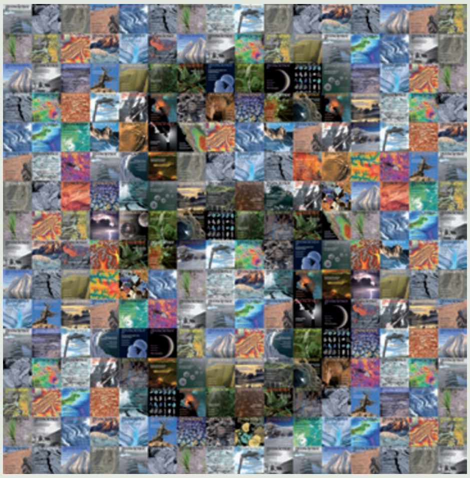
Five years of Earth science



Nature Geoscience launched five years ago. This timescale, just enough to complete a research project or two, may not seem a long time. But a lot has happened in the collective of disciplines that are covered in our journal. Some of the most violent plate-boundary earthquakes have shaken the planet; public perception of climate change has been on a rollercoaster ride (from the 2007 Nobel Peace Prize to Climategate); and planetary missions have ventured to new horizons. We have asked nine Earth and planetary scientists to look back at fields where scientific understanding, or the public's perception of the science, is now substantially different than it was in 2007. Some of the pieces mark step changes, and others more gradual progress — but they all provide a glimpse at the rapid evolution of an exciting science, both in the past half-decade and into the future.

Adapting the assessments

The current assessment of climate change is nearing completion. It is now time to consider how best to provide increasingly complex climate information to policymakers, suggests **Thomas F. Stocker.**

The five years since the launch of *Nature Geoscience* in January 2008 have been a rough ride for climate scientists. When the journal's first issue appeared, the public was well informed about current and projected future climate change. Since then, many people's trust has been shaken in the concerted attack on the climate sciences (that was termed Climategate), and this trust has had to be painstakingly rebuilt.

Back in 2008, decades of climate research had produced results based on reliable observations, quantitative palaeoclimate reconstructions, theoretical studies, and numerical modelling using the most powerful computers. This body of work was recognized by the public and the media as a solid scientific foundation for the understanding of the climate system and its changes. The Intergovernmental Panel on Climate Change (IPCC), a unique process of assessing and presenting complex scientific findings to policymakers and the wider public, was an important element in the dissemination of information on the state of the climate system and possible future change as a result of human activities. Public regard for climate science culminated when the diagnosis of unequivocal warming, mostly caused by human activities, was made in the fourth assessment report of the IPCC in February 2007. The award of the Nobel Peace Prize in the same year, jointly to Al Gore and the process and institution of the IPCC, lent further recognition to climate scientists and their work. In this atmosphere of public support, hopes were high for the Copenhagen Summit in December 2009, which hosted the fifteenth Conference of the Parties to the United Nations Framework Convention on Climate Change, intended to transfer knowledge about climate change into firm commitments by the world's governments.

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Three weeks before the summit, however, a perfectly orchestrated break-in at the University of East Anglia's e-mail server and the unauthorized release of thousands of e-mails between climate researchers initiated a skyfall in the public regard of the climate sciences, particularly in the United States and the United Kingdom. Claims about a grand scientific conspiracy were made, based on text from a select few e-mails among the thousands on that server. Some blogs were used for anonymous defamations and systematic slandering attacks. Even political assaults were launched on individual climate scientists, leading to very difficult personal situations and tragedies for those targeted. The tactic of doubt-mongering is not particularly innovative. But when it hit climate scientists, they were unprepared.

In the mean time, the integrity of climate science has proved robust to such blunt attacks and manoeuvres. No fewer than six independent investigations were carried out, all concluding that there is no substance to the allegations of foul play. When the IPCC called for expert volunteers to participate in its fifth assessment report, the response was overwhelming. And the latest surveys around the world show that public opinion on natural and human-induced climate change is again more in line with the hard scientific evidence.

The next five years of climate science will continue to produce new and deeper insight into this extremely complex system of our planet. By the end of the year 2014, policymakers and the public will receive from the IPCC the most up-to-date account of a changing world, a comprehensive scientific assessment of the climate system, its past, present and projected future changes. The assessments will also reflect on the impacts of further fossil fuel emissions on the physical climate system, on ecosystems and on human systems, and on the options that remain for mitigating climate change.

But the next five years will also be challenging. Once more, the IPCC will deliberate on how to carry out its scientific assessment most effectively. Comprehensive periodic reports were a great success in the past: the IPCC process with its sequence of carefully formulated, thoroughly reviewed, robust consensus documents is now being considered as a template by bodies assessing other global-scale problems, such as biodiversity. But since the IPCC started in 1988, climate science has grown into a wide, multidisciplinary field. The number of studies and their level of complexity have all increased by orders of magnitude, as a natural consequence of scientific progress. For example, the volume of the model data obtained from coordinated climate model simulations for the assessment reports has increased from 35,000 gigabytes in 2007 to over 1.7 million gigabytes (1.7 petabytes) by the end of 2012, an amount that would fill the hard discs of some 3,400 personal computers. The data are now stored in a dedicated open archive maintained by the Program for Climate Model Diagnosis and Intercomparison (PCMDI), accessible to all who would like to contribute to their analysis. Nevertheless, even the transfer of some of this volume of data to the research centres has become a serious technical challenge that calls for innovative solutions.

Apart from occasional serendipitous step-changes in understanding, the knowledge gain per time tends to decline in a mature scientific field. Hence the questions must be raised whether the IPCC's 5- to 7-year assessment cycles can still be maintained with a reasonable effort, whether the volunteer scientists who act as lead authors are equipped with an adequate infrastructure for this Herculean task, and whether enough researchers will continue to donate their time.

We may want to explore alternative approaches to achieve the same goal of disseminating the best and most robust understanding of "the scientific basis of risk of human-induced climate change". One possibility is a carefully selected series of assessments that are narrower in scope and each deal with a specific, policy-relevant issue. Alternatively, each of the previous reports' chapters — for example on sea-level change, or on near-term climate change — could be run as a series of assessments that are updated individually, rather than all at the same time, in line with specific scientific progress in the respective fields. Chapters on observations might then follow a different pace from, for example, chapters on climate model evaluation, or computer-intensive analysis of projection simulations.

The IPCC's unique and extremely successful all-round climate assessments must also be considered in the context of the climate services that are now being established around the world. Climate services have the task of preparing information on climate-related issues for local communities, regional policymakers, practitioners and the public, but that information will need to reflect the context of continuing global climate change. To make the climate services sustainable and successful, a common understanding of the long-term change, from global to regional scales, is therefore indispensable. Such an evolving consensus can only grow from comprehensive assessments of the peer-reviewed scientific literature, independent from the daily business of climate services.

Nature Geoscience has made an important contribution to the climate sciences in the past five years, by providing a platform for scientific high-impact publications. In view of the changes ahead, the next five years of *Nature Geoscience* will be no less interesting and enlightening than the first five. ❐

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The epoch of humans

People have changed the world irrevocably. **Jan Zalasiewicz** discusses whether formalization of the Anthropocene as an epoch in geological time will help us understand our place in Earth history.

Humans are just another animal species, albeit with peculiar habits: buildings, factories, oil rigs, cars and travel. Magnified a few billion times across the Earth, human activity adds up to some remarkable geology. There's been nothing remotely like it since the world began.

The idea that humans have propelled a new chapter in Earth history is not new. In 1778, George-Louis Leclerc de Buffon, a French naturalist, wrote *Epochs of Nature*, demarcating episodes in history of an Earth he suggested was an outlandish seventy-five thousand years old (privately, Buffon guessed three million years, but dared not publish that yet more heretical age). The last epoch was one in which humans dominated — and a good thing too, he thought: to slow the cooling of a planet he thought destined for frozen oblivion. Buffon's ideas did not catch on. And although ideas of human domination of our planet's geology have surfaced at intervals since, they were generally dismissed. For humans, in their minuscule time-span on Earth, could not — surely — rival the great forces of nature.

Little more than a decade ago, though, the atmospheric chemist and Nobel-Prize-winner Paul Crutzen suggested that humanity was indeed a force of nature. We no longer live in the Holocene, he said, but in the Anthropocene. The chemical, physical and biological changes are dramatic and sometimes frankly alarming: atmospheric carbon dioxide concentrations are now at levels last seen more than two million years ago and rising fast; invasive species have been introduced to every continent and a sixth great mass extinction event may be with us in mere centuries; landscapes are transformed. Imagining a look back from some far future, it is hard to see how the twenty-first century could not be seen as a turning point in Earth history.

The idea of the Anthropocene has spread widely in the past five years or so. The term is used in both scientific papers and popular articles. No less than three journals devoted to Anthropocene science will shortly appear. The concept provides both a summation of the diverse human impacts on Earth and a vivid reminder that we live in a deeply changed world — and that humanity must learn to ride this new planetary tiger as it leaps into the unknown.

Interest in the Anthropocene stems partly from its potential formalization

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— the idea that it may be so real that it will one day feature on the geological timescale. To be useful to geologists, the Anthropocene must be thought of not just as history, but as rock — strata deposited during the Anthropocene that geologists can see and map. But what strata could physically have formed within a few centuries, a geological blink of an eye?

We might consider the changing landscape. Burgeoning cities comprise 'urban strata' — a geologically durable mass of brick, concrete, glass and metal. In another sense, they are an entirely novel and quite gargantuan trace fossil system, one that extends kilometres deep into older rock in the form of millions of boreholes and mineshafts. Out to sea, most of the continental shelves have now been scraped and smoothed by trawler-nets, altering both sediments and biota: these churned deposits might also form part of Anthropocene strata. There will be chemical signals in modern strata, too. These will come from carbon that is isotopically lightened by the influx from fossil fuels, and from nitrogen that is altered by the Haber-Bosch process that creates the fertilizer required to sustain the Earth's growing population.

Mapping the Anthropocene's complex products — within the deep-time context of the rock record — will help us understand our place in Earth history. But does it matter whether the Anthropocene is formalized? The term is currently informal, without even an agreed beginning. Yet, it looks set to stay, formal or not, and to spread to a much wider community than just geologists. The concept has already entered discussions of international law, where formalization may carry weight in the demarcation of human rights and responsibilities in a changing world. As the geological past is summoned as context for our tumultuous present, perhaps formalization of the Anthropocene should not only depend on scientific justification (as that is a given), but also on its use to the world beyond geology. ❐

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The mystery of atmospheric oxygen

Readily available O_2 is vital to life as we know it. **James Kasting** looks at how and when the first whiffs of oxygen began to reach the Earth's atmosphere.

The early history of the Earth's atmosphere has long fascinated both geologists and biologists. Geologists were intrigued because the atmosphere influences the types of mineral deposits that formed back then — some of which, such as banded iron-formations, still have economic importance today. Biologists were interested, because atmospheric composition most certainly influenced the early evolution of life and, in some theories, life's origin as well. In the past years, atmospheric scientists (like me) and astronomers have also taken an interest in this subject. We atmospheric types want to understand the basic processes that control atmospheric composition and climate over long timescales. Astronomers, who are now on the verge of being able to search for Earth-like planets around other stars, want to know what such planets might look like from afar and whether they might be able to use our knowledge of the early Earth to determine whether these planets harbour life.

Two main questions have guided investigations of oxygen in the early Earth's atmosphere: how much O_2 existed before the advent of life, and what exactly caused the rise of atmospheric O_2. The issue of prebiotic O_2 levels is not new. In the late 1960s, it was suggested that O_2 could have built up to an appreciable fraction of its present level, simply by photodissociation of water vapour followed by escape of hydrogen to space. But advances in our understanding of hydrogen escape to space showed that the amount of O_2 that could accumulate from this process is extremely small, about 10^{-13} times the present atmospheric level. More detailed calculations showed, however, that an O_2 layer, analogous to today's ozone

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layer, could form in the stratosphere as a consequence of photolysis of CO_2. Through this mechanism, the stratospheric O_2 abundance could reach around 10^{-3} times present-day levels.

But it is the question of the timing of the rise of atmospheric oxidation levels that has seen the greatest advance in the past few years. It was the recent application of multiple sulphur isotopes to Archaean-aged rocks that allowed us to constrain the irrevocable rise of atmospheric oxygen levels. Termed the Great Oxidation Event by Heinrich Holland, who sadly passed away in the first half of 2012 and will be sorely missed, the rise in oxygen is generally thought to have occurred rather precisely 2.45 billion years ago, although a few workers are still calling for a much earlier origin of oxygenation. And in one sense, everyone agrees on its broad cause: cyanobacteria. Cyanobacteria are single-celled organisms — true Bacteria to a biologist — that are capable of performing both oxygenic and anoxygenic photosynthesis. But a new debate has sprung up: namely, exactly when cyanobacteria started producing O_2. And, if this date was earlier than the Great Oxidation Event, what kept atmospheric O_2 from increasing right away?

These questions are currently driving considerable research. Organic biomarkers that are characteristic of cyanobacteria or O_2-dependent organisms have been reported in sediments as much as 2.7 billion years old. But it is unclear whether these compounds are indigenous to these old rocks or whether they were carried there at some later time, for example by oil migration. More subtle oxygen indicators such as enhancements in molybdenum and rhenium have been identified in shales dated at 2.5 billion years. These elements bind tightly to sulphur, and so their high concentration in Late Archaean shales suggests that weathering of sulphide minerals on land under oxygenated conditions was occurring — at least regionally — some 50 million years before the Great Oxidation Event. Other evidence for the weathering of sulphides tentatively pushes oxidative weathering back to 2.7–2.8 billion years ago.

Evidence for early oxidative weathering might well reconcile putative early oxygen production and the timing of the Great Oxidation Event. If oxygenic photosynthesis did indeed originate well before the main oxidation, O_2 could have been produced by cyanobacteria living in localized oxygen oases in the near-shore surface ocean. Plumes of O_2 emanating from these oases could have drifted inland and oxidized sulphides in the areas they passed over. Although this hypothesis has not been studied quantitatively, it seems rather unlikely. More plausibly, the entire atmosphere might have become oxidizing for brief periods before switching back to the dominantly reducing conditions of the Late Archaean eon.

A switch between reducing and oxidizing atmospheric conditions is easily triggered, similar to an acid–base titration: O_2 (or pH) stays low until just the critical amount of oxygen (or base) is added. Equivalently, O_2 could have stayed low until the input of reductants such as reduced volcanic gases fell below some critical level. Because the rate of reductant input is unlikely to have been steady, atmospheric O_2 could have risen and fallen multiple times. And certain signals of brief whiffs of oxygen, the sulphur isotope signal in particular, could conceivably be invisible within the broader geologic record.

Answers to questions about the nature of the Earth's early atmospheric evolution may, however, not lie in the sulphur isotope record, or even on the Earth itself. Instead, future insights may be found outside our Solar System, on Earth-like planets circling other stars. If we build proposed missions such as NASA's Terrestrial Planet Finder and the European Space Agency's Darwin we can begin to observe such Earth-like planets, but neither mission is actively being pursued at this time. Some exoplanets found by these missions may be similar to the present-day Earth, and some may be analogues to the Earth during its ancient geological history. Ultimately, by studying them, we can hope to understand how both the Earth and life itself evolved. ❐

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The great sea-ice dwindle

Record minima in Arctic summer sea ice have been trumping each other. **Marika Holland** reflects on the likely fate of the northern sea ice cap.

This past summer, the Arctic experienced the most rapid rate of sea-ice retreat ever recorded. On 16 September 2012, sea ice extent bottomed out at a new record minimum. The ice remaining in the Arctic at that date, about 3.4 million square kilometres, was roughly half of the ice cover during the 1990s when I was a graduate student starting research on Arctic climate. Rapid and alarming Arctic change is now a reality — and it came with a warning from climate modelling.

Before 2007, the Arctic had experienced considerable ice retreat with record summer minima in 2002 and again in 2005. But in 2006, climate models indicated that significantly more rapid ice loss was likely in the near future[1]. In the simulations, long-term retreat was punctuated by instances of abrupt loss, over four times faster than anything that had yet occurred. The most dramatic of these simulated events showed a loss of 4 million square kilometres — about 60% of the September sea ice — within only 10 years, and resulted in near ice-free Septembers by 2040. At the end of 2006, this result caused alarm and garnered considerable media attention.

In the next summer, the evolution of the melt season provided a second profound shock. Day after day, the ice cover receded relentlessly. By September 2007, the ice extent had dramatically undercut all previous record minima, the latest set only two years earlier. At the time, Arctic scientists wondered whether the weird summer weather of that year with persistent high sea-level pressure had kicked sea ice over the edge, and would result in an abrupt transition to widespread ice-free conditions that could no longer be halted. Alternatively, a coincidence of conditions detrimental to the ice, a 'perfect storm', could have acted on a thinned and vulnerable ice pack. In the latter case, the ice might recover and return to the more gradual loss rates of the past. Either way, the 2007 Arctic sea-ice loss was a wake-up call. Model predictions that had looked surprising only nine months earlier were rapidly aligning with reality.

The concern of a tipping point in sea ice is quite valid. Because of non-linear chaotic behaviour, dynamical systems such as sea ice can exhibit threshold behaviour, such that when crossed, rapid and irreversible change will ensue. This is akin to a canoe: gently rock it back and forth, and it remains upright. Lean over a bit too far, beyond the tipping point, and you flip it — a state from which it is difficult to recover. Indeed, some idealized models had suggested that such a tipping point in sea ice could exist, fuelled by ocean heating associated with reductions in surface reflectivity as bright ice gives way to dark water.

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A great deal of work has since been done on the potential for sea-ice tipping points. Climate model studies, our best tools for addressing these questions, suggest that irreversible change is unlikely[2]. If so, we should be able to slow and even reverse Arctic sea-ice loss through climate mitigation efforts.

Natural variability has turned out to be influential, too: instances of rapid ice loss occur when natural variations enhance greenhouse-gas-forced change, but natural variability can also counteract the response to human activity, leading to periods of relative ice stability even on decadal scales[3]. Efforts are underway to better understand the predictability of these natural sea-ice variations, which may ultimately lead to skilful forecasts on multiyear timescales. In the longer term, however, there is strong consensus that with a continued increase in greenhouse gas emissions, the enhanced radiative forcing will overwhelm natural variations and result in a summer ice-free state. The timing of the first Arctic summer without ice remains uncertain. But a mid-twenty-first century date, or even sooner, now seems likely.

We have learned a lot since the 2007 shock. But in some ways, we find ourselves right back where we were five years ago. The 2012 Arctic ice extent reached the lowest level ever recorded, again undercutting the previous record by a substantial margin. And, much like in 2007, the record ice loss incited discussions of unusual weather and ice loss mechanisms. It currently appears that a different flavour of perfect storm has occurred in 2012, but it is hard to quantify relative factors, given the dearth of Arctic observations. Notably, the observed losses to date, although extreme, have not reached the rate of rapid ice-loss events simulated in 2006[1]. More surprises may yet be in store.

Five years ago, the events of the past summer would have been staggering. But in Arctic climate science, shocking has become almost routine. ❐

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Megathrust surprises

Numerous earthquakes have occurred at subduction zones in the past 5 years, and some were devastating. **Kelin Wang** describes what we have learned about the seismicity of the shallow zone.

Since January 2007, there have been 18 earthquakes with a magnitude greater than 7.5 in subduction zones around the world. We look back at these earthquakes with mixed feelings. With awe and sadness, we remember the devastation caused by the tsunamis that some of these earthquakes triggered, especially the tsunami in Japan in March 2011 that caused some 20,000 deaths. With excitement, we note how our understanding of earthquake processes has deepened, thanks to recent revolutionary improvements in instruments and methods to observe these earthquakes.

The March 2011 Tohoku earthquake in Japan has brought into focus how much seismic power rests in the shallowest portion of subduction zones. Seafloor adaptation of the Global Positioning System and seafloor seismic surveys indicate a slip of 50 m or more along the shallowest segment of the megathrust — the fault that marks the boundary between the tectonic plates. After initial hesitation, researchers studying other types of seismic and tsunami records of this earthquake also converged on the view that the shallow megathrust at Tohoku is capable of hosting earthquakes and thereby generating powerful tsunamis.

The brief hesitation is understandable. In the past, we had thought the shallow megathrust would normally resist rupture. For example, in March 2005 at Sumatra, the shallow fault segment resisted rupture during a magnitude-8.7 earthquake, but afterwards crept slowly and aseismically. There are

different explanations for what happened in the Tohoku earthquake: the shallow megathrust in this area may never resist rupture, or the resistance may be too small to contain a very large rupture. Alternatively, the shallow megathrust may resist initially, but then give in by suddenly losing strength once a critical slip rate is acquired — a phenomenon known as dynamic weakening. Laboratory experiments, seafloor or sub-seafloor monitoring, and numerical modelling are being carried out to explore these possibilities.

The much smaller Mentawai earthquake in Sumatra in 2010 has also modified our view of the shallow megathrust. The Mentawai event was unexpected because it happened directly above the rupture zone of a larger earthquake in 2007, on the same megathrust fault. During the 2007 quake, the shallow part of the fault resisted rupture — only to fail in 2010, and in an unusual fashion by triggering a tsunami that was disproportionally large compared with the size of the earthquake. A series of delayed ruptures along neighbouring fault segments is not uncommon along the length of a plate-boundary fault, but in the upwards direction of a subduction zone, such a delayed domino effect came as a surprise. The sequence of these two earthquakes provides new information on how fault behaviour changes with space and time, and implies that up-fault triggering could be a mechanism for tsunami generation.

The deeper parts of megathrusts also look different from today's point of view. Earthquake rupture processes reconstructed from seismic waves, including those measured thousands of kilometres away, show that much of the high-frequency seismic energy that caused violent ground-shaking during the earthquakes in Sumatra in 2004, in Chile in 2010, and most evidently in Japan in 2011 came from way down in the fault zone, at depths of 30 to 50 km. So whereas the shallow, large slip led to tsunami generation and related damage along the coast, local shaking could be attributed to a deeper source.

We have made other great strides in our understanding of subduction-zone earthquakes. For example, there is increasing evidence that physical barriers on the down-going plate, such as subducted seamounts, could help to halt the propagation of earthquake rupture through the subduction zone. This limits the magnitude of the earthquake, reinforcing the notion that not all subduction zones are capable of the biggest, magnitude-9 earthquakes. We have also gained better knowledge of how megathrust earthquakes trigger quakes on other faults, and vice versa. And it is clear now that regular earthquakes and the phenomenon of slow slip and tremor represent a spectrum of fault slip behaviour, even if much of the detail still has to be worked out.

Valuable practical lessons have also emerged. The disaster at the Fukushima nuclear power plant is a poignant reminder that natural hazards, if not adequately assessed, can be exacerbated by human activities. In both tragic and positive ways, the 2010 Chile and 2011 Japan earthquakes demonstrated the value of tsunami awareness and importance of evacuation plans. For local evacuation, the best tsunami warning signal is the duration and strength of earthquake shaking. Where strong shaking is not felt, such as in areas far away from the earthquake, or for rare earthquakes (such as the 2010 Mentawai, Sumatran event) that generate a large tsunami without very strong shaking, official warnings are more useful.

In mitigating the impact of ground-shaking, Chile and Japan provide good examples for the world to follow. Because of well-designed and implemented building codes, very few buildings collapsed during the intense shaking, and thousands of lives were saved. In Japan, automatic early-warning systems that used faster seismic waves to warn against the ensuing slower but much more damaging waves also proved to be valuable.

Nevertheless, preparation for rare and extreme events like the Tohoku earthquake remains a great practical challenge. To save as many lives as possible, we need to get better at expecting the unexpected. ❐

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A steep learning curve

Ocean acidification, caused by the uptake of anthropogenic carbon dioxide, is a significant stressor to marine life. Ulf Riebesell charts the rapid rise in ocean acidification research, from the discovery of its adverse effects to its entry into the political consciousness.

When the German Chancellor Angela Merkel visited us at GEOMAR | Helmholtz Centre for Ocean Research in Kiel last year, the 'other CO_2 problem' was well known. Not just to her, but also to the pack of journalists tailing her. One of the first questions Merkel asked was, "Will marine organisms be able to adapt to the acidifying oceans?" I couldn't give a definitive answer, but her question gave me confidence that the message of ocean acidification posing a threat to marine life had reached our policymakers and communicators.

In 2007, when *Nature Geoscience* announced its first call for papers, the Intergovernmental Panel on Climate Change (IPCC) had just published its Fourth Assessment Report. In the 52-page synthesis, only 10 lines were devoted to the issue of ocean acidification. The report concluded that "while the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (for example, corals) and their dependent species".

How did the awareness of ocean acidification evolve from being a side note in the 2007 IPCC Report to grabbing the attention of Chancellor Merkel? The story of the rise in ocean acidification research actually begins three years earlier, at the first symposium on the *Ocean in a High-CO_2 World* in Paris in 2004. The term 'ocean acidification' had just been coined, and possible impacts on marine life had barely been investigated. The symposium was, in fact, mainly set up to evaluate strategies to artificially enhance ocean carbon uptake to mitigate the rise in atmospheric carbon dioxide concentrations. By the end of the meeting, however, it was clear that oceanic uptake of anthropogenic carbon dioxide had the potential to change seawater chemistry sufficiently to endanger marine organisms and ecosystems ocean-wide, even when just natural uptake was considered. The symposium marked a turning point in our view of the priceless service the ocean provides by taking up large quantities of anthropogenic carbon dioxide.

On the heels of the Paris meeting, a remarkable scientific endeavour followed. A report on ocean acidification by the Royal Society of London in 2005 marked the starting point of what was to become an amazingly steep learning curve — yet it wasn't until 2008 that research on ocean acidification gained substantial momentum in terms of funding. Since then, this field of research has become one of the fastest-growing areas in marine science. From barely 20 publications per year on the possible impacts of CO_2-induced changes in ocean chemistry in 2004, research output rose to over 200 publications per year in 2010, and is expected to surpass 300 in 2012.

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Important challenges remain. Although much knowledge has been gained about the effects of ocean acidification on individual organisms, in particular calcifying taxa, we still know little about responses at the community and ecosystem levels. We are just beginning to study the ability of organisms to adapt to an acidifying ocean. Moreover, ocean acidification does not happen in isolation. It occurs simultaneously with other changes such as ocean warming and a loss of oceanic oxygen, and interacts with other human-induced stresses such as over-fishing and eutrophication. Without proper knowledge of these interacting effects at the ecosystem level, it is difficult to project the biogeochemical consequences and climate system feedbacks resulting from ocean acidification, let alone the economic and social impacts.

Considering the evidence available today, the IPCC's Fifth Assessment Report, due out in 2014, is likely to come to a different conclusion about the impacts of ocean acidification. Today we know that its adverse effects are not restricted to shell-forming organisms. Observed impacts range from shifts in microbial species composition to reduced egg production in zooplankton, and, further up the food chain, from delayed larval development to abnormal flight behaviour in fish. Moreover, impacts of acidification on marine biota have been well documented in the field. So too have some of the economic impacts, such as the collapse of shellfish production in oyster hatcheries related to the acidification of their feed-water on the west coast of the United States.

Even though many uncertainties about the impacts of ocean acidification on marine life remain, we now know enough to predict with reasonable confidence that significant changes in marine ecosystems and biodiversity will occur within our lifetimes, if the oceans continue to acidify at the current rate. And we know how to prevent it — by cutting back on carbon dioxide emissions. ❐

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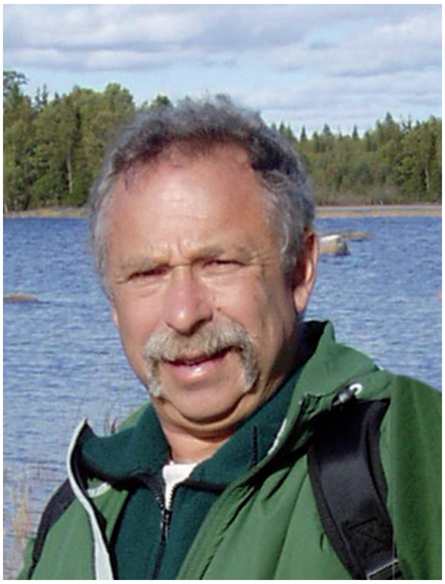
Freshwater in flux

A surprising fraction of Earth's element cycling takes place in inland waters. **Jonathan Cole** suggests that interactions between these water bodies and the terrestrial biosphere are more extensive and interesting than previously thought.

Rivers, streams, lakes, reservoirs and groundwater are increasingly being recognised as hotspots of biogeochemical activity. Collectively referred to as inland waters, these water bodies occupy just a small area. As a result, their role in the global cycling of elements, energy and matter has long been overlooked. This has changed in the past five to ten years, particularly with our understanding of the carbon cycle.

For the burial of organic carbon on the continents, lakes have emerged as hotspots. Surprisingly, the global annual rate of carbon burial in lakes has been found to be equal to or larger than that observed in the — far larger — global ocean. Unlike soil or forest biomass, with carbon turnover times of years to decades, lake sediments can endure for tens of millennia in glaciated regions, and for millions of years in deep tectonic lakes. For example, tectonic lakes in the African Rift Valley store an estimated 1,200 Pg carbon, equivalent to the total carbon inventory in terrestrial soils[1]. Furthermore, new estimates suggest that glacially formed lakes accrued around 1,400 Pg carbon during the Holocene epoch[2]. This makes lake sediments one of the largest stores of organic carbon on the continents. Artificial water impoundments — from reservoirs to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rice paddies — also accumulate carbon at high rates, on the same order of magnitude as net carbon sequestration on land. As such, carbon burial in artificial impoundments could represent a significant component of the land anthropogenic carbon sink. The mechanisms that retard or prevent more complete decomposition of organic carbon in freshwater sediments are not yet clear. We hope to learn more during the next five years.

The role of methane in supporting food webs in lakes, and perhaps even beyond their shores, has come as a surprise. Organic matter decomposition in anoxic waters and sediments of stratified lakes, especially those with low concentrations of sulphate, yields methane. In the presence of oxygen, methane serves as a source of carbon and energy for methane-oxidizing bacteria. Biogenic methane from lake sediments typically has very depleted values of ^{13}C. In the 1990s, limnologists first measured depleted values of ^{13}C in zooplankton and chironomids, a type of non-biting midge that serves as an important food source for fish. They thought that the depleted values could be a sign of the midge larvae consuming methane-oxidizing bacteria. In the past five years, we have learned that in some lakes up to 60% of the carbon biomass in chironomids comes from methane[3].

Chironomids live their larval life in sediments, but emerge as flying adults, sometimes in huge abundance. This metamorphism from aquatic to land creature sets up the tantalizing possibility that spiders, predatory insects and even insect-eating birds could potentially be subsidized by methane-consuming bacteria in lakes. Indeed, the ^{13}C signature of spiders near a lake in Germany undergoes a large seasonal shift that coincides with the hatching of lake chironomids[3]. And fish in a Brazilian lake have been shown to be depleted in ^{13}C, and to contain the same suite of fatty acids found in methane-consuming bacteria[4]. The notion that lake methane partially supports higher organisms in surrounding terrestrial environments fundamentally changes our understanding of how aquatic food webs work.

As terrestrial carbon is used in inland waters, significant quantities of CO_2 are released to the atmosphere. This carbon efflux has two implications. First, if we ignore the aquatic component of gas flux, we overestimate net carbon sequestration on the continents. Second, the magnitude of the emissions is a measure of the terrestrial subsidy to aquatic systems. Thus, dissolved and particulate organic matter that has escaped decomposition on land seems to be actively metabolized in aquatic systems and incorporated into aquatic food webs. Some of the key members of aquatic food webs, from zooplankton to benthic invertebrates and fish, bear the isotopic or fatty-acid signatures of terrestrial organic matter, indicative of at least some degree of terrestrial support. Why and how does organic matter that has been stable on land for years to centuries become available to the food web once it enters aquatic systems[5]? The idea that aquatic food webs are supported by terrestrial sources is controversial. A few scientists continue to believe that food webs, particularly in the main body of lakes, are supported entirely by primary production that occurs within the lake[6].

Out of controversy comes strong science. I expect to see a proliferation of studies using multiple independent approaches to find out how much terrestrial systems subsidize aquatic ecosystems, and vice versa. ❐

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A crowded Solar System

The last five years have seen a boom in exploration of the Solar System. **Barbara Cohen** explains that the biggest gains have been right here on Earth.

Robotic spacecraft are currently engaged in missions to Mercury, Venus, our Moon, Mars, near-Earth and main-belt asteroids, Jupiter, Saturn and its moons, Pluto, comets, and even to the very edge of our Solar System. Geoscientists around the world are working with a profusion of data that will be mined for decades to come. It has been an amazing few years, and both scientists and the public are more excited about space than they have been in a long time. Washington, however, has been a tougher nut to crack.

This past year has been rife with discussion about how the planetary science community can better communicate the value of planetary exploration and research to the public and policymakers during this time of budget cuts. But much of the public is already with us. My informal poll, asking for votes on memorable planetary achievements on Twitter and Facebook, was retweeted to reach several thousand followers. The interested, non-scientist public cited water on the Moon, the Curiosity landing on Mars and MESSENGER mission results from Mercury as their favourites — clearly demonstrating full awareness of the achievements of the planetary science community. For example, it has been noted widely that the MESSENGER mission has revealed an entire hemisphere of Mercury that had not been imaged before, showing us vast northern volcanic plains, the enormous Caloris basin, enigmatic polar volatile-rich deposits and a magnetic field that is offset far to the north of the planet's centre.

Social media has revolutionized our way of communicating planetary science to the public. Gone are the days of press releases constructed around discrete discoveries. Instead, the everyday processes of science and engineering are broadcast in a personalized manner. Bloggers have followed as US and international orbiters worked together to direct the long-lived Opportunity rover on Mars towards clay-rich outcrops at Endeavour Crater, which may contain a record of habitable conditions. Data from these same orbiters suggested that water once flowed in Gale Crater, but confirmation came when the Curiosity rover touched down on Mars this past summer and got up close to gravel-bearing deposits, evidence for water flowing hip-deep some time in Mars's past. An equally astonishing accomplishment by Curiosity was the enormous multimedia success of its landing, where promotion of the "seven minutes of terror" involved in the complex landing brought the public in, and gave scientists the chance to engage them in the scientific questions being explored.

Beyond Mars, the Dawn mission's year-long exploration of the asteroid Vesta, and Rosetta's fly-by of the asteroid Lutetia, added rich detail to our inventory of main-belt objects, complete worlds unto themselves. Vesta revealed itself as a geologically active body that underwent an amazing variety of processes to form its brecciated, grooved and crater-pocked surface. The Japan Aerospace Exploration Agency's Hayabusa mission that returned to Earth in 2010, after a slew of spacecraft malfunctions had sent it spinning off near-Earth asteroid Itokawa, was both an engineering triumph and a scientific boon that captivated scientists and the public alike. These bodies are not only of scientific interest: private organizations have targeted asteroids, both for Earth's safety by tracking potential Earth-crossing objects and economic gain by planning to exploit their natural resources.


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One of the most surprising results of the past half-decade is the detection of water on what we previously thought was a bone-dry Moon — by analyses of Apollo samples from the lunar surface, and with a bang when the LCROSS mission slammed into Cabeus crater near the Moon's south pole and observed water, along with other volatile substances. The next investigations of lunar water may not even come from a government-run space agency. It seems amazing that entire business plans are springing up around planetary missions of this scale. This includes two dozen privately funded teams competing for the Google Lunar X-prize to land a robotic explorer on the Moon by 2016.

Space science discoveries are now shared by scientists, students, educators and the general public. Using the abundance of data, citizen science efforts have taken off, where amateurs train online to map lunar craters, find Kuiper Belt objects and analyse extrasolar planets. Whether Pluto is a planet continues to be a controversy taught in classrooms, even as the New Horizons mission makes its way to Pluto and its growing number of known moons. The Cassini mission has revealed Titan's complex surface of land and lakes, but amateur observers were the first to call attention to a giant storm on Saturn and multiple instances of impacts into gaseous Jupiter. Planetary science has evolved into a unique field in which anyone with a little time and inquisitiveness can contribute.

As promising as private missions may be, stable, long-term government funding remains the largest driver of new missions and data analysis, enabling citizen science, multimedia interest and follow-on market opportunities in the private sphere. It is sometimes hard for decision-makers to understand why we spend money beyond Earth's orbit. But of course, discoveries in space and the technology developed to enable those discoveries pay dividends back to us on Earth. Examples abound of technological advances, commercial spin-offs and leaps in scientific knowledge. But beyond those, planetary science is a gateway for children and adults alike to learn about the natural world and the scientific principles that underpin it, cultivating crucial skills and knowledge for our technologically dependent society.

The public cares about our Solar System, evidenced by petitions with more than 20,000 signatures that the Planetary Society delivered in 2011 to Congress and the White House supporting space exploration in the face of a 21% cut to the Planetary Science Division at NASA. Solar System exploration is a peaceful, international and increasingly public enterprise. Scientists, citizens and entrepreneurs are eager to continue one of the greatest achievements in human history, and we want to take all of society with us. ❐

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A sensitivity to history

Questions about the sensitivity of Earth's climate to greenhouse gas forcing challenge our understanding of climate change. **Matthew Huber** looks at what we can learn from past greenhouse periods.

Predicting the climatic responses to post-industrial greenhouse gas perturbations is one of climate science's grand ambitions. A key parameter in these predictions is climate sensitivity — that is, the equilibrium temperature response to the doubling of atmospheric CO_2 concentrations. For considerations of climate change in the coming century, climate sensitivity is often restricted to feedbacks that respond quickly, such as clouds and sea ice. Model-derived estimates for this parameter range widely, from 2.1 to 7.1 °C per CO_2 doubling. Attempts to further constrain climate sensitivity typically rely on empirical calculations with historical observations of temperature and forcing; for example, CO_2 change[1]. Further constraints can be derived by comparing palaeoclimate model predictions with data from ancient climates[2,3]. Indeed, a comparison of past greenhouse proxy data with model output may be the only validation of model climate sensitivity most of us are likely to see in our lifetimes.

Two intervals, the Pliocene warm period about 3 million years ago and the early to middle Miocene about 23 to 11 million years ago, have emerged as test beds for climate models of the coming century or two. Both intervals featured atmospheric CO_2 concentrations between 350 and 450 ppmv, compared to present values of 390 ppmv. In both periods, Antarctica was glaciated — but not Greenland — and global mean temperatures were 3–7°C higher than today. Periods of extreme greenhouse warmth, such as the Cretaceous period 145 to 65 million years ago and the early Palaeogene epoch 65 to 35 million years ago, provide a glimpse of a potential distant future world, should greenhouse gas emissions continue unabated for the next century: atmospheric CO_2 concentrations higher than 1,000 ppmv, mean temperatures more than 10 °C higher than today, and the total loss of ice sheets in Antarctica and Greenland.

But, even if a perfect estimate of climate sensitivity existed for past greenhouse episodes, it would be at best an imperfect analogue for the future. It is often implicitly assumed that climate sensitivity is constant. But there is little evidence to support this assumption. If sensitivity itself depends on the current climate state or on atmospheric CO_2 levels, then knowledge of past sensitivity would be most useful in weeding out unsuccessful models, and not so much for direct estimates of future climate. Models that do not accurately simulate past climate sensitivity cannot be trusted to project future climate correctly, but blind extrapolation is also not a trustworthy approach.

In the real world, there is the complicating fact that estimates of past climate sensitivity are imperfect. Reconstructions of palaeoclimate from proxy data often require assumptions that do not necessarily hold under past, extreme environmental conditions. Or original climate signals in proxies are overprinted by later alteration — a phenomenon that has led generations of climate dynamicists to chase phantom climates along fascinating but ultimately dead-end pathways.

Taking this into account, several robust features have emerged over the past few

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years from reconstructions of greenhouse climate intervals, largely because of new proxies and new proxy records. Global mean temperatures were warmer than today, even at similar CO_2 levels; warmth was particularly pronounced in continental interiors and at high latitudes; and tropical sea surface temperatures were significantly warmer than today, but the temperature difference between the tropics and the high latitudes was more muted. The different degrees of warming at low and high latitudes resulted in shallow equator-to-pole temperature gradients, which are difficult to reproduce in numerical simulations. Intriguingly, from the viewpoint of sensitivity, greenhouse climates were often variable despite the overall warmth, and proved sensitive to carbon cycle perturbations.

It is the tropical warmth, and its effect on mean global temperature, that is fuelling most questions about our understanding of climate sensitivity. This is most evident in our understanding of the Eocene epoch, which began about 56 million years ago. Once thought to be only 4 °C warmer on average than present, current estimates of early Eocene climate incorporating the warm tropics show that global temperatures were more than 10 °C higher than today. This is incompatible with low values of climate sensitivity. But the actual value of that sensitivity is difficult to discern, because estimates of atmospheric CO_2 levels range from 400 to 4,000 ppmv. Most climate models generally require CO_2 levels of at least 1,000 ppmv to reach reconstructed Eocene temperatures, but some require over 4,000 ppmv, suggesting that the latter models may underestimate climate sensitivity.

There are a few climate periods for which both surface temperature and atmospheric CO_2 concentration changes are reasonably well constrained. The mid-Miocene is ripe for such an attempt, but tropical temperatures are largely missing. One good candidate is the Eocene–Oligocene transition 35 million years ago, for which we obtain estimates of about 5.7 °C warming per CO_2 doubling, with some large error bars. More important than those error bars, however, are the conceptual caveats. It is unclear how much of the climate change comes from CO_2-independent forcing such as ocean gateway-induced circulation changes, how much from slow feedbacks such as the initiation of ice sheets, and how much from quick changes like clouds. Separating slow and fast feedbacks and non-CO_2 forcing requires physical modelling, and consequently will only be as accurate as the current state of modelling. Alternatively, we could focus instead on the total sensitivity, but this limits the utility of the estimate for improving prediction of climate change on century timescales, and begs the question of whether the slow feedbacks that occurred across the late Eocene are relevant to future climate, as the response may be state-dependent.

A trend has emerged in the past few years towards warmer reconstructed temperatures than those produced by models at the estimated CO_2 concentrations. Our models may thus underestimate the sensitivity of Earth's climate to changes in atmospheric greenhouse gas levels. This may be due, in part, to the neglect in models of the long timescale feedbacks in the climate system. On the other hand, this systematic error could arise through forcings and feedbacks not directly related to CO_2. Clouds and aerosols are the biggest uncertainty in the modern climate system, and it would be surprising if their behaviour was more predictable in the past. The problem is that there are no proxies for clouds, and aerosols are very weakly constrained. Ultimately, we have realised that it is more difficult to identify past climate sensitivity and to use this information than we had hoped. The only way forward is a synthesis of data and models, and the rejection of invalid models. ❐

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