Climate change in the geological record

The geological record captures multiple episodes of climate change. Dan Lunt and colleagues report on the use of past climate-change reconstructions and modelling to better understand the dynamics of the climate system and the range of possible impacts under current warming

Even the fastest natural climatic transitions of the past were slow compared with the pace of recent changes

HUMAN-INDUCED climate change affects us all and has economic, sociological, political, and ecological consequences. In 2019, the Geological Society and the UK Palaeoclimate Society jointly convened an expert working group to produce a statement on climate change. Led by Carrie Lear (Cardiff University, UK), the statement entitled "What the geological record tells us about our present and future climate" was published in the *Journal of the Geological Society* at the end of 2020. With the aim of exploring the themes laid out in the statement, which were centred around nine key questions, the Geological Society hosted a conference, *Climate Change in the Geological Record*, in May 2021.

What does the geological record of climate change look like?

The geological record provides evidence of huge swings in past climate (as discussed in a presentation by Jess Tierney, University of Arizona, USA). The extremes range from the cold Snowball Earth conditions that were prevalent about 700 million years ago, evidenced by glacially derived dropstones and striations found in many places around the globe, to the super-warmth of the early Eocene about 50 million years ago, evidenced by crocodile fossils in the Arctic, for example. However, even the fastest natural climatic transitions of the past, such as the Paleocene-Eocene Thermal Maximum about 55 million years ago, were slow compared with the current anthropogenic aberration.

Why has climate changed in the past?

On geological timescales, tectonic, orbital, solar and greenhouse gas forcings, determine climate change, as well as feedbacks between the climate, ice sheets and CO_2. However, when these processes are incorporated into climate models with quantitative representation, it becomes apparent that the observed geological record cannot be explained without a significant role for CO_2 (Paul Valdes, University of Bristol, UK).

Is our current warming unusual?

Analysis of the geological record indicates that it has been a long time since our planet has been as warm as it is today. Recent decades were likely warmer than all other decades during the past 2,000 years and probably warmer than any sustained period since the peak of the Last Interglacial, 125,000 years ago. Darrell Kaufman (Northern Arizona University, USA) showed that the Earth system is changing rapidly: since 1900, observed global mean sea level has risen at a rate unprecedented in at

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least the last 2,500 years. Unlike previous naturally-occurring climate change, the effects of recent warming are occurring on top of other human-induced stressors, such as deforestation.

What does the geological record indicate about global versus regional change?

Drawing on examples from tropical Indian oceans during the Last Glacial Maximum 21,000 years ago, Kau Thirumalai (University of Arizona, USA) showed that clear non-linearities exist between global and regional climate, and that the geological record of past climates can provide perspective on future regional climate change and impacts. However, there is still much to learn about the mechanisms associated with past cold and warm climate states.

When Earth's temperature changed in the past, what were the impacts?

Focusing primarily on marine ecosystem change, Daniela Schmidt (University of Bristol, UK) showed that, in general, species have migrated to maintain their optimum temperature during episodes of past climate change, for example, moving towards the poles during periods of global warming. Extreme events →

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and compound events of warming, acidification, and oxygen depletion have resulted in extinction and loss of ecosystems.

How does the geological record inform our quantification of how sensitive Earth is to CO_2?

Past climates can provide important information to quantify Climate Sensitivity – a key policy-relevant metric (Anna von der Heydt, Utrecht University, Netherlands). However, some uncertainties make this challenging, such as the role of fast versus slow feedbacks, the dependence of sensitivity on background state, the degree of equilibrium in models versus the real world, and the need to account for tipping points.

Are there past climate analogues for the future?

Defining a palaeoclimate analogue as “An interval in Earth history that shares similar climatic conditions/characteristics to model simulations of future climate change”, Alan Haywood (University of Leeds, UK) presented examples where past climates can inform our understanding of future processes, for example, those associated with ice-sheet and sea-level change during the last deglaciation, atmospheric-circulation change during the Pliocene (~3 million years ago), and temperature changes during the Eocene.

How can the geological record be used to evaluate climate models?

Bette Otto-Bliesner (National Center for Atmospheric Research, USA) showed how climate models are usually evaluated by their performance compared to historical meteorological records from the last 150 years. However, comparison to the historical record does not “stress-test” the model over more extreme changes in CO_2.

Using west-east gradients in tropical sea-surface temperatures during the Pliocene, and global mean temperatures during the Late Glacial Maximum, Bette showed how data from the geological record can test model outputs under more extreme climate conditions. Bette also highlighted that geological data have perhaps their greatest potential when used to develop models, not just evaluate them.

What is the role of geology in dealing with the climate emergency for a sustainable future?

To meet targets set by the Paris Agreement, it may be necessary to actively remove CO_2 from the atmosphere. Rachael James (University of Southampton, UK) emphasised that geology can play a key role in speeding up natural processes of CO_2 removal, for example enhancing carbonate formation by injecting CO_2 into rocks containing high quantities of calcium and magnesium ions, or by enhancing rock weathering by applying calcium and magnesium-rich rocks to agricultural soil (see page 16). Rachael also noted that to meet the demand for battery storage and photovoltaics requires extraction of metals such as selenium, neodymium, and lithium – geologists clearly have an important role to play here.

Optimism for the future

Five upcoming scientists, Aidan Starr, Rebecca Orrison, Pam Vervoot, Rachel Brown, and Margot Cramwinckel, presented their exciting doctoral and postdoctoral research, supporting the Geological Society’s commitment to early career scientists.

Finally, in a plenary talk, Maureen Raymo (Colombia University, USA) presented the geological evidence for variations in the stability of the polar ice sheets and past sea-level change. During the Last Interglacial, for example, relatively small increases in temperature led to large changes in sea level. Future sea-level changes will not be the same everywhere, but the impacts will be felt from the largest cities to the smallest villages. Maureen emphasised the benefits of co-production of knowledge, whereby scientists work closely with local communities, for example when studying sea-level rise in Greenland, to aid progress and improve mitigation against the impacts of climate change. Despite the challenges we face, Maureen finished with some optimistic words for the future: Rates of change are crucial for understanding climate change in the geological record. There is hope to be gained in the recent rapid increase in the level of engagement with climate-change issues by the business community, corporate leaders and foundations, as well as governments – let’s hope that this is one rate that does continue to rise!

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