How the seas stimulate rainfall

Waters of the Earth

The ocean and the atmosphere have a long-lasting relationship. At the global scale, winds give the water its momentum and affect its buoyancy. The waters of the Earth are constantly trading heat and moisture with the atmosphere, and these exchanges have a big impact on where and when rainfall occurs around the world. Recent investigations have revealed just how big this impact is.

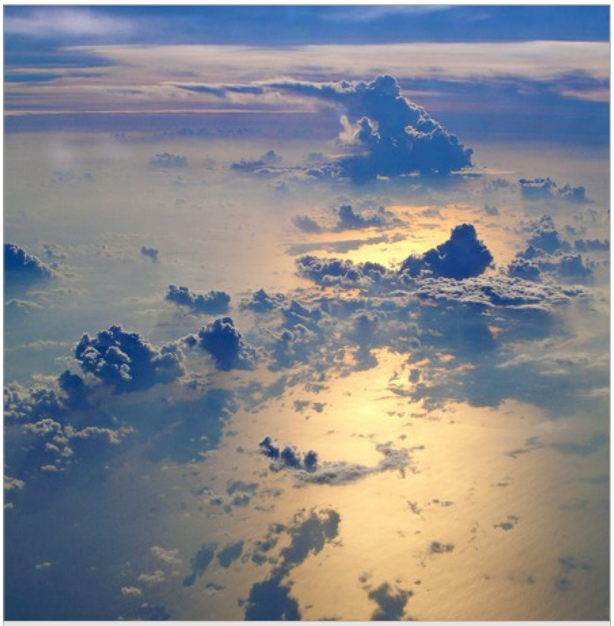
Snatching heat from the Southern Hemisphere

North and south of the equator, the same basic circulation systems are shifting air around the planet, but there are huge differences in tropical weather and climate either side of this line. To the north, it is much wetter and many countries are affected by heavy rains, particularly when the monsoon comes into season. In the past, this difference in rainfall between the Northern and Southern Hemispheres has been attributed to the amount of land vs. the amount of water either side of the equator, but there are other forces at work.

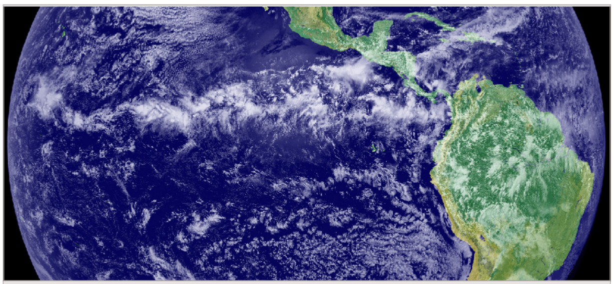
The region where the mass of rainfall forms is the Inter-Tropical Convergence Zone (ITCZ), and its position shifts with the seasons. The ITCZ snakes across the Northern Hemisphere between May and July, forming the hemisphere's wet season. The rain band shifts to the south for the southern wet season from November to February, but throughout the year there's still more rain in the north. Why?

Within the oceans, heat is redistributed via the thermohaline conveyor belt. In the Atlantic, for example, warm surface water flows north, cools, sinks and returns south at depth. This cold, deep water upwells in the Southern Ocean and warms as it flows towards the equator, where the process begins again. A recent study, led by Dargan Frierson, from the University of Washington, has revealed that this circulation system is responsible for shifting the ITCZ further north.

Frierson found that the flux of energy from the ocean to the atmosphere in the north is far higher than its southern equivalent at almost every latitude beyond 20°. The water cycle is more vigorous when there's more energy in the system, so more heat means more rainfall. But because the Southern Hemisphere receives slightly more radiation from the Sun over the course of a year than its northern counterpart, this couldn't explain why there was more heat being exchanged in the north. There had to be some mechanism taking the heat from the south and setting it free in the Northern Hemisphere – ocean circulation. Using a model of a world without continents, Frierson found that small gradients in surface heat flux from the ocean were enough to cause the ITCZ to be displaced northward, dispelling the idea that geography was the cause of the rain band's position.



The amount of moisture the atmosphere picks up over the ocean is strongly influenced by sea surface temperature. Generally, the warmer it is, the more moisture the air picks up from the ocean. This leads to greater cloud cover and an increase in rainfall. (Credit: Jorge Magalhães, distributed via imaggeo.egu.eu)



The Inter-Tropical Convergence Zone (ITCZ) is the region where trade winds from the Northern and Southern Hemispheres converge and create a low pressure area characterised by high rainfall. The location of the ITCZ varies over the course of a year and with extreme weather events, but generally lies just north of the equator. (Credit: NASA Earth Observatory/GOES Project Science Office)

The eddy effect

While it is well-known how the oceans and atmosphere interact at the global scale, what happens at the mesoscale has remained more of a mystery – especially just outside the tropics. Circular currents spanning some 10–100 kilometres in diameter are found all over the ocean. These circling masses are known as mesoscale eddies, and have an effect on the Earth's winds, clouds and rainfall.

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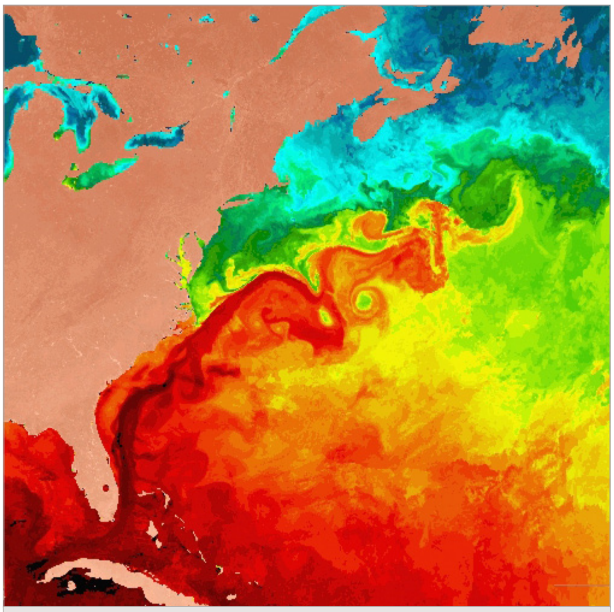

Eddies bud off large ocean currents, like the Gulf Stream, bringing packages of cold water into warmer regions and pockets of warmer water into colder regions. These 10–100 km across masses of water have a big impact on local wind and rainfall patterns. The colour is indicative of relative water temperature. (Credit: National Science Foundation/NOAA)

An eddy can be a package of warm water in an otherwise cold ocean, or a pocket of cold in the warm, and they affect the atmosphere differently, depending on their temperature.

The effect of an eddy on atmospheric circulation has, until now, been rather overlooked, as they were initially thought to be too small to have a significant impact. A group of Swiss scientists set out to solve the mystery of how eddies effect the atmosphere by looking at some 600,000 eddies in the Southern Ocean. Using satellite data, they tracked both eddies and the properties of the surrounding atmosphere, taking into account temperature, cloud cover, wind and rainfall. They found the warmer eddies in the Southern Ocean were typically 0.5°C warmer than their surroundings and the cold ones were 0.5°C colder than the water beyond. Throughout the Southern Ocean, these temperature anomalies correspond to changes in cloud cover and water content, as well as the frequency and probability of rainfall. The reason? They alter the flux of heat between the ocean and the atmosphere.

In the atmosphere, low pressure systems are the ones that generate rainfall. As these systems pass cold-core eddies, which have less heat to release, the cloud cover drops, moisture declines and rainfall reduces by 2-6%. The converse is true for warm-core eddies, which stimulate rainfall in their local vicinity.

As well as providing the fuel for rain-filled clouds, the oceans shape where rain forms and falls around the planet. The heat energy heist undertaken by the Northern Hemisphere as it harvests energy from the south drives the differences in rainfall either side of the equator. And an eddy in the ocean is all that's needed to create a small, but significant, change in the amount of rainfall close to the water mass. Combined, these studies highlight just how wonderfully connected the waters of the Earth are.

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EGU Communications Officer

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Evolution, extinction and the fossil record

Life of the Earth

Recent research suggests that the Earth is entering a biodiversity crisis and we may be on the brink of our planet's sixth mass extinction. Under these circumstances, an understanding of macroevolutionary patterns in diversification and extinction will be vital to guide conservation strategies. In a recent analysis, Barnosky and colleagues from the University of California showed current extinction rates are highly elevated when compared to background rates in the geological past. If extinctions continue at this pace, we could be seeing an event that qualifies as the Earth's sixth mass extinction (defined by a loss of at least 75% of species) in as little as 300 years from now. Fortunately, the team also discovered that it may not be too late to slow down extinction rates and avoid a catastrophic event. So far we have only lost a few percent of species, and we may be able to reduce extinction rates by targeting conservation where it is most needed, or will be most effective.

Uncertainty remains in these estimates, though. To get a clear picture of which conservation approaches could avoid a mass extinction, it is important to address this uncertainty. A huge amount of information is available on present day extinction patterns and risk factors, but this is only a snapshot of the 3.5 billion years that life has existed on Earth. To map out and truly understand macroevolutionary processes that could help us today, we have to use data from fossils, and the researchers emphasise that integration of palaeontological and present day data will be crucial. Previously, the differences between these types of data have often made it difficult

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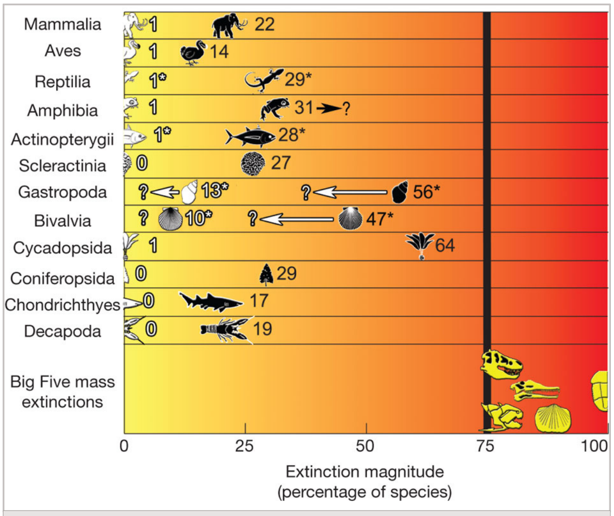
to use both of them in combination. However, advances in methods used to analyse the fossil record, and an increase in data available from ongoing collection efforts, have led to interesting insights into the interrelated factors that have shaped the diversity of life on Earth as we see it today.

In their paper, Barnosky's team outline the key complications in merging fossil and recent data, the most apparent of which is timescale. Modern data goes back a few hundred years at the most, whereas fossil data are recorded on geological timescales, and the majority of past mass extinction events are estimated to have occurred over millions of years. The apparent rate of extinction varies with the time period over which it is measured, so this is a particularly important problem to solve.

Other difficulties include the sparsity of fossil data: estimated sampling rates are around 70% for the very best preserved fossil groups, but are generally more like 10% at the most. Out of the species that we have discovered, many are in fact only known from a single specimen (and sometimes a single tooth!). Some ancient groups had high preservation potential – such as marine gastropods and bivalves – but, unfortunately, these groups have received far less research attention in the present day than larger and more easily accessible groups like birds and mammals.

Fortunately there is some hope for improving the basis for comparison, in the form of phylogenies. A phylogeny is a hypothesis of the evolutionary relationships between species, represented as an evolutionary 'tree' with branches scaled either to the time the species lived for, or the amount of evolutionary change along a branch. In a 2008 review focussing on understanding patterns in extinction, Andy Purvis summarised the progress that has been made in uncovering rates of speciation and extinction using phylogeny as a framework. He also showed how extinction patterns relate to phylogenetic relationships between species (i.e. do close relatives go extinct at the same time?), in different scenarios. Phylogeny can be used to test whether factors like the geographic range of a species or a particular physical trait correlate with extinction proneness. This is often done in present day analyses, but less so for the geological past. He finished by calling for more work in improving methods to model combined data sets in a phylogenetic framework.

In a review published last year, Graham Slater and Luke Harmon summarise innovative new methods based upon phylogeny that are being employed to help tackle some of these data comparison and modelling problems. One such method can be used to stochastically scale evolutionary trees of fossil taxa to time, and will allow palaeobiologists to more accurately estimate the timescales of evolutionary change and extinction in the fossil record. This, in turn, will enable them to make valid comparisons with the rate of events in the present day. In addition, Slater and Harmon point to several new methods that will allow researchers to develop and analyse phylogenies that include similar numbers of extinct and living species, and to more accurately model phenotypic change using fossil and living data in tandem. Further data collection by conservation biologists on the modern day groups that have the most well researched fossil records will also improve results.



Extinction magnitudes in the geological past and the present day. Numbers next to each icon indicate the percentage of species extinct. White icons indicate species 'extinct' and 'extinct in the wild' over the past 500 years. Black icons add currently 'threatened' species to those already 'extinct' or 'extinct in the wild'. Yellow icons indicate the big five mass extinctions, with a black line at the 75% benchmark for comparison. (Reprinted by permission from Macmillan Publishers Ltd: Nature, Barnosky et al., 2011)

These new methods can be used to untangle the relative importance of factors such as body size, population size and ecological specialism, so that we can begin to identify the species most at risk of extinction, and those whose survival will be most effective for maintaining biodiversity. To move forward from these advances we must incorporate them into the effort to standardise different types of data, and into developing predictive models of how different risk factors interact.

A final and particularly interesting idea to come out of Barnosky's research is that of the 'perfect storm'. Past mass extinctions often seem to have occurred during synergies of unusual events. The Earth's current changing climate dynamics, in combination with new ecological stressors like habitat fragmentation, pollution, overfishing and invasive species, may represent such a synergy. The fossil record could act as an ideal natural laboratory to formulate, model and test this hypothesis. Although the Earth has recovered from catastrophic extinction events in the past, it has never before supported 7 billion humans, and modelling macroevolutionary patterns in order to help mitigate against escalating extinction threats may be key in determining our own future as a species.

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How the Earth's atmosphere shows its face

Atmosphere of the Earth

Looking from outer space, the Earth's atmosphere appears as an encapsulating fluid that flows in patterns caused by the rotation of the planet and the heating from the Sun. Up close, however, the atmosphere shows its face in much more detail, helping researchers understand the complex interactions in the Earth system.

Temperature of the atmosphere

The temperature of the Earth is much like the temperature of a person: it is a symptom of everything else that is going on in that person's body. It may seem like a basic property of the atmosphere, but it is a product of many other aspects of the Earth system, including land and oceans.

Recently, there has been much discussion of the so-called 'temperature hiatus', the weakening of the trend in global mean surface air temperature since the late 1990s. Observations, such as those from the HadCRUT4 dataset, appear to show temperatures in the past decade rising more slowly than in the preceding two decades (see figure below).

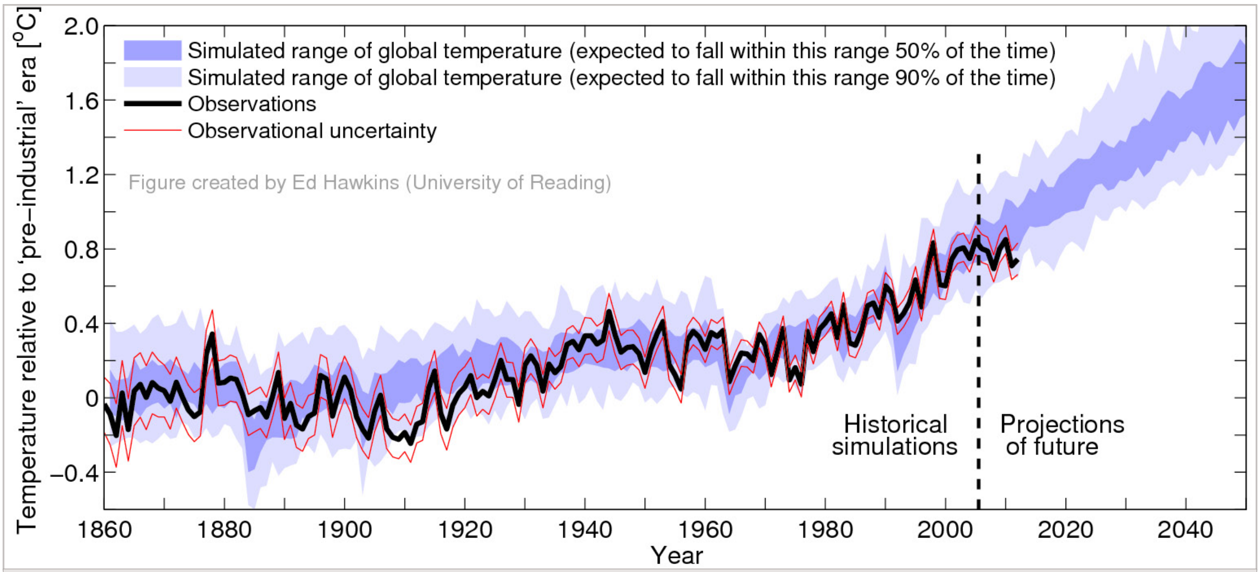
The HadCRUT4 dataset is a combination of ground-station and sea surface temperature measurements, which represent about 85% of Earth's surface. Recent analysis by Cowtan and Way has tested whether this data contains a bias due to incomplete coverage of the globe, and they conclude that it has led to an underestimate of recent global warming. The authors point out that satellite data, models and isolated weather station data show that regions not covered by the dataset, especially the Arctic, have warmed faster than other parts of the world. Accounting for this gives a trend two and a half times greater than that from HadCRUT4, for temperature since 1997.

So even establishing the magnitude of the temperature hiatus is an ongoing area of research. The range of different studies investigating the causes of it is indicative of just how many different factors affect the air temperature.

Work by Estrada, Perron and Martínez-López explores global temperature data sets and radiative forcing variables (greenhouse gases in the atmosphere, natural changes in composition and land use, and solar irradiance) using statistical techniques. Their method interrogates the data without the use of models, and the authors conclude that the temperature record and the radiative forcing (which describes whether the Earth system has a net warming or cooling) can be described by linear trends punctuated by breaks. In this picture, the hiatus is simply a period with a different trend following a break. But what caused this break to occur?

The results suggest that the predominant cause was an unintended consequence of the 1987 Montreal Protocol, the international treaty to stop the destruction of stratospheric ozone by chlorofluorocarbons (CFCs). CFCs are also greenhouse gases, so reducing them to protect the ozone layer also led to a relative cooling of the atmosphere. Pretis and Allen tested this finding in an energy balance model and found that global mean temperatures are 0.1°C cooler because of the Montreal Protocol.

Estrada and colleagues also attributed a cooling from the reduction in the methane growth rate in recent years. Methane is a potent but short-lived (about a decade) greenhouse gas, with major natural and anthropogenic sources. The amount of methane in the atmosphere had been growing in the latter half of the 20th century, until it levelled off in the period around 2000 to 2006. The cause of this stagnation is in itself an active research area, with changes



This graph of average global temperatures is generated using 42 different climate simulators, assuming 'medium' (Representative Concentration Pathway: RCP4.5) future emissions of greenhouse gases, and compares their projections to observations from the HadCRUT4 dataset. A common reference period of 1961–1990 is used, but the temperatures are presented relative to the 'pre-industrial' era. (Image and caption: Ed Hawkins, Climate Lab Book)

The dome of the Jungfraujoch atmospheric observatory in Switzerland is seen in the distance in this photo. (Credit: Michelle Cain)

to agricultural practices, variability of wetlands, and changing fossil fuel emissions being likely factors.

Others have looked to the oceans to find a cause for the temperature hiatus. Modelling work by Kosaka and Xie shows that it can also be explained by recent La Niña events. La Niña events are characterised by cooler tropical Pacific sea surface temperatures and cooler surface air temperatures. By putting observed tropical Pacific sea surface temperatures in to an atmospheric model (which also contained the observed greenhouse gas concentrations), the authors were able to reproduce the hiatus.

This is not necessarily in contradiction to the Estrada study, as Kosaka and Xie do not specify what is causing the sea surface temperatures to be La Niña-like – the cause could be linked to greenhouse gas warming. A trend towards more La Niña-like conditions since 1950, coinciding with increases in global mean surface temperature, has been identified by L'Heureux et al..

These studies illustrate some of the complex interactions between atmospheric temperature, composition and climate. If temperature is the symptom, then we have seen that the make-up of the atmosphere is one of the many causes. To complicate things further, the symptom can also feed back into the cause. For example, wetland emissions of methane depend on temperature, so a warming Arctic may cause increased methane emissions and therefore even more warming.

Composition of the atmosphere

We are finding ever more sophisticated ways of measuring the atmosphere's composition: continuous ground-station measurements, sensors attached to weather balloons, aircraft- and ship-based instruments, drones, and satellites are all used to analyse the components of the atmosphere. This array of measurements at different scales is used in combination with models to paint the clearest picture of the atmosphere possible, within current understanding.

The MACC (Monitoring Atmospheric Composition and Climate) project has done just this, by assimilating satellite data into a global model of the atmosphere to produce an 8-year data set of atmospheric composition. The data for carbon monoxide, ozone, nitrogen dioxide and formaldehyde are evaluated against independent satellite, weather balloon, ground station and aircraft observations in Inness et al., which goes on to highlight where the discrepancies lie and also indicates the direction for future work. With so much varied data to consider, this kind of large modelling study is a good way of bringing together the current knowledge of atmospheric composition.

These are just a few facets of the atmosphere, with weather patterns, climate modes, aerosol, boundary layer flows, and interactions with the surface being some of the other parts of the atmospheric system that we take interest in studying in just as much depth. It is thanks to the multitude of ways of observing and describing this encapsulating fluid we have today, that we get the atmosphere to show its face.

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Shrinking mountains

Rocks of the Earth

A cool climate may be to blame for eroding some of the world's highest summits in the past.

The silent peaks of the Himalayan mountain range pierce the cloudy Asian sky. You could be fooled into thinking this is a peaceful place, but mountains are endless construction sites. Continental plates collide and force the Earth's crust upwards while, at the same time, erosion counteracts this process by slowly weathering the planet's surface. Rivers, glaciers and landslides scour through the bedrock and move sediment back down to lower ground.

What exactly the forces at play in mountain building and destruction are is controversial. Scientists on one side argue the main influence on high altitude erosion is tectonics, which is constantly heaving sediment to the surface. Others, such as Peter Molnar and Philip England, suggested that climate is a bigger factor in the long term, wearing away mountain peaks.

Now a new study by Frédéric Herman of the University of Lausanne, Switzerland, and collaborators shows for the first time that erosion rates can speed up when the global temperature drops. "This study gives a unique contribution to one of the most intriguing debates in Earth Sciences today," says Vivi Pedersen at the Department of Earth Science, University of Bergen, who was not involved in the study.

Swings and roundabouts

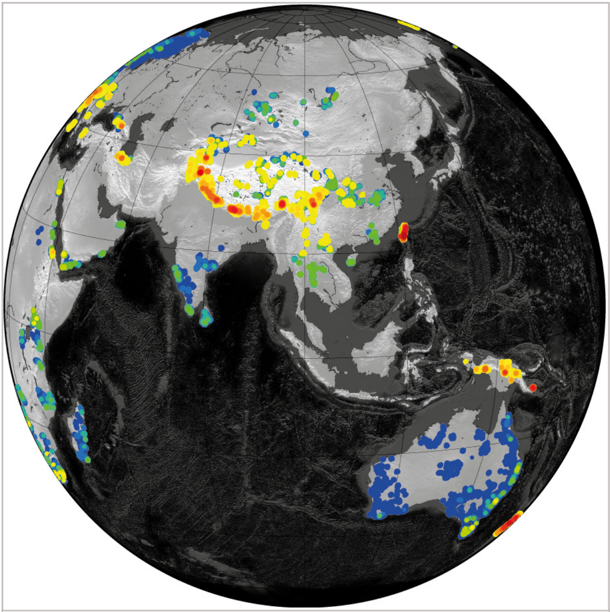
The Earth's climate naturally fluctuates between warm and cold periods. A strong cooling trend began six million years ago and, using sediment records, scientists observed a rapid increase in erosion rates around that time. In particular, since the onset of the Quaternary period some 2.5 million years ago, erosion increased dramatically by at least a factor of two.

But, until now, no-one was able to show why exactly that happened. Sudden changes have often been put down to capricious tectonic movements, but high rates of erosion followed a pattern that suggested something else. At latitudes between 30° and 50°, where glaciers and large ice sheets would have iced the continents, erosion increased significantly. This led scientists to consider the role of climate, and, particularly, the role of glaciers in mountain building and destruction.

Hot rocks

Herman and his team used the thermal ages of rocks – a technique known as thermochronology – to determine past changes in erosion rates. As rocks move away from the heat of the Earth's core, the minerals begin to cool and change. The scientists used the natural abundance of a mineral's radioactive isotope and its decay products to find how fast the rock moved towards the surface and, therefore, its age. The closure temperature – when the mineral has cooled enough to stop isotopes diffusing out of the rock – is used as the starting point. A cooling history can be found by dating two minerals (apatite and zircon) with different closure temperatures in the same rock. Age is then converted into erosion rates using a thermal model.

The glaciers of southern Tibet carve valleys in the Himalayan mountain range. (Credit: Amos Aikman)



Erosion rates between 2 Myr ago and 0 Myr ago, as determined by Herman et al. (2013). The colours represent varying degrees of erosion rate, from about 0.01 mm/yr (blue) to 7 mm/yr (red). Along mountain ranges such as Himalayas and the New Zealand Southern Alps the rates of erosion during this time period were up to four times higher than 6–4 Myr ago. (Credit: Frédéric Herman)

Map the world

The ages were then matched together in a global set. Global patterns of erosion emerged in separate plate-tectonic regions. "We found [that] erosion rates are sensitive to changes in climate even though tectonic activity always has some control," says Herman.

View of one of the peaks of the Southern Alps. (Credit: Frédéric Herman)

Eighteen thousand rock ages were used in the project – a huge job. “The course of one PhD usually identifies around 30 rock ages so we benefited from a large number of people’s work,” says Herman.

“A global signal requires a global cause, and the strong correlation found with global climate change shows that cooling is a very good candidate for the causing mechanism,” says Pedersen. “This study gives persuasive evidence for a strong link between highly variable cold climates and erosion rate, especially linked to glacial and periglacial proceses.”

Pointing to glaciers as a cause of the erosion makes sense: glaciers can scour relatively flat topography into a rugged, jigsaw-like landscape within several thousand years. The rock currently on the surface of the fjords in the New Zealand Southern Alps, for example, used to lie two kilometres deep just 2.5 million years ago – a rapid change in geological terms. However it’s not just glaciers that can have an influence. These Southern orogens – belts of the Earth’s mountainous crust – receive high amounts of rainfall, which can trigger landslides and add to the erosive action.

Missing years

But the climate versus tectonic debate does not stop here. Thermochronometry is based on the idea that a rock’s age can be converted into an erosion rate. The rocks must have been moved a couple of kilometres through the Earth before a rock age can be taken, a process that only occurs in areas where there is enough tectonic activity, such as the Alps, Patagonia and Himalaya.

Philippe Steer, who used a different method, found erosion increased by a factor of 20 during the past five million years. Even with such a huge increase, the total erosion remains too small to be detected by the technique used by Herman and his colleagues, so this study was restricted to certain parts of the world only.

“We don’t know every cycle and are only seeing one part of the signal. Therefore this study is just the tip of the iceberg,” says Herman. “We are now developing techniques to isolate shorter timescales to, say, 100,000 years.”

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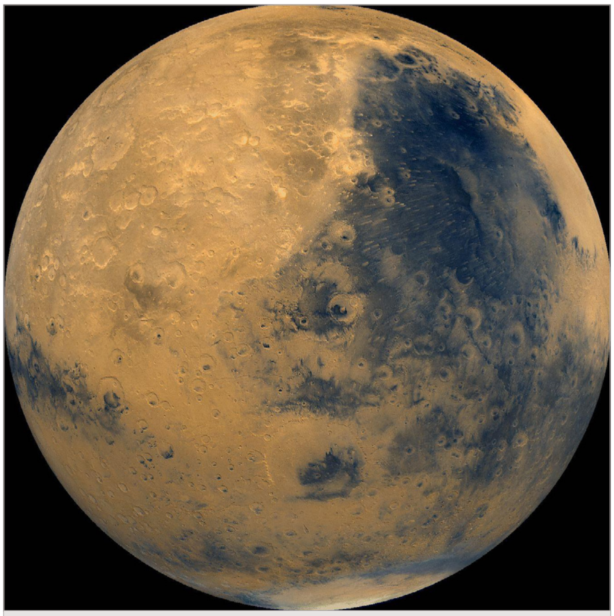
A glimpse of Mars’ early history

Space and the Earth

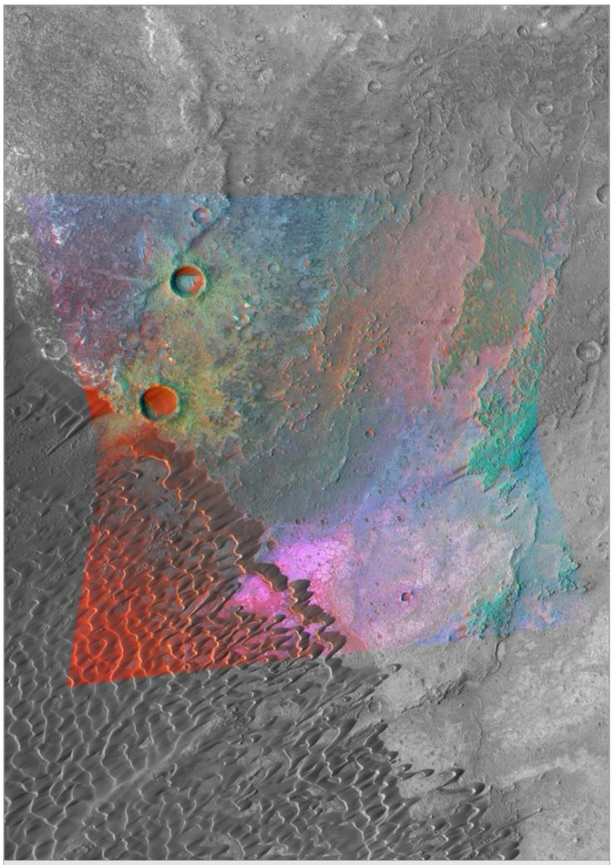
Finding increasing evidence of rocks previously thought to be non-existent on Mars sheds new light on the composition and early evolution of the planet.

Termed the Goldilocks Planet because of its ideal distance from the sun, which allows the planet to have liquid water on its surface, the Earth is also the perfect size to have maintained plate tectonics over the past 4,600 million years. Mars was likely too small to develop plate tectonics in its early years, cooling too quickly to maintain the hot core needed to power large-scale motions on the surface of the planet. Tectonics are the key to the variety of rocks we have on Earth: the tectonic system works as a giant conveyor belt that transports elements from deep within the planet up to the surface and back again. Mars, without the ability to maintain a tectonic cycle, was left with a largely basaltic composition. So, recent articles by Wray et al. (2013) and Carter and Poulet (2013) describing Martian rocks containing large amounts of iron-rich feldspar (a group of aluminium silicate minerals not commonly found in basaltic rocks) are unexpected and exciting.

In both studies, the researchers used data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter to identify the feldspars. Usually, feldspar is undetectable by CRISM, unless there are small amounts of metal such as iron within the mineral structure. CRISM detected very weak absorptions in the wavelength range typically associated with iron, but not strong enough to indicate the presence of iron-rich minerals like olivine and pyroxene common in basalt. Because of



Mars (Credit: NASA)



Mars surface as imaged by the Mars Reconnaissance Orbiter. Magenta coloured areas are high in feldspar. (Credit: NASA Jet Propulsion Laboratory)

the weak absorptions, both teams have associated the findings with extremely high levels of feldspar in the rocks, specifically iron-bearing plagioclase feldspar. Where the studies begin to differ, however, is on the identification of the host rock.

Carter and Poulet argue that the feldspar is indicative of a rock called anorthosite. The absorption spectra show an electronic transition band at 1.25 μm, which is characteristic of iron-bearing feldspar. The same band has also been detected when spectrally imaging the Earth and the Moon. The Moon has widespread occurrences of anorthosite, and the rock is also present on Earth, but in general, it is rare in the Solar System. Wray et al., although acknowledging the possibility of anorthosite on Mars, do not rule out the possibility that the presence of the feldspars could indicate rocks that contain quartz (pure silica), such as granite or dacite, or even selective hydrological weathering of other iron-rich rocks. In either case, these rocks have a significantly different (more silica rich) composition than other, typically basaltic rocks, such as those erupted by the Martian super-volcano Olympus Mons.

In the case that the feldspars do represent either anorthosite or granite, both studies are in agreement about the implications for altering our understanding of Mars' early evolution. Many silica-rich rocks on Earth, such as granite and dacite, are formed at subduction zones, or 'hotspots' (where super-hot magma from the mantle rises up below a plate and forms volcanoes, like Yellowstone) and some formed very early in the Earth's past, in the Archean, where the hot primordial Earth melted the plates at shallow depths. In all of these processes partial melting or fractional crystallisation is likely to occur, leading to the formation of silicate rocks. In fractional crystallisation of magma, minerals such as olivine and pyroxene crystallise first (forming basaltic rocks), leaving behind a silica-rich 'evolved' residue. Partial melting melts silica-rich rocks first, as these have low melting temperatures. Until now, these types of prolonged magmatic processes were not thought to have been present on Mars, but the presence of feldspar leaves open new avenues of investigation for planetary and space scientists.

In addition to needing slow magma crystallisation, the formation of granitic rocks requires the presence of water. Granitic rocks are also the core of many continents, their relative density to basalts being lighter. The possible presence of granitic rocks on Mars indicates that maybe it was not always so different from Earth: there was water present and even the possibility of a brief magnetic field.

As most of Mars is swept by winds and battered by meteorites, it is rare to get a glimpse of past processes in its early history. Currently, the quest for water on Mars tends to make the headlines, but maybe knowing more about the planet's geochemistry can help us answer this question and begin to ask some more: is Mars a 'failed' Earth and if so, what could this teach us about our own planet's future?

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