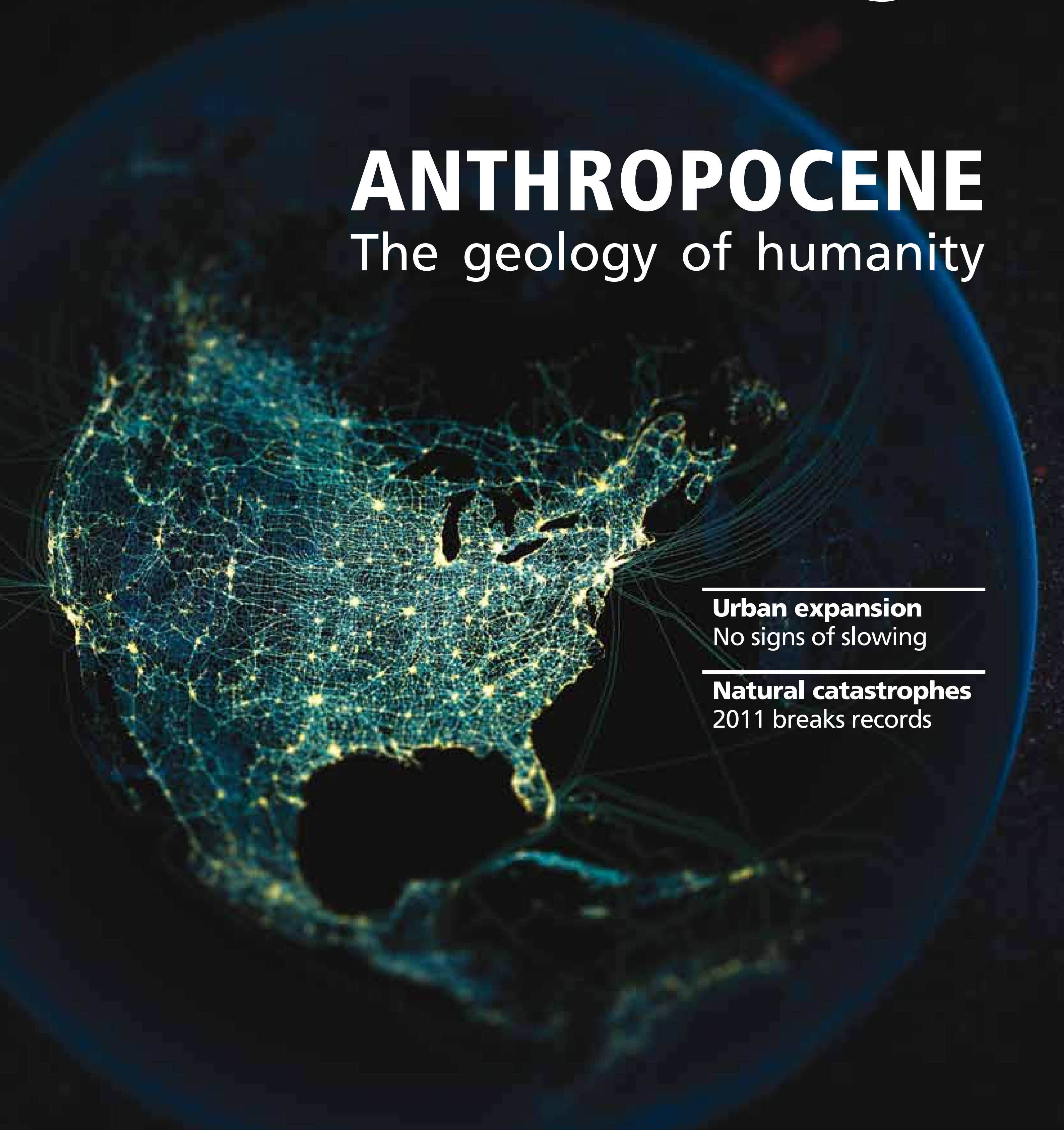
# Global Change

International Geosphere-Biosphere Programme

Issue 78 ▮ March 2012



## ANTHROPOCENE
### The geology of humanity

**Urban expansion**
No signs of slowing

**Natural catastrophes**
2011 breaks records

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**

A composite impressionist map of North America and its surroundings depicting urban areas, roads, railways, transmission lines, pipelines, shipping lanes and undersea cables (not to scale). The map highlights the human impact on the Earth.
Felix Pharand-Deschênes, Globaïa. http://globaia.org/en/anthropocene/




*Global Change* primarily publishes articles reporting science from within the extensive IGBP network.

Published by:
IGBP Secretariat,
The Royal Swedish Academy of Sciences
Box 50005, SE-104 05, Stockholm, SWEDEN

To inform us of a change in address, email:
charlottew@igbp.kva.se

Printed by Bergs Grafiska, Sweden

ISSN 0284-5865

Circulation: 6000 copies

If you have an idea for a feature article or news, email Ninad Bondre.

Editor: Ninad Bondre
ninad.bondre@igbp.kva.se

Director of Communications: Owen Gaffney
owen.gaffney@igbp.kva.se

Graphic Designer: Hilarie Cutler
hilarie@igbp.kva.se

Nordic Environmental Label 341 034 Printed matter

Sybil Seitzinger, Executive Director, IGBP

In 1988, Swedish academic Bert Bolin and colleagues set up the Intergovernmental Panel on Climate Change (IPCC). This body was to assess the science produced by the World Climate Research Programme and IGBP, themselves driven by the far-sighted Bolin. IPCC has proven to be highly successful and credible.

In the two decades or so since IPCC was set up, we have come to see that global challenges from poverty eradication and fisheries depletion to climate change and the financial crisis are interconnected and interdependent. What is now needed is a science-policy interface that connects the dots, proposes solutions and sounds alarm bells on emerging issues. It is striking that there is of yet no independent, impartial assessment that provides a comprehensive and integrated look at all the issues the planet faces.

For several years we at IGBP have been discussing the need for greater integration. In the policy brief "Interconnected risks and solutions for a planet under pressure" for Rio+20, commissioned by the Planet Under Pressure conference and led by IGBP, periodic global sustainability assessments are explicitly called for. One option is to create a multi-stakeholder panel with a focus on risks and solutions to produce regular state-of-the-planet assessments that include the environmental, social, economic and political dimensions. An assessment of this type would not compete or negate existing assessments such as the IPCC and Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES). On the contrary, it could build on them and maximise their effectiveness to provide the knowledge necessary for achieving global sustainability.

Recent developments suggest that things are finally moving in the right direction. The UN Secretary-General's High Level Panel on Global Sustainability has called for a sustainable development outlook report. And the first draft of the Rio+20 outcome document recommends regular state-of-the-planet assessments. We at IGBP have spoken regularly with the Secretary-General's panel since its inception and are delighted to see our thinking resonated in the panel's report. IGBP also submitted a similar proposal to the Rio+20 draft outcome document. We now need a mechanism to implement these recommendations, including a full analysis of what structure will work best – a multi-stakeholder panel might be deemed too cumbersome, so a refined model may be required.

The new Future Earth – Research for Global Sustainability initiative could have an important role in this context. This ten-year initiative, being developed by the International Council for Science and other leading international organisations, including UN bodies and major science funders, is expected to emerge from the realignment of IGBP and the other global-change programmes. If this initiative is to be as successful as its predecessors, it will need an international policy forum that can use the new knowledge generated and synthesised. A new, overarching assessment that brings together all global interconnected challenges could provide this focus.

> "What is now needed is a science-policy interface that connects the dots.

## International Year of Deltas mooted

IGBP CHAIR James Syvitski and other researchers from the IGBP community are among those who have called for 2013 to be declared as an International Year of Deltas in an article published in *Eos*. Deltas support large populations, rich biodiversity and important ecosystems, but are severely threatened by human activities. Nothing short of a truly interdisciplinary and international effort will suffice to find sustainable solutions, the authors say. IGBP has endorsed the initiative. Foufoula-Georgiou E *et al*. (2011) *Eos* 92: 340-341.

## Exploring Planetary Stewardship

THE IGBP secretariat in Stockholm organised an international workshop entitled Planetary Stewardship: Solutions for Responsible Development, which was hosted at the Royal Swedish Academy of Sciences, 13-15 June 2011.

The workshop brought together 30 leading experts from diverse disciplines to discuss an optimal approach to stewardship. Also present was a representative from the High Level Panel on Global Sustainability, set up by UN Secretary-General Ban Ki-moon. Breakout groups focused on three themes: sustainable cities, sustainable resource chains and the sustainable planet.

Participants explored the links between global change, health, climate and resource security. There was broad agreement that equity and governance were important issues, and that urban regions – the source of several problems – can also contribute to solutions if managed carefully.

Data visualisation and the concept of planetary boundaries were discussed, as were several cases elucidating resource flows in space and time.

## IGBP inputs to SBSTA

PROFESSOR Mary Scholes of the University of Witwatersrand participated on behalf of IGBP in a side event organised by the Subsidiary Body for Scientific and Technical Advice (SBSTA). The side event, entitled Updates from Climate Change Science – Special Focus: Africa, was held during the 17th Conference of the Parties (COP17) in Durban, South Africa, in December 2011. IGBP has been invited to provide research updates to this body – a permanent body to the United Nations Framework Convention on Climate Change – for the past several years.

## Future Earth initiative

THE VISIONING process initiated by the International Council for Science (ICSU), IGBP's sponsor, calls for the establishment of a new ten-year initiative entitled Future Earth – Research for Global Sustainability.

The initiative is being developed along with the Belmont Forum, a group of major funders of global-environmental-change research, and other international organisations. It aims to deliver knowledge for societies to meet their sustainable-development goals in the coming decades.

Future Earth will build on the existing global-change research programmes and their projects, and will develop new projects while coordinating and focusing international scientific research on global sustainability.

A new governing body is expected to be appointed by the end of 2012. The initiative will be announced in two stages in 2012 – at the Planet Under Pressure conference in March and the UN Conference on Sustainable Development (Rio+20) in June.

# IGBP SCIENCE FEATURES PROMINENTLY IN PRESENTATION TO THE DALAI LAMA

THE GREAT Acceleration graphs from IGBP's first synthesis were among the programme's science that featured in a presentation made to the Dalai Lama recently by Diana Liverman. Liverman is the former chair of the Global Environmental Change and Food Systems (GECAFS) project and co-chair of the team guiding the transition to the new Future Earth initiative.

The presentation was made at "Ecology, Ethics and Interdependence", the Mind and Life XXIII conference with the Dalai Lama in dialogue with contemplative scholars, activists and ecological scientists.

The conference was held in Dharamsala, India, 17-21 October 2011. See IGBP website for more information: www.igbp.net.

The Office of His Holiness the Dalai Lama

## IGBP DIARY

### 2012

**March**

**24-25.** PAGES Scientific Steering Committee meeting. London, United Kingdom.

**25.** AIMES Scientific Steering Committee meeting. London, United Kingdom.

**30.** March-1 April. LOICZ Scientific Steering Committee meeting. London, United Kingdom.

**May**

**7-10.** SOLAS Open Science Conference. Cle Elum, Washington State, USA.

**11-13.** SOLAS Scientific Steering Committee meeting. Cle Elum, Washington State, USA.

**14-16.** GLP Scientific Steering Committee meeting. Amsterdam, The Netherlands.

**21-23.** 27th IGBP Scientific Committee meeting. Bergen, Norway.

**24.** One-day symposium in conjunction with the IGBP Scientific Committee meeting. Norwegian science highlights: Bio-geochemical Cycles and Sustainable Pathways in the Ocean, Atmosphere and Land. Bergen, Norway.

**June**

**12-14.** IMBER Scientific Steering Committee meeting 2012. La Paz, Mexico.

**September**

**17-21.** 12th IGAC Open Science Conference: Atmospheric Chemistry in the Anthropocene. Beijing, China.

**15-16.** IGAC Scientific Steering Committee meeting. Beijing, China.

**24-27.** The Ocean in a High-$CO_2$ World. Monterey, California, USA.

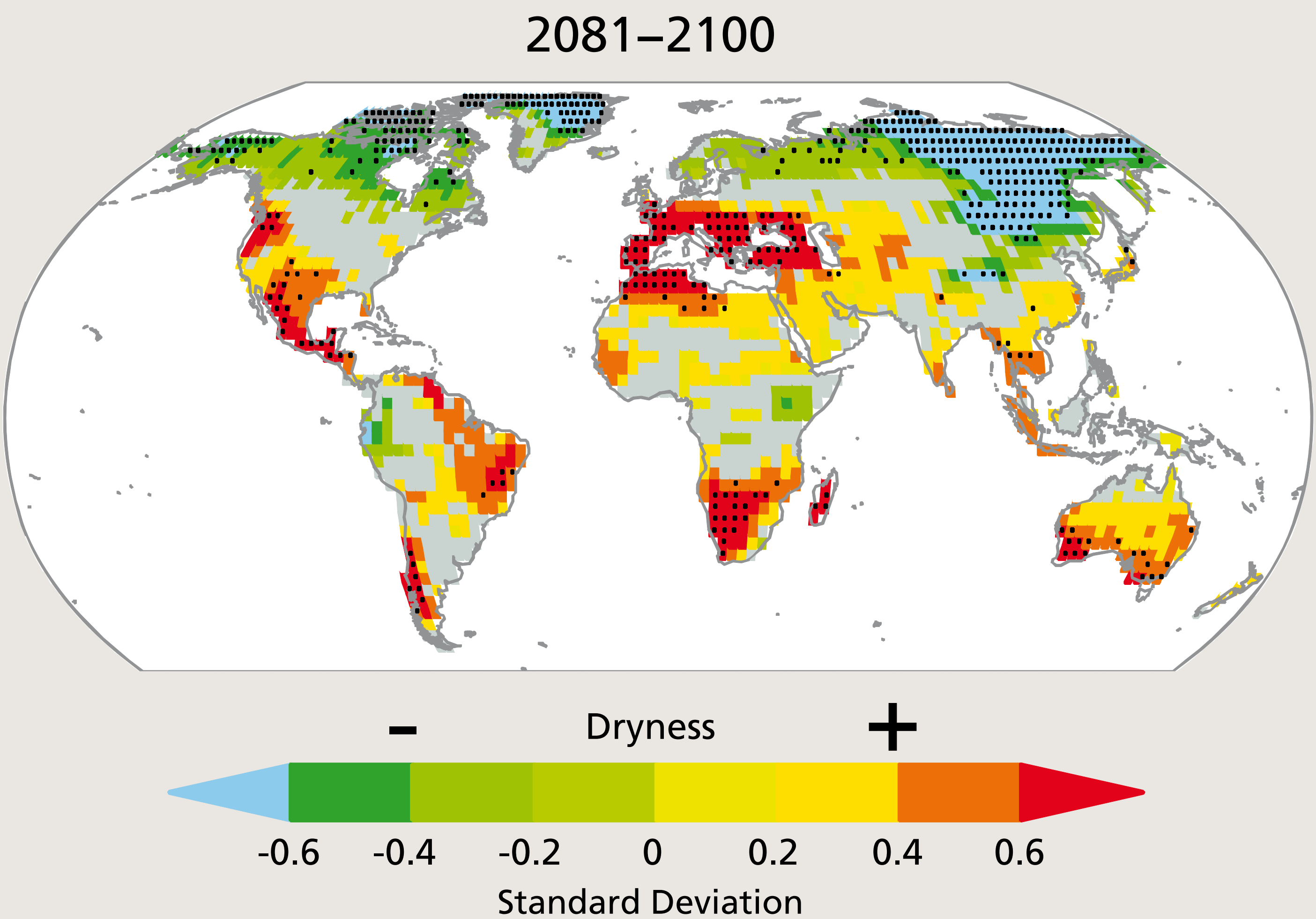
# THE FUTURE OF EXTREME EVENTS

HEAT WAVES and the frequency of heavy precipitation are likely to increase in the 21st century, according to a report recently published by the Intergovernmental Panel on Climate Change. Although we may expect climate-related extremes to increase in a warmer world, a comprehensive assessment of the role of climate change in altering the characteristics of extreme events was lacking. This is now provided by the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX).

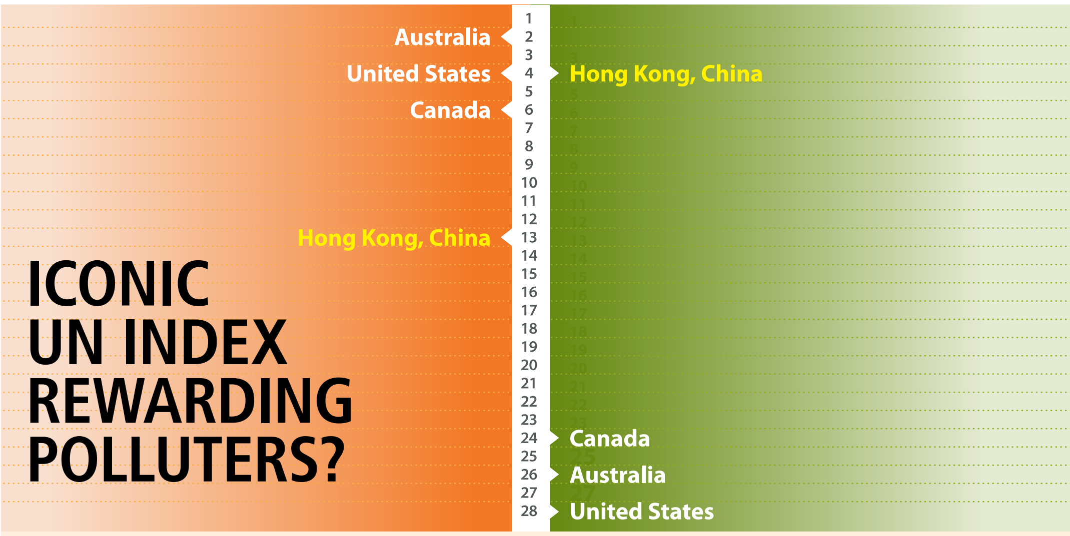
The projected precipitation and temperature changes imply changes in floods. However, the report states that there is low confidence at the global scale regarding climate-driven changes in the magnitude or frequency of river-related flooding due to limited evidence and because the causes of regional changes are complex. The assessment suggests with medium confidence that droughts in several parts of the world will also increase in the 21st century. And, echoing recent reviews, the report finds that the frequency of tropical cyclones will either decrease or stay the same.

The report also explores how the combined expertise from the fields of climate science, disaster risk management and adaptation can help manage risks related to extreme climate events. It incorporates case studies that illustrate specific extreme events and their impacts in different parts of the world, as well as a range of risk-management activities. It states that both incremental steps as well as transformational change are essential for reducing risk from climate extremes.

IGBP researchers Qin Dahe (co-chair of IPCC's Working Group I), Pauline Dube, Sonia Seneviratne and Mark Pelling were among the authors of the summary for policymakers.




The figure shows the change in annual maximum number of consecutive dry days (precipitation <1 mm) for the period 2081-2100 based on model projections. Increased dryness is indicated with yellow to red colours; decreased dryness with green to blue. From IPCC (2011) Summary for Policymakers, in Intergovernmental Panel on Climate Change *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, edited by Field C B *et al.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.




# ICONIC UN INDEX REWARDING POLLUTERS?

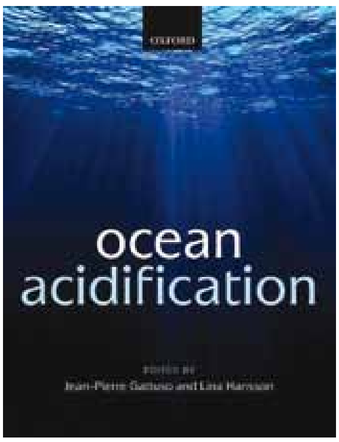
CHULUUN TOGTOKH, vice-chair of IGBP's Global Change National Committee in Mongolia, has called for the United Nations to overhaul its flagship development index, which he says wrongly promotes polluting countries as role models. "If the UN continues to encourage countries such as Mongolia to aspire to the US lifestyle, we will all be in serious trouble," he says, in a World View column in the journal *Nature*.

Togtokh says that the UN's annual Human Development Index (HDI), released in 2011, is flawed because it fails to take into account sustainability. "Worse still, the index celebrates gas-guzzling developed nations. It is time this failure – hidden in plain sight – was exposed and corrected," he says.

Togtokh has recalculated the index to take account of *per capita* carbon emissions from each nation, alongside the UN's traditional measures of health, education and income levels. He names his new metric the Human Sustainable Development Index (HSDI).

The results are striking: Australia slides from 2nd place to 26th, the United States drops from 4th to 28th, and Canada falls from 6th to 24th.

"The HDI has shifted the target of development beyond the almighty dollar; the proposed HSDI would go one step further and change the role models for development," he says. "My country is likely to become one of the fastest growing economies in the world, but the current HDI offers no encouragement for it to grow sustainably."




## Synthesis book on ocean acidification

THE EUROPEAN Project on Ocean Acidification (EPOCA) has published a book that synthesises the most recent information about the consequences of ocean acidification so as to inform both future research agendas and marine-management policy. The book, entitled *Ocean Acidification*, is edited by Jean-Pierre Gattuso and Lina Hansson, and is published by Oxford University Press.

## Land-use transitions in South America

LAND-USE transitions will continue to be important in South America as the region seeks to balance economic growth with environmental sustainability. Against this background, a group of scientists met in November 2011 in Ilhabela, Brazil, for a workshop sponsored by IGBP's Global Land Project and Brazil's National Institute for Space Research (INPE). The scientists discussed four main topics dealing with the future sustainability of the region: governance and institutions, vulnerability, environmental services, and modelling and data provision and analysis. The participants agreed that one of the key challenges is to better understand global processes (social, economic and political) affecting land-use transitions across the region. http://www.inpe.br/wsglp2011/.

# EVENTS

## 2012

### March

**22-24.** DIVERSITAS Scientific Committee meeting. London, United Kingdom.

**24-25.** IHDP Scientific Committee Meeting. London, United Kingdom.

**26-29.** Planet Under Pressure: New Knowledge Towards Solutions. London, United Kingdom.

**30.** National Global Change Research Committees' Day. London, United Kingdom.

### April

**17-20.** Dynamic Deltas International Conference. Vlissingen, The Netherlands.

**19-22.** Arctic Science Summit Week (ASSW) 2012. Montreal, Canada.

**22-27.** International Polar Year (IPY) "From Knowledge to Action". Montreal, Canada.

### June

**20-22. Rio+20**: United Nations Conference on Sustainable Development. Rio de Janeiro, Brazil.

**27-29.** IIASA 40th Anniversary Conference. Vienna and Laxenburg, Austria.

### July

**14-22.** COSPAR 2012 – 39th Scientific Assembly of the Committee on Space Research (COSPAR) and Associated Events. Mysore, India.

**16-19.** The XXXII SCAR Open Science Conference: Antarctic Science and Policy Advice in a Changing World. Portland, Oregon, USA.

### October

**13-20.** ISCCRS VII: Interdisciplinary Climate Change Research Symposium. Colorado Springs, CO, USA.

**21-24.** SCOR General Meeting. Halifax, Nova Scotia, Canada.

## Ho Chi Minh City highly susceptible to flooding

THE SERIOUS flooding that hit Thailand in 2011, inundating large areas of its capital Bangkok, has raised concerns about similar risks faced by Vietnam.

Located on the lower reach of the Saigon River, Vietnam's capital Ho Chi Minh City is nearly at sea level and thus very sensitive to rising sea levels.

In the coming 10-15 years this city could also witness the type of flooding that deluged Bangkok some months ago, according to Dr Nguyen Huu Ninh, vice-chair of IGBP's Vietnamese national committee.

Speaking to *Thanh Nien Weekly*, Ninh cited poor drainage in the city as the most important factor contributing to the risk of flooding. He pointed out that new buildings and industries have come up in the south of the city at the expense of reservoirs. And the drainage system of the city hasn't seen the sort of improvement that is critically needed to reduce the risk of flooding.

Ninh told the *Weekly* that Ho Chi Minh City should heed the experience of Bangkok and take timely action to improve drainage and implement adaptation strategies.

## IGBP second synthesis update

AT THE 2009 Scientific Committee (SC) meeting, IGBP decided to synthesise available knowledge about several policy-relevant topics with a view to providing a snapshot of the state of the planet. The past year or so witnessed several workshops relating to nitrogen and climate, air pollution and climate, geoengineering and megacities in the coastal zone. The policy community participated actively in these workshops, which received funding from several agencies beyond IGBP. Outcomes will include peer-reviewed papers, commentaries and summaries for policymakers, and are expected to feed into the Planet Under Pressure conference and international assessments including the IPCC Fifth Assessment Report. For more information about the synthesis, see http://www.igbp.net/4.1b8ae20512db692f2a680001259.html




THE MOST obvious way to tackle anthropogenic climate change is to reduce the emissions of carbon dioxide. Unfortunately, it is not the easiest way: there is apparently too little incentive, as years of tangled negotiations have shown. As a result, the search for less contentious solutions has gained momentum. The harmful health effects of black carbon and tropospheric ozone are well known, as is the adverse effect of the latter on crops. But their climate effects are complex and less well understood. A study published in *Science* now suggests that cutting down on black carbon and methane – a precursor of tropospheric ozone – could prove to be a win-win solution. Besides leading to obvious health benefits, it could reduce global mean warming by around 0.5°C by the middle of this century.

The study emerged from the UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone. The research team, led by Drew Shindell and including some researchers associated with IGBP's IGAC project, first used a model to test the effectiveness of hundreds of pollution control measures. Based on the climate impact of the measures, they came up with a list of measures that both improve air quality as well as reduce warming. Of the top 14 measures that together achieve most of the reduction in warming, 7 address black carbon and 7 address methane. The team's analysis suggests that if implemented simultaneously with substantial reductions in carbon-dioxide emissions, it might be possible to limit global warming to <2°C during the coming 60 years.

Whereas the benefits in terms of reduced warming would be spread more or less evenly around the world, the benefits for health and improved crop productivity would be particularly marked in certain parts of the world. For example, hundreds of thousands of premature deaths could be avoided in India and China, and along with the United States, these countries could also witness large increases in crop yields. The study's authors state that the co-benefits of reducing black carbon and methane emissions could provide strong incentives for appropriate policies.

Shindell D *et al.* (2012) *Science* 355: 183-189.

## Assessments of sustainability, state of the planet recommended

A COMPREHENSIVE international report on global sustainability is needed according to UN Secretary-General Ban Ki-moon's Global Sustainability Panel, which reported recently.

The panel, made up of heads of state and senior national ministers, argued that no single comprehensive report exists to bring together the assessments across sectors. Yet, issues as diverse as climate change, poverty, water security, energy, the global economy and biodiversity loss are all interconnected.

A new "sustainable development outlook report" could join the dots, and reduce fragmentation of the science-policy interface, the panel argues. The panel recommends such a report should fall under the direct control of the Secretary-General.

The panel made 56 recommendations to be taken to Rio+20 including the appointment of a chief scientific adviser to the Secretary-General, or establishing a scientific advisory board.

Former IGBP vice-chair and co-chair of the Planet Under Pressure conference Mark Stafford Smith addressed the panel's advisers in 2011 outlining a series of recommendations to strengthen the science-policy interface. Also in 2011, IGBP director Sybil Seitzinger met the Global Sustainability Panel secretariat in New York to discuss improving fragmentation of the science-policy interface by, for example, creating something like an assessment on global sustainability.

The first draft of the Rio+20 outcomes document, also published recently, contains similar recommendations: "We stress the need for a regular review of the state of the planet and the Earth's carrying capacity and request the Secretary-General to coordinate the preparation of such a review in consultation with relevant international organizations and the UN system."

The draft also called for the UN to consider appointing a High Commissioner for Future Generations.



## GLOBAL EMISSIONS ON THE REBOUND

GLOBAL emissions of carbon dioxide increased by a record 5.9 percent in 2010 following the dampening effect of the 2008-2009 Global Financial Crisis, according to the Global Carbon Project (GCP). The project, co-sponsored by IGBP, published a summary of its annual analysis in *Nature Climate Change*. The analysis finds that the impact of the financial crisis on emissions has been short-lived owing to strong emissions growth in emerging economies and a return to emissions growth in developed economies.

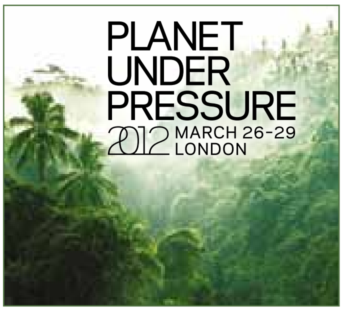
Contributions to global emissions growth in 2010 were largest from China, USA, India, the Russian Federation and the European Union, with a continuously growing global share from emerging economies. Coal burning was at the heart of the growth in fossil-fuel and cement emissions, accounting for 52 percent of the total growth. The atmospheric concentration of carbon dioxide in 2010 rose to 389.6 parts per million, the highest recorded in at least the last 800,000 years.

"The global financial crisis was an opportunity to move the global economy away from a high emissions trajectory. This opportunity has not been realised but developed countries have moved some way closer to their emissions reduction commitments as promised in the Kyoto Protocol and the Copenhagen Accord," said GCP's Executive Director Pep Canadell, a co-author of the paper and a scientist at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO).

GCP produces an annual report card with the latest figures on all major carbon exchanges that result from human activities. Dr Mike Raupach of CSIRO and a co-author of the paper said the 2010 figures represent the highest annual growth recorded, and the highest annual growth rate since 2003.

Peters G P *et al.* (2012) *Nature Climate Change* 2: 2-4, doi: 10.1038/nclimate1332.

Carbon Budget 2010: http://www.globalcarbonproject.org/




## Planet Under Pressure

AT THE time of going to press, almost 2200 delegates had registered for the Planet Under Pressure conference. The conference timing, just two months before the UN Rio+20 Summit, has made it an attractive draw for policymakers, scientists, industry and NGOs.

The conference is designed along a Hollywood blockbuster thriller narrative. Day one will focus on the global crisis. Day two, the innovative solutions. Day three, the barriers to action. And day four – the high-level policy day – the path forward. A conference statement on behalf of the co-chairs, former IGBP vice-chair Mark Stafford Smith and UNESCO policy head Lidia Brito, will be published on the final day.

The conference will bring together new communities to discuss solutions and develop a new research agenda for the next decade. Organisations such as the World Trade Organization, the World Bank and Oxfam are involved.

As mentioned elsewhere, the new Future Earth initiative will be discussed during the conference and at Rio+20. Planet Under Pressure will also launch a new website "Welcome to the Anthropocene" (www.anthropocene.edu).

The conference plenary and a one-hour news programme will be streamed live thanks to generous support from the US National Science Foundation.

Natural Environment Research Council (NERC)

## New Executive Director for the International Council for Science

DR STEVEN WILSON will take over from Professor Deliang Chen as the Executive Director of the International Council for Science (ICSU) from 1 April 2012.

Dr Wilson holds a doctorate in chemistry and has worked at the UK Natural Environment Research Council (NERC) for over a decade, most recently as Acting Chief Executive Officer.

## Is Africa REDDy?

SEVERAL challenges will need to be overcome to pave the way for effective implementation of the UN-sponsored Reducing Emissions from Deforestation and forest Degradation (REDD) initiative in Africa, according to a recent analysis. Among the challenges are the existence of a number of redundant and parallel initiatives, and weak technical and institutional capacities. The REDD initiative seeks to cut down on greenhouse-gas emissions while supporting alternative development pathways and increasing the adaptive capacity of local populations. The analysis was led by IGBP Scientific Committee member Cheikh Mbow and was funded by the START programme co-sponsored by IGBP.

Mbow C *et al*. (in press) *GLP Report* 5. GLP-IPO, Copenhagen.

© iStockphoto.com/Johann Helgason

## A VOLCANIC TRIGGER FOR THE LITTLE ICE AGE?

TODAY'S world of Arctic warming and disappearing sea ice was preceded by several centuries of unusually cold conditions – the Little Ice Age. Despite evidence of expanding glaciers and anomalously cold summers, we know little about what caused this cooling and when exactly it began.

A new study argues for an abrupt onset of cold conditions in response to a series of large volcanic eruptions. Sustained expansion in Arctic sea ice helped maintain cool summer-air temperatures for hundreds of years following the eruptions.

Gifford H Miller and colleagues used radiocarbon dates and sediment records to constrain the timing of the expansion of small ice caps in Arctic Canada and Iceland. The data point to relatively sudden cooling towards the end of the 13th century, coincident with four large, explosive volcanic eruptions. The eruptions spewed millions of tons of sulphur dioxide, which was converted in the atmosphere to sulphate aerosols: these fine droplets are known to reflect solar radiation and cause cooling. Of course, it did help that the eruptions occurred at a time when the solar radiation reaching the northern hemisphere had been declining. The study also found evidence for the volcanic triggering of an episode of ice-cap expansion during the mid-15th century, but it was less conclusive.

Volcanic cooling is short lived, however, for the aerosols stay in the atmosphere for only two to three years. So what explains the persistence of cold conditions for hundreds of years? The answer, the researchers say, lies in a positive feedback involving sea ice and the ocean. Simulations showed that eruption-induced cooling led to an expansion of Arctic sea ice, causing changes in ocean circulation. These changes, in turn, prevented the sea ice from melting and ensured cool summer-air temperatures for the centuries that followed.

Low solar activity can lead to a decrease in solar radiation reaching the Earth. For example, there was a marked sunspot minimum during the mid-17th and early 18th centuries. Although the decreased radiation could have added to the impact of the volcanic eruptions, the results of this study do not point to a solar trigger for the cooling.

Miller G H *et al.* (2012) *Geophysical Research Letters* 39: L02708.

## Snow and rain

WHETHER land-cover change in a high-$CO_2$ world will warm or cool a region depends on how snow and rainfall will vary in that region, according to a recent study involving researchers from IGBP's iLEAPS project.

Land-cover change affects temperature in several ways, for example by changing the reflectivity of a landscape or altering evapotranspiration. Deforestation tends to cool mid- to high-latitude regions and warm tropical regions. But will this also be the case in an even warmer future world when regional climate change is to be expected? Andy Pitman and colleagues used a climate model to investigate the impacts of land-cover change under high-$CO_2$ conditions. They focused on three different regions of the world. They found that the changes in temperature in these regions resulting from land-cover change are strongly dependent on the changes in snow cover or rainfall. For example, the Asian region – which warmed in response to increasing cropland under relatively low atmospheric $CO_2$ concentrations – cooled instead under high-$CO_2$ conditions because of increases in rainfall linked with elevated carbon dioxide.

The authors recommend that models seeking to gauge the impact of future changes in land cover in a particular region accurately simulate changes in snow and/or rainfall in that region. This may be beyond the capacity of existing climate models.

Pitman A *et al.* (2012) *Nature Climate Change* 1: 472-475.

## GLP, IMBER project offices move

THE International Project Office (IPO) of the Global Land Project has moved to São José dos Campos, Brazil, and is hosted by the National Institute of Space Research (INPE). The IPO was previously based at the University of Copenhagen in Denmark for six years. Giovana de Espindola has taken over from Tobias Langanke as the Executive Officer.

The IPO of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project moves to the Institute of Marine Research (IMR) in Bergen, Norway, in April. The IPO is co-funded by the Research Council of Norway and IMR. The IPO has been located at the Institut Universitaire Européen de la Mer in Plouzané, France, since 2005, supported by a consortium of French funding agencies.

## Eugene Stoermer (1934-2012)

EUGENE F Stoermer, Professor Emeritus at the University of Michigan, passed away on 17 February 2012. Stoermer's research focused on the world's great lakes and he was a pioneer in research on various aspects of diatoms. Along with former IGBP vice-chair Paul Crutzen, Stoermer coined the term Anthropocene in an article published in IGBP's *Global Change* newsletter in the year 2000. Stoermer had been using the term in lectures since the 1980s to describe the current time in Earth's history. The Anthropocene has received renewed attention during the past year or so, and efforts are ongoing to declare it Earth's newest epoch. The IGBP community gratefully acknowledges Stoermer's contribution to elucidating what has become a powerful concept to signify humanity's impact on the planet.


## ANTHROPOCENE WEBSITE TO BE LAUNCHED THIS YEAR

IN 2012, IGBP and partners will launch a new website on the Anthopocene, a proposed new geological epoch driven by human activities.

The website, which will contain a wealth of images and data visualisations, will be aimed at a very broad audience to inspire, educate and engage the public in the concept of the Anthropocene. The concept was first officially proposed by former IGBP vice-chair Nobel laureate Paul Crutzen and Eugene Stoermer (1934-2012) in the IGBP newsletter *Global Change* (March 2000).

IGBP's director of communications Owen Gaffney originally proposed the idea: "The concept of the Anthropocene gives people a new perspective of our place in the world. We can no longer consider ourselves at the mercy of great natural forces. We have an active role in global change, in many cases we are driving it."

"So it is odd, then," he adds, "that there is no website for the public to bring all ideas about the concept together."

World-leading data visualisation expert Phelix Pharand is the project's creative director.

The project is being developed by Planet Under Pressure sponsors (IGBP, IHDP, DIVERSITAS, WCRP and ESSP), the Stockholm Resilience Centre, Stockholm Environment Institute, CSIRO and Globaïa. A scientific advisory panel has been set up.

## New network for sub-Saharan Africa

THE Equatorial African Deposition Network (EADN) was formally launched at an inaugural workshop held 5-9 December in Kisumu, Kenya. The workshop participants discussed several aspects, including the location of monitoring sites and the links to policy.

The network will monitor dry and wet atmospheric deposition rates of phosphorus, nitrogen and other chemical constituents at a number of sites throughout the region, with an emphasis on the African Great Lakes. Data collected by the network will be used, along with remote-sensing data and modelling tools, to determine the spatial and temporal patterns of atmospheric nutrient transport and their relationship to land-use patterns.

The network's lead coordinator is Professor Eric Odada (eodada@uonbi.ac.ke), a founding member and former vice-chair of IGBP.

# CLIMATE-CHANGE INDEX 2011: RISING TREND CONTINUES

THE 2011 edition of the climate-change index published by IGBP continues to show an unequivocal rising trend. The index rose for the 15th year running. The latest update includes values for the four years from 2008 through 2011.

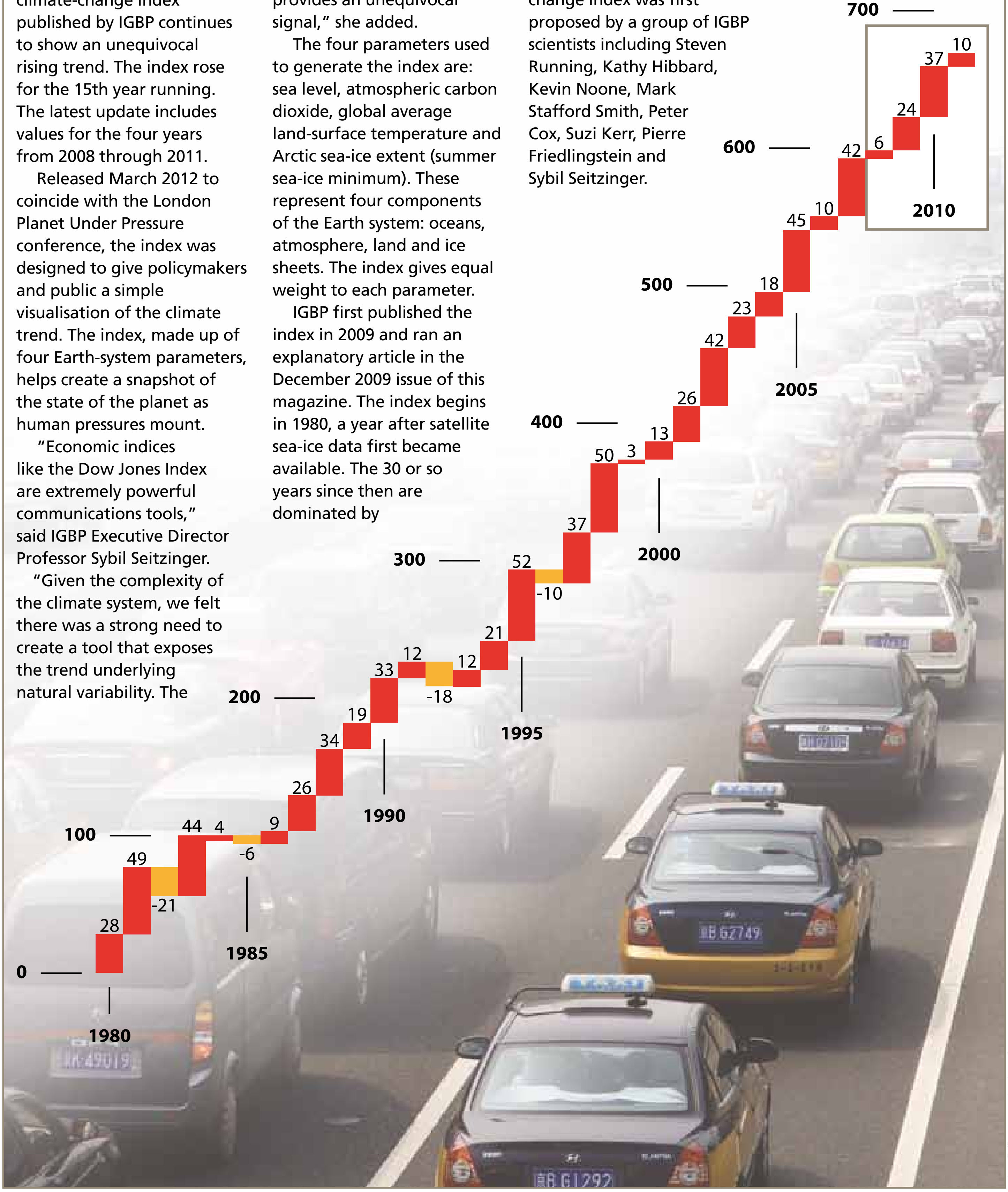
Released March 2012 to coincide with the London Planet Under Pressure conference, the index was designed to give policymakers and public a simple visualisation of the climate trend. The index, made up of four Earth-system parameters, helps create a snapshot of the state of the planet as human pressures mount.

"Economic indices like the Dow Jones Index are extremely powerful communications tools," said IGBP Executive Director Professor Sybil Seitzinger.

"Given the complexity of the climate system, we felt there was a strong need to create a tool that exposes the trend underlying natural variability. The IGBP climate-change index provides an unequivocal signal," she added.

The four parameters used to generate the index are: sea level, atmospheric carbon dioxide, global average land-surface temperature and Arctic sea-ice extent (summer sea-ice minimum). These represent four components of the Earth system: oceans, atmosphere, land and ice sheets. The index gives equal weight to each parameter.

IGBP first published the index in 2009 and ran an explanatory article in the December 2009 issue of this magazine. The index begins in 1980, a year after satellite sea-ice data first became available. The 30 or so years since then are dominated by a rising trend. The climate-change index was first proposed by a group of IGBP scientists including Steven Running, Kathy Hibbard, Kevin Noone, Mark Stafford Smith, Peter Cox, Suzi Kerr, Pierre Friedlingstein and Sybil Seitzinger.



# Anthropocene: An epoch of our making

Humans have affected the Earth in myriad ways, be it through agriculture, mining or urbanisation. But are our impacts epochal? Absolutely, says **James Syvitski.**

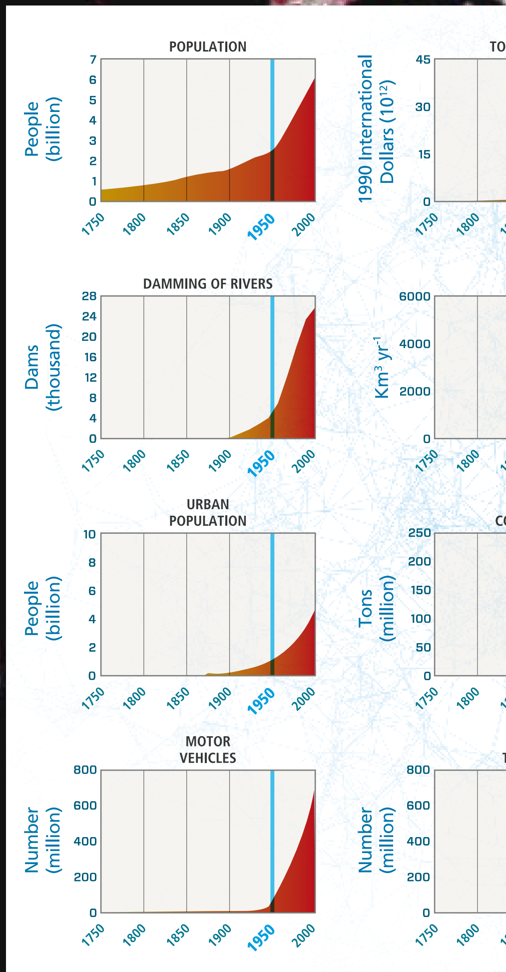
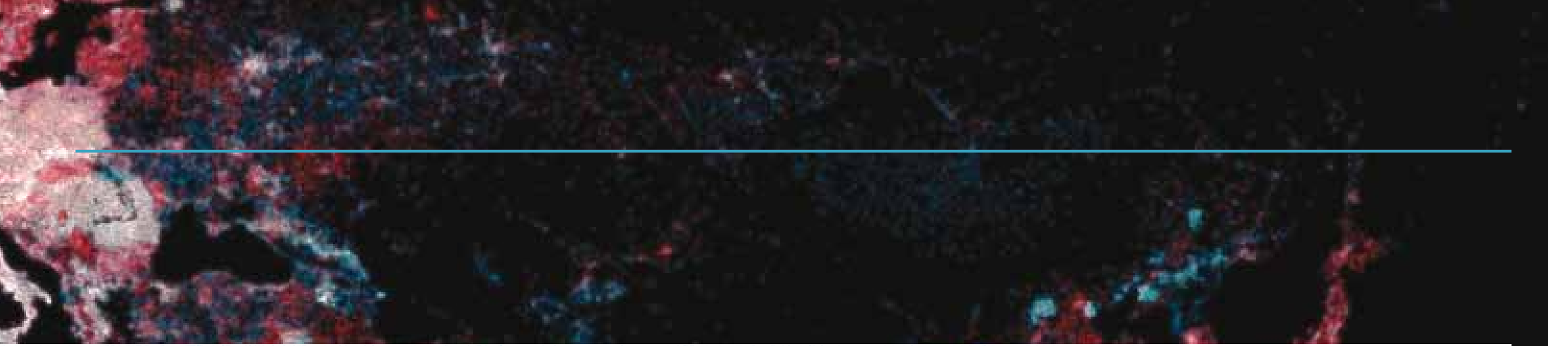


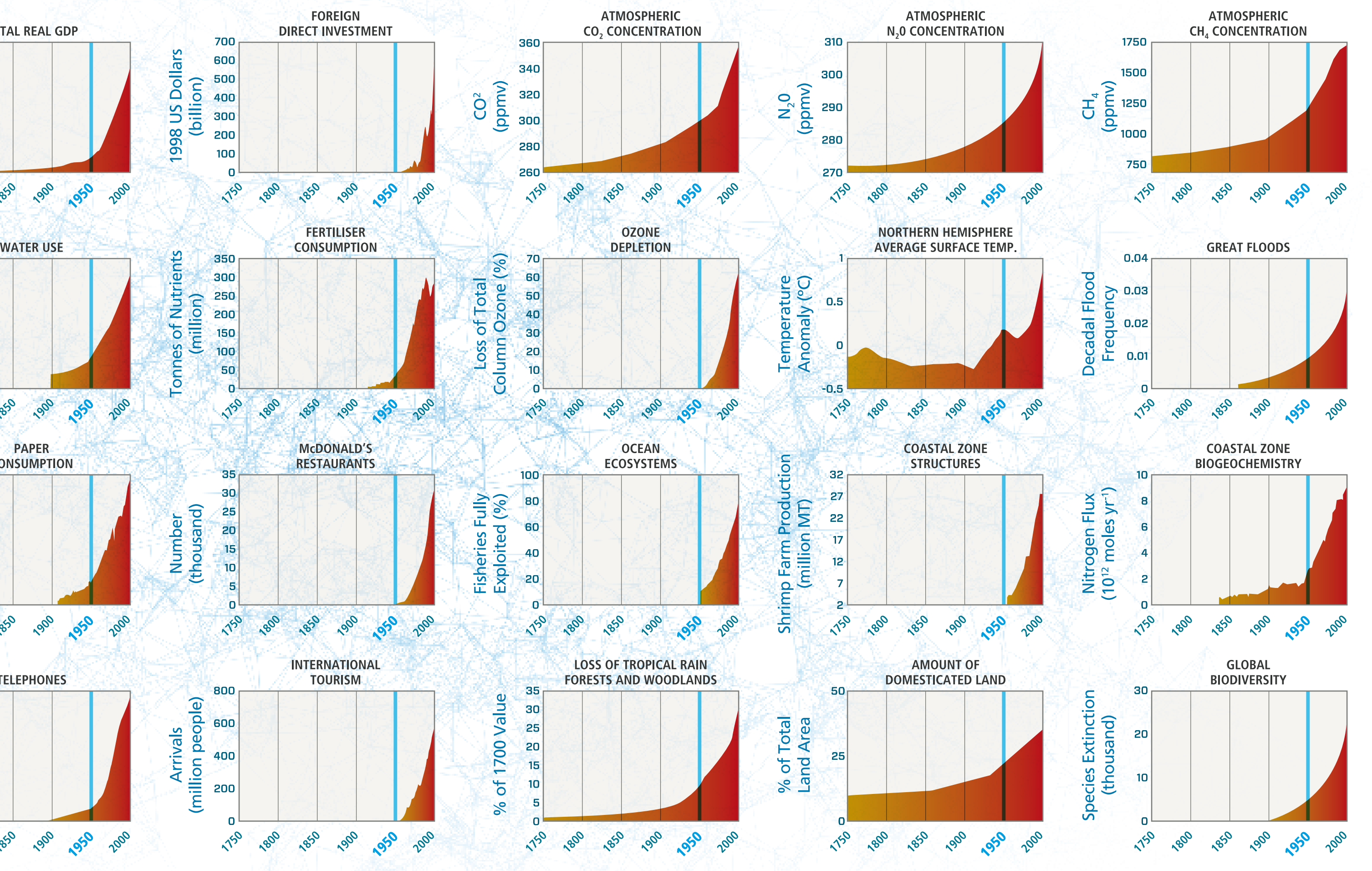

Figure 1. An enterprise to reckon with. Human m
Modified after Steffen W *et al.* (2004).

As rapidly receding ice sheets brought the Pleistocene epoch to an end around 12,000 years ago, the warmer and more stable climate heralded the inception of the Holocene. No longer constrained by the ice age, humans were free to finally make their mark. And make their mark they did. We moved from hunting and gathering to farming; we built major cities and civilisations. We came to rely more and more on technology. At some point, we graduated from adapting to our environment to making it adapt to us. The effects on the Earth were gradual at first: it is huge, after all, and its biogeochemical and physical systems are extremely resilient. As long as our numbers were few and ambitions modest, we had little impact on the planet as a whole. But now we regularly decelerate and accelerate natural processes, focus energy in extraordinary ways and alter, destroy or create ecosystems. Stealthily at first, but then at an astonishing pace, we have left the Holocene behind and embraced the *Anthropocene* (Box 1).

Momentum is building to officially declare the *Anthropocene* a new geological epoch (Syvitski and Kettner 2011; Zalasiewicz *et al.* 2011), prompting high-profile publications and scientific workshops/conferences to discuss the relative merits and demerits of doing so. Interestingly, while portions of society still refuse to acknowledge the role of humans in affecting global climate, they appear more willing to accept that the modern world is anything but pristine and strongly under the influence, if not control, of society.

Epochs are by themselves merely subdivisions of Earth's geologic timescale; it is what happens during these intervals that gives epochs their unique characteristics. The progression from one epoch to another is marked by some easily distinguishable, global stratigraphic 'event', such as a mass extinction, bulk change in the composition of sedimentary rocks or shift from one climate regime to another. The traits of past epochs can be inferred from the rocks that were deposited during those time intervals. Have our activities created a biological, geochemical or sediment signal that will be preserved as a rock record for millions of years (Zalasiewicz *et al.* 2011) and that






anipulation of their environment began in earnest during the Industrial Revolution and accelerated markedly after the 1950s, as IGBP's Great Acceleration graphs show.

Background image created by Gregor Aisch; http://driven-by-data.net/about/global-digital-divide/.

will be sufficiently different from that of the Holocene epoch? If so, where does the Holocene end and the *Anthropocene* begin?

IGBP's Great Acceleration graphs (Figure 1), part of the programme's first synthesis (Steffen *et al.* 2004), collectively highlight the accelerating human enterprise and its impacts on the biophysical Earth system. From these data we can infer that the *Anthropocene* began sometime around the Industrial Revolution in Europe (circa 1800), when new and powerful ways of manipulating the environment became available. Things progressed relatively slowly for a century and half before the stage of great acceleration (1950 onwards). Consumption brought on by affluence and technology overtook population as the greater driver of change (see also page 20 of this issue), a trend that continues to date.

## How big is our footprint?

The big regional ice sheets of the Pleistocene epoch removed the soil cover of higher latitude regions, reorganised continental drainage patterns, left large regional areas covered with thousands of lakes and marshes, and mantled continental-scale tracts of land with ice-sheet deposits. Life and ecosystems had to adjust accordingly. Things changed drastically during the Holocene, when everything from ocean circulation to river hydrology or land vegetation responded to the end of the ice age. And of course, human activities accelerated. But are the effects during the past two centuries comparable with, say, those of the Pleistocene ice ages? Do they permit the recognition of a new epoch?

Humans have changed the Earth in a number of fundamental ways (Syvitski and Kettner 2011), many of which are far less known than global warming. This is not surprising when you consider the rapid changes portrayed by the Great Acceleration graphs. Since the 1950s, human population, urbanisation, resource consumption and even the number of Macdonald's restaurants have all grown by leaps and bounds. Granted there are large regional variations, but the impacts on at least some components of the biophysical Earth system have been global and represent similar temporal trends. Atmospheric carbon dioxide, global surface temperatures and human-induced nitrogen fluxes to the coastal zone have all increased.

Particularly striking is the extent and rate at which we have modified Earth's surface. Deforestation for wood and land clearing for cultivation is an obvious example; the direct effects include soil erosion, hill slope failure and downstream sedimentation. But infrastructure – dams, cities, transportation networks and coastal-management measures – has led to lasting and profound impacts. Prior to human interference, the world's rivers collectively delivered 15 gigatons (Gt) of sediment per year to the coastal ocean. We now easily match the capacity of rivers to move sediment in diverse ways. In the 1930s, a proliferation of small farms employing poor tilling at a time of drought in the US Great Plains region led to one of the world's largest erosion events: 12.5 Gt of topsoil was removed over more than 9 million hectares.

The construction of the Palm Islands will add 520 km of beaches to the city of Dubai, United Arab Emirates, and displace more than 3 Gt of rock, sand and limestone.

But we are also sequestering more sediment on land than would be sequestered naturally (Figure 2). The large dams we have built during the past two centuries trap more than 2.3 Gt of sediment every year in reservoirs. This starves deltas of sediment and, in combination with the mining of water, oil and gas, has led to a situation where large deltas are sinking at four times the rate of sea-level rise. Humans now irrigate deserts throughout the world. We have delayed the flow of freshwater to the ocean by weeks to months through diversions and reservoirs. By any unbiased and quantitative measure, humans have affected the surface of the Earth at a magnitude that ice ages have had on our planet, but over a much shorter period of time.

Clues to our impact are being recorded in sediments that will form part of the rock record in the future. Be it a rapid sediment pulse, a sudden change in composition or evidence for a mass extinction, it will not be hard to distinguish the *Anthropocene* from the Holocene millions of years into the future. Cities could make for particularly interesting deposits, as an article in the May 28 issue of *The Economist* points out cheekily (http://www.economist.com/node/18741749).

## Box 1. The emergence of a paradigm

The concept of the *Anthropocene* has manifested itself in the scientific literature for over a century under various guises. In the 1990s the term *Anthroposphere* was widely used in the Chinese science literature under the influence of Chen Zhirong of the Instute of Geology and Geophysics at the Chinese Academy of Sciences in Beijing. *New York Times* journalist Andrew Revkin introduced the terms *Homogenocene* and *Anthrocene* in his 1992 book *Global Warming.* Sometimes the concept appeared without a moniker, as in Vitousek *et al.* (1997).

The *Anthropocene* was formally introduced in 2000 by Nobel laureate and former IGBP vice-chair Paul Crutzen and colleague Eugene Stoermer (1934-2012) in IGBP's *Global Change* magazine (then a newsletter). Professor Stoermer, an ecologist, had been using the term since the eighties. In one 1995 email, Stoermer described terrestrial and neritic oceanic production during the *Anthropocene.* The term and concept quickly caught on, nicely encapsulating IGBP science (Steffen *et al.* 2011). Before 2003, the term yielded 416 web hits; by 2011 that number had increased to over 450,000.

Still, the *Anthropocene* isn't as well known as global warming, which two out of three people had heard of by 2008, according to a Gallop Poll (http://www.gallup.com/poll/117772/Awareness-Opinions-Global-Warming-Vary-Worldwide.aspx). But the former is a more effective paradigm in describing the cumulative impact of civilisation, making global warming and its consequences but one of many ways in which humans have modified the Earth. Narrow focus on global warming might suggest that we simply need to stop emitting greenhouse gases and use renewable energy to abate the planet's pressures. The human footprint is much larger than that.

**What are the thresholds we need to worry about?**

## Living in an Anthropocene world

The preceding discussion might have given the impression that we know a lot about our footprint. And we do indeed. But there is much that we know little about. For example, what are the thresholds we need to worry about and how likely is it for one or more of the so-called tipping points to be crossed? What can we do to prevent this from happening? We need to have a cold hard look at the available evidence and continue to collect missing information. As this is an unfolding story of a change in our Earth system, we must continue to deploy and maintain appropriate observing systems. But we need to do better than repeat the business-as-usual approach that favours observations of the more easily sensed atmosphere and surface oceans. Monitoring the complexities of the terrestrial environment more effectively is just as important.

If addiction is a recurring compulsion to engage in some specific activity despite the knowledge of its harmful consequences, humans are certainly afflicted by one. As discussed on page 20, we continue to extract and consume resources at rates that are clearly unsustainable. Can we change

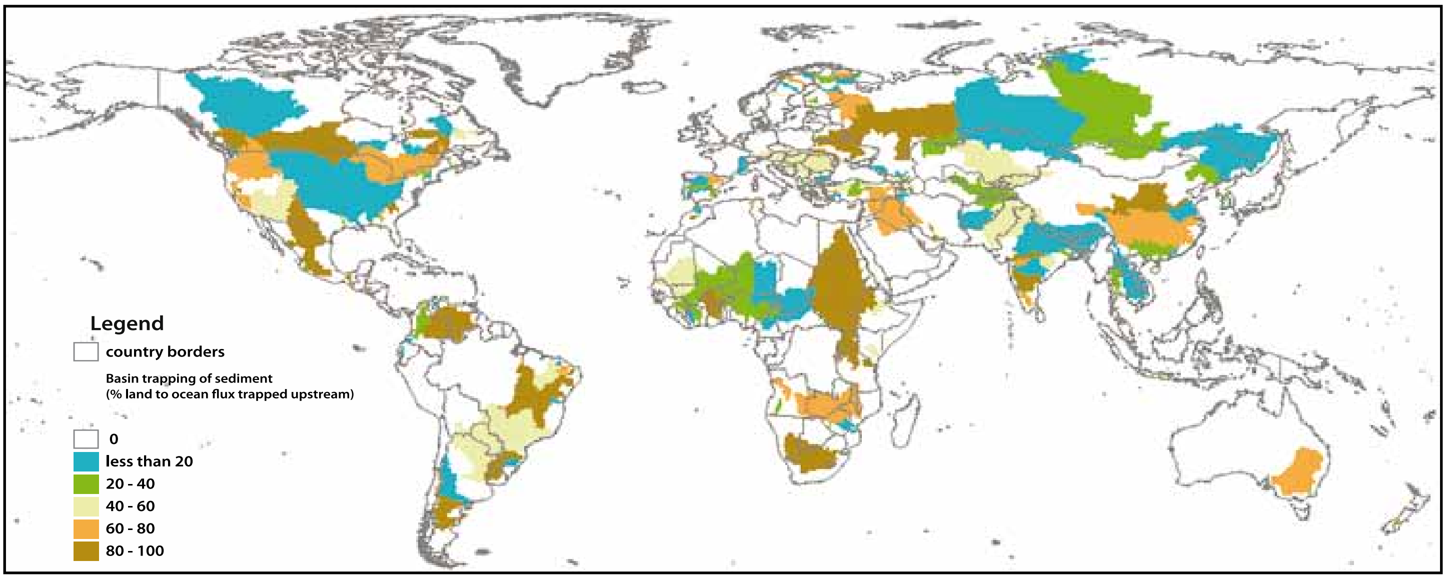



Figure 2. Sediment trapping by large dams. Reservoirs around the world retain sediment that would otherwise have been transported to the ocean. Source: GWSP Digital Water Atlas (2008). Map 51: Sediment Trapping by Large Dams (V1.0). Available online at http://atlas.gwsp.org.

our behaviour and embrace a more sustainable way of living, and if so, how? Unfortunately this is proving to be a far tougher question to answer, for the constraints are not merely poor information or less sophisticated models. What if the answer entails a transformation of our societies, political systems, economies and even international power relations?

Clearly, answering the big questions pertaining to sustainability requires diverse expertise and a solutions-based approach. Existing global-change research programmes like IGBP have contributed immensely to our understanding of the Earth system and of its modification by humans. It is now time to build on this foundation and harness this knowledge to explore creative solutions to the planet's problems. The current research on global change needs to be supplemented by that on societies, policy and economics. Inputs from industry will need to be solicited, for it will need to be part of any solution. The structures that do this aren't in place yet, but the planned Future Earth initiative is a step in the right direction. Contours of the initiative are being worked out at the moment by a team reporting to an alliance that includes the International Council of Science, the International Social Science Council, big funders of global-change research and some UN agencies. The Planet Under Pressure conference in London this year might be a good place to find out how an integrated approach to solutions might look like (http://www.planetunderpressure2012.net/).

We have entered the *Anthropocene*, without question. Some of the changes, for example those brought about by large reservoirs and megacities, are here to stay for hundreds if not thousands or even millions of years. We will simply have to get used to and find a way of living with such changes. But there are things we can and should change to keep improving human wellbeing and to avoid crossing potentially dangerous thresholds. Our strength as humans is the capacity to recognise problems, to understand them and to develop solutions. The final chapter of the *Anthropocene* story is yet to be written: the narrative will depend on our collective self-awareness and the capacity to correct our course, for the relentless pressure on our planet portends unprecedented destabilisation. ▮

**The final chapter of the Anthropocene story is yet to be written.**

JAMES P M SYVITSKI, IGBP's Chair, is the Executive Director of the Community Surface Dynamics Modeling System, University of Colorado-Boulder, Campus Box 545, Boulder, CO 80309-0545, USA. Email: james.syvitski@colorado.edu

## REFERENCES

Vitousek P M *et al.* (1997). *Science* 277 (5325): 494-499.

Crutzen P J and Stoermer E F (2000). *Global Change Newsletter* 41: 17-18.

Steffen W *et al.* (2004) *Global Change and the Earth System: a Planet under Pressure*. The IGBP Book Series. Berlin, Germany: Springer.

Steffen W *et al.* (2011). *Philosophical Transactions of the Royal Society* A 369: 842-867. doi:10.1098/rsta.2010.0327.

Syvitski J P M and Kettner A J (2011). *Philosophical Transactions of the Royal Society A* 369: 957-975

Zalasiewicz J *et al.* (2011). *Philosophical Transactions of the Royal Society A* 369: 835-841.

Feature

# THE RISE AND RISE OF URBAN EXPANSION

New cities are sprouting up virtually every day as the world urbanises rapidly. But the projections for the coming decades vary widely. **Michail Fragkias** and **Karen C Seto** analyse the facts and discuss the implications.

Humans have been building cities for thousands of years, but the global shift from rural to urban living has been a defining trend during the past century or so. Even then, contemporary urbanisation – in terms of the combination of demographic, economic and biophysical changes that make cities what they are – is unprecedented in its magnitude and rate. More than half of us live in cities today, and by the end of the century, the number of urban dwellers will swell by another three billion. Although megacities with tens of millions of inhabitants are often in the limelight, most of the urban growth is in fact expected to take place in small- and medium-sized cities of a million or fewer inhabitants (UN 2010). The world will add approximately one new city of a million every five days until 2050. In countries such as India this process is unfolding literally under our eyes: urban centres exist today where villages did only a decade ago.

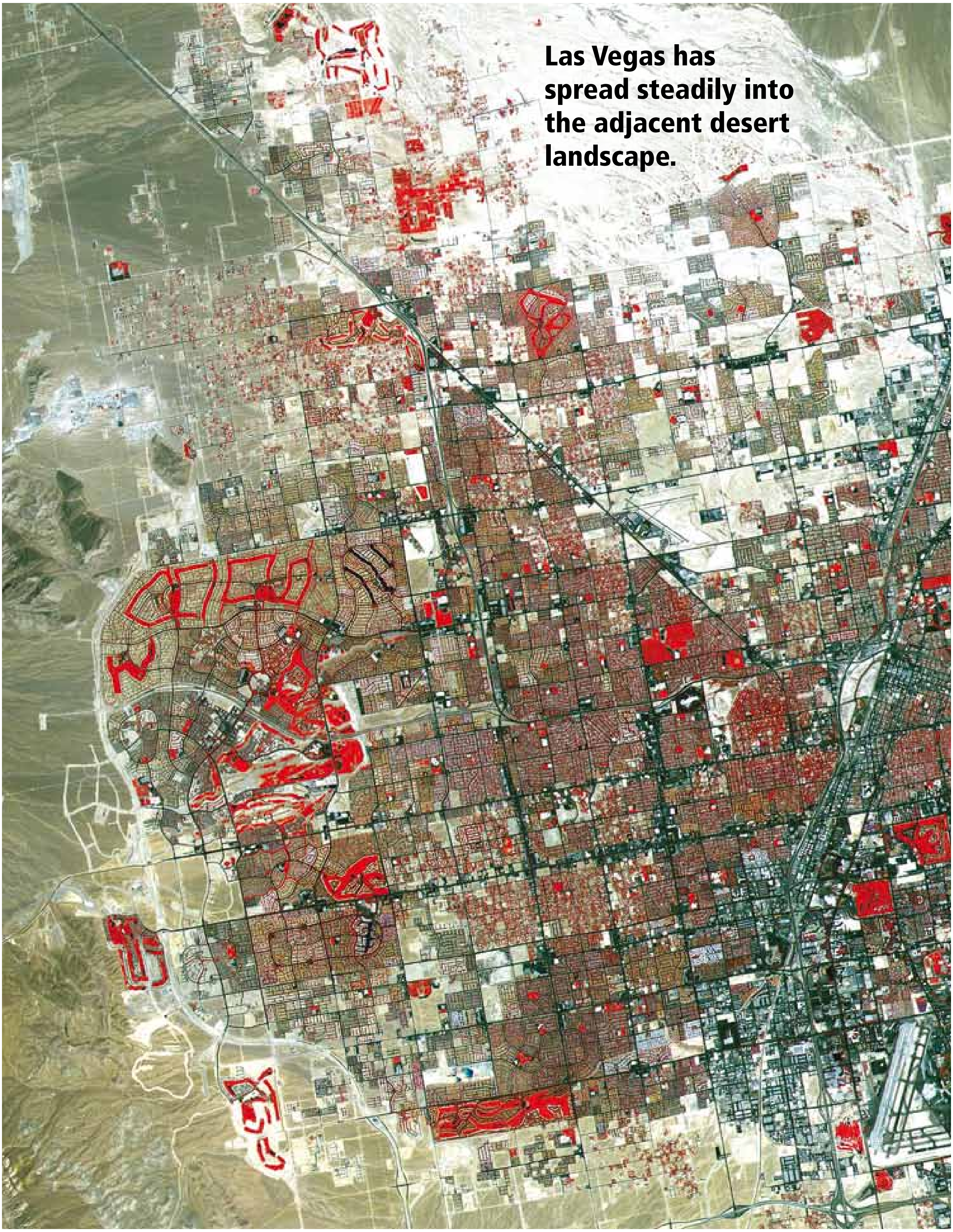
**There are no global datasets of urban land expansion.**

Cities have been the dominant players in the world's socio-economic, cultural, political and environmental spheres. However, today it is urban areas – sometimes cities but at other times more nebulous places that include large swaths extending towards the countryside – that are increasingly important. Such areas produce more than 90 percent of the world's Gross Domestic Product (GDP) (Gutman 2007) and more than 70 percent of the global greenhouse gas emissions. As global centres of production and consumption, they draw resources from around the world. The size and scale of urban population growth and the concomitant urban land-use change pose major challenges to local and regional ecosystems and ultimately the global environment (Grimm *et al*. 2008; Seto *et al*. 2010). At the same time, the dynamism of cities can lead to creative solutions. Two aspects of future urbanisation will determine both how cities might change the world and the extent to which they will be able to adapt to the changes already under way. *Where* urban areas develop – whether in low-lying coastal zones, in agricultural areas, in forested regions or near existing urban centres – will affect their vulnerability to climate change and their ability to draw on the resources needed to provide essential services. *How* urban areas develop – whether expansive or compact, with or without public transportation or with mixed-use or single-use zoning – will determine resource consumption and the urban social fabric, and ultimately global sustainability.

Projections of the urban population for the coming decades are obviously important to understand future urbanisation. The utility of the datasets developed by the United Nations is hampered by the fact that there is no universal definition of what constitutes urban. But these data are available for every country, and until recently, our understanding of the magnitude and rate of global urbanisation was based exclusively on measures of urban population. We know much less about the future rate of growth of urban land area despite the fact that land-use and land-cover change associated with urbanisation is one of the key drivers of global change. There are no global datasets of urban land expansion.

## Tracking urban expansion

One way of exploring future urban land expansion is to look at past trends of the same. A recent meta-analysis of 326 peer-reviewed studies based




NASA / GSFC / MITI / ERSDAC / JAROS, and U.S. / Japan ASTER Science Team on remote sensing (Seto *et al.* 2011; referred to as the Seto *et al.* study henceforth) reports a worldwide increase in urban land area of almost 60,000 $km^2$ from 1970 to 2000: this is about twice the area of Belgium. The rates were the highest in India, China and Africa, whereas the largest change in total urban extent occurred in North America. Annual growth in GDP per capita drives approximately half of the observed urban land expansion in China but a much smaller fraction in India and Africa; urban land expansion here is driven more by urban population growth.

Rates of urban land expansion by decade reveal three distinct typologies: declining annual rates (Central and South America, Europe, Oceania and Africa), no trend (China, North America and India) and uneven trajectories (Southwest Asia, South East Asia and East Asia). Declining rates of urban land expansion is expected for regions such as South America and Europe, which were already highly urbanised in the 1970s. In contrast, declining rates of urban land change are surprising for Africa, where urban population levels were only 24 percent in 1970.

Much of the observed variation in urban expansion was not dominated by a single variable (population and GDP, for example) in the model. Contemporary urban expansion seems to be governed by a variety of factors difficult to observe comprehensively at the global level, including international capital flows, the informal economy, land-use policy and generalised transport costs.

What about the coming decades? The *Special Report on Emissions Scenarios* (SRES) of the IPCC (http://sres.ciesin.columbia.edu/) provided scenarios at the UN regional level for 2050 based on projections of the global population and GDP.

**We can expect considerable increases in urban land.**

Taking these into account, Seto and colleagues developed four urban land expansion scenarios for the year 2030 based on the three different assumptions about the initial urban land cover in 2000/2001. Depending on the initial extents, they forecast increases in global urban land cover of between just over 400,000 and well over 12,000,000 $km^2$. The primary reason for the large variance in the forecasts is the more than tenfold difference in estimates of contemporary urban land cover. When only MODIS data (which provide reliable estimates at 1 km resolution) are considered, the variation decreases but is nevertheless quite high across the four socio-economic scenarios (Figure 1). The difference in estimates between the highest and lowest scenarios is over a million square kilometres.

Angel *et al.* (2011) also provided projections of urban land cover globally (across all countries and regions) up to the year 2050. They combined population data for thousands of urban agglomerations with populations of over 100,000 people in the year 2000 with the (perceived) highest quality estimates of built-up area for each agglomeration. Assisted by the urban population projections of the United Nations and devising three scenarios of possible changes in density patterns (based on previous global and historical studies), the authors used regression techniques to project land cover to the year 2050. Based on historical observations from cities from different nations and across different world regions, their high, medium and low projection scenarios assumed a 2 percent, 1 percent and 0 percent annual rate of density decline respectively. Their medium projection scenario shows that globally urban land will increase from about 600,000 $km^2$ in 2000 to over 1,250,000 $km^2$ in 2030 and to almost 2,000,000 $km^2$ in 2050.

The situation regarding the urbanisation projections is not too different from that of the projections of global temperature increases – depending on the scenario used the values vary by several degrees. The predictions made by the two studies discussed above deviate significantly and warrant further exploration. The methodologies are distinct, but an important difference is the urban extent assumed for the year 2000. Whereas the Seto *et al.* study uses information from the MODIS Urban Land Cover map at a 1000-metre resolution, the Angel *et al.* study uses data at 500-metre resolution. The sensitivity of the results to this aspect deserves further study. Despite the differences between the studies as well as between individual scenarios in each study, we can expect considerable increases in urban land during the coming decades.

## Future urbanisation: challenges and opportunities

About a third of the locations in the Seto *et al.* meta-analysis fall within 10 metres of low-elevation coastal zones. For these areas the average rate of urban land expansion from 1970 to 2000 is almost 6 percent, statistically higher than urban areas elsewhere. In view of the impacts of climate change and projections of regionally varying sea-level rise and storm surges, it seems like humanity has unknowingly been increasing the vulnerability of its urban populations. Also, almost half of the case studies are within 10 kilometres of a terrestrial protected area. Urban land expansion is thus as likely to take place near protected land as elsewhere, and being near a protected area does not necessarily slow the rate

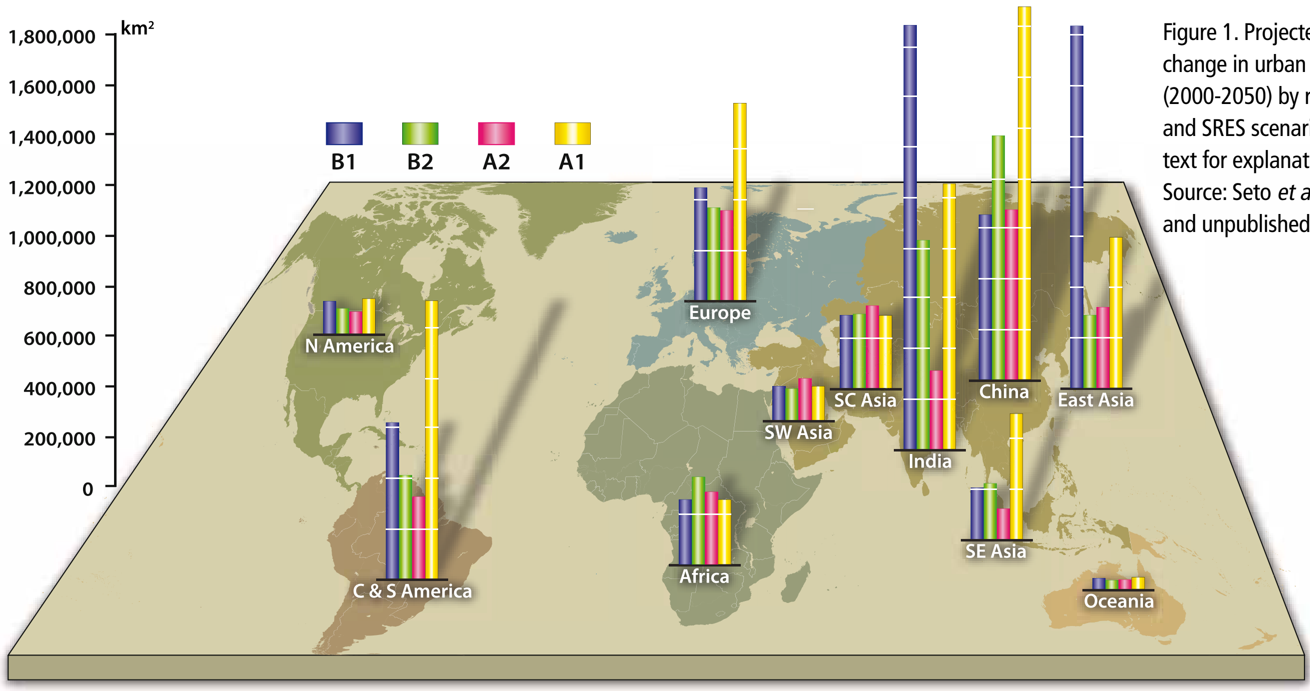



Figure 1. Projected change in urban land area (2000-2050) by region and SRES scenario. See text for explanation. Source: Seto *et al.* (2011) and unpublished data.

of urban-land conversion.

Interestingly, across all regions and for all three decades, urban land expanded at a rate higher than or equal to that of urban population growth. Contrary to what one might expect given the international attention to and calls for sustainable development, urban growth is becoming more expansive than compact. Nowhere do the two studies find evidence of a global increase in urban land-use efficiency or urban population density. Fragmented governance institutions and lack of coordination as well as persistent behavioural norms have prevented the materialisation of international calls for sustainability for two decades. Although action is being undertaken on various issues related to global environmental change, the sheer amount of expected growth can overwhelm the response.

The analysis by Angel and colleagues paints a rather gloomy planning / governance picture. Excluding the case of a significant exogenous shock, the projected expansion of urban land cover is not likely to be contained and difficult to manage. We must accept this fact and be prepared to adapt to it, the authors say. Among the measures they suggest include the realistic projection of urban-land needs, the extension of metropolitan boundaries, acquiring the rights of way for an arterial road grid that can carry infrastructure and public transport, and the selective protection of open space from incursion by formal and informal land development. But the full set of consequences for global environmental change and the wider implications of the urban responses to this change remain unclear.

Contemporary urbanisation has the potential to help the transition to sustainability because of its contributions to innovation, productivity and efficiency. The challenge is to agree on the optimum scale, form and rate of urbanisation, and to build opportunities for sustainability in both the developed and developing countries. An important step would be to employ multidimensional and multiscale approaches to better understand the complexity of urbanisation in the 21st century. ▮

**Contemporary urbanisation has the potential to help the transition to sustainability.**


MICHAIL FRAGKIAS, the Executive Officer of the Urbanisation and Global Environmental Change (UGEC) project, is at the Global Institute of Sustainability, Arizona State University, PO Box 875402, Tempe, AZ 85287, USA.
Email: Michail.Fragkias@asu.edu

KAREN C SETO is Associate Professor of the Urban Environment at the Yale School of Forestry & Environmental Studies, 195 Prospect Street, New Haven, CT 06511, USA.
Email: karen.seto@yale.edu


## REFERENCES


Angel S *et al.* (2011) *Progress in Planning* 75(2): 53-108.

Gutman P (2007) *Ecological Economics* 62: 383-387.

Grimm N B *et al.* (2008) *Science* 319: 756-760.

Seto K C, Sanchez-Rodriguez R. and Fragkias M (2010) *Annual Reviews of Environment and Resources* 35: 167-194.

Seto K C *et al.* (2011) *PLoS one* 6 (8): e23777, doi:10.1371/journal.pone.0023777.

UN (2010) *World Urbanization Prospects: The 2009 Revision.* Population Division of the Department of Economic and Social Affairs, United Nations, New York.

# ADDICTED TO RESOURCES

## Industrialisation is consuming natural resources at rates that are demonstrably unsustainable in the long term, points out **Helmut Haberl.**

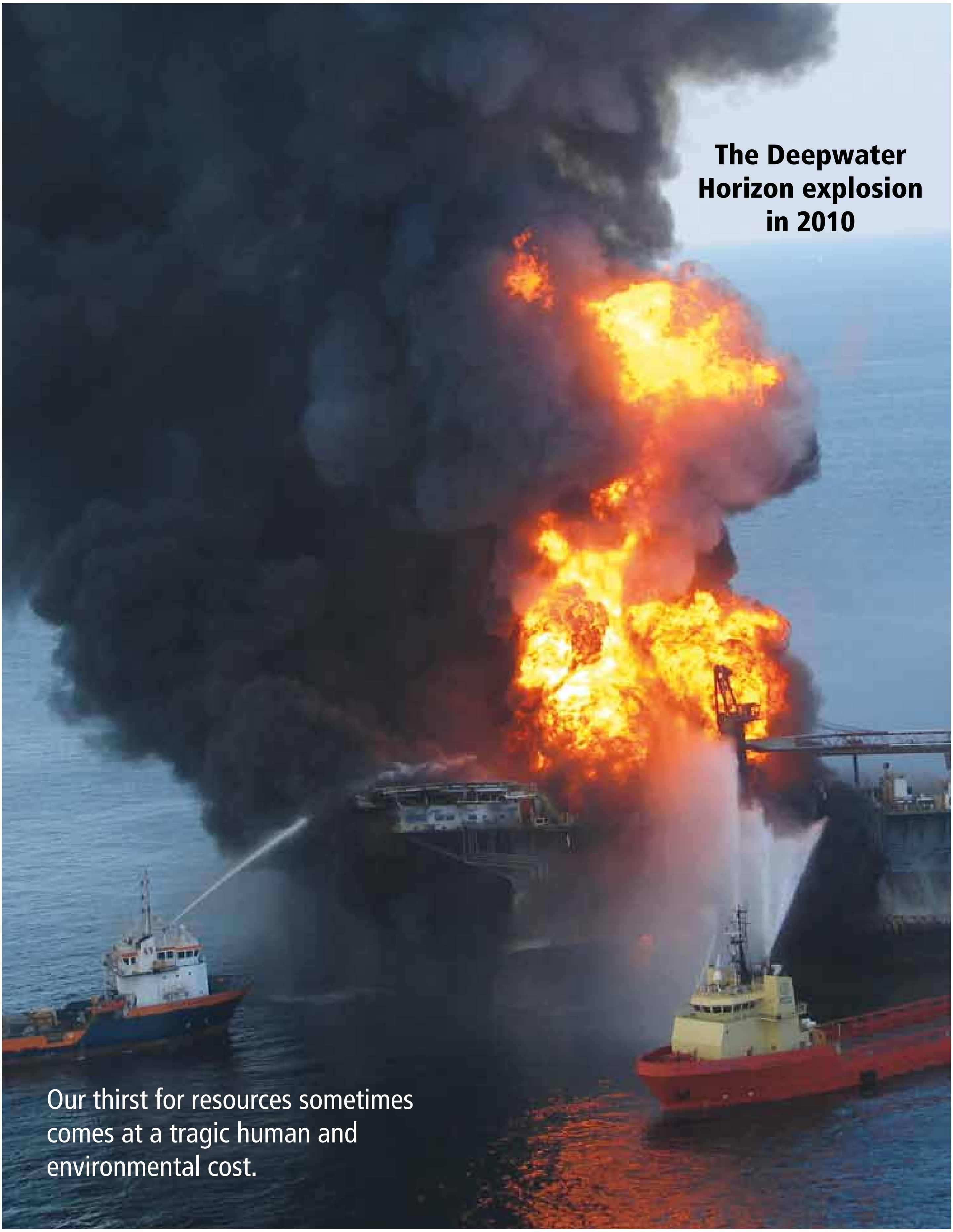
We don't know when exactly the planet saw the arrival of the seven-billionth human during the past few months. Or perhaps that will happen during the coming few months. Humanity has added a billion individuals in only about 13 years after the world's population surpassed six billion, with most growth occurring in the developing world. Although this is a staggering rate, most demographers agree that it will decline – the annual growth rate has been plummeting since the late 1960s – and will eventually grind to a halt as the world population reaches between nine and ten billion people in the next decades.

But stabilisation or even decline of human population will not decrease the world's hunger for resources. According to the Food and Agriculture Organization (FAO), 850 million people – 13 percent of the world population – are at present chronically undernourished. To reduce malnutrition in a growing world population we will need substantial increases in food production, perhaps some 70 percent more than today in the year 2050, according to FAO estimates. Even this surge in agricultural production will not suffice to eradicate malnutrition as long as current levels of inequality in food supply remain. Reducing world hunger depends at least as much on reduced poverty as on increased food production.

**Food is only one driver of the growing global resource use.**

Food is only one driver of growing global resource use: in fact, during the last century global resource use grew by a factor of 9.5, but biomass use grew by a factor of 3.8 and lagged behind other groups of resources (Figure 1). The yearly use of fossil fuels grew more than 13-fold, ores and industrial minerals 31-fold and construction minerals more than 40-fold.

A major driver behind the trajectory of global resource use displayed in Figure 1 is the global spread of industrialisation; that is, the transition from agrarian subsistence with limited consumption to industrial societies powered by fossil fuels and demanding large amounts of ores and minerals. Industrial society emerged as a historical singularity in England in the 17th and 18th centuries and has since spread across the globe. At present, perhaps a quarter to a third of the world's population has more or less completed the agrarian-industrial transition




United States Coast Guard Service

and much of the rest is on its way. Some regions are at the initial stages (rural regions in parts of Africa, for example), while others including India and China are moving far more rapidly. Other regions like many urban regions in Latin America and Southeast Asia are almost there (Fischer-Kowalski and Haberl 2007). Such industrialisation is premised on surges in the use of non-renewable resources, which currently account for 70 percent of global resource supply. No matter which side of the heated *peak everything* debate one is on, it is clear that this trajectory cannot be sustainable.

Two additional points need to be made. First, "renewable" doesn't necessarily mean "environmentally benign". 50-70 percent of Earth's land surface is used to produce 20 Gigatons of biomass every year (Erb *et al*. 2007). This puts an array of pressures on ecosystems and is one important driver of biodiversity loss. We cannot increase food supply in the coming decades simply by increasing cultivated area; we also need to intensify land use (Lambin and Meyfroidt 2011). Reaping the benefits of intensification while minimising its substantial adverse effects will be a major challenge. Second, even if resource supply were limitless, the capacity of the biosphere and biogeochemical cycles to absorb the effects of use is not. For example, we need to reduce drastically the accumulation of carbon in the atmosphere to avoid disastrous climate change (Meinshausen *et al*. 2009). And we need to manage the application of fertilisers far more carefully to avoid harming coastal ecosystems.

**We need no less than a new development model.**

Several nations of the Global South are currently following the same resource-intensive path to industrialisation paved by Europe and North America. This is clearly unsustainable, especially while consumption in the industrialised world shows no sign of abating. We need no less than a new development model that allows improvements in human wellbeing throughout the world without harming the Earth system irrevocably. The contours of such a model, however, remain a huge challenge given the issues such as equity and historical responsibility. The difference between a sustainable society and our current industrial one will probably be almost as large as that between the current industrial society and the agrarian subsistence economies that prevailed in Europe some 200 to 300 years ago (Haberl *et al*. 2011).

Resource efficiency – deriving more income or wellbeing from

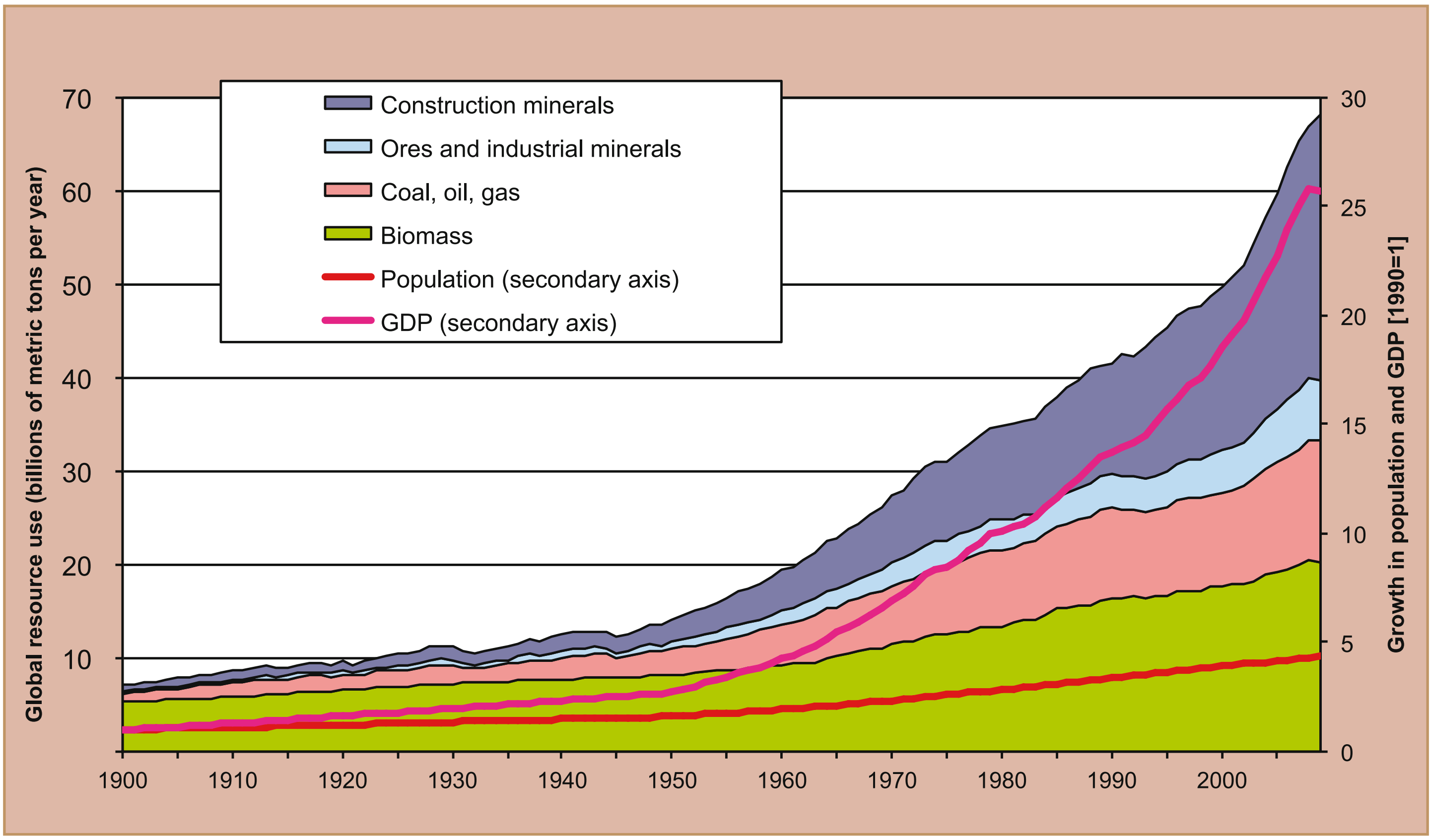



Figure 1. Increasing consumption. The left axis shows global resource use between 1900 and 2009 measured in billions ($10^9$) of metric tons per year. The right axis (1900=1) shows the growth in population and Gross Domestic Product (GDP) during the same interval. GDP is measured in constant 1990 Geary-Khamis Dollars. Data source: Krausmann *et al.* 2009, updated using data available at http://www.uni-klu.ac.at/socec/inhalt/3133.htm

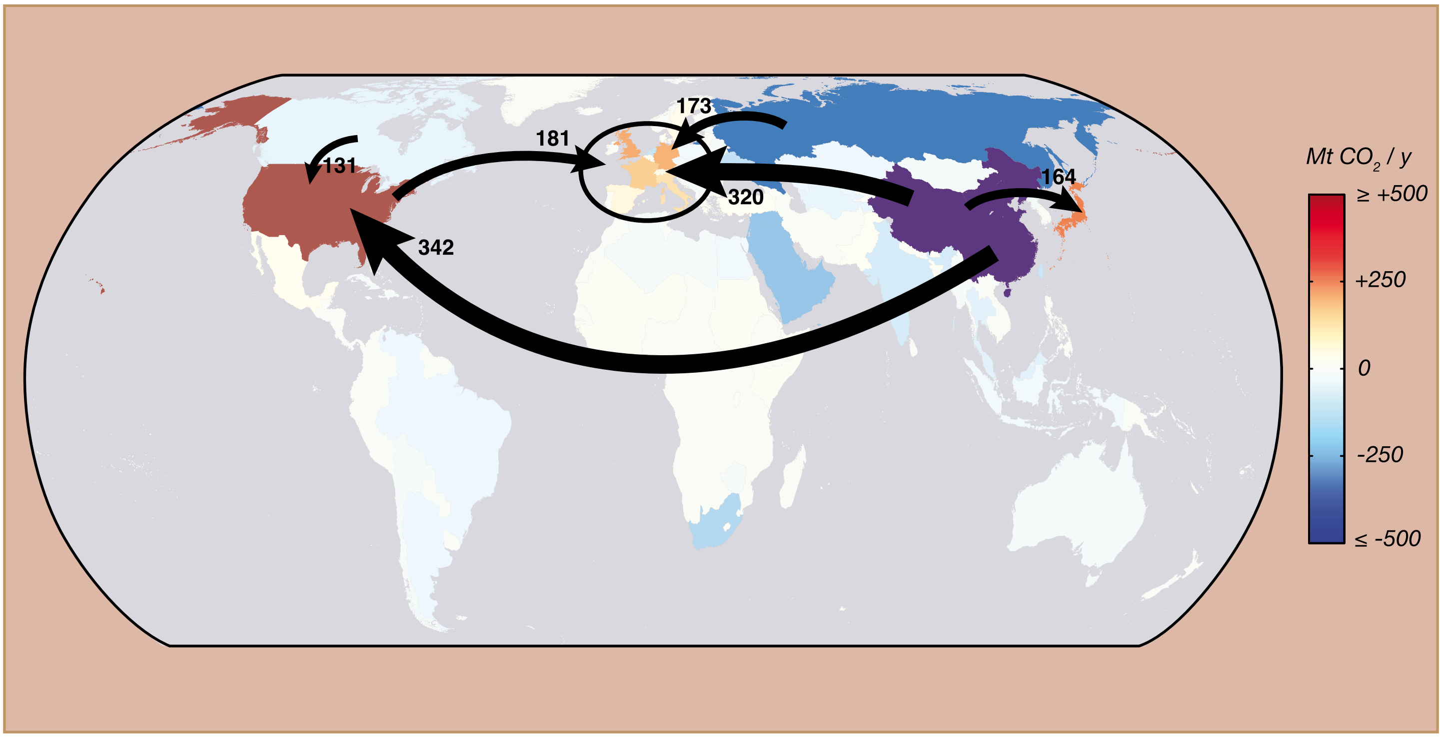



Figure 2. Trade in focus. The net effect of emissions embodied in goods and services based on millions of tons (Mt) of $CO_2$ trade in 2004. Arrows depict the largest interregional fluxes of emissions (Mt $CO_2$ / year) from net exporting countries (blue) to net importing countries (red). The threshold for arrows is 100 Mt $CO_2$ per year. From Davis S J, Peters G P and Caldeira K (2011). *Proceedings of the National Academy of Sciences* 108: 18554-18559.

less resources – is necessary but unlikely to be sufficient to achieve sustainability. After all, between 1900 and 2009, global GDP in constant dollars grew by a factor of 26 – two to three times faster than total resource use or fossil-energy supply (Figure 1). Efficiency gains are business-as-usual and have not so far resulted in stabilisation, let alone reduction, of resource use. Improving wellbeing and incomes have instead triggered an increase in consumption. Also, production and consumption are increasingly globally integrated (Figure 2). For example, the greenhouse-gas emissions (GHG) "embodied" in global trade are growing rapidly, therefore causing increasing carbon leakage from the regions that have agreed to binding emission reductions under the Kyoto Protocol to those that have not (Peters *et al*. 2011).

Although most of us would agree on the need to change current patterns of resource use and consumption, there is no agreement on how to go about doing this. The existing model of improving wellbeing is premised on economic growth fuelled by consumption. Is there a workable alternative whereby we could live well despite reduced resource throughput? What behavioural and institutional changes would this entail and how could we make those happen? The positive news is that our knowledge about resource use and flows is improving by the day. Such information is already informing management decisions at local and regional scales (for example, cities) and remains available to support any steps taken at the international level towards a transition to sustainability.

HELMUT HABERL is director of the Institute of Social Ecology Vienna, Alpen-Adria Universitaet Klagenfurt, Vienna, Graz.
Email: helmut.haberl@aau.at

**Production and consumption are increasingly globally integrated.**

## REFERENCES

Davis S J, Peters G P and Caldeira K (2011). *Proceedings of the National Academy of Sciences* 108: 18554-18559.

Erb K-H *et al.* (2007) *Journal of Land Use Science* 2, 191-224.

Fischer-Kowalski M and Haberl H, eds (2007) *Socioecological Transitions and Global Change. Trajectories of Social Metabolism and Land Use.* Edward Elgar, Cheltenham and Northampton.

Haberl H *et al.* (2011) *Sustainable Development* 19: 1-14.

Krausmann F *et al.* (2009) *Ecological Economics* 68: 2696-2705.

Lambin E F and Meyfroidt P (2011) *Proceedings of the National Academy of Sciences* 108: 3465-3472.

Meinshausen M *et al.* (2009) *Nature* 458: 1158-1162.

Peters G P *et al.* (2011) *Proceedings of the National Academy of Sciences* 108: 8903-8908.

# Risky BUSINESS

A sequence of devastating earthquakes and a large number of weather-related catastrophes made 2011 the most expensive year ever for natural catastrophe losses for insurance companies. **Owen Gaffney** spoke to the world's largest reinsurance company Munich Re's Head of Geo Risks Research, **Peter Höppe**.

### What is Munich Re's analysis of events in 2011?

2011 is a very special year in terms of natural catastrophes. By the end of the first half of the year we were already at a record level for total economic losses caused by natural catastrophes. In the second half to date we have had even more large natural catastrophes, for example the flooding in Thailand and Hurricane Irene in the US. Never before have we seen such high losses.

### Which are the key events?

The predominant contribution has been the earthquake in Japan: this quake has been the most costly natural catastrophe in history. Much more expensive than Hurricane Katrina, which was up until then the most expensive natural catastrophe.

But it is not just earthquakes. It's the weather too. We had extreme floods in Queensland at the end of last year and early this year. These were caused by record precipitation in many places in Australia, associated with the highest sea-surface temperatures ever measured off the coast of Australia. The losses caused by large thunderstorm-related events such as tornadoes and hail in the US are at a record high, about 50 percent higher compared with 2010.

**Never before have we seen such high losses.**

### What is the significance of the high sea-surface temperature?

Like many climate researchers, we see a link between the high sea-surface temperatures, increasing intense-precipitation events and the intensification of tropical storms. Increasing sea-surface temperatures are a logical consequence of global warming. They lead to more evaporation and thus a higher potential for extreme precipitation, and they provide more energy for tropical storms.

Also one of the largest and most intense cyclones in recorded history made landfall in Queensland this year. The warmer seawater provided its energy.

### What is the long-term trend?

The long-term statistics of sea-surface temperature off the coast of Australia, but also in other ocean basins, show a significant trend upwards for the last 100 years. December 2010 had the highest sea-surface temperature on record off the Australian coast (Figure 1). The rise can only be explained by global warming.

### What about La Niña this year? Doesn't that phenomenon cause periodic fluctuations?

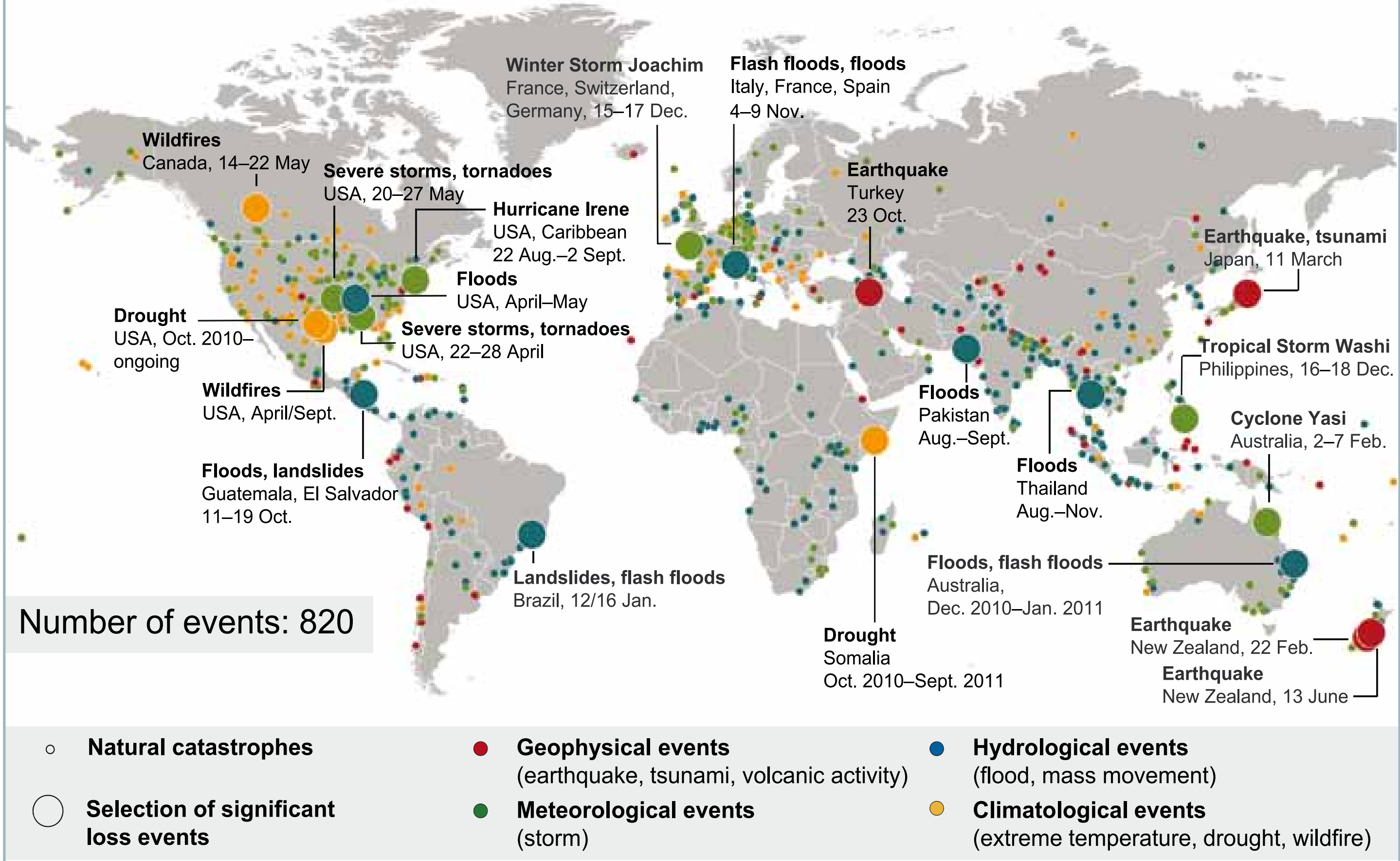
We do have year-to-year fluctuations in weather and sea

## The forgotten catastrophe

While the insurance industry reeled from heavy losses, 2011's greatest humanitarian catastrophe unfolded in Africa. Famine caused countless deaths in the midst of the worst drought in decades on the Horn of Africa. These fatalities and economic losses are not included in calculations of insured losses, a fact not overlooked by Munich Re.

## Natural Catastrophes 2011

Munich RE




### Natural catastrophes in 2011

| | The figures of the year 2011 | The figures of the year 2010 | Average of the last 10 years 2001-2010 | Average of the last 30 years 1981-2010 |
|---|---|---|---|---|
| Number of events | 820 | 970 | 790 | 630 |
| Overall losses in US$ m (Original values) | 380,000 | 152,000 | 113,000 | 75,000 |
| Insured losses in US$ m (Original values) | 105,000 | 42,000 | 35,000 | 19,000 |
| Fatalities | 27,000 | 296,000 | 106,000 | 69,000 |

### The five largest natural catastrophes of 2011
**Ranking by overall losses**

| Date | Country/Region | Event | Fatalities | Overall losses in US$ m | Insured losses in US$ m |
|---|---|---|---|---|---|
| 11.3.2011 | Japan | Earthquake, tsunami | 15,840 | 210,000 | 35,000-40,000 |
| 1.8-15.11.2011 | Thailand | Floods, landslides | 813 | 40,000 | 10,000 |
| 22.2.2011 | New Zealand | Earthquake | 181 | 16,000 | 13,000 |
| 22-28.4.2011 | USA | Severe storms/ tornadoes | 350 | 15,000 | 7,300 |
| 22.8-2.9.2011 | USA, Caribbean | Hurricane Irene | 55 | 15,000 | 7,000 |

temperatures associated with El Niño and La Niña events. But in the long term – as the IPCC special report (see page 5 of this issue) assumes – there will be an increase in average tropical cyclone maximum wind speeds in some ocean basins. Again, we don't see this only around Australia. We see increasing sea-surface temperature on a global level.

EPP Group

Peter Höppe, Head of Geo Risks Research, Munich Re

### The United States has been hit hard this year.

If you put it all together, we had an extreme record drought in Texas. We had record floods in the Missouri and Mississippi region. We had an almost record season for tornadoes in terms of the total number. But an absolute record in terms of economic losses. If you take the tornadoes as a single event, then the tornado season of 2011 is the fifth costliest natural catastrophe in US insurance history.

### Do you see any long-term trends there?

We've done an extensive study on this. There is a long-term trend visible on the so-called convective event losses – all the losses from big thunderstorms – including hail, tornadoes, flooding. We see a significant upward trend in the US during the last decades. This is in line with some trends from meteorological data where we see a rising number of days with the potential to develop these large thunderstorm systems. When comparing regions in the trends of frequencies of weather-related natural catastrophes, we see the largest increase in North America, followed by Asia.

### As the world's largest reinsurance company you seem convinced you are seeing strong links between the trend in weather-related natural catastrophes and anthropogenic climate change.

**We see increasing sea-surface temperature on a global level.**

An individual event cannot be taken as proof of climate change. Each of the events we have seen in the last decades could have happened without climate change. As you say, we are the largest reinsurer and we have good data on such weather-related extreme events. Our statistics, however, indicate significant changes. We think we can only explain the full range of these significant changes by the contribution of global warming.

### An increasing global interconnectivity seems to amplify the impact of natural catastrophes. Do you see that?

We see more global connections, particularly with these large events. Take the earthquake in Japan. That had an effect on car manufacturers in the US and Europe because some parts made in Japan could not be produced anymore so they ran out of these parts and could not produce their cars.

It also had surprising political influence. If you just think of the Fukushima event. The damaged nuclear power reactors had repercussions on the energy policies of Germany, Switzerland and Italy. This has triggered new laws to phase out nuclear energy, or in the case of Italy, to cancel plans to start building such power plants.

### Did it affect the global recession?

I don't think so as most of the disasters have affected wealthy countries rather than being spread around the world. Man-made disasters like 9/11 have more of an effect on financial markets. While the financial losses are high and this means a lot in an economic sense, I don't think they are big enough to influence the long-term international financial markets. And indeed, after such big catastrophes the repair work can boost economies.

### What's your take on the trend of global weather-related disasters?

First, the upward trend in the frequencies of loss events from natural catastrophes is predominantly down to weather-related events, not geophysical.

Losses are increasing, however, for all kinds of natural catastrophes, and the main drivers are population growth, rising wealth and increasing settlement in risky regions.

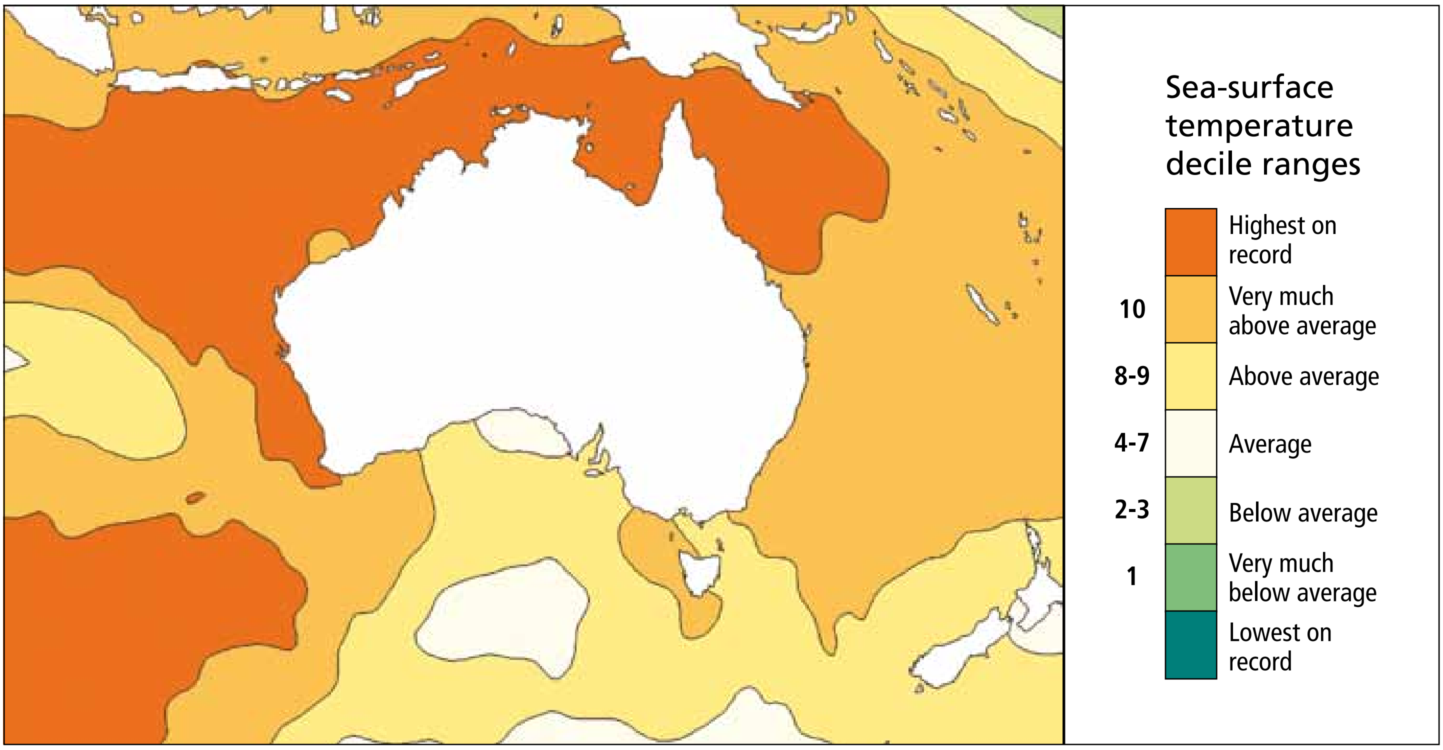



Figure 2. Sea-surface temperature off Australia for the year 2010. Deciles are calculated with respect to the 1900-2010 period from the NOAA Extended Reconstructed Sea Surface Temperature (NOAA_ERSST_V3) data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA. Figure courtesy: Bureau of Meteorology of the Australian Government.

## 2011 in numbers

With some 820 loss-relevant events, the figures for 2011 were in line with the average of the last ten years. 90 percent of the recorded natural catastrophes were weather-related – however, nearly two-thirds of economic losses and about half the insured losses stemmed from geophysical events, principally from the large earthquakes. Normally, the dominant loss drivers are weather-related natural catastrophes. On average over the last three decades, geophysical events accounted for just under 10 percent of insured losses. The distribution of regional losses in 2011 was also unusual. Around 70 percent of economic losses in 2011 occurred in Asia.

**But what happens when you normalise this adjusting for GDP and population growth?**
Our own analyses and those done in collaboration with the London School of Economics suggest that for normalised insured losses there are significant trends upwards in the US and Germany.

If you look at the number of loss events then socio-economic influences have a smaller influence. We see an increase in the number of events. It is important to note we see a big difference between the geophysical events – tsunamis, earthquakes and volcanoes – and weather-related events. We would assume that in both cases population growth and reporting has a similar influence. For example, 30 or 40 years ago we may not have documented a small earthquake with few casualties or economic losses. Today, we would be more likely to document these kinds of events in our database. This creates a slight increase in the number of geophysical loss events we are recording.

But if you do the same for flood events and windstorm events they have increased far more. For flood events they have increased by more than a factor of three. And windstorm events have increased by a factor of about three.

It seems that this difference is driven not by population growth or value growth but rather by more of these extreme events and more intense events. The logical conclusion is that climate change is playing its part, be it natural variability or anthropogenic global warming. This is also what meteorologists and climate researchers are telling us. More evidence for this assumption has been provided by the IPCC special report on extreme events (see page 5 of this issue) and new studies conducted in Germany. There are indications there will be increasing losses caused by storms and floods driven by climate change during the coming three decades. ▮

**The logical conclusion is that climate change is playing its part.**

OWEN GAFFNEY is the Director of Communications at IGBP.

Human infrastructure both contributes to and is affected by global change. The engineering and climate research communities must work together to respond and adapt to such changes, say **Faisal Hossain** and **Julia Pongratz.**

# BUILDING OUR FUTURE

As the world urbanises rapidly, our cities are becoming larger (see page 16 of this issue); they are growing as fast as, or faster than, urban population. The modification of Earth's surface for urban living is irreversible on human timescales and affects the local and global climate and the environment. Previous work has shown that changes in land properties such as albedo, roughness and moisture content can significantly influence climate variability at the regional scale and also affect extreme events (for example, Seneviratne *et al*. 2006). Several initiatives are currently fine-tuning our understanding of the impact of land-cover change on climate, including the IGBP synthesis on land-use change and climate.

While providing fodder for global-change researchers these rapid changes – coupled with the possibility of increased climate variability and economic uncertainty – are creating new challenges for the infrastructure engineering community. Urban settlements have an insatiable appetite for energy and resources, a steady supply of which needs to be assured. Take water, for example. A traditional but ubiquitous source is artificial reservoirs created by damming rivers upstream of cities. These large-scale infrastructures trap a sufficiently large amount of water from the local or regional water cycle to make up for a shortfall when demand exceeds the variable supply from nature. Although few new projects are being undertaken in the United States or Europe, large dams are being constructed and contemplated in several other nations to support agriculture as well as rapidly growing urban agglomerations. For example, the Southeast Anatolia Project in Turkey, the Three Gorges Dam in China and the proposed project to link Indian rivers.

The long-term planning of such infrastructure and the maintenance of existing infrastructure is complicated by the possibility of changing weather patterns during the coming century. But model results do not necessarily agree with each other and lack the resolution that would allow robust regional or local-scale projections. Climate models do not yet provide the kind of information needed by engineers and planners – for example, the Probable Maximum Precipitation and Probable Maximum Flood values projected into the late 21st century – that would allow testing the future functional resilience of dam infrastructure.

Despite obvious links, collaborative studies involving the engineering and climate-research communities are not common, and there is little co-design of research. There is much scope for engagement between the two communities to understand change and develop resilience.

## An opportunity for engagement

Climate change will put pressure on existing infrastructure and pose new challenges for the infrastructure being contemplated by shifting mean climate and increasing the frequency and intensity of extreme climate events. In many regions the water balance will be altered by temperature and precipitation changes significantly beyond what

had been anticipated when reservoirs were built. As return intervals of flooding increase, dam systems and wastewater infrastructure may exceed their capacities – for example, the Folsom Dam on the American River near Sacramento. Heat waves, such as in the summer of 2003 in Europe, which caused yield losses and ten thousands of deaths, are expected to become more frequent. Infrastructure will have to adjust to ensure sufficient resilience of energy generation and transmission, approaches to cool public facilities will need to be changed and urban green spaces will need to be increased to avert public health risks (IPCC 2011).

Of course, infrastructure itself contributes to land-use/land-cover change. We know well the first-order changes in atmospheric temperature (for example, urban heat islands) or humidity (for example, cooler environment near reservoirs or irrigated regions) caused by infrastructure. More recently, second-order impacts on climate have been identified. For example, the downtown high-rise regions of a city can split wind and create convergence downwind leading to lifting of air and higher precipitation in certain circumstances. Increased air pollution in cities can also affect the mechanisms leading to precipitation. Incidentally, some of these effects have been also known to overwhelm city sewer systems (Reynolds *et al*. 2008).

Besides direct climate effects, such as changed albedo, flood control or hydropower dams can trigger a faster pace of urbanisation of the downstream valley regions, whereas irrigation dams intensify agricultural production in the vicinity of the reservoir. In a study of about 100 large dams in the US, Degu and colleagues (2011) found that dams in the Mediterranean and arid climates exerted the greatest and most detectable mesoscale impact on temperature, humidity and other storm-forming properties, whereas humid regions were least affected. This study underscores the need for a broader view of the change a dam can typically trigger during its lifespan, and has important implications for climate-change adaptation too.

**There is increased emphasis on understanding fundamental land-atmosphere processes.**

In recent discussions on promoting resilience of water infrastructure, the issue of "climate change" has featured prominently as a path forward for the 21st century in some countries such as the UK (www.defra.gov.uk/environment/climate/sectors/infrastructure-companies/). This is timely, but the primary focus has so far been on adapting infrastructure in a top-down fashion to the changing extremes expected from climate-model projections. This misses the possibility of interaction of local-to-regional climate effects of large infrastructure with global climate change. For example, a warmer atmosphere implies greater capacity for holding water vapour, which might amplify the local climate impact of infrastructure. The research community studying the climate impacts of land-use/land-cover change has demonstrated clearly the impacts of local changes on the climate at various scales – the engineering community needs to pay greater heed to such research.

At the same time, the land-use/land-cover change and climate researchers are also beginning to recognise the need for better engagement with the engineering community. There is increased emphasis on understanding fundamental land-atmosphere processes and fingerprinting the direct human impact on climate. Urbanisation and other land-use change in the US and China led to an important component of the increase in mean temperatures and the decrease in diurnal temperature range observed over the last decades (e.g. Kalnay and Cai 2003). Earth-system models are consequently increasingly extended to account for effects of infrastructure on climate: for example, some General Circulation Models can use detailed information on urban structure where this is available (Oleson *et al*. 2010). A wide field for close collaboration may open with the new generation of General Circulation Models that allow local grid refinement in global climate simulations. Some regional climate models today already work on the level of watersheds and aim to predict local hydrological changes under given scenarios. Earth-system models will thus increasingly be able to make use of inputs about local and regional infrastructure, and may eventually allow quantification of infrastructural feedbacks on climate from the local to global scale.

Inputs from the engineering community are also needed to assess future intended and unintended consequences of human activity on climate. Scenarios of infrastructural change form part of the broader socioeconomic scenarios underlying all climate projections. As the infrastructure that might determine future climate change is largely yet to be built (Davis *et al.* 2011), information on infrastructural changes will be key to projections. Information on infrastructural scenarios is also needed for gauging the climatic effects of "new" or expanding land uses related to alternative energies. Large-scale wind power has been shown to have local to regional temperature effects (e.g. Keith *et al*. 2004). Significant changes in global mean climate seem likely only for massive deployment of wind power; the plausibility of such scenarios needs to be assessed together with the engineering

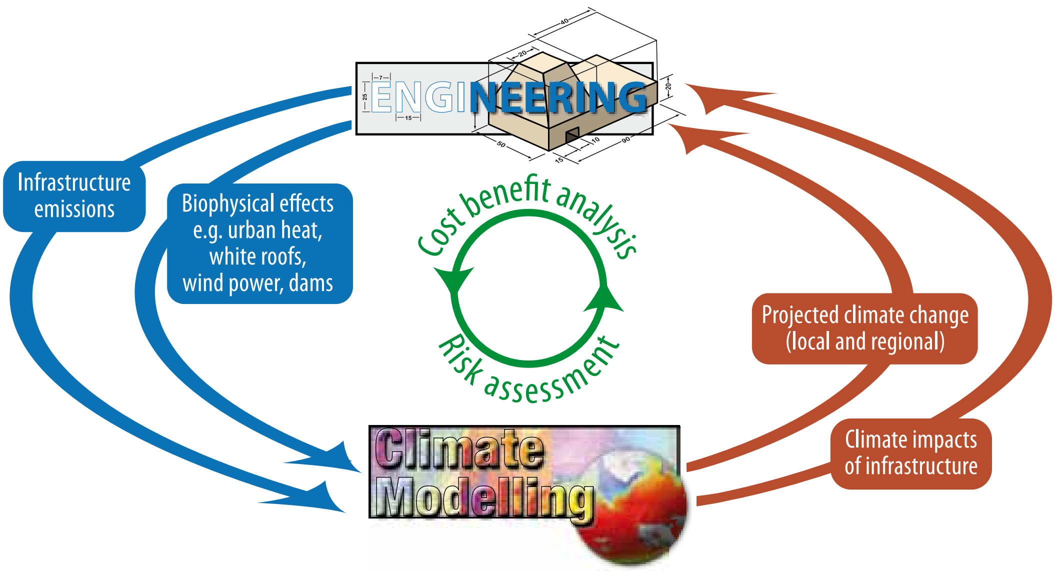



Figure 1. Collaboration for co-benefits. Projecting future climate change requires, among other things, scenarios of infrastructural change. Maintaining current and planned infrastructure and adapting to future climate change requires climate projections at local and regional scales. This interdependence can form the basis of a closer collaboration between the engineering and climate-research communities. It can help elucidate the possible local climate impacts of infrastructure.

community. Methods such as white roofs have been suggested as mitigation strategies and indeed found relevant for local to regional climate (Oleson *et al*. 2010). Strong local effects are also clearly relevant for the assessment of adaptation needs. Close collaboration between the engineering and climate communities is needed for a complete cost-benefit analysis of such proposed mitigation tools (Figure 1).

## Collaboration for co-benefits

Researchers studying land-use/land-cover change are already working closely with climate modellers to provide land-use and land-cover information as boundary conditions for climate models to be included in the fifth assessment report of the Intergovernmental Panel on Climate Change (Hibbard *et al*. 2010). A next step could be to involve engineers during the planning stages of research to ensure that the results can better inform design, operation and management practices. Adaptation is best served if approached locally from bottom up (e.g. Hossain *et al*. 2011). The engineering community should thus identify the types of information that could inform the optimal adaptation strategy for specific locations. For example, the engineering community of China might want to understand the potential impact of the land-cover change associated with large dams like the Three Gorges – and the expected increase in urban population growth – on the Asian monsoon. This requirement could then be passed on to researchers studying the impacts of land-use/land-cover change and thereby to climate modellers.

Political discussions and decisions on mitigation/adaptation options and alternative energy, for example, require a complete and comprehensive cost-benefit analysis that is currently lacking. There is growing recognition that closer collaboration between engineers and climate scientists is an important requirement for developing such analysis. Collaboration needs to be encouraged in every way possible. ▮

**A next step could be to involve engineers during the planning stages of research.**

FAISAL HOSSAIN is an associate professor at the Department of Civil and Environmental Engineering, Tennessee Technological University, Prescott Hall 332, 1020 Stadium Drive, Box 5015, Cookeville, TN 38505-0001, USA. E-mail: fhossain@tntech.edu

JULIA PONGRATZ is a postdoctoral research scientist at the Department of Global Ecology, Carnegie Institution, 260 Panama Street, Stanford, CA 94305, USA. E-mail: pongratz@carnegie.stanford.edu

## REFERENCES

Davis S J, Peters G P and Caldeira K (2011). *Proceedings of the National Academy of Sciences* 108: 18554-18559.

Degu A M *et al.* (2011). *Geophysical Research Letters*, doi:10.1029/2010GL046482.

Hibbard K *et al.* (2010). *International Journal of Climatology*, doi:10.1002/joc.2150.

Hossain F *et al.* (2011). *ASCE Journal of Hydrologic Engineering*, doi:10.1061/(ASCE)HE.1943-5584.0000541.

IPCC (2011). Summary for Policymakers, in *Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, edited by Field C B *et al.* Cambridge University Press.

Kalnay E and Cai M (2003). *Nature* 423: 528-531.

Keith D *et al.* (2004). *Proceedings of the National Academy of Sciences* 101: 16115-16120.

Oleson K W, Bonan G B and Feddema J (2010). *Geophysical Research Letters* 37: L03701.

Reynolds S *et al.* (2008), in Reliable Modeling of Urban Water Systems, edited by James W. *Computational Hydraulics International*, Guelph, Ontario, Canada, 99-122.

Seneviratne S I *et al.* (2006). *Nature* 443: 205-209.

GLOBAL IGBP CHANGE

International Geosphere-Biosphere Programme

# JOIN THE IGBP NETWORK

## WWW.IGBP.NET

### IGBP core projects

Analysis, Integration and Modelling of the Earth System (AIMES)

Global Land Project (GLP)

International Global Atmospheric Chemistry (IGAC)

Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS)

Integrated Marine Biogeochemistry and Ecosystem Research (IMBER)

Land-Ocean Interactions in the Coastal Zone (LOICZ)

Past Global Changes (PAGES)

Surface Ocean-Lower Atmosphere Study (SOLAS)

### Global-environmental-change joint projects

Global Carbon Project (GCP)

Global Water System Project (GWSP)

Global Environmental Change and Human Health (GECHH)

### Second synthesis topics

Ecosystem impacts of geoengineering

Megacities in the coastal zone

Nitrogen and climate

Earth-system impacts from changes in the cryosphere

Impacts from changes in the cryosphere on the biota and societies in the arid Central Asia

Global environmental change and sustainable development: the needs of least developed countries

The role of land-cover and land-use change in modulating climate

Air pollution and climate

### ICSU's global-environmental-change programmes

DIVERSITAS – an international programme of biodiversity science

International Geosphere-Biosphere Programme

International Human Dimensions Programme on Global Environmental Change

World Climate Research Programme

Earth System Science Partnership

ICSU International Council for Science

IGBP is an ICSU global-environmental-change programme.

**IGBP focuses the international research community on the planet's key biogeochemical processes – the carbon, oxygen, nitrogen, water, phosphorus and sulphur cycles. Our work includes understanding and predicting how these cycles are changing and the impact of human activities on them.**