. But certainly Ban Ki-moon has recognised the incredible importance of climate change as the one underlying issue that affects everything else the UN is doing. We will not be able to deliver Millennium Development Goals if we don't resolve climate change. Even if we somehow meet these goals we cannot maintain them without resolving climate change. These linkages are clear to him. And now he is working through this panel to try to improve the response of the system to address the collective challenges that all these issues pose to the world and to the United Nations. ▌

Janos Pasztor, Chief Scientific Advisor to the UN Secretary-General.

I can assure you that the scientific community is a key sector we will be working with.

OWEN GAFFNEY is Director of Communications at IGBP.

PHOSPHORUS: How much is enough?

Phosphorus, crucial to agriculture and life, is at present derived from non-renewable sources. Demand will eventually outstrip supply, but when this will happen is a matter of debate. **Ninad Bondre** takes stock.

Can science feed the world?, asked the cover of *Nature* earlier this year. Sustainability and global-change researchers have long had this question on their minds. The *Nature* issue highlighted the key concerns – limited land and water, for example – we must address if we are to provide adequate nutrition to an anticipated human population of nine billion by the year 2050. It emphasised too the need for higher crop yields with less fertiliser and water inputs. But it did not explicitly mention phosphorus. This omission, some researchers would say, points to a failure to recognise the extent to which the availability of this element could limit agricultural productivity in the future. The global markets, on the other hand, seem to have been quite alert to this possibility: the price of phosphorus spiked by almost 800 percent in 2008. Although it declined rapidly, it remains much higher than in the preceding decade or so.

Phosphorus is indispensable to many life processes, and its role cannot be performed by any other element. Plants take up phosphorus in large quantities, along with other macronutrients such as nitrogen and potassium. Healthy and robust plant growth requires an assured supply of these elements, so it is no surprise that the green revolution of the last century relied on substantial inputs of fertilisers.

Phosphorus is indispensable to many life processes.

We need to urgently tackle widespread malnourishment in some parts of the world while also bearing in mind the nutritional needs of a growing world population. Minimising wastage and maximising equitable distribution will help, but we will also need to produce more food. Simply expanding the currently available land for agriculture will probably come with its own set of problems – land grabs (*see* MBow 2010) and large-scale deforestation, for example. If we want to enhance the production potential of existing agricultural land, we will need to apply fertilisers, even with newer crop varieties and altered management practices.

Producing nitrogen fertilisers is not a problem. We know how to artificially "fix" it to generate forms that can be used by plants. It is so abundant in the atmosphere that we will never run out of it. Phosphate-rich rocks formed slowly over geologic time and are not renewable on human timescales. Potassium is also mined from non-renewable sources. Eventually, we will begin running out of sources that are economically (and environmentally) viable to mine and to process (*see also* Gilbert 2009).

Soils contain a pool of phosphorus that is available for absorption by plants. For any given soil and farming system, there is a critical value at which plants (and hence farmers) benefit the most and the risk of leaching into surface waters is minimal (Syers *et al*. 2008). Before large-scale mining of phosphate rock for use in fertilisers began, agriculture had relied largely on this natural soil reservoir of phosphorus, which was replenished by inputs of human and animal waste, leaf-litter and organic manure. As human populations began to surge and sanitation habits changed, such replenishment was no longer sufficient to keep up with the growing demand for crops and meat. First, societies turned to guano, the phosphorus-rich droppings of birds. Then, as guano stocks ran out, mining for phosphate rock began in earnest (see figure on facing page).

Farmers in the developed world have applied phosphorus fertilisers extensively during the past century or so, which has resulted in soils that have adequate, if not excessive, levels of phosphorus (for example, Tiessen 1995). In contrast, soils in large parts of Africa and

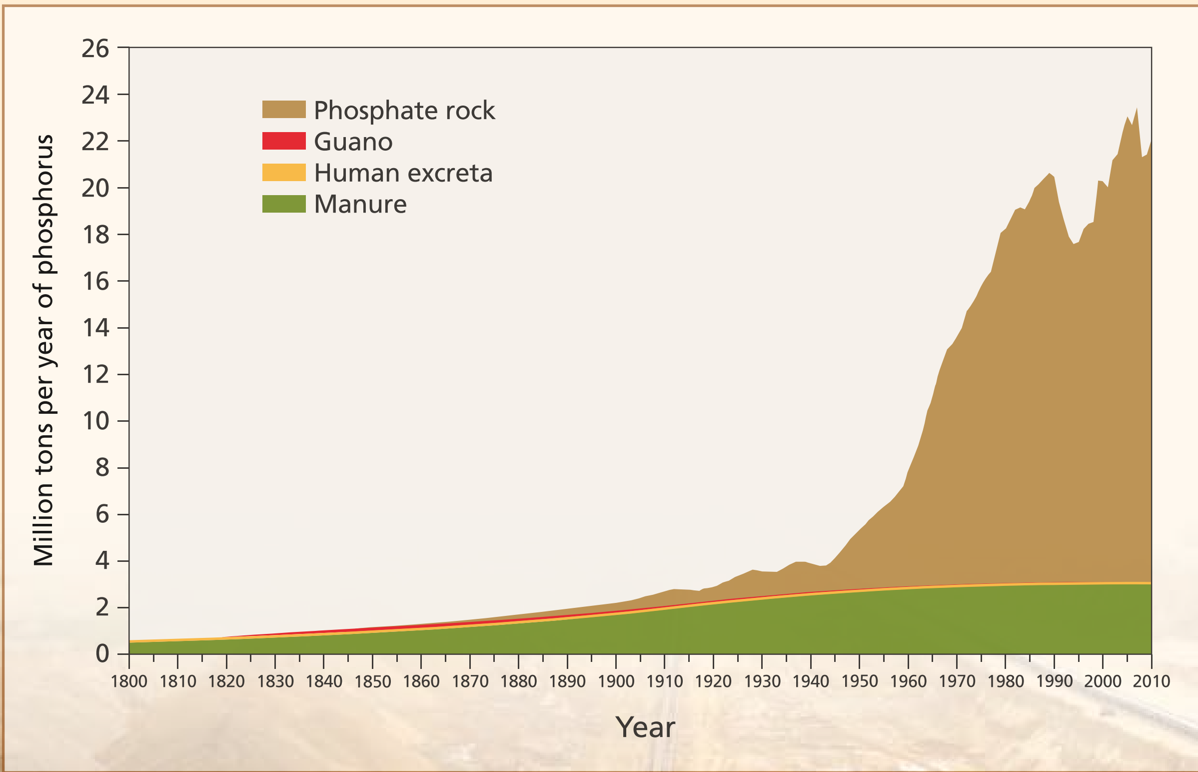


Figure courtesy Dana Cordell. Modified after Cordell *et al.* (2009).

Phosphate mining in Togo.

many parts of Asia are deficient in phosphorus. These are also the regions of the world where we expect most population growth to occur during the coming decades. Economic and socio-political considerations permitting, fertiliser use in these parts of the world is expected to increase in the foreseeable future. Tiessen (1995) reports that phosphorus use may have to double in Asia and quadruple in Africa. In an analysis published this year, Van Vuuren and colleagues conclude that the global demand for phosphorus will likely increase, but how much depends on the path that society chooses to follow during the coming decades. For example, the continued increase in meat consumption will trigger increased phosphorus demand.

How much phosphorus?

Just how much phosphorus is available for human use? The answer, it turns out, depends on whom you ask. Phosphate-rock reserves – proven and quantified material that is currently economic to mine – are on the order of 16 billion tons according to a compilation by the United States Geological Survey (USGS 2010). In addition to this is material that has not been fully quantified and is currently costly or uneconomical to mine; in principle this material could be used in the future. Such material amounts to another 35 billion tons or so according to the USGS. However, as with other strategic commodities, such as oil and important trace elements, figures pertaining to phosphate are to be taken with a pinch of salt. Mining companies often treat such data as a closely guarded secret, and so do nations. The availability of phosphorus is not independent of the demand, the quality of its sources, the technical constraints on mining and recovering the element, and the economic and environmental costs involved. Not surprising, then, that the outlook on future availability of phosphorus varies.

Not surprising, then, that the outlook on future availability of phosphorus varies.

Concerns about how much phosphorus is available are not new; in fact, the discussion about phosphorus sources began in earnest in the early 1970s. Studies highlighting depleting reserves were quickly countered by other studies that presented more optimistic estimates. What is happening in the field during the past few years is not too different.

Dana Cordell and the Global Phosphorus Research Initiative that she co-founded have been at the forefront of recent discussions about phosphorus availability and its implications. Cordell has recently completed her doctoral research on phosphorus and food security (Cordell 2010), which she undertook jointly at Linköping University and the University of Technology in Sydney. She conducted an exhaustive review of published and unpublished material pertaining to phosphorus sources, and supplemented it with interviews with a variety of stakeholders. Her analysis, in agreement with some earlier studies, suggests that the production of phosphate rock will peak before the middle of this century. This means that we could run out of the high quality and easy-to-mine reserves within a century. The situation is complicated by the fact that only a handful of countries – Morocco and China, for example – hold most of the phosphate-rock reserves. Geopolitics will therefore always be in the equation.

Stephen Jasinksi, USGS's mineral commodity specialist, agrees that reserves are geographically restricted and that production will likely peak around the year 2050 based on current estimates. But he is more optimistic about future prospects, and he estimates that there may be enough to last for at least another 175 years. Weighing into this estimate is the fact that several new mines are being opened this year, for example in Australia and Saudi Arabia. Technological improvements may facilitate extraction of phosphorus from material that is currently not economic to mine. Jasinski adds that although US production of phosphorus peaked in the late 1900s and was expected to decline, it has stayed much higher than predicted. Better use of resources and changing global supply patterns played an important part.

The latest twist in the tale is a report commissioned by the International Fertilizer Development Center (IFDC): this report analysed publicly available information to come up with an estimate of reserves that is about four times that of the USGS. The report authored by geologist Steven Van Kauwenbergh, while mentioning that the estimate is preliminary, dismisses the possibility of a production peak by the middle of the century. It suggests that at current rates of production, phosphate rock reserves should last for the coming three to four centuries.

Responding to this report, Dana Cordell points out that the upward revision in estimates is almost entirely because of revised figures for Morocco – reserves she says are based on uncertain and preliminary data. Moreover, the new estimates raise further concerns about the geopolitical implications of Morocco and China controlling over 90 percent of the reserves. She emphasises that production rates are likely to increase in the future and that processing remaining reserves will cost more, need more energy and will generate more waste.

The future

How long viable phosphorus sources will last is clearly open to debate: we can resolve this debate only after substantial additional work and access to proprietary data. If the recent IFDC report is correct and if geopolitical and technical considerations are favourable, the world would probably have enough phosphorus to last several centuries. But there might just be much less phosphorus than we thought. And technical issues or costs might preclude mining the poorer quality and difficult-to-access sources. Van Vuuren and colleagues, in spite of a detailed analysis of demand and supply, can only come up with three scenarios that range from the relatively optimistic to the relatively problematic because of the uncertainties. Clearly the number of "ifs" and "buts" suggests that more substantive effort is needed to collect/make available data on phosphorus sources.

A complex range of factors was responsible for the phosphorus price spike of 2008, one of which was the real or perceived increase in demand for fertilisers. The same year, China imposed an export tariff of 135 percent on phosphate rock perceiving the need to secure reserves for domestic crops; this tariff was subsequently removed. Mining companies and nations are highly attuned to the possible scarcity in similar commodities arising from future demand from agriculture and perhaps the biofuel sector. The Australian mining company BHP Billiton recently launched a hostile bid to take over Potash Corporation, the Canadian fertiliser producer. Writing for the *New York Times*, Cyrus Sanati mentions that this move can be interpreted as BHP's recognition that the demand for potash – the ore of potassium – is bound to increase in concert with the demand for food by a growing population. At the time of writing this article, there is a possibility that Sinochem, a Chinese company, may be seeking government support to launch a counter bid by making the argument that securing potash supplies is critical to ensuring food security for China's large population.

Whether we have a little or a lot of phosphorus remaining, the majority of mined phosphorus is wasted throughout the production and supply chain, from fertiliser production to crop harvest to food retailing. Some of this makes its way to water bodies, causing eutrophication, a process that leads to oxygen depletion, which has been flagged as a serious global environmental problem. Cordell points out that in spite of these sorts of links, those studying the various aspects of phosphorus – economic, social and environmental, for example – seldom work together. As a result, we have tended to treat phosphorus pollution as an issue separate from, say, food security. This is in contrast to carbon or even nitrogen, the multiple facets of which are now studied in a far more integrated fashion. Cordell and her colleagues are now setting up a global network of various stakeholders interested in the sustainable use of phosphorus. One way to achieve greater sustainability in phosphorus use would be to minimise losses and substitute chemical fertilisers with composted crop residues, and human and animal wastes.

Some argue that technological change and market forces will solve resource problems, such as those caused by finite supplies of oil. This argument is a well-entrenched one, and indeed, it is borne out to an extent by human history: animal-driven carriages were replaced by cars running on petrol, and these cars in turn may well be replaced by electric and solar-powered vehicles. But even new technologies can themselves rely on rare, non-renewable material – highly efficient solar panels, for example, require indium and gallium, which are rare metals that are likely to get rarer (Ragnarsdottir 2008). And although some resources can have substitutes, there is none for phosphorus: it cannot be replaced by, say, cadmium as fossil fuels can be by other substances. The renewed discussion of phosphate rock reserves raises the more general issue of our dependence on non-renewable materials. This is an issue we will inevitably need to confront while planning for a future socio-economic system based on more sustainable principles.

We have tended to treat phosphorus pollution as an issue separate from, say, food security.

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REFERENCES

Cordell D, Drangert J-O and White S (2009) *Global Environmental Change* 19: 292-305

Cordell D (2010) The story of phosphorus: Sustainability implications of global phosphorus scarcity for food security. PhD thesis. http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-53430.

Gilbert N (2009) *Nature* 461: 716-718.

Mbow C (2010) *Global Change* 75: 20-23.

Ragnarsdottir K V (2008) *Nature Geoscience* 1: 720 – 721, doi: 10.1038/ngeo302.

Syers J K, Johnston A E and Curtin D (2008) *FAO Fertilizer and Plant Nutrition Bulletin* 18. Food and Agriculture Organization of the United Nations: Rome, Italy.

Tiessen H (1995) *Scope 54: Phosphorus in the global environment: Transfers, cycles and management.* John Wiley & Sons Ltd., 462 pp. Also at http://www.icsu-scope.org/downloadpubs/scope54/TOC.htm.

US Geological Survey (2010) *Mineral commodity summaries 2010*, 193 pp.

Van Kauwenbergh S J (2010) *World phosphate rock reserves and resources.* IFDC, 48 pp.

Van Vuuren D P, Bouwman A F and Beusen A H W (2010) *Global Environmental Change* 20: 428-439.

http://dealbook.blogs.nytimes.com/2010/08/17/why-bhp-wants-potash/

CLIMATE GEOENGINEERING Could we? Should we?

Radical technological responses to counteract global warming are receiving increased attention as a possible policy option. But is geoengineering a potential safety net, a distraction or a dead end? **Phil Williamson** explores.

"Only fools find joy in the prospect of climate engineering".

The author of that quote, Ken Caldeira of the US Carnegie Institution, is clearly no cheerleader for technological tinkering with the Earth system. Yet Caldeira strongly supports research into geoengineering. This apparent contradiction is central to an emerging debate: should we deliberately intervene in global processes to deliver planet-saving outcomes? Many environmental groups vehemently oppose the idea. The "Hands Off Mother Earth" campaign, the ETC Group (Action Group on Erosion, Technology and Concentration) and Greenpeace believe that precaution trumps all other concerns. To them, geoengineering is a dangerous illusion, a Pandora's box that ought to remain closed. Nevertheless, some scientists, business leaders and politicians consider that technological solutions to engineer the climate might provide an insurance policy, in which case we urgently need to explore their strengths and weaknesses. Only then would we find out whether geoengineering might provide an effective and acceptable means to avoid – or at least reduce – the predicted dire consequences of global warming.

Even the most optimistic scenarios for future action risk overshooting "safe" levels of climate forcing.

The concept of engineering the climate (Box 1) is not new. Researchers suggested many of the basic ideas, such as mirrors in space and ocean fertilisation, more than 20 years ago. These approaches are now being revisited, and new ideas have recently been proposed, for two closely linked reasons. First, we recognise more clearly that future, human-driven climate change threatens global economic development, food supply and, for many people, survival. Second, we have collectively failed to address fully the cause underlying this change – the increase of greenhouse gases in the atmosphere.

We may still achieve international commitment to major emissions reductions, if not at Cancún in November (COP 16 of the UN Framework Convention on Climate Change), then over the next few years. But even the most optimistic scenarios for future action risk overshooting "safe" levels of climate forcing, resulting in environmental perturbations that gain a momentum of their own for hundreds if not

Box 1. Climate geoengineering schemes: a wide spectrum

Geoengineering can mean different things to different people, covering a very wide spectrum of concepts and ideas. But broadly speaking we can group climate-altering technologies into two categories.

The first of these, **solar radiation management** (reflecting sunshine) includes technologies seeking to increase the brightness of clouds, land or the ocean surface, or reduce the solar radiation reaching the Earth.

The second category, **carbon dioxide removal,** involves drawing down carbon dioxide that is already in the atmosphere. The list below is not exhaustive but is aimed at giving an idea of the options being contemplated. For additional details, see the Royal Society's 2009 report.

Solar radiation management techniques:
- Enhancing surface brightness
- Enhancing cloud brightness
- Increasing stratospheric aerosols
- Placing reflectors in space

Carbon dioxide removal techniques:
- Afforestation, reforestation and avoidance of deforestation
- Biochar
- Enhancing weathering of carbonate or silicate rocks
- Air-capture of carbon dioxide
- Ocean fertilization

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Solar radiation management schemes on land and in the oceans. Proposed schemes include, for example, solar reflectors, cloud-seeding balloons and ships, and plane exhausts.

thousands of years, and having a chaotic impact equivalent to changes between past geological epochs. Indeed, if the boundary between safe and dangerous is defined as either 350 parts per million of atmospheric carbon dioxide or an increase of 1 watt/m^2 in radiative forcing, society has already exceeded those thresholds (Rockström *et al.* 2009).

Prevention is undoubtedly better than cure: it is preferable to tackle problems, of whatever kind, at source rather than trying to deal with their consequences. Yet when prevention fails, a cure is needed. And if such a remedy does not yet exist, we should try to find one. In a recent open discussion on geoengineering, Tim Kruger from the University of Oxford compared climate change and AIDS: many of the criticisms directed against geoengineering, including unintended consequences, misallocation of resources and moral hazard, could also be applied to efforts to treat HIV infection. Current antiretroviral therapies are expensive, have unpleasant side effects and do not provide a fully effective cure; nevertheless, they do dramatically increase survival rates. Kruger concluded that improved AIDS treatments and geoengineering should both be investigated, in addition to and not as a replacement for, the pursuit of preventive approaches.

Dig deeper, though, and that medical analogy becomes less convincing. Individuals decide for themselves whether to be treated for a disease (assuming treatment is available and affordable); approval procedures require that drug efficacy has been convincingly demonstrated; and control-based trials are used to quantify the

When prevention fails, a cure is needed.

risks of any side effects. For geoengineering, equivalent informed consent is impossible: everyone everywhere has to take the medication, whether or not they agree to the action taken. Furthermore, success is inherently uncertain because comparative controls are impossible for treatments that involve the Earth system as a whole.

Scrutinising the remedy

Wide uncertainties about the effectiveness of proposed geoengineering schemes are undeniable; yet these can be reduced through science and increased understanding. A strong case can therefore be made that, at the very least, we should bring together existing information for expert evaluation – to assess the feasibility of the proposed technologies not only with regard

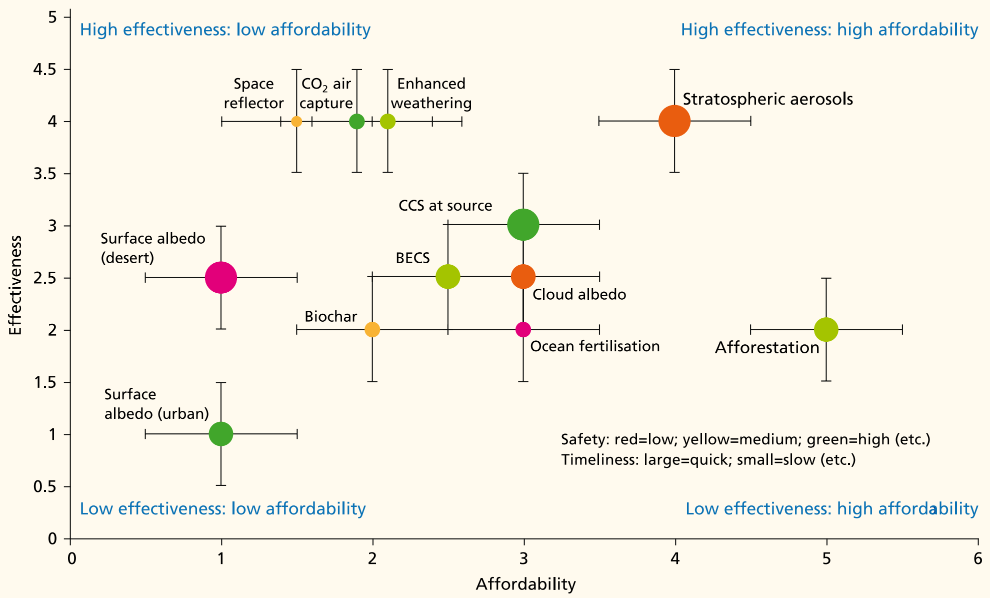

Figure 1. Evaluation of various geoengineering techniques on the basis of effectiveness and affordability.
CCS: Carbon capture and storage (CCS at source included for comparative purposes); BECS: Biomass with carbon sequestration.
Figure from UK Royal Society (2009). Reproduced with permission.

to their mechanistic performance and impacts, but also their economic and political viability.

We lack detailed option-specific evaluations based on such considerations but there have been efforts in this direction. For example, in 2009 the UK Royal Society provided an overview report, and Tim Lenton and Nem Vaughan published a preliminary assessment of the performance of geoengineering technologies in terms of their radiative forcing potential. There has also been a small UK study on the public acceptability of geoengineering (Box 2). IGBP will make its own contribution to the evaluation of geoengineering through two workshops in 2011-12 associated with its second synthesis. These workshops will focus on the possible consequences, intended and unintended, of different geoengineering options on Earth's ecosystems and biogeochemical cycles, and their findings will be reported at the global-change open science conference to be held in 2012 in London (Planet under pressure: New knowledge towards solutions).

IGBP will make its own contribution to the evaluation of geoengineering through two workshops.

The Royal Society report considered seven geoengineering techniques based on solar radiation management and nine based on carbon dioxide removal (Figure 1; see also Box 1 for the options). The authors rated various schemes on the basis of effectiveness, affordability, safety and timeliness, with estimates of uncertainty for the first two parameters. There were no clear winners: options that scored highly on effectiveness scored low on safety or cost, whereas those that were affordable and safe were less effective (Figure 1). Safety considerations covered the risk of undesirable regional climate change, ecosystem impacts, termination effects – effects resulting from stopping a particular geoengineering project – and reduction in crop yields. Arguably all solar radiation management techniques should score low on safety because ocean acidification would continue unabated (although not strictly speaking a side effect).

Although the grouping of geoengineering technologies under solar radiation management and carbon dioxide removal has a strong scientific rationale, an arguably more pragmatic grouping would be governance-based, distinguishing: 1) where manipulations and potential adverse impacts are limited to national jurisdictions (for example, afforestation and air-capture of carbon dioxide); 2) manipulations that are nationally-based, but with the possibility of trans-boundary impacts (e.g. large-scale land-albedo changes, geoengineering in coastal seas); and 3) where both manipulations and impacts involve the use of globally-shared resources (for example, open-ocean fertilisation, and atmospheric- or space-based solar radiation management).

Concerns that geoengineering is inherently undesirable and politically unworkable primarily relate to the third category, where one country might derive benefit at the expense of others. For example, a "sunshade" reduction in incoming solar radiation would produce regional disparities in its effects on mean temperature, while also changing the risk of floods, droughts or storms. The broad-scale impacts of such geoengineering, distinguishing winners and losers, can be investigated by modelling (see, for example, the recent work of Peter Irvine and colleagues). Negative effects on, say, crop production could, in theory, be compensated for. But extreme weather events are difficult to predict even in a non-geoengineered climate, and the separation of natural disasters that might have happened anyway from those that were caused by geoengineering would become nearly impossible, risking considerable international tension.

The crunch issues

No country currently includes the riskier forms of geoengineering in its national strategy for tackling climate change, and research to date has been small-scale or indirect. But many less-developed nations are worried about what would happen if richer countries decided that such geoengineering were preferable to reducing their carbon emissions. Partly as a result of this, the regulation of geoengineering is rising up the political agenda, on the basis that international governance frameworks to address such scenarios are needed sooner rather than later.

The research community needs to be aware of, and preferably participate in, these governance discussions to ensure that legitimate scientific studies, without significant impacts, can continue. But this is not always easy. The case of ocean fertilisation – the addition of nutrients to the oceans to encourage biological productivity and thereby sequester carbon – is instructive in this regard, with controversy surrounding the legality of the 2009 Indo-German LOHAFEX iron-addition experiment. Several international bodies and governance instruments are involved in the use and stewardship of the global ocean (including the Convention on Biological Diversity, the London Convention and London Protocol, and the Intergovernmental Oceanographic Commission). It is proving to be a long and complex process for such bodies to agree how ocean fertilisation research ought to be approved. Formal international agreement on "the real thing", with large-scale impacts potentially lasting years or centuries, could therefore be at least as difficult as negotiating carbon emissions reductions. Or it may even be unobtainable.

Not all geoengineering techniques present such problems. The air-capture of carbon dioxide and its subsequent storage would seem relatively benign, and could be carried out within existing national and international legal frameworks. In fact, storage is already under way in locations such as the Sleipner Field in the North Sea. But deployment of this technology would have to be on a massive scale to be globally effective, and that would be expensive. If costs were covered by a carbon tax, energy costs could double, and participating countries would be at a competitive disadvantage. Similar economic factors are a fundamental reason why the switch to low-carbon energy has not been more rapid, with neither UN conventions nor carbon trading so far succeeding in providing the socio-economic drivers to seriously tackle climate change – preventing carbon emissions in the first place, rather than having to capture the carbon afterwards.

It is highly unlikely that the various groups concerned with geoengineering will reach consensus. Yet, the research community is reaching a common understanding that deliberate climate control through geoengineering is not simply Plan B, providing an alternative to Plan A – reducing emissions. Instead, it may need to become Part 2 of Plan A, to be implemented in addition to very stringent carbon controls. We thus need to scrutinise the environmental risks, public acceptability and geopolitical constraints associated with different geoengineering approaches just as much as their technological feasibilities.

Box 2. The public weighs in

Opinion polls usually involve a representative sample size of around 1000. But asking that number of people their views on geoengineering isn't going to work: the overwhelming answer would be "don't know". So instead a UK polling company invited 85 individuals to three public dialogue events, commissioned by the Natural Environment Research Council and other partners. Public participants were provided with basic information on nine geoengineering technologies; they then debated which approaches should be researched in the future and whether any might be needed at all.

The outcome (Ipsos MORI 2010) was cautious public support, favouring research on those technologies (such as afforestation and biochar) that were perceived as most natural, but not those seen as expensive and risky (for example, mirrors in space). Participants were keen that geoengineering should not conflict with mitigation, but should augment it as much as possible.

The organisers of the public dialogue emphasised that its results were indicative rather than quantitative. Nevertheless, important understanding was gained on how non-scientists make judgements on scientific information. There was recognition that for potentially controversial topics such as geoengineering, decisions to fund research should take into consideration the views and concerns of common people around the world.

The regulation of geoengineering is rising up the political agenda.

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FURTHER INFORMATION

Bronson D, Mooney P, Wetter K J (2009). www.etcgroup.org/en/node/4966

Ipsos MORI (2010) www.nerc.ac.uk/about/consult/geoengineering.asp

Irvine P J, Ridgwell A and Lunt D J (2010) *Geophysical Research Letters* 37, L18702, doi: 10.1029/2010GL044447.

Lenton T M and Vaughan N E (2009) *Atmospheric Chemistry & Physics* 9: 5539-5561.

Rockström J *et al.* (2009) *Nature* 461: 472-475.

UK Royal Society (2009) *Geoengineering the Climate: Science, Governance and Uncertainty.* http://royalsociety.org/geoengineering-the-climate/

CLIMATE CHANGE'S FAMOUS COUSIN

Ocean acidification has transitioned from a little-known phenomenon to a buzzword within a span of five years. The concomitant explosion of research on this topic has provided many general insights into its effects. But as **Sarah Cooley** reminds us, many of the specifics regarding its consequences for humans and ecosystems await elaboration.

Ocean acidification refers to the progressive decrease in ocean pH and carbonate-ion (CO_3^{2-}) concentration as the oceans take up anthropogenic carbon dioxide from the atmosphere. The term appears in the media under many colourful aliases including "the other carbon dioxide problem" and "climate change's evil twin." The speed at which this phenomenon has gained nicknames reflects the exponential rise in research over the past five years.

A milestone in our awareness of this issue was the First Symposium on the Ocean in a High-CO_2 World, which was held in Paris in 2004. Since the first report of acidification's harmful effects on pteropods – creatures such as sea snails – appeared in 2005, the number of published scientific articles on the topic has approximately doubled each year from 2006-2009 (red bars, Figure 1). The rate for the first half of 2010 suggests that the trend may indeed continue. Compared with the steadily increasing number of papers on climate change mentioning the ocean (blue bars, Figure 1) over two decades, the number of ocean-acidification research papers has simply exploded.

Anthropogenic carbon dioxide is profoundly affecting marine chemistry.

The message from this research is clear: anthropogenic carbon dioxide is profoundly affecting marine chemistry and many marine organisms are likely to be affected. If ocean acidification alters ecosystem services such as shellfish harvests, humans are likely to feel the sting. It is this potential to cause economic (and thus perhaps socio-political) disruption that has led policymakers to take a special interest in the process. Along with research articles, summaries for policymakers are also proliferating. Nevertheless, gaps in understanding remain and it is still too early to develop comprehensive management plans that account explicitly for the effects of acidification. Such plans might eventually become necessary components of strategies to adapt to global change, which is why broad research to integrate and extend our understanding of acidification is essential.

A multifarious problem

Until atmospheric carbon dioxide levels began rising rapidly due to human industrial activities and land-use changes in the late nineteenth century, air-sea carbon dioxide exchange remained in a state of balance. Rising atmospheric carbon dioxide in the past two centuries, however, has disturbed the equilibrium: to restore it, surface seawater is now taking up more of this gas. Dissolved carbon dioxide reacts with water to generate carbonic acid, and some of the carbon dioxide also reacts with carbonate ions – used by organisms to make their shells – in seawater to form bicarbonate ions (See 'Basics of acidification' on the following page). In geologic terms, the ocean's uptake of anthropogenic carbon dioxide is faster than the blink of an eye. Before we used fossil fuels, compensatory changes in rock weathering or carbonate burial occurred over millennia. Marine life adapted to changing ocean chemistry over thousands or millions of generations. But we are now emitting carbon dioxide much faster than geologic controls can mop it up, so the ocean's pH and carbonate-ion concentration have decreased measurably since the start of the industrial age.

We know from studies conducted over the past few years that ocean acidification can have several effects. Many studies show that ocean acidification robs marine organisms such as some molluscs and corals of the raw material they need to build calcified shells and skeletons. Rising carbon dioxide levels increase photosynthesis in some phytoplankton and enhance nitrogen fixation in others. This could alter global biogeochemical cycling of carbon and nitrogen, and it could influence the marine food web by changing the types of phytoplankton available for predators. In some larger organisms, the effects of acidification depend on metabolic rate. More active animals can more easily regulate physiological processes over the short periods that have been studied so far, whereas those with low metabolic rates may be more susceptible to acidosis, metabolic depression

Basics of acidification

Dissolved carbon dioxide (CO_2) reacts with water to generate carbonic acid (H_2CO_3), which dissociates to release hydrogen ions (H^+), bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}):

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3^- \leftrightarrows 2H^+ + CO_3^{2-}.$$

Some of the carbon dioxide also reacts with existing carbonate ions, but this reaction does not change the pH:

$$CO_2 + H_2O + CO_3^{2-} \leftrightarrows 2HCO_3^-.$$

The net effect of these reactions is to lower pH by releasing hydrogen ions and reduce the supply of carbonate ions in seawater.

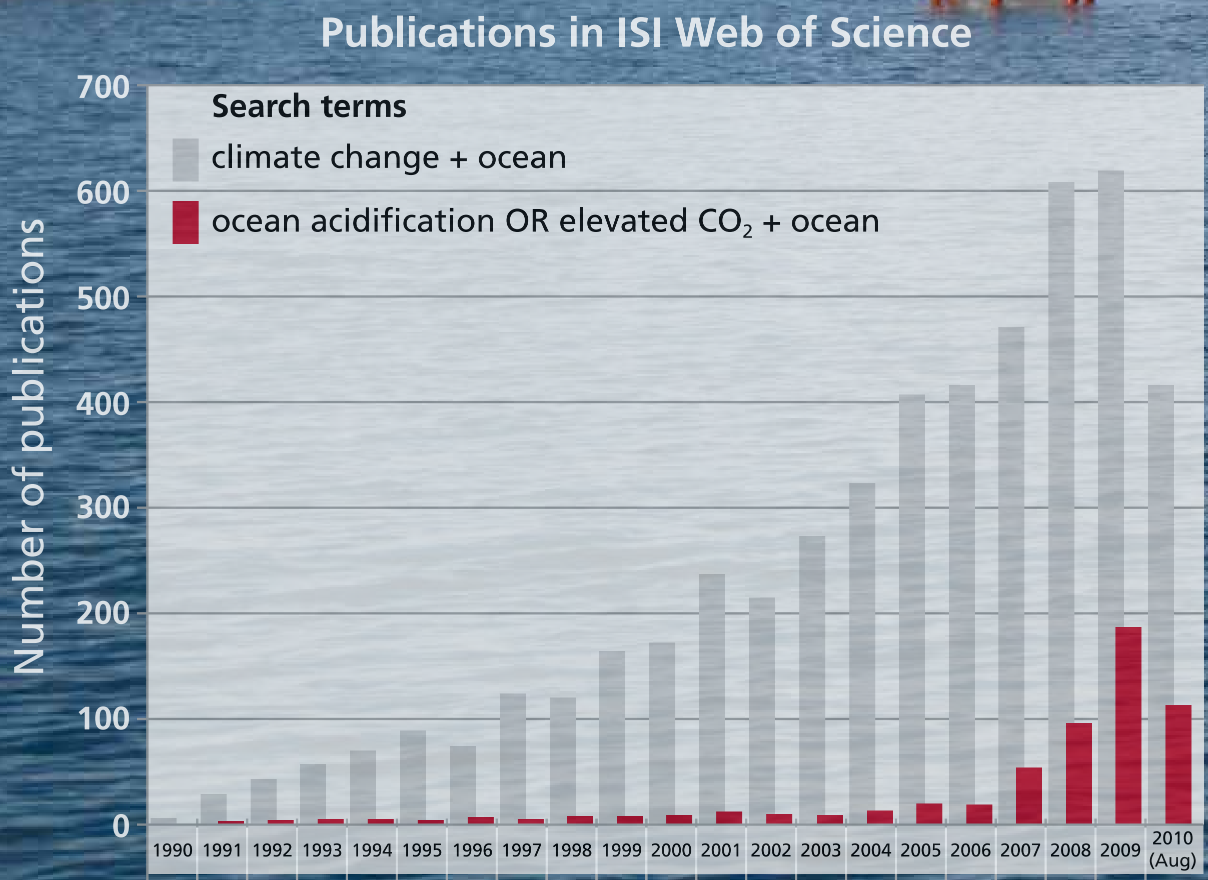

Photo: Ulf Riebesell; IFM-GEOMAR

or reduced respiratory efficiency. Acidification also affects marine organisms in unusual ways, for example, by slightly increasing sound transmission and making very quiet areas of the ocean a bit noisier. Such differing and subtle responses make forecasting consequences difficult.

In addition to affecting single organisms, ocean acidification could also alter interactions among them, which could alter whole populations. For example, carbon-dioxide-loving sea grasses could overtake damaged coral reefs and provide food and habitat for a different set of species. Food-web interactions would then convey and magnify these changes through the ecosystem. After regime shifts like this in which a profound ecosystem-wide transition occurs, diversity is likely to decline. Ecosystems with decreased biodiversity because of climate change or disease have become less resilient and suffer more from multiple stressors. Early data suggests that population-level effects seem poised to alter ecosystems profoundly by favouring a different array of organisms (Box 1).

Ocean acidification occurs in combination with other stressors such as climate change and human activities. Anthropogenic climate change increases temperatures and alters freshwater cycling, both of which change the layering of oceans. This in turn modifies nutrient cycling and insolation, affecting phytoplankton. Human activities alter coastal zones by diverting rivers or increasing erosion. Rising temperatures and melting sea ice may encourage new ocean-acidification-tolerant predators to invade high latitudes, where ocean-acidification-sensitive organisms suffer from direct effects of chemical change as well as from temperature change, habitat shifts and overfishing.

We now know quite a bit about ocean acidification. However, new research results often raise more questions. And placing results in context or applying them to other times and places remains a challenge. Deeply integrated efforts are required to advance our knowledge about ocean acidification henceforth (see the research priorities outlined recently by the United States National Research Council).

Box 1. Ecosystem-level effects

In the Mediterranean Sea, near Ischia (Italy), Jason Hall-Spencer and his colleagues studied ecosystems surrounding natural volcanic carbon dioxide (CO_2) vents to examine what might happen in future high-CO_2 oceans. The researchers used distance from these vents as a proxy for time: compared with seawater, locations moderately close to the vent had slightly lower pH values and slightly higher concentrations of carbon dioxide. Locations very close to the vent, though, had much lower pH values and much higher carbon-dioxide concentrations. The researchers found that the permanent concentration gradient governed the entire ecosystem structure in this environment. Non-calcareous algae replaced calcareous algae, sea urchins, limpets and barnacles as carbon dioxide levels rose and pH dropped near the vents. Moreover, they did not observe any juvenile calcifiers near the vents and noted that adult calcifiers appeared damaged.

Hall-Spencer J M *et al.* (2008) *Nature* 454: 96-99, doi:10.1038/nature07051.

Ocean acidification occurs in combination with other stressors such as climate change.

A large unknown is how ocean acidification will affect coastal zones. In the global ocean basins, open-ocean pH and carbonate-ion variability are low and trends are apparent. But what happens near coastlines, where seawater chemistry already varies greatly due to biological activity, runoff and physical circulation? Here, small progressive changes from ocean acidification are not easy to detect among all the other strong natural and anthropogenic signals. Positive or negative feedbacks may occur from nutrient cycling, weathering, upwelling and acid rain. Coastal regions' responses to ocean acidification will depend on all such factors.

Another issue awaiting resolution is to what extent the effects of ocean acidification will vary among species. For example, numerous laboratory experiments have shown that the net calcification rates for many organisms such as temperate corals and oysters decrease in response to lower pH or increased CO_2, and shells of some organisms even dissolve. Other organisms with calcified shells, such as crustaceans, seem not to behave the same way (Ries *et al.* 2009). To add to the complexity, responses sometimes vary among species within the same genus (Miller *et al.* 2009). To know why some species, but not others, are susceptible, we will need to understand the physiological mechanisms behind varying responses. Are organisms more sensitive during certain life stages? Does early damage affect individuals throughout their lives, or are some individuals simply always more susceptible?

The outlook

To take our understanding of ocean acidification to the next level, we need to determine how ecosystems, and not just individual organisms, will respond to acidification. Some ecosystem responses to perturbations may be similar regardless of cause; for example, coral "flattening" due to climate change – where reduced architectural complexity decreases diversity and species make-up – may also result from other stressors like ocean acidification (Alvarez-Filip 2009). Changes in species abundance and biodiversity often follow ecosystem perturbations, so understanding general or

Box 2. Fisheries under pressure

If mollusc harvests in the US decrease due to ocean acidification, direct losses could amount to several billion dollars by the middle of the century, a recent study suggests. Indirect losses, which would result from the impact on allied businesses (wholesale and retail sales, transportation), would therefore also affect regions with marine-dependent economies. In this situation, fishing communities like New Bedford in Massachusetts – already under economic duress – could lose over a billion dollars by the middle of the century. And jobs will inevitably be lost as well. Commercial fisheries, including processing and sales, contribute tens of billions of dollars to the US Gross National Product (GNP) and generate tens of thousands of jobs. Recreational fishing and associated spending also substantially contributes to the GNP and generates hundreds of thousands of jobs. Because of the many unknowns regarding how ocean acidification could affect ecosystem services, these types of economic impact analyses are preliminary and are accompanied by large uncertainties. But such analyses are an important first step towards guiding policies and encouraging interventions. They are also a call for continued research on ocean acidification at local, regional and global scales.

Cooley S R and Doney S C (2009) *Environmental Research Letters* 4, doi:10.1088/1748-9326/4/2/024007.

specific responses to disturbance is vital to understanding and predicting ecosystem change due to ocean acidification.

We have learned and continue to learn a lot from laboratory experiments but we now also need experiments in natural environments involving real-world conditions. One way to do this is to employ mesocosms – large-volume enclosures, essentially plastic bags – suspended in the sea. In these bags, researchers vary carbon dioxide levels and observe the response of organisms within. The European Project on Ocean Acidification (EPOCA), for example, brought together researchers from around the world to do this type of study in the Arctic Ocean in June and July this year. Studies like this will help us figure out how natural systems respond to sudden changes, and they may indicate the limits of ecosystems' resilience to change.

Finally, given the potentially large economic and social implications of ocean acidification (Box 2), we need more integrated research that can inform development of management strategies. Policymakers at all levels and marine resource users are becoming aware of ocean acidification and are beginning to seek information that can support decisions. Various countries are developing multidisciplinary ocean acidification research programmes. Activities as focused as topical workshops (e.g., the November workshop of the Monaco Environment and Economics group) or as broad as international working groups are under way to link oceanographic issues to socioeconomics (e.g., the IMBER human dimensions working group now being developed). Moreover, the IPCC will address the oceanographic and human dimensions of ocean acidification in its fifth assessment report. The organisational efforts now under way aim to bring together researchers and users in ways that incorporate everyone's perspectives, approaches and needs.

Relating ocean acidification to other decision-relevant issues like climate change will contribute to more universal management plans. For example, since ocean acidification was widely recognised, proposed climate-change mitigation strategies now usually include reducing atmospheric carbon dioxide to combat both climate change and acidification. Nevertheless, it is clear that a great deal of research is still needed to answer the many unknowns specific to ocean acidification and to plan for the future. ■

We need more integrated research that can inform the development of management strategies.

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REFERENCES

Alvarez-Filip L, Dulvy N K, Gill J A, Côté I M and Watkinson A R (2009) *Proceedings of the Royal Society (Biological Sciences)* 276: 3019-3025).

National Research Council (2010) Washington, D.C., The National Academies Press. http://www.nap.edu/catalog.php?record_id=12904#toc.

Miller A W, Reynolds A C, Sobrino C and Riedel G F(2009). *PLOS ONE* 4 (5): e5661.

Ries J B., Cohen A L and McCorkle D C (2009). *Geology* 37: 1131-1134.

IGBP PARTICIPATION

In 2009, IGBP's marine projects IMBER and SOLAS launched a working group to coordinate international research on ocean acidification and to conduct regular syntheses. The group has at its core the European Project on Ocean Acidification EPOCA, and hopes to facilitate the involvement of the ocean acidification community in the IPCC assessments.

Climate variability in the southern hemisphere

Most studies that reconstruct the climatic conditions of the past centuries to millennia tend to focus on the northern hemisphere. But now an intriguing multicentennial record of temperature and precipitation in southern South America is available. **Raphael Neukom** and **Jürg Luterbacher** elaborate on its significance.

We need to know about past climate because it is important both for understanding how the climate system works and for improving the accuracy of projections of future climate change. But the instrumental climate record covers just the past 150 years or so. To overcome this limitation, reconstructions of the climate further back in time rely on what are termed as "proxies" – historical documents or natural archives that allow indirect estimates of variables such as temperature and rainfall. Yet, much of this research has focused on the northern hemisphere; the southern hemisphere mostly remains *terra incognita*. Now, results of an international research initiative mean we can begin to quantify continental-scale climate variations in southern South America before the instrumental record began.

South America is an especially important landmass in the southern hemisphere.

These results, synthesised by Neukom *et al*. (2010), provide a high-resolution record of temperature and precipitation in South America going back several hundred years.

South America is an especially important landmass in the southern hemisphere, for it spans a range of climates that are influenced by multiple drivers such as the El Niño Southern Oscillation, Antarctic Climate and the high Andes, for example. Although proxies with good age control are sparse in tropical South America, the southern half of the continent provides many more proxies that we can use to infer past climatic fluctuations. Ice cores from Andean glaciers and ice fields, drilled at up to 6100 metres above sea level, record snow accumulation and the chemical composition of the atmosphere over time. Trees living up to 3500 years and growing at altitudes up to 5000 metres above sea level respond to variations in temperatures and/or drought, recording this information in the width of their annual growth rings. We derived additional information from lake and marine sediments. Furthermore, we used historical documents from the time of the Spanish colonisation, now stored in many different archives in Europe and the Americas, that report on agricultural yields and the climatic (and non-climatic) causes of yield fluctuations.

It is one thing to have proxy records, though, and another to pool together available information for specific locations and then infer the palaeoclimatic history of half a continent. In the area of investigation, proxies were not distributed evenly in space and time. Some proxies were more suited to estimating summer temperatures than winter ones. And some were actually from areas outside of southern South America but were known to have the same set of controls on their climate. All of this meant that we needed an elaborate statistical methodology to reconstruct the annual history of summer and winter temperatures, and of precipitation (rain and snow) of the region. We now have summer temperatures stretching back more than 1000 years. But winter temperatures could be reconstructed only for the past 300 years or so due to the more limited number of proxy data that resolve winter temperature conditions. We constructed summer and winter precipitation to the late 15th and late 16th centuries respectively.

Comparisons and contrasts

The new records now allow us to compare the climate evolution of both hemispheres, leading to some interesting observations. Consider the comparison between the summer and winter

Polylepis tarapacana trees are highly sensitive to climate changes in the Andean Altiplano, and store information about such changes in their annual growth rings.

temperature trends for southern South America and Europe, for which seasonally resolved temperature reconstructions are available (Figure 1). During some periods, the summer temperatures in the two regions seem to have fluctuated quite synchronously, for example in the 17th and 20th centuries. This co-variation could arise from global controls such as changes in solar irradiation, large volcanic eruptions or decadal-scale changes in the behaviour of globally relevant climate phenomena such as the El Niño-Southern Oscillation. It could just as well be a chance phenomenon. Other periods do not show a synchronicity for summer temperatures, and the winter temperatures generally do not seem to vary in consort. It is likely that the effects of the global forcing mechanisms were superimposed with and perturbed by strong regional to hemispheric-scale influences during these periods. To pinpoint the causes of these variations, we will require reconstructions from other regions and climate-model simulations.

Notably, in South America the 20th-century warming was less pronounced in the context of the preceding centuries than for instance in Europe, especially during the summer (Figure 1). For example, we found that the average surface temperature in southern South America rose 0.44°C in the 20th century. European records representing northern hemisphere conditions show a more pronounced rise of 0.79°C. The lower rate of warming in the southern hemisphere, which is also evident in climate models, can be explained by the role played by the waters in this hemisphere. The Southern Ocean has a large capacity to take up heat and store it in its waters, which leads to a smaller warming at the surface. The southern, water-dominated hemisphere thus reacts with a certain lag to global warming as compared to the northern, land-dominated hemisphere. This could be why the temperatures in southern South America are not yet extraordinary compared with previous centuries. In contrast, comparable northern-hemisphere reconstructions do show 20th-century temperatures that are markedly different from past centuries. In fact, changes in atmospheric dynamics have even led to cooling over a small area in coastal Chile in recent decades (Falvey and Garreaud 2009).

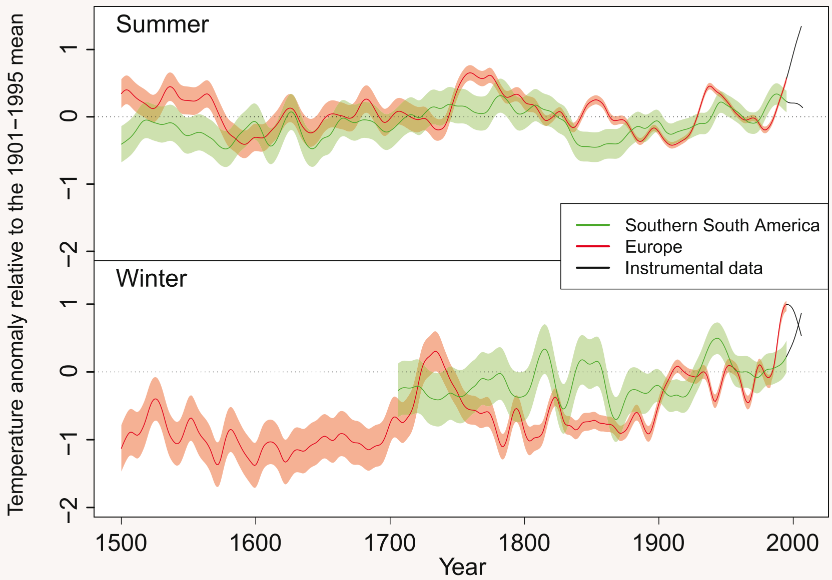

Figure 1. Decadal-scale summer (top) and winter (bottom) temperature fluctuations in southern South America (Neukom *et al.* 2010) and Europe (Luterbacher *et al.* 2007) over the past 500 years, expressed as anomalies with respect to the 1901-1995 reference period. Shaded areas represent the reconstruction uncertainties expressed as two standard errors. The black lines extend the temperature curves to the present using instrumental data.

The new records now allow us to compare the climate evolution of both hemispheres.

In contrast to the more muted warming, we find that in recent decades precipitation has changed substantially in some areas of southern South America. For example, the patterns of annual rainfall during the past four centuries in the catchment of the Laguna Mar Chiquita, a large lake in northern Argentina, are rather different from those in central Chile (Figure 2). In the former region, a large jump in rainfall amounts (an increase of more than 100 millimetres per year on average) occurred in the 1970s, signalling a shift from a relatively dry regime to the presently wet one. In contrast, central Chile currently suffers from a prolonged drying; modern conditions are probably drier than at any time over the last four centuries. In general, our data and analysis suggest that summers in many parts of southern South America have become progressively wetter, whereas winters have become drier.

Societal implications

We know that key historical events in this region may have coincided with changes in climate. Earlier work has shown, for example, that periods of warfare and migration to fortified sites in the Andean Altiplano in the 14th and 15th centuries coincided with and may have resulted from severe drought. Climate reconstructions of the sort discussed in this study can help provide a far more detailed context for these events. They also have implications for contemporary societies. The economies on both sides of the Andes are highly dependent on

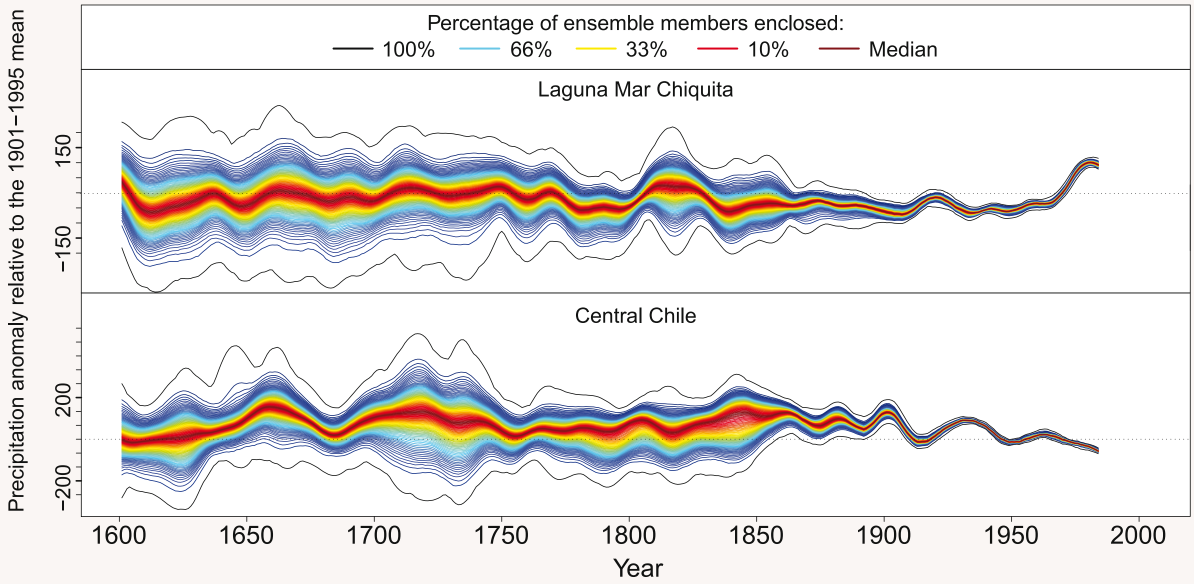

Figure 2. 400 years of annual precipitation history at Laguna Mar Chiquita (northern Argentina; upper panel) and Central Chile (lower panel). Precipitation was reconstructed using a probabilistic "ensemble reconstruction" approach. The median represents the most probable values. The dotted line represents 0-millimetre anomalies (reference period 1901-1995). Modified after Figure 3 from Neukom *et al.* (2010).

the fresh water that stems from the mountains for irrigation and hydropower generation. Recent changes in the total amount and the seasonal distribution of precipitation have significant consequences for these sectors. Our reconstructions show that such changes have occurred in the past and should be incorporated into future economic planning and adaptation strategies.

Climate-model simulations for the 21st century project up to 50 percent reduction in precipitation relative to the present day conditions, mainly in the central Chile area. In combination with future melting of Andean glaciers, this may lead to critical reductions in water availability, which may strongly affect agriculture, freshwater supply and hydropower generation in some areas. In the northern and southern parts of the study area, models project rather wetter conditions, which may benefit the agricultural sector in the highly populated area between Buenos Aires and Rio de Janeiro.

The southern hemisphere has not received the kind of attention from climate researchers that it deserves. Our research is the first to reconstruct the regional climate in any part of this hemisphere at a high temporal resolution. Although the results raise more questions than they answer at this stage, we hope they will provide a foundation for further regional studies in South America in particular and the southern hemisphere in general. More importantly, they are expected to refine our understanding of how and why climate changes at local and regional scales, and thereby guide our responses to future change.

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Precipitation and associated uncertainties has changed substantially in some areas of southern South America.

This research was conducted under the auspices of the LOTRED-SA project, an initiative of IGBP's Past Global Changes (PAGES) project and the recently launced PAGES 2K initiative. This initiative aims to reconstruct the climatic variation of all continents at high temporal and spatial resolution over the past two millennia. http://www.pages.unibe.ch/science/last2millennia.html

REFERENCES

Falvey M and Garreaud R (2009) *Journal of Geophysical Research* DOI:10.1029/2008JD010519.

Luterbacher J *et al.* (2007) *Geophysical Research Letters*, DOI: 10.1029/2007gl029951.

Neukom R *et al.* (2010) *Climate Dynamics*, DOI: 10.1007/s00382-010-0793-3.

Neukom R *et al.* (2010) *Geophysical Research Letters*, DOI: 10.1029/2010glo43680.

Mountain glaciers *face the* HEAT

The recognition of an error in the fourth assessment report of the Intergovernmental Panel on Climate Change put the spotlight on glaciers. Not all glaciers are about to disappear but their recession is real and so are the impacts the loss of this "stored water" will have on ecosystems and societies, **Ray Bradley** asserts.

The discovery in 1991 of a mummified body emerging from a melting ice field high in the Italian Alps was one of the most sensational archaeological findings of recent decades. "Ötzi" as he came to be known, together with his clothing and personal belongings, was preserved so well that studies of his remains claimed the attention of many scientists for two decades. The insights gained from these studies virtually rewrote what we know about early farming and herding life in the high mountains of southern Europe around 5 300 years BP (before present), a testimony to Ötzi's remarkable posthumous contributions to science.

Over recent years, many other well-preserved prehistoric artefacts have been recovered from melting snowfields on high mountain passes of the European Alps, and the western mountain ranges of North America. Hikers and climbers have found leather shoes and clothing, baskets, bows and arrows and other important samples of early technology, providing new insights into the lives of prehistoric hunter-gatherers in these remote mountain regions. But while melting snowfields and receding glaciers have proven to be a boon for archaeology, they also call attention to the magnitude of environmental changes taking place in mountain regions around the world. These changes have broad significance as they also affect the societies and ecosystems beyond the mountains that rely on mountain rivers and streams for their sustenance.

Glacier retreat is one of the most visible symbols of global warming.

Mountain glaciers and perennial snowfields comprise only a small fraction of the global cryosphere (the realm of snow and ice), accounting for about 100,000 km^3 of the 28 million km^3 of frozen water on Earth's landmasses. If all the glaciers and small ice caps outside of Greenland and Antarctica were to melt, global sea level would rise by just about a quarter of a metre. So on the face of it, mountain glaciers would seem to be relatively insignificant compared with the large ice sheets of Greenland and Antarctica. However, glaciers play a critically important role in the hydrology and river ecosystems of many regions, providing meltwater for drinking, irrigation, hydropower production and downstream river traffic.

Furthermore, unlike large ice sheets, glaciers respond relatively quickly to changes

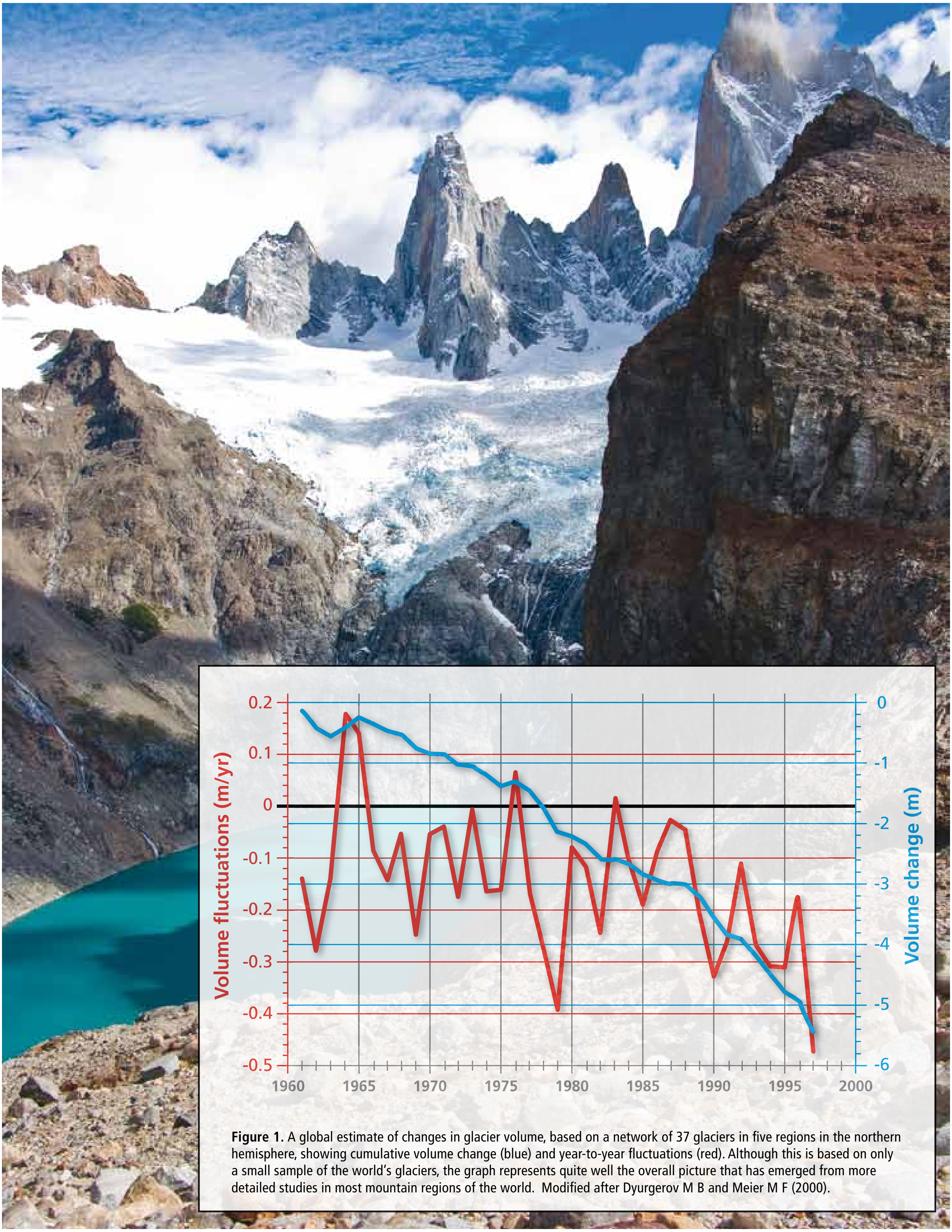

Figure 1. A global estimate of changes in glacier volume, based on a network of 37 glaciers in five regions in the northern hemisphere, showing cumulative volume change (blue) and year-to-year fluctuations (red). Although this is based on only a small sample of the world's glaciers, the graph represents quite well the overall picture that has emerged from more detailed studies in most mountain regions of the world. Modified after Dyurgerov M B and Meier M F (2000).

in climate (temperature and precipitation). Glaciers continually flow downhill. If the snowfall sustaining a glacier declines, or if there is an increase in ice loss (ablation), these will result in recession of the glacier or an overall thinning of the ice mass (or both), generally within a few years. So, as temperatures have risen almost all over the planet, the retreat of glaciers from mountain valleys is one of the most visible symbols of global warming. Rates of glacier recession vary from one region to another, and in a few areas glaciers have actually advanced in recent years. However, the overall picture of widespread recession is unequivocal (Figure 1) and reflects the familiar record of global warming. Where glaciers have bucked this trend, the explanation is generally due to regional circulation changes that have resulted in more winter snowfall, or to the fact that the retreat of some large glacier systems lags behind contemporary climate. This means that the recession of those glaciers is likely to be seen in future years.

Glacial meltwater has important ecological and economic value.

A tale of decline

In spite of sparse data for some regions, glaciers have been feeling the heat all over the world. Since 1850, the European Alps have seen glacier area plummet by 50 percent, with a corresponding 65 percent loss of ice volume. The rate of ice loss has accelerated significantly in the last 30 years. But this is still less than many high mountain regions of the tropics and subtropics. For example, between 1997 and 2008, Ecuador's glaciers lost 41 percent of their area. Between 1986 and 2000, northern Chile's glaciers declined by 40 percent. A recent study suggests that Columbia's glaciers may disappear in the coming two decades (Poveda and Piñeda 2009). In the mountains of East Africa and New Guinea, similarly high rates of ice loss have been recorded, and some high mountain ranges have become completely ice free. In a few cases, it is possible to place the magnitude of these changes in a long-term perspective.

In all likelihood, Ötzi had been ice-covered since he died in that remote location, 5 300 years ago. It is unlikely his body and fragile artefacts found with him would have survived exposure to the atmosphere. Similarly, leather artefacts found high on snowfields in the Swiss Alps, dating from 4900-4500 years BP, must have been buried in snow and ice throughout the intervening years. In Peru, plant material found beneath the receding edge of the Quelccaya Ice Cap (the largest ice cap in the tropics) was radiocarbon dated at ~5200 years BP. These and other studies suggest that the current recession of mountain glaciers and snowfields, across almost the entire globe, is greater than anything seen for many thousands of years, and provides support for the argument that anthropogenic effects on the climate system are unprecedented on the scale of recent human history.

Glacier recession is a symptom of global warming, and there is evidence that warming has been even greater at high elevations. In eastern Tibet, for example, the rate of warming over the last 50 years is two-to-three times greater above 4500 m than in areas below 1000 m. General circulation models used to assess the climate changes expected with increased levels of greenhouse gases show that high mountain regions in the tropics will experience higher temperatures than regions at lower elevations, and this may lead to a further decline in the extent of glaciers and perennial snowfields in those regions.

The glacial see-saw

During the last major ice age, about 21,000 years ago, vast ice sheets covered much of North America and Scandinavia, and sea-level was ~130 metres lower than it is today. As the position of the Earth in relation to the Sun changed, these ice sheets began melting and eventually disappeared almost completely around 6000 years ago, in the mid-Holocene period. Temperatures declined again in response to further changes in the Earth's orbital position, leading to a rejuvenation of glaciers in many mountain regions of the world during what is called the Neoglacial period. During the past few thousand years, glaciers have advanced and retreated in response to different factors – explosive volcanic eruptions occasionally cooling the Earth, changes in solar irradiance, changes in circulation patterns such as El Niños or other atmospheric modes and a host of local issues specific to different mountain ranges. From the 13th to the middle of the 19th century, a period dubbed "The Little Ice Age", mountain glaciers advanced throughout the world. Most scientists attribute this to a period of more frequent explosive volcanic eruptions, which reduced the amount of solar radiation reaching the Earth's surface.

Recently this pattern of glacier advances has abruptly shifted to one of widespread recession, as increased levels of greenhouse gases from fossil-fuel combustion overwhelmed natural factors, causing temperatures to rise to their highest level for over a thousand years. Today, in many mountain ranges, glaciers are disappearing, but the main polar ice sheets of Greenland and Antarctica remain. Nevertheless, even in those remote regions, evidence of glacier recession and ice-shelf collapse is growing, raising concerns about the stability of these vast ice masses and their potential to raise global sea-level significantly over the next century.

Global problem, regional twists

Glacial meltwater has important ecological and economic value, and any decrease is bound to affect downstream areas. But the specific impacts will likely vary based on location and context. Ecosystems and societies in parts of Central and South America are particularly vulnerable. A city like Lima in the dry coastal zone of Peru, for example, relies heavily on water that originates in the glaciated mountain ranges of the High Andes. In many countries in this region, run-off from glaciers is an important resource for hydropower generation. For example, 80 percent of electricity in Peru and 50 percent of electricity in Ecuador derives from hydropower. The World Bank estimates that the mean annual energy output from Peru's Cañon del Pato hydropower plant on the Rio Santa would drop from 1540 gigawatt-hours to 1250 gigawatt-hours with a 50 percent reduction in glacier run-off, and would be reduced further to 970 gigawatt-hours if the glacier run-off contribution disappeared completely.

Recent work (for example, Immerzeel *et al*. 2010; page 8 of this issue) suggests that the situation in Asia is more complex. Although there seems to be a general loss of ice in this region, some regions such as the Karakorum show an increase, and uncertainties about rates of change are considerable. Several major rivers – Indus, Ganges, Brahmaputra, Yangtze and Yellow – originate at high altitudes in the mountains of south-central Asia. But the relative contribution of meltwater (which includes glaciers as well as annual snowfall) and rainwater to each river basin varies.

In the lower Indus river valley, for example, much of the water for irrigation – which sustains a population of over 200 million people – comes from the high mountain glaciers and snowfields of the Himalayas. Similarly, meltwater amounts to about a quarter of the total discharge in the downstream areas of the Brahmaputra. For the other three rivers, the contribution is less than ten percent. Simulations by Immerzeel and colleagues suggest that the effect of climate change on water availability and food security in this region will be complex, with the Indus and Brahmaputra basins being severely affected and the Yellow River basin potentially benefiting.

Planning for the inevitable

To those with only a casual interest in the science of global warming, glacier recession may be the most visible expression of the complexity of environmental changes that are taking place throughout the Earth system. The loss of glaciers and upland snowfields certainly affects the aesthetics of mountain landscapes, and to many this effect by itself signals a tragic loss. But to millions of people living far from the mountains that provide life-sustaining water, the disappearance of glaciers will have a more profound significance and directly affect their way of life. As the above discussion suggests, there is a need for careful evaluation of region-specific response of the cryosphere to a changing climate and the impact this will have on societies and ecosystems.

Without policies to limit greenhouse gases and the associated relentless rise in global temperatures, the pattern of glacier recession is likely to continue. And even if mitigation policies were implemented today, nothing much can be done to save many glaciers. Some societies will thus need to adapt to these profound changes, and they will need all the help they can get from their governments and the international community.

Some societies will need to adapt to these profound changes.

The need to assess the probable impacts of cryospheric changes in the mountain regions of the world has never been greater.

A good start would be to increase monitoring of environmental changes in the high mountains (particularly meteorological conditions at high elevations and hydrological regimes downstream from glaciers) and to evaluate potential hazards that may arise as glaciers recede. General circulation climate models, which are the normal tools used to simulate future climate, are of very limited value for mountainous regions where the topography is complex. High-resolution regional models and downscaling techniques are needed to obtain a more realistic picture. Such actions would be cost-effective investments that would support science-based planning to manage future changes that, at least in some parts of the world, now seem inevitable. ■

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REFERENCES

Immerzeel W W, van Beek L P H and Bierkens M F P (2010) *Science* 328: 1382-1385.

Poveda G and Piñeda K (2009) *Advances in Geosciences* 22: 107-116.

Dyugerov M B and Meier M F (2000) *Proceedings of the National Academy of Sciences of the United States* 97(4): 1406-1411.

THE PERFECT STORM

Soil moisture patterns seem to be the trigger for new storms in the dusty Sahel. **Chris Taylor** recounts his experience of one such storm and discusses how the Sahel soil influences weather patterns.

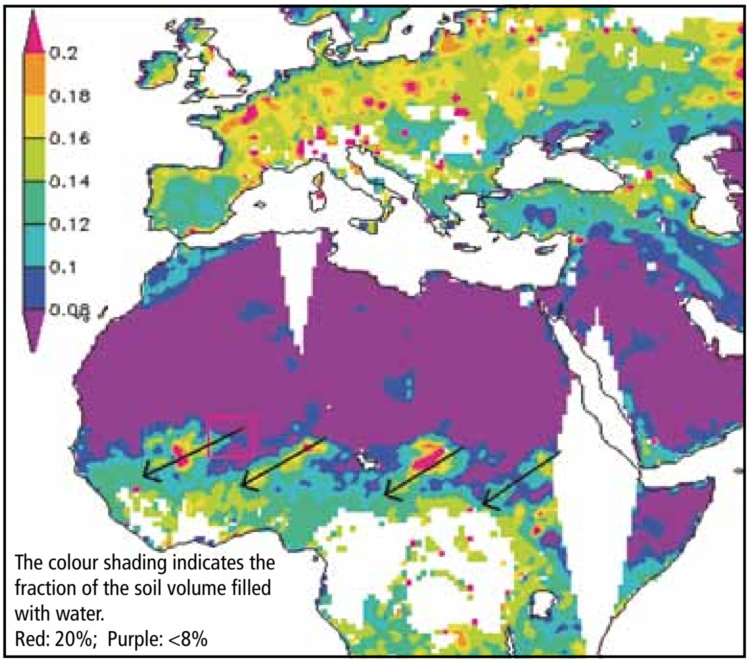

Figure 1. Soil moisture detected by satellite on a day in the 2006 wet season. Arrows denote the passage of recent storms. From Taylor C *et al.* (submitted) New perspectives on land-atmosphere feedbacks from the African Monsoon Multidisciplinary Analysis (AMMA). *Atmospheric Science Letters.*

No region has suffered more severely from drought in recent decades than the Sahel. This region, which stretches across northern Africa, separates the Sahara Desert in the north from moist tropical forests to the south. It is a key component of the global weather system – many storms in the Atlantic form over this region. The Sahel encompasses some of the least developed countries in the world – Niger, for example – and the impact of drought on agriculture, water resources and health has been profound. Dry conditions, set up by global and regional ocean temperatures, have been amplified by land feedbacks in the late 20th century. Models in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change do not offer a consensus about whether Sahelian rainfall will rise or fall in the coming decades. But feedbacks with vegetation and soil moisture are likely to influence future climate in the region, much as they have in the past.

The triggering of afternoon showers in the Sahel plays a critical role for the hydrology of the region.

Yet, predicting how soil moisture, vegetation, eva poration and rainfall interact with each other is fraught with uncertainty. Thanks to measurements over the past decades, we now understand how climate affects soil moisture and evaporation from the land. Less clear has been the extent to which the suppressed evaporation driven by the dry soils in turn influences rainfall. Recent measurements by the African Monsoon Multidisciplinary Analysis (AMMA) indicate that suppressed evaporation provides a potentially powerful positive feedback: the land can amplify and prolong dry periods, leading to more intense droughts.

Weather prediction and climate models have traditionally provided much of the insight into storm generation. However, we still missed some of the pieces of the jigsaw: detail of the processes going on within storms and detail about the huge variations in land conditions across a region. Within AMMA, we addressed this lack of basic knowledge with an observational campaign designed to measure the atmospheric response to different land conditions. We exploited a characteristic of the Sahelian wet season, the tendency for storms to occur typically every three or four days. These storms travel west across the region, depositing typically tens of millimetres of rain on the land in a swath that is often hundreds of kilometres across (Figure 1).

For the first day or two after rain, much of the solar energy reaching the ground gets used up evaporating water from the wet soil. However, once the soil has dried out after four or five days without rain, the energy goes into heating the atmosphere instead. On any given day in the rainy season, parts of the region will be wet and other parts dry. We used a combination of aircraft and satellite data to examine differences in the atmosphere above wet and dry surfaces to infer how soil moisture affects storms. Before the AMMA observational campaign, we had analysed satellite data and found, perhaps surprisingly, that

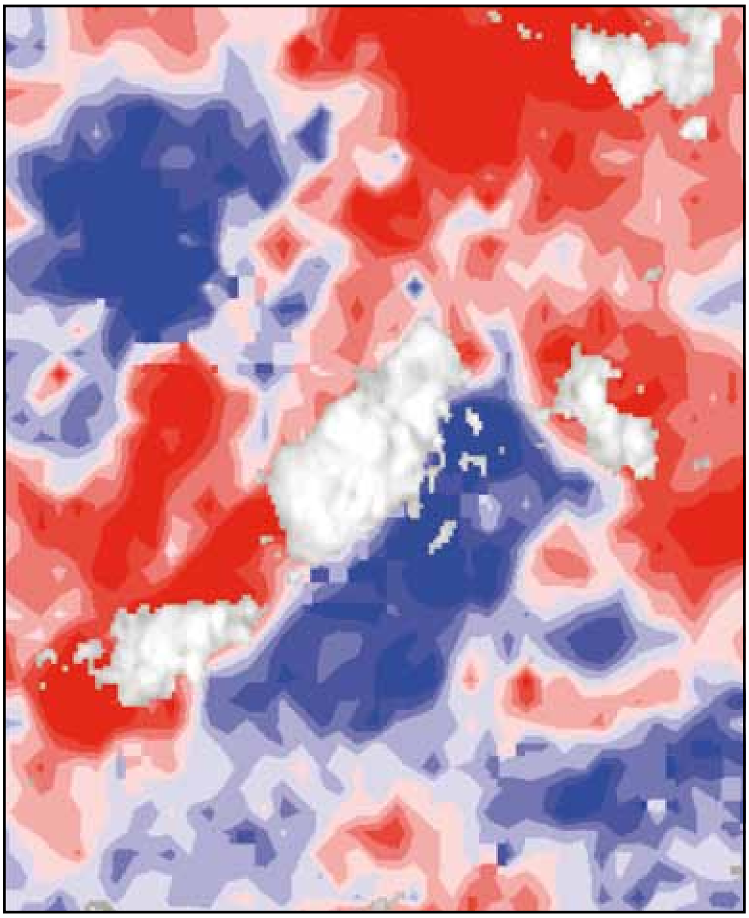

Figure 2. Early development of storm clouds (grey/white) above patches of soil moisture. The red and blue shading denotes dry and wet areas of soil, based on land surface temperature data prior to the storm. From Taylor C M, Harris P P, and Parker D J *et al.* (2010) Impact of soil moisture on the development of a Sahelian mesoscale corrective system: A case study from the AMMA Special Observing Period. *Quarterly Journal of the Meteorological Society* 136: 456-470.

afternoon storm clouds were about 40 percent more prevalent over dry soils when compared with wetter areas. However, we had been unable to isolate the mechanism underlying this feedback. We were hoping that the detailed *in situ* measurements from the aircraft campaign could provide this.

As anticipated, our aircraft data showed increased atmospheric temperature and reduced humidity in the areas where it hadn't rained. This was evident even when the dry areas were only five kilometres across, a surprising result given that turbulent eddies tend to mix the lower atmosphere rather effectively during the daytime. We also found that where dry soils met wet soils, the differences in temperature were large enough to affect the winds, in a manner analogous to sea breezes. Anyone who has ever sat on a beach watching the clouds will recognise the importance of such breezes for cloud development, and sometimes, sharp showers. Although generally unwelcome on the beach, the triggering of afternoon showers in the Sahel plays a critical role for the hydrology of the region. Some of these storms grow very rapidly, moving from a single cloud to a major storm covering an area the size of Wales in a matter of two or three hours. These systems produce the vast majority of Sahelian rainfall.

We had the good fortune to witness one such transformation during a research flight over northern Mali. We had set out that afternoon to take measurements above an interesting soil moisture pattern, anticipating calm conditions as had been forecast. But when we approached our target area, the radar indicated clouds directly ahead of us, forcing us to radically change our flight plan. Two hours later I was looking out of the airplane window and marvelling at the towering collection of cumulonimbus clouds that reached over 15 km above the ground. I was left wondering how a centimetre or two of water in the soil could possibly influence such a powerful phenomenon. Subsequent analysis of satellite data showed that soil water did indeed have a crucial role in the triggering of this storm. The storm subsequently travelled over 1500 km to reach the Atlantic Ocean. It had developed precisely where the breeze theory predicted, right along the boundary between previously wet and dry soils (Figure 2). It provided a powerful illustration of how rain on one day could trigger new storms in the region.

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Conditions in the Sahel allowed us to isolate the impact of soil moisture on convective storms. Similar processes are likely to influence rain in the many parts of the world where soil moisture limits evaporation rates. But it is not easy to use our understanding to improve the representation of such feedbacks in climate and weather models, not least because of the coarse nature of models, which cannot represent individual clouds growing over locally realistic land conditions. An important ongoing development is the use of increasingly accurate land-surface data, acquired by satellites, in weather models. In particular, the recent launch of the Soil Moisture and Ocean Salinity (SMOS) mission is providing information globally about soil water that occurs several centimetres beneath vegetation. It is hoped that this will significantly improve predictions of rainfall in the near future. ■

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