The Geological Society

# Climate change in the geological record

**26-27 May**

## What the geological record tells us about our present and future climate

By reconstructing past climate changes, we can better understand the dynamics of the climate system and hence the range of impacts possible under current warming. This symposium will address key questions about past climate change and what those past changes tell us about the future.

**#GSLClimate**

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# Climate change in the geological record

## *What the geological record tells us about our past and future climate*

## Conference Programme

### 26 May 2021

| Time | Speaker | Title |
|---|---|---|
| **14:15** | Mike Daly | President's address |
| **14:20** | Convenors | Welcome address |
| **14:30** | Paul Valdes | Invited: Why has climate changed in the past? |
| **15:00** | Aidan Starr | ECR Flash talk: Antarctic icebergs reorganize ocean circulation during Pleistocene glacials |
| **15:10** | Anna von der Heydt | Invited: How does the geological record inform our quantification of climate sensitivity? |
| **15:40** | Rebecca Orrison | ECR Flash talk: Mechanisms of South American Monsoon System response to external variability over the last millennium |
| **15:50** | Darrell Kaufman | Invited: Is our current warming unusual? |
| **16:20** | Break | |
| **16:45** | Bette Otto Bliesner | Invited: How can the geological record be used to evaluate climate models? |
| **17:15** | Pam Vervoort | ECR Flash Talk: Negative carbon isotope excursions: an interpretative framework |
| **17:25** | Maureen Raymo | Plenary Lecture: What the geological record tells us about our present and future climate |
| **18:15** | End | |

### 27 May 2021

| Time | Speaker | Title |
|---|---|---|
| **14:15** | Conveners | Welcome address |
| **14:30** | Daniela Schmidt | Invited: When Earth's temperature changed in the past, what were the impacts? |
| **15:00** | Rachel Brown | ECR Flash talk: Late Miocene $CO_2$ and climate: divorced or an old married couple? |
| **15:10** | Alan Haywood | Invited: Are there past climate analogues for the future? |
| **15:40** | Margot Cramwinckel | ECR Flash talk: Strongly reduced meridional gradients in water isotopes in the early Eocene hothouse |
| **15:50** | Jess Tierney | Invited: What does the geological record of climate change look like? |
| **16:20** | Break | |
| **16:45** | Kaustaubh Thirumalai | Invited: What does the geological record indicate about global v. regional change? |
| **17:15** | Poster talks | One minute flash talks from the poster authors |
| **17:40** | Rachael James | Invited: What is the role of geology in dealing with the climate emergency for a sustainable future? |
| **18:10** | Poster breakouts | |

# Poster presentations

| Presenter | Title |
|---|---|
| Brian Richard Lewis Catt | The Physics of Climate Systems - Cause, Effect and Observations |
| Howard Dewhirst | The contribution of fossil fuel emissions and the Pause to Global Warming |
| Ashley Francis | Comparison of warming onset timing and warming rates post-LIA using glacier, sea level and HadCRUT4 surface temperature observations |
| Thomas Gernon | Mobilization of lithospheric mantle carbon during the Palaeocene-Eocene thermal maximum |
| William R Gray | Poleward shift in the Southern Hemisphere westerly winds synchronous with the deglacial rise in $CO_2$ |
| Roger Higgs | Global warming and cooling for last 2,000 years mimic Sun's magnetic activity, not $CO_2$: scientific literature synthesis |
| Gordon Inglis | Climate-biogeochemistry feedbacks during rapid warming events |
| Amy Jewell | Reconstructing regional North African aridity through the late Quaternary |
| Olaf K Lenz | Impacts of long- and short-term climate variations during the Paleogene greenhouse on a coastal wetland in Northern Germany |
| Valeria Luciani | Biotic impact of past warm events: effects of Early Eocene Climatic Optimum on planktic foraminifera |
| Alan Maria Mancini | Calcareous nannofossils and benthic foraminifers highlight the cyclical climatic and environmental changes during the Messinian: a possible analogue for the future impact on the Mediterranean ecosystem? |
| Christopher John Matchette-Downes | Consider the Hippopotamus, and The Eemian |
| Peter Francis Owen | Cycles of Climate Change |
| Benjamin Petrick | New multi-million year records of climate change from the shelf of Australia |
| Ellie Pryor | Understanding provenance changes in sediments supplying the South East African Margin |
| James Rae | Atmospheric $CO_2$ over the Past 66 Million Years from Marine Archives |
| Tammo Reichgelt | Plant proxy evidence for terra viridis australis: high rainfall and productivity in the Australian early Eocene |
| Marci Robinson | Paleoclimate signals in Atlantic Coastal Plain sediments |
| Matthew L Staitis | Investigating Deccan-induced environmental changes, prior to the K/Pg mass extinction |
| Douwe George van der Meer | A tectonic and glacio-eustatic sea level reconstruction for the Phanerozoic |
| Aja Watkins | Using Temporal Scaling to Establish Paleoclimate Analogues |

# Climate change in the geological record

## *What the geological record tells us about our past and future climate*

## Flash talk and poster abstracts by theme

**1. What does the geological record of climate change look like?**

### Understanding provenance changes in sediments supplying the South East African Margin

Ellie Pryor* (School of Earth and Environmental Sciences, Cardiff University, Cardiff, CF10 3AT, United Kingdom), Ian Hall (School of Earth and Environmental Sciences, Cardiff University, Cardiff, CF10 3AT, United Kingdom), Morten Andersen (School of Earth and Environmental Sciences, Cardiff University, Cardiff, CF10 3AT, United Kingdom), Daniel Babin (Department of Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University, USA), Sidney Hemming (Department of Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University, USA), Jeroen van der Lubbe (Department of Earth Sciences, Cluster Geochemistry & Geology, VU University Amsterdam), and Margit Simon (NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway).
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The South African region provides abundant archaeological evidence of cultural and technological innovations of anatomically modern humans during the Middle Stone Age (MSA), 100-50ka BP. It has been widely speculated that these industries were facilitated by specific climatological and environmental conditions in this region. In order to reconstruct these MSA environmental settings, a multiproxy study is being completed utilising modern-day river sediments collected along the South East coast of South Africa (29°48.583 S - 34°18.8 S) as well as long marine sediment cores retrieved from the adjacent offshore Agulhas Current System.

Marine sediment core MD20-3591 (36°43.707 S; 22°9.151 E, 2464m water depth) which spans 450 ka was retrieved from the Agulhas Passage, ~ 150 km offshore of Blombos Cave, a key MSA archaeological site. This marine core has the potential to record both marine (Agulhas Current) and terrestrial hydrological (river discharge) variability.

During the last glacial low stand, the wide continental shelf South of Africa was sub-aerially exposed, and rivers flowed across this plain within a subdued incised valley delivering their sediments to the ocean.

Understanding the provenance of these deposited sediments could play an important role in reconstructing sediment delivery by different rivers related to terrestrial hydrology. This is of key importance for understanding transport history and characterising sediment source regions in the marine and terrestrial environment.

Here, we present initial results of the present-day radiogenic isotopic fingerprints (Neodymium and Strontium isotopes and clay mineralogy) of South African river catchment signals from river sediment samples with the aim to gain a broad spatial coverage of the source rock geology in the region and their relative contributions of terrigenous sediment delivered to the ocean. This information will be applied to MD20-3591 which likely received a significant amount of terrigenous material from the African continents via riverine input. Of particular interest is the sensitivity of the radiogenic isotopic signatures to grain size variabilities and how this relationship can help to define local vs distal sediment sources. Finer lithogenic sediments originating from more distal river catchments might be transported by the strong flowing Agulhas Current to the core site, whereas the coarser material may represent a more local signature.

These records will allow us to explore variability in regional hydroclimate in relation to the archaeological record during the MSA of southern Africa.

**1. What does the geological record of climate change look like?**

## Plant proxy evidence for terra viridis australis: high rainfall and productivity in the Australian early Eocene

Tammo Reichgelt* (University of Connecticut), David R. Greenwood (Brandon University), John G. Conran (University of Adelaide), Leonie J. Scriven (Botanic Gardens and State Herbarium of South Australia)
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During the early to middle Eocene, Australia occupied latitudes 40–70° S, as opposed to its position at 10–40° S today. Enhanced latitudinal transport of moisture, in addition to a generally more active hydrological cycle in the globally warmer early to middle Eocene world would have likely increased water supply on land and contribute to a “greener” Australian continent than today. Here, we revisit twelve plant megafossil sites from the early to middle Eocene of Australia to generate ensemble temperature, precipitation and seasonality paleoclimate estimates based on three leaf morphological proxies and one plant taxonomical paleoclimate proxy. Additionally, we compare megafossil to modern-day Southern Hemisphere leaf morphology and apply a novel approach to cross-correlate leaf morphology to net primary productivity (NPP) in order to reconstruct the vegetation type and its carbon sequestration capacity at this time. The early to middle Eocene temperature reconstructions from Australian megafloras are uniformly subtropical with mean annual temperatures of 18.9–20.3 °C, mean summer temperatures of 22.5–26.5 °C and mean winter temperatures of 13.5–16.9 °C. Precipitation was less homogeneous, with inland sites of the Lake Eyre Basin mean annual precipitation of ~600 mm and sites <100 km from the Australo-Antarctic Gulf or the Tasman Sea with > 1000 mm. Precipitation may have been seasonal, close to monsoonal, with the driest month receiving between 2–7× less precipitation as mean monthly precipitation. NPP estimates were 1100–1500 gC m-2 yr-1, which suggests much higher productivity than modern, in particular for Lake Eyre Basin and South Australia sites, where modern NPP is -200–200 gC m-2 yr-1. The most similar modern vegetation type was shown to be modern-day eastern Australian subtropical forest, although some distance from coast and latitude may have led to vegetation heterogeneity.

**1. What does the geological record of climate change look like?**

## Paleoclimate signals in Atlantic Coastal Plain sediments

Marci Robinson* (US Geological Survey), Harry Dowsett (USGS), Kevin Foley (USGS), Jean Self-Trail (USGS), Seth Sutton (University of Wisconsin - Madison) and Whittney Spivey (USGS)
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Changes in climate over millennial and longer time intervals are best observed in deep sea sediment cores where orbital resolution micropaleontologic and geochemical studies can illuminate climate extremes and their transitions. Coastal plain outcrops and sediment cores, however, can capture climate change data during warm intervals when sea levels were high in higher resolution than in deep sea cores due to high nearshore sedimentation rates. While marine coastal plain deposits are usually discontinuous, they contain excellent snapshots of extreme climate states that capture the magnitude and speed of dynamic changes in shallow water ecosystems.

We sampled marine outcrops and sediment cores from the Atlantic Coastal Plain of Virginia and Maryland, USA, for the Paleocene-Eocene Thermal Maximum (PETM), Miocene Climate Optimum (MCO), middle Miocene Climate Transition (MMCT) and mid-Piacenzian Warm Period (MPWP). Specifically, we analyzed the sedimentology, micropaleontology and geochemistry of the Paleocene Aquia Formation and Eocene Marlboro Clay in the South Dover Bridge (SDB) and Mattawoman Creek-Billingsley Road (MCBR) cores, the middle Miocene Calvert Formation in the Calvert Cliffs outcrops and the Baltimore Gas & Electric (BG&E) core, and the mid-Piacenzian Yorktown Formation in the Rushmere outcrops and the Holland Ball Park and Dory cores. Although high resolution age models are often difficult to attain from coastal plain sediments using methods based on microfossil content (i.e., biostratigraphy, oxygen isotopes) due to the paucity of desired species, we were able to generate age models for these sections by combining calibrated first and last appearances of age-diagnostic species with alkenone biomarkers, used as a tool for stratigraphic correlation.

Results from the PETM, MCO/MMCT, and MPWP include improved age models as well as estimates of sea surface temperature, relative degree of ocean acidification, productivity and sea level. We have 1) documented surface ocean warming and acidification in two discrete pulses at the PETM onset, 2) generated the first MCO and MMCT sea surface temperature data and documented extremely high primary productivity associated with the MCO along the US mid-Atlantic Coastal Plain, and 3) characterized benthic foraminifer community changes associated with the PETM, MCO/MMCT, and MPWP, leading to a better understanding of the mid-Atlantic shallow marine ecological response to different rates and magnitudes of temperature and sea-level rise. Our results show that, though discontinuous, marine sedimentary records from the Atlantic Coastal Plain contain valuable quantitative paleoecological data. These data are especially useful to better understand regional and global responses to climate change because the initial response is often first recorded on the shallow shelf.

**1. What does the geological record of climate change look like?**

## A tectonic and glacio-eustatic sea level reconstruction for the Phanerozoic

Douwe George van der Meer* (CNOOC), Benjamin J. W. Mills, Chris Scotese, Appy Sluijs, Aart-Peter van den Berg van Saparoea
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Global mean sea level variations are of interest to the earth sciences, biology, and climatology. Traditionally sea level curves have been based on stratigraphic analyses. However, the validity has remained controversial and the amplitude and time scales of global Phanerozoic long-term sea level variability is poorly constrained and does not separate tectonic and glacio-eustatic driving forces. To provide a novel method of sea level reconstruction, using an independent dataset, recently a low-frequency sea-level curve was reconstructed by estimating the effect of plate tectonics (i.e. mid-ocean ridge spreading) from the strontium isotope record. However, changes in sea level from climatologic variations in water volume (storage in land ice) were not previously incorporated. Here, we use a recent compilation for global average paleo-temperature, which was derived from δ18O data and paleo-Köppen zones. First, we estimate the volume of land ice as a function of paleotemperature and combine this with paleogeographic reconstructions. Ice thickness is calibrated with a recent paleoclimate model for the late Cenozoic ice-house. Sea level variation as a result of glaciations reaches up to 100m, similar to and at times dominant over plate tectonic derived eustasy. We superimpose the glacio-eustatic effect on to the plate tectonically driven eustasy and compare our resulting sea level curve with stratigraphically derived sea level estimates and continental flooding from paleogeographic mapping. We thereby show how both plate tectonics and climate change contribute to sedimentation in basins and therefore are critical factors for the geological record

**2. Why has climate changed in the past?**

## Mobilization of lithospheric mantle carbon during the Palaeocene-Eocene thermal maximum

Thomas Gernon* (University of Southampton), Ryan Barr (University of Southampton), Godfrey Fitton (University of Edinburgh), Thea Hincks (University of Southampton), Jack Longman (University of Oldenburg), Andrew Merdith (Universite of Lyon), Ross Mitchell (Chinese Academy of Sciences), Martin Palmer (University of Southampton)
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The early Cenozoic exhibited profound environmental change influenced by plume magmatism, continental breakup, and opening of the North Atlantic Ocean. Global warming culminated in the transient (170 thousand year, kyr) hyperthermal event, the Palaeocene-Eocene thermal maximum (PETM) 56 million years ago (Ma). Although sedimentary methane release has been proposed as a trigger, recent studies have implicated carbon dioxide (CO2) emissions from the coeval North Atlantic igneous province (NAIP). However, we calculate that volcanic outgassing from mid-ocean ridges and large igneous provinces associated with the NAIP yields only one-fifth of the carbon required to trigger the PETM. Rather, we show that volcanic sequences spanning the rift-to-drift phase of the NAIP exhibit a sudden and ~220-kyr-long intensification of volcanism coincident with the PETM, and driven by substantial melting of the sub-continental lithospheric mantle (SCLM). Critically, the SCLM is enriched in metasomatic carbonates and is a major carbon reservoir. We propose that the coincidence of the Iceland plume and emerging asthenospheric upwelling disrupted the SCLM and caused massive mobilization of this deep carbon. Our melting models and coupled tectonic–geochemical simulations indicate the release of >10^4 gigatons of carbon, which is sufficient to drive PETM warming. Our model is consistent with anomalous CO2 fluxes during continental breakup, while also reconciling the deficit of deep carbon required to explain the PETM.

**2. Why has climate changed in the past?**

## Poleward shift in the Southern Hemisphere westerly winds synchronous with the deglacial rise in CO2

William R Gray* (Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPSL)), Casimir deLavergne (LOCEAN), Robert Wills (University of Washington), Laurie Menviel (University of New South Wales), Paul Spence (University of Sydney), Mark Holzer (University of New South Wales), Masa Kageyama (LSCE/IPSL), Elisabeth Michel (LSCE/IPSL)
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The Southern Hemisphere westerly winds strongly influence deep ocean circulation and carbon storage. While the westerlies are hypothesised to play a key role in regulating atmospheric CO2 over glacial-interglacial cycles, past changes in their position and strength remain poorly constrained. Here, we use a compilation of planktic foraminiferal d18O from across the Southern Ocean and constraints from an ensemble of climate models to reconstruct changes in the westerlies over the last deglaciation. We find a 5±2° (95% CI) equatorward shift and about a 25% weakening of the westerlies during the Last Glacial Maximum (about 20,000 years ago) relative to the mid-Holocene (about 6,000 years ago). Our reconstruction shows that the poleward shift in the westerlies over deglaciation closely mirrors the rise in atmospheric CO2. Experiments with a 0.25° resolution ocean-sea-ice-carbon model demonstrate that shifting the westerlies equatorward substantially reduces the overturning rate of the abyssal ocean, leading to a suppression of CO2 outgassing from the Southern Ocean. Our results establish a central role for the westerly winds in driving the deglacial CO2 rise, and suggest natural CO2 outgassing from the Southern Ocean is likely to increase as the westerlies shift poleward due to anthropogenic warming.

**2. Why has climate changed in the past?**

## Global warming and cooling for last 2,000 years mimic Sun's magnetic activity, not CO2: scientific literature synthesis

Roger Higgs* (Geoclastica Ltd)
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Most scientists urge shifting to nuclear and/or renewable energy, amply justified by air pollution, dwindling fossil fuels and, many believe, global warming by CO2.

For the last 2,000 years Earth's average surface temperature (by proxies and post-1750 thermometers) closely matches solar-magnetic output (SMO) (ice-core proxies, sunspots, neutron detectors, magnetometers), after applying a ~100-year temperature lag. Both fell for 1,000 years from ~400AD into the Little Ice Age (LIA; ~1400-1900). Then SMO surged from ~1700AD (Maunder Minimum), the largest rise in 9,000 (sic) years, growing 130% in the 20th Century alone, reaching the strongest solar 'grand maximum' (1937-2004; peak 1991). (Contrast <0.5% parallel increase in total solar irradiance [TSI].) Temperature surged too, from the final LIA nadir ~1830 (Berkeley-HadCRUT data) to 2016, the largest warming (~1.3C) and highest peak in 2,000 years. The temperature and SMO graphs share two further characteristics, besides overall 'hockey-stick' shape: (A) multi-decadal up-down 'sawteeth', with superimposed 3-to-20-year sawteeth (longer than ENSO); and (B) surge amplitude about twice the 1,000-year decline. Three simple cross-matches confirm the ~100-year lag: (1) LIA's three coldest peaks (~1470, 1610, 1830) mimic three SMO extreme minima (~1330, 1450, 1700); (2) the Sun's 310AD peak (second-highest) aligns with a prominent ~450AD warm peak (with abundant geological-archaeological evidence for a ~3-metre sea-level rise in <100 years); (3) successive HadCRUT sawteeth cusps at 1910, 1945 and 1975 correspond to 1810, 1840 and 1890 (sunspot 30-year-smoothed chart).

In contrast CO2 has six mismatches with the 2,000-year temperature profile: (1) CO2 was trendless before its modern rise from ~1850 by industrial emissions; (2) warming began (~1830, above) before CO2's rise; (3) CO2's rise was continuous (except seasonal sawteeth [Keeling Curve] and slight decline 1940-44), unlike very punctuated warming (supra-annual sawteeth, above; 30-year coolings 1880-1910, 1945-75; pause 1998-2013); (4) CO2 has steadily accelerated from 1944, but warming has not (after its 1975 resumption); (5) the 1975-2016 warming episode had the same gradient as the previous one (1910-45), while the CO2 gradient increased fourfold; (6) the Berkeley-HadCRUT dataset includes solar frequencies, unlike CO2. Evidently, CO2 and temperature are uncorrelated.

The foregoing evidence collectively indicates that the Sun governs global temperature, consistent with Svensmark's SMO-cosmic ray-cloudiness theory. Volcanic mega-eruptions, commonest during exceptional SMO minima, augment solar-driven cooling (LIA "volcanic-solar downturns"). The ~100-year temperature lag is attributable to oceanic thermal inertia (high heat capacity, slow mixing). This 'ocean-lag', variably estimated by previous authors as 10-100 years, explains why warming persists today, despite solar weakening since 1991.

The logical conclusion is that negative feedbacks cancel CO2's greenhouse effect. A "potentially very important" but poorly constrained natural feedback acknowledged by IPCC but omitted in their climate models is rising 'BVOC' aerosol emissions from forests growing faster by enhanced photosynthesis ('CO2 fertilization'). Other IPCC climate-model errors include: assuming negligible solar influence because TSI changes are trivial (ignores SMO); and disregarding ocean lag. Further Sun-driven warming is predictable, ending ~100 years (lag) after the 1991 solar peak. Reviewers: Drs Gary Couples and Tom Moslow. Literature sources (dozens) in ResearchGate papers 348689944, 348369922, 346792725 and 332245803.

**2. Why has climate changed in the past?**

## Mechanisms of South American Monsoon System response to external variability over the last millennium

Rebecca Orrison* (University at Albany; SUNY), Mathias Vuille [University at Albany; SUNY]
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Constraints on climate variability in the Last Millennium (LM) help to define the climatic context of the current warm period. Sufficiently detailed evidence in the geologic record, such as from stable oxygen isotopes, can provide insight into both how the climate responds to external forcings as well as the influence of internal variability. On a regional scale, characterizing the range of variability is aided when paleoclimatic records can be sampled at high-density. Estimating regional climate processes and feedbacks, particularly on a relatively short timescale such as the LM is important to fill in the details of globally imhomogenous change. Moreover, some regional changes can be subtle, but important nevertheless in detailing impacts of modern global warming on regional systems. Monsoon systems, characterized by interannual changes in regional circulation and hydroclimate, are sensitive to both global external forcings and local modulation of internal variability. Understanding how they will respond to climate change will require a detailed estimation of the envelope of current variability as established during the LM.

In this work, we evaluate the modes of variability drawn from a network of stable oxygen isotope records influenced by the South American Monsoon System (SAMS), disentangling the signals that influence regional hydroclimate from those of local variability. Stable isotope proxies in South America are more spatially representative of hydroclimate than proxies strictly for precipitation, providing insight into various environmental characteristics which modulate and drive hydroclimate such as atmospheric circulation variability and changes in the regional energy budget. Though the application of a Monte Carlo Empirical Orthogonal Function (MCEOF) decomposition of a network of 14 stable isotope records from the Last Millennium, we are able to characterize the modes of regional isotopic variability associated with the SAMS. The physical underpinnings of these statistical modes are explored through comparison with spatiotemporal features of the SAMS. The first three mode of variability correspond to 1) an upper-tropospheric Rossby wave response to condensational heating over the Amazon basin during the mature phase of the monsoon, 2) the monsoon trough region and local precipitation, and 3) SAMS variability modulated by the El Niño-Southern Oscillation. Reconstructing how these modes vary through time establishes a baseline envelope of variability against which future change can be compared and highlights key processes in the system. This enhances our understanding of how different components of the SAMS may respond to future changes in internal variability and external forcings.

**2. Why has climate changed in the past?**

## Cycles of Climate Change

Peter Francis Owen* (Retired)
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The geological record demonstrates that there has never been a stable climate on Earth, based on various measurements of proxies for temperatures. In the very recent past, both temperatures, and dates have been measured accurately. Ice cores, recovered from both North and South Polar regions, are subject to dating uncertainty, both due to the coarseness of depth sampling (1m. corresponds to several hundred years) and to variations in absolute timing. In the stratigraphic record, an unusual level of chronological accuracy has been achieved from a detailed investigation of Eocene lake sediments, but further back in time the precision of dating is limited.

Analyses of the nature of the varves, and their biological content, from the sediments in Lake Messel (Lenz, et al,2011) demonstrated cyclical variations, with periods corresponding with the Schwabe, (11years), Hale (22 years), Yoshimura (66 years) and Gleissberg (84 years) cycles. A later palynological study of the sediments (Lenz. et al. 2017) found evidence of longer period solar cycles in plant populations around the margin of the lake. They were the De Vries/Suess (210 years) and the Eddy (950 years) cycles; their “Cycle 5” contains components that are close to the Bond cycle (1400 years).

For the Pleistocene, ice core sampling of 1m (corresponding to approximately 500 years) is insufficient to resolve most of the solar cycles, but the effect of the Earth’s orbital cycles is clear from them. The temperature changes recorded there precede, more often than not, the changes in carbon dioxide (Gest et al. 2017).

For the last 170 years, the HADCRUT compilation of global temperatures is the most dependable. It is possible to model those measurements closely by combining the effects of the seven solar cycles named above, and adding a factor for ENSO events over the period for which it has been recorded. Although this may be dismissed as a coincidence, a peculiarity of the model is that the amplitude of the temperature scalar for each cycle is in the same proportion to the square root of its wavelength. The match of the model is well within the quoted uncertainty of the measurements.

The conclusion to be drawn from the geological record is that the same solar and orbital cycles have dominated changes in climate for at least the last 50 million years. By comparison, atmospheric carbon dioxide has negligible influence, as is clear from the lack of correlation between ice extent and carbon dioxide in figure 1 of the “G.S.L. Scientific Statement”, 2021.

**2. Why has climate changed in the past?**

## New multi-million year records of climate change from the shelf of Australia

Benjamin Petrick* (CAU Kiel Institute of Geology), Lars Reuning (CAU Kiel), Gerald Auer (University of Graz) , David De Vleeschouwer (MARUM), Alexandra Auderset (Max Planck Institute of Chemistry), Alfredo Martinez-Garcia (Max Planck Institute of Chemistry).
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The ITF is a gateway controlling the flow of heat and salt between the Pacific and Indian Oceans and is thought to play an important role in modulating the meridional overturning circulation. However, the behaviour of the ITF across the Mid-Pleistocene Climatic Transition (MPT), is not well understood. IODP Site 1460 provides sea surface temperature (SST) and aridity (Ti/Ca) records from the west coast of Australia, spanning the past 2.5 Ma. Our records show a decrease in glacial temperatures around 1.5 Ma, and 0.6 Ma, suggesting a restriction of the ITF during these intervals. These restrictions were caused by changes in sea level during glacials. These SST drops coincide with changes in benthic d13C gradients across the Atlantic and Pacific basins, suggesting that the restriction of the ITF could have influenced the evolution of global ocean circulation. This is the first evidence of the possible influence of the ITF on the thermohaline circulation over the MPT. Newer work has also shown that there are significant changes in productivity at the site at the same time suggesting an intensification of the local Leeuwin around 900ka. Furthermore, IODP Site 1460 fits with other cores taken from IODP expedition 356, which preserve shifts in the ITF and local current systems over the last 5 Ma. These show that shifts in the ITF around 3.6-3.3 impacted the entire eastern Indian Ocean. This confirms in greater detail that changes in the ITF have an impact on a global scale. It also shows that like for the more recent changes these might have been driven as much by changes in sea level as tectonics. Finally, we hope to expand this project by reconstructing SSTs and nutrients from the nearby Coral Sea. These records should help extend our understanding of this critical area back to at least 12 Ma and help investigate the impact of oceanic changes during the mid to late Miocene in the documented loss of coral reefs. Therefore, our work has enabled us to provide a new understanding into the role of changes around Australia in global cooling since the mid Miocene.

**2. Why has climate changed in the past?**

## Antarctic icebergs reorganize ocean circulation during Pleistocene glacials

Aidan Starr* (Cardiff University), Ian R. Hall (Cardiff University), Stephen Barker (Cardiff University), Thomas Rackow (Alfred Wegener Institute), Xu Zhang (Lanzhou University; Chinese Academy of Sciences), Sidney R. Hemming (Lamont-Doherty Earth Observatory of Columbia University), H. J. L. van der Lubbe (Vrije University Amsterdam), Gregor Knorr (Alfred Wegener Institute), Melissa A. Berke (Notre Dame), Grant R. Bigg (University of Sheffield), Alejandra Cartagena-Sierra (Notre Dame), Francisco J. Jiménez-Espejo (CSIC-UGR Armilla; JAMSTEC), Xun Gong (Alfred Wegener Institute), Jens Gruetzner (Alfred Wegener Institute), Nambiyathodi Lathika (NCPOR Goa), Leah J. LeVay (IODP Texas A&M), Rebecca S. Robinson (University of Rhode Island), Martin Ziegler (Utrecht University) & Expedition 361 Science Party
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The geometry and vigour of the Atlantic Meridional Overturning Circulation (AMOC) influences global climate on various timescales. Palaeoceanographic evidence suggests that during glacial periods of the past 1.5 million years the AMOC was markedly different from today, however an absence of evidence on the origin of this phenomenon means that the sequence of events leading to global glacial conditions remains unclear. Here, we show multi-proxy evidence and iceberg trajectory model results demonstrating that northward shifts in Antarctic iceberg melt in the Indian–Atlantic Southern Ocean (0–50° E) systematically preceded deep-water mass reorganizations during Pleistocene-era glaciations, resulting in a considerable redistribution of freshwater in the Southern Ocean. This, in concert with increased sea-ice cover, enabled positive buoyancy anomalies to ‘escape’ into the upper limb of the AMOC, providing a teleconnection between surface Southern Ocean conditions and the formation of deep water in the North Atlantic. The coeval increase in magnitude of the ‘southern escape’ and deep circulation perturbations implicate this mechanism as a key feedback in the transition to the ‘100-kyr world’, in which glacial–interglacial cycles occur at roughly 100,000-year periods.

**3. Is our current warming unusual?**

## The Physics of Climate Systems - Cause, Effect and Observations

Brian Richard Lewis Catt* (Institute of Physics)
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My presentation comes in three main elements, that address your points of interest in the round, as a total system, and is intended to give some big picture context of how the physics works to the more specialist areas that geologists know best, in terms of both scale and structure, and how that may have changed in the last 50 years in particular. The system is explained and assessed in terms of the natural observations from well known proxy and direct sources.

This presentation describes, holistically, and necessarily summarily in view of the time available, the primary physical controls of the Earth’s climate system. It focusses on describing this system by applying established physics and the most well known, recent, direct and proxy data from 21st Century observations. The focus is on the last 10Ka plateau of the short warm interglacial era, and in particular using the big picture and natural data to assess the anomalies between the geological proxy data from pre-industrial civilisations and the direct measurements of the recent industrial period. The presentation comes in three inter related and inter dependent parts.

(i) The global climate system is described in macro level terms of the primary sources of energy and the major factors controlling their delivery to the surface and return to space, directly reflected and re radiated as infra red. In particular how the macro level planetary climate control system within the surface environment adjusts itself to maintain a stable equilibrium within the relatively narrow range of temperatures we observe. This will include the range of cyclic effects that the proxy record shows, the natural response to perturbations from internal end external causes, both cyclic and exceptional, that are further quantified for scale, and hence how the observed stability is delivered, and the likelihood of tipping points at the proximal extremes to today.

(ii) Within this system, the relative contribution to and cause of the various components of the lapse rate are briefly described, and how the lapse rate creates higher surface temperatures relative to space, compared to the theoretical "vacuum Earth” temperature, with particular reference to the contribution of the greenhouse effect. This includes a summary of the relative contributions of the physical mechanisms of radiation, convection and conduction to heat transport to space, as regulated by the overall control system introduced in the first section. The effects of the fundamental geological differences between Northern and Southern hemispheres on the climates of their respective hemispheres are briefly discussed, as they affect the observations in particular..

(iii) Finally, the reality of what the geological proxy temperature data from both hemispheres tells us about the recent interglacial period, its extremes, natural ranges, cycles and trends, closes with how the geological proxy data from the past compares to the direct and pervasive observations of satellites since 1979, that has made reliable and consistent temperature observations uniformly available across the entire surface of the Earth for 40 years.

**3. Is our current warming unusual?**

## The contribution of fossil fuel emissions and the Pause to Global Warming

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The question posed in the Society's latest position paper 'Is the current warming unusual?' is a curious one, because the world's average temperature, which increased markedly between 1910 and 1942 and again from 1978 to the El Niño of 1998, began cooling from the beginning of this century. This pause in warming was then interrupted by the 2016 El Niño and 2019 ENSO-IOD warming events, and the world is now in the throes of a La Niña cooling. It may be valid to claim that the 21st century contains some of the warmest days/weeks/months on record since the Industrial Revolution began, but it is misleading, as they are the temporary result of natural fluctuations in what is an overall cooling trend. The AGW conjecture that rising human CO2 emissions are causing an increase in global warming, is shown to be incorrect.

The annual increase in atmospheric CO2 appears to rise smoothly, but year-on-year fluctuations of up to 3 ppm are too large to have been caused by fossil fuel emissions, which show little-to-no change in rate over time. Such changes in rate that do occur, while large in relative terms, are much too small volumetrically to impact global concentrations..

The data examined are primarily atmospheric CO2 records from a series of world-wide measuring stations, fossil fuel CO2 emissions, from the BP Annual Energy Review 2020, and a selection of global temperature data sets kept by NOAA, UAH, CSIRO and others. Abundant geological data demonstrates that changes in atmospheric CO2 always follow temperature changes, in accordance with Henry's Gas Law, but with a variable time lag. Importantly, results of the analysis are presented in graphical form, based not on models or hypotheses, but on observations.

The IPCC once described the world's climate as a "coupled non-linear chaotic system", for which "the long-term prediction of future climate states is not possible." Yet they continue to predict catastrophes that do not happen. Despite these repeated failures of fact, western governments plan to replace fossil fuel-based energy with unreliable renewables.

The phrase Climate Change is not only a pleonasm, but is deeply confusing, because there is not one single climate, but a number of very different types, all part of a global dynamical system that is not in equilibrium, with multiple feedback processes involving several spatiotemporal orders of magnitude. Such nonlinear, nonequilibrium systems characteristically fluctuate, as witnessed from the disciplines of electronics and mechanical engineering, simple population dynamics and the stock market; where long term linear trends always overturn. With so many contributing and counteracting processes, the chance that only one of them, human CO2 emissions could be the system's mainspring, is vanishingly small, a conjecture well supported by the climate data examined. Nevertheless, the scientific view widely promulgated still appears to be that human emissions since around 1950, are fully responsible for all of the warming that has occurred since then. The data presented here indicate that this is incorrect.

**3. Is our current warming unusual?**

## Comparison of warming onset timing and warming rates post-LIA using glacier, sea level and HadCRUT4 surface temperature observations

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Surface temperature observations are used to construct global temperature averages. The different versions available are based on the same underlying station data. HadCRUT4 is selected as it has (a) the most stable change log with time and (b) is not spatially interpolated. For consistency with CMIP5 climate models, output is used up to 2011.

HadCRUT4 time series can be roughly characterised into four time intervals defined as general trends. These are: neutral or slightly cooling 1852 - 1910; warming 1910 - 1945; neutral or slightly cooling 1945 - 1980 and stronger warming 1980 - 2011. The onset of modern warming is circa 1900 - 1910. The ratio of the warming rates of the two periods is 1.5x.

CMIP5 (and CMIP6) climate models respond only to imposed prior forcing curves as a function of time which are used as inputs. The net forcing follows the same trend pattern described above for HadCRUT4. Like HadCRUT4 the climate model forcing input and resultant temperature output also show the onset of warming from about 1900 - 1910. The ratio of average net forcing 1975-2005 to 1910-1945 shows the later period is modelled with 3x the net forcing of the earlier period and this is also evident in the resultant climate model temperature output. There is therefore a factor of two discrepancy between modelled and observed warming rates.

Two other direct physical measurements are sensitive to temperature: global sea level (SL) and glacier length (GL) data. Using the SL dataset of Jevrejeva (2014), the ratio of the SL rate for the two C20th warming periods is 1.3x, consistent with HadCRUT4 observations but not with climate models. The onset of the linear SL trend commences in 1856, but a cross-correlation of the rate of change of the SL data and HadCRUT4 (30 year slope, 100 year window) gives a cross-correlation peak of R=0.91 with a lag of 16.3 years. Adjusting for this lag, the observed onset of SL rise would require the onset of a temperature trend no later than about 1840. This finding contradicts both HadCRUT4 and the climate model results.

Glacier data is based on the comprehensive and exhaustive dataset of Leclercq et al (2014) and the temperature reconstruction of Leclercq and Oerlemans (2011). The L&O2011 temperature reconstruction from GL data shows glacier response to a warming trend to have started no later than 1850 and potentially as early as 1833. The ratio of the GL derived warming rates for the two C20th century periods is 1.4x, close to the temperature observations but also contradicting the climate model results.

Finally, the glacial retreat timing is also consistent with the Arctic sea ice reconstruction of McKay &Kaufman (2014) which shows a likely warming onset 1810 - 1820. Arctic sea ice is expected to be very sensitive to temperature changes and would be expected to have a more sensitive/earlier response time than the glacier database which average around tor=60 years.

**3. Is our current warming unusual?**

## Consider the Hippopotamus, and The Eemian

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This presentation discusses the previous and warmest of the current 100Ka series of ice age cycle interglacials, the Eemian, in the context of the entire series of 41Ka and 100Ka period ice age cycles over the last 3Million years. The discussion will relate this event to the current Holocene interglacial, that is nearing its probable end, to assess how anomalous the current interglacial is in terms of past interglacials, and what the Eemain can tell us about the natural operation of the climate system.

The detail of the natural reality is presented in terms of the direct geological observations, the available proxy climate data, and, in particular, the actual flora and fauna of Northern Europe during the Eemian is discussed, relative to today.

The records presented include the well known and tested ice core and other proxy temperature indicators, also other ice core data, including carbon dioxide levels throughout the periods discussed, also the changes observed in the overall climate in terms of the range and rate of change in global temperature observed in the record over the studied time.

In conclusion the presentation reviews the stability of the planetary control system under the known range of natural conditions that have applied, and the apparent role of CO2 in this, which is then contrasted with the recent observed change during the industrial period of the Holocene. This poses interesting questions for discussion as regards the reality of tipping points suggested as an existential threat, the actual relationship between surface temperature and changing CO2 levels, and the actual observed extent of the anomalies between today's temperature change and that of other interglacials. In particular the Eemian, when Hippos and Elephants were native to the rivers of Northern Europe, and Lions roamed the riverbanks.

**4. What does the geological record indicate about global v. regional change?**

## Strongly reduced meridional gradients in water isotopes in the early Eocene hothouse

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Projections indicate that together with global warming of Earth's climate will come an increase in global mean precipitation and extreme precipitation events. While these changes are critical for both human societies and natural ecosystems, large uncertainty exists on the specific shifts in regional and seasonal rainfall patterns in the future. While the general paradigm holds that "wet areas gets wetter, dry areas get drier" under higher global temperatures, the warm Miocene and Pliocene instead seem to record increased precipitation in the arid subtropics. Here, we contrast this to hydrological cycling during the warm early Eocene, characterised by $CO_2$ levels and temperature distributions similar to those expected for 2150 under high emission scenarios. We employ water isotopes of precipitation (δD, $\delta^{18}O$) as a means of tracking the dynamics of the hydrological cycle. Specifically, we present a new compilation of late Paleocene – early Eocene (LPEE) δD of precipitation, based on newly generated and compiled data of δD measured on fossil leaf wax n-alkanes. In line with earlier work, our preliminary results indicate a strongly reduced meridional gradient in δD of precipitation over land, with much less depleted high latitude precipitation than at present. Regional variability is high in the subtropical band, which is interesting in light of the proposed wet-wetter, dry-drier hypothesis and Miocene-Pliocene reconstructions. In order to interpret our proxy-based δD patterns and meridional gradient in a mechanistic sense, we employ early Eocene simulations using the water isotope-enabled Community Earth System Model version 1.2 (iCESM).

**4. What does the geological record indicate about global v. regional change?**

## Reconstructing regional North African aridity through the late Quaternary

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North Africa is home to millions of people living in nation states considered to be particularly vulnerable to anthropogenically-driven climate change. The region is very likely to warm over the 21st Century but there is fundamental disagreement among model projections about the magnitude, and even sign, of the rainfall climate response. Geological records of wind-blown Saharan dust accumulating in marine sediment cores in the North Atlantic Ocean provide a way to assess the response of North African rainfall climate to past changes in global climate.

Dust is transported to the North Atlantic Ocean from North Africa via two main routes, a summer (northern) route and a winter (southern) route. Virtually everything we have learnt so far from marine sediment cores about North African hydroclimate comes from drill sites located beneath the summer (northern) dust plume. Here we report high resolution geochemical records (radiogenic isotope ($^{87}Sr/^{86}Sr$ and eNd) and XRF core scanning) from ODP Site 662 in the eastern equatorial Atlantic. We show that ODP Site 662 is ideally situated to study the palaeo-history of the winter dust route and present records of winter dust provenance for the last glacial cycle.

Comparison of our late Holocene data to the geochemically fingerprinted preferential dust source areas (PSA) of North Africa (Jewell et al., 2021, EPSL) shows that the central PSA is the main source of terrigenous material to the winter plume today. The central PSA encompasses palaeolake Megachad and the Bodélé Depression, Earth's most productive dust source today. Large downcore excursions in radiogenic isotope composition of the silicate fraction at Site 662 show that the contribution of these central Sahelian palaeolakes varied on precessional timescales over the last glacial cycle. Minima in dust supply from these sources are suggested for all the insolation maxima of the last 100 kyrs, signifying palaeolake high stands even when insolation forcing was comparatively modest. Our results shed new light on the provenance of dust supply to the North Atlantic Ocean and on the linearity and regionality of the response of African hydroclimate to insolation forcing.

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

## Climate-biogeochemistry feedbacks during rapid warming events

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Anthropogenic warming is expected to trigger a cascade of terrestrial biogeochemical feedbacks, which may weaken or strengthen the global temperature response. Warming is expected to enhance methane emissions from wetlands, resulting in further warming. However, this feedback was not fully assessed in the Intergovernmental Panel on Climate Change Fifth Assessment Report.

The geological record can act as a platform to explore these changes and to provide insights into the known (and unknown) biogeochemical feedbacks that may operate in the future. Here we employ a novel geochemical approach to study wetland methane cycling during the most rapid warming event of the last 66 million years (the Paleocene-Eocene Thermal Maximum; ~56 million years ago). Our results confirm a major perturbation of the methane cycle during the onset of the Paleocene-Eocene Thermal Maximum. If some of this methane escaped into the atmosphere, it would have led to additional planetary warming. Intriguingly, elevated methane cycling does not persist into the early Eocene, despite evidence for high temperatures. This suggests it is the onset of rapid global warming that is particularly disruptive to methane cycling in wetlands, a finding that is particularly concerning given the rapid global warming we are experiencing now.

More information: https://doi.org/10.1130/G48110.1

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

## Impacts of long- and short-term climate variations during the Paleogene greenhouse on a coastal wetland in Northern Germany

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A number of studies is devoted to the effects of the recent rise in $CO_2$ in the atmosphere and the resulting rise in global temperatures on plant communities because they act as important sources and sinks for $CO_2$. However, long-term effects of present global warming on plant communities on timescales beyond those covered by the human record of the last few centuries are still a matter of speculation. Since long-term greenhouse periods and short-term warming events occurred repeatedly in the history of the earth, they may be the subject for detailed studies on the reaction of plant communities to global warming on different timescales. The Early Eocene Climatic Optimum (EECO) and its superposed short-term warming events such as the Paleocene-Eocene Thermal Maximum (PETM) represent the last greenhouse period before today which is especially suited for comparisons to the presently developing greenhouse since fauna and flora had reached an evolutionary state already similar to today.

The sedimentary succession of the former Helmstedt Lignite Mining District in northern Germany, which includes the upper Paleocene to lower Eocene Schöningen Formation and the middle Eocene Helmstedt Formation, covers the entire Paleogene greenhouse phase and its gentle demise almost continuously in an estuarine situation at the southern edge of the proto-North Sea. Due to the interaction between changes in sea level, salt withdrawal in the subsurface and climate-related changes in runoff from the hinterland the area was subject to frequent changes between marine and terrestrial conditions, repeatedly leading to peat formation. Today, such near-coastal wetlands play a major role in the global carbon cycle by storing large quantities of terrestrial organic carbon but also as a primary source of methane emissions to the atmosphere. Therefore, peatlands are likely to contribute significantly to the future balance of greenhouse gas emissions. The more than 200 m thick succession of the Helmstedt Lignite Mining District with 13 up to 15 m thick lignites offers the rare opportunity to study Paleocene–Eocene near-coastal ecosystems and to trace the effects of long- and short-term climate perturbations on the diversity and composition of the plant communities across 10 million years during the Paleogene greenhouse. As far as known, the succession at Schöningen is worldwide unique due to the completeness of the record in time. The aim of an ongoing project is to study the response of the vegetation in this paralic environment to the long-term event of the EECO but also to short-term events such as the PETM by making use of pollen and spores as proxies. A new robust stratigraphic framework for the succession is based on a combination of biostratigraphy and eustatic sea-level changes. It now allows for an exact correlation of distinct carbon isotope excursions in the bulk organic matter $\delta^{13}$CTOC record to the individual thermal events.

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

## Biotic impact of past warm events: effects of Early Eocene Climatic Optimum on planktic foraminifera

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The Early Eocene Climatic Optimum (EECO; ~ 53-49 ma) impacted planktic foraminiferal assemblages significantly with at least three different aspects. A first major change includes the turnover between two dominant genera, the mixed-layer symbiont-bearing Morozovella and Acarinina. This turnover occurred rapidly at multiple sites from diverse latitudes (Atlantic and Pacific Oceans, Tethys) near the onset of EECO and very close to the “J” carbon isotope excursion (CIE). Specifically, the abundance and diversity of *Morozovella* decreased significantly and permanently while *Acarinina* concurrently increased in abundance and diversity. Second, a reduction in morozovellid test-size occurred across EECO as recorded from Atlantic ODP sites 1051, 1258 and 1263. Several potential stressors may explain both the reduced size and the permanent morozovellid decline. These include algal photosymbiont inhibition (bleaching), increase in temperature, decrease in pH and/or calcite saturation state. Even though a bleaching test at Site 1051 revealed only a transient reduction of algal-symbiont relationships just after the morozovellid abundance decline, a general reduction in $\delta^{13}C$ gradient (~ 0.5 ‰) between morozovellids and the thermocline dweller *Subbotina spp.* through the EECO is recorded from the Atlantic sites. This suggests that the former group became less reliant on photosymbionts and/or may have moved to slightly deeper depth in the mixed-layer. Third, the coiling direction of *Morozovella* species switched from predominantly dextral to mostly sinistral within the EECO, slightly after the K/X CIE. This coiling switch is recorded at the three aforementioned Atlantic sites and at the tropical Pacific Site 1209 (unpublished data) and may be somewhat related to the morozovellid decline. Stable carbon isotopes on numerous sinistrally and dextrally coiled morozovellids (that may represent cryptic species) from the Atlantic sites show that sinistral morphotypes typically have lower $\delta^{13}C$ values. The dominance of sinistral morphotypes that survived, though in low abundance, at the expense of dextral forms within EECO, coupled with the lower $\delta^{13}C$ signatures of the former, suggests that the sinistral morphotypes were less dependent on their photosymbiotic partnerships and thus able to tolerate paleoceanographic changes. Preliminary Mg/Ca data from Site 1263 reveal that *Morozovella crater* and *M. subbotinae* record a major warming across EECO, and more than that of *Acarinina coalingensis* and *A. soldadoensis*. Increased temperature is considered a primary cause of bleaching in present tropical larger benthic foraminifera. The higher rise in temperature recorded by morozovellid may explain the reduced symbiotic relationship and one reason for their reduction in abundance and size, even though other potential stressor such as pH decrease should be explored. The virtual disappearance of the genus *Chiloguembelina* at the EECO beginning in the Atlantic Ocean is an additional evidence of the environmental stress induced by the ECCO interval. A combination of reduced food supply, increase in thermocline temperature and oxygen content within the oxygen minimum zone may explain the decline of chiloguembelinids in the early EECO.

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

## Calcareous nannofossils and benthic foraminifers highlight the cyclical climatic and environmental changes during the Messinian: a possible analogue for the future impact on the Mediterranean ecosystem?

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Huge anthropogenic CO2 emissions are altering the global biogeochemical cycles resulting in an increase in the global temperature, that are expected to severely impact the marine ecosystem.

The marginal basins and restricted marine conditions are characterised by more fluctuating environmental parameters compared to the open ocean, making them an excellent case study for better constraining the timing and magnitude of the climate change and its impacts on the marine biota. In this perspective, the Mediterranean Neogene sedimentary succession represents an excellent record of the  past climatic changes. The impact of the current rising temperature on the marine ecosystem could be constrained from the geological record analysing time interval characterised by similar pattern. The Messinian, with warmer sea surface temperature compared to the present, may represents an ideal candidate for this purpose, and a possible analogue for the near future impact scenarios of the Mediterranean sea.

Here we present the calcareous nannofossil and benthic foraminifers response (changes in the assemblage, absolute abundance and morphometry) to the climatic variation recorded in the Messinian sediments of the marginal basin of Sorbas (S-E Spain) and spanning a 25 kyr long time interval preceding the inception of the Messinian Salinity Crisis (~ 6 Ma). Our aim is to better constrain the environmental changes associated with climatic instability and suggests possible future impacts scenario on the Mediterranean ecosystem.

Variation in the Earth orbital parameters, mostly precession ($\simeq$ 21000 yrs), resulted in the deposition of quadripartite sedimentary cycles composed of organic rich marls (e.g. sapropel) and diatomite sandwiched between massive marls; each lithology was characterised by peculiar micropaleontological content, reflecting the environmental condition at the time of its deposition.

The sapropel deposition were triggered by enhanced primary productivity in the water column starting at the precession maxima (insolation minima); this resulted in an increase in the organic carbon rain to the sea floor and to the establishment of bottom anoxia and the consequent organic carbon preservation in the sediments. The upper part of the sapropel records a progressive shift toward a warmer/humid climate (insolation maxima); at this time, the bottom anoxic condition was maintained by relatively high productivity and export from the deep photic zone, where a Deep Chlorophyll Maximum (DCM) was established. When the temperature and the freshwater input started to decrease, a weakening of the export to the bottom from the DCM occurred, restoring bottom oxygenated conditions and promoting the deposition of massive marl. This study highlights the ecosystem response to the cyclical climatic variation that occurred in a context which was warmer than today. Our study reveals that the rising temperature characterising the actual climate change may lead to a deoxygenation and to an increase in carbon burial in the Mediterranean marginal basins. This feedback in response to the rising temperature will significantly impact the Mediterranean ecosystem, especially the benthic one.

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

## Investigating Deccan-induced environmental changes, prior to the K/Pg mass extinction

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~66 million years ago, the Earth experienced two major events – the Chicxulub bolide impact and the eruption of the Deccan Traps Large Igneous Province. Whereas the Chicxulub impact is widely implicated as the main driver of the Cretaceous-Paleogene (K/Pg) mass extinction, the exact environmental and biotic impacts of the preceding Deccan trap volcanism require further research focus. My MScR research project will use paired planktic and benthic trace element (B/Ca, Mg/Ca) and stable isotope ($\delta^{11}B$, $\delta^{18}O$, $\delta^{13}C$) analyses to quantify the changes in climate and carbonate chemistry (related to ocean acidification) during the Late Maastrichtian Warming Event (LMWE) at ODP 1262. I will investigate; (a) whether ocean acidification occurred during the Late Maastrichtian Warming Event (LMWE), (b) the magnitude of temperature changes that occurred during the Latest Maastrichtian, and (c) if similar trends in $\delta^{18}O$ and $\delta^{13}C$ occurred in both the surface and deep ocean during Late Maastrichtian Warming Event (LMWE) in ODP 1262 samples. I anticipate: (1) a positive correlation when the new B/Ca and $\delta^{11}B$ data are compared to established % CaCO3 records, but a negative correlation when compared to established Fe intensity records at ODP 1262. (2) A positive correlation between the new Mg/Ca trace element data and the established $\delta^{18}O_{Benthic}$ record at ODP 1262. (3) A positive correlation between both the planktic and benthic $\delta^{18}O$ and $\delta^{13}C$ records at ODP 1262. The results of my research project will contribute to improving our understanding of the environmental response to Deccan volcanism, prior to the K/Pg mass extinction.

**6. How does the geological record inform our quantification of climate sensitivity?**

## Late Miocene $CO_2$ and Climate: divorced or an old married couple?

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Earth's climate cooled markedly during the Late Miocene (12-5 million years ago, Ma) with far-reaching consequences for global ecosystems, but the mechanistic driving forces of these changes remain controversial. A major obstacle to progress is the uncertainty over the role played by greenhouse gas radiative forcing. Here we present a new record of carbon dioxide (CO2) change for the interval of most rapid cooling, the Late Miocene Cooling (LMC) event (7 to 5 Ma) based on the boron isotope composition of planktic foraminifera. Our record suggests that CO2 declined by ~100 ppm over this two million year-long interval to a minimum at ~5.9 Ma. Comparing our record of radiative forcing from CO2 with a new record of global mean average surface temperature change and after accounting for non-CO2 greenhouse gasses and slow climate feedbacks, we estimate Equilibrium Climate Sensitivity (ECS, global mean surface temperature change for a doubling of CO2) to be 3.9˚C (1.8-6.7 ˚C at 95% confidence). We conclude that changes in CO2 and climate were closely coupled during the latest Miocene and that ECS was within the range of estimates for the Pliocene, Pleistocene and the 21st century as presented by the Intergovernmental Panel on Climate Change (IPCC).

**6. How does the geological record inform our quantification of climate sensitivity?**

## Atmospheric $CO_2$ over the Past 66 Million Years from Marine Archives

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Throughout Earth's history, $CO_2$ is thought to have exerted a fundamental control on environmental change. Here we review and revise CO2 reconstructions from boron isotopes in carbonates and carbon isotopes in organic matter over the major climate transition of the last 66 million years. We find close coupling between CO2 and climate throughout the Cenozoic, with peak CO2 levels of ~1,500 ppm in the Eocene greenhouse, decreasing to ~550 ppm in the Miocene, and falling further into ice age world of the Plio–Pleistocene. Around two-thirds of Cenozoic CO2 drawdown is explained by an increase in the ratio of alkalinity to dissolved inorganic carbon, likely linked to a change in the balance of weathering to outgassing, with the remaining one-third due to changing ocean temperature and major ion composition. Earth system climate sensitivity is explored and may vary between different time intervals. The Cenozoic CO2 record highlights the truly geological scale of anthropogenic CO2 change: Current CO2 levels were last seen around 3 million years ago, and major cuts in emissions are required to prevent a return to the CO2 levels of the Miocene or Eocene in the coming century.

**6. How does the geological record inform our quantification of climate sensitivity?**

## Negative carbon isotope excursions: an interpretative framework

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Climate sensitivity is the greatest uncertainty in future climate predictions. Natural CO2-release events of the past with evidence of simultaneous global warming offer crucial insights into the CO2-temperature relationship at that time and help narrowing down the uncertainty. Precise, high-resolution paleo-CO2 reconstructions are however difficult to obtain. Beyond the age of ice-cores, negative carbon isotope excursions (nCIEs) in sedimentary records can be used to identify episodes of carbon release and the nCIE magnitude and duration inform us about the associated mass of carbon release, assuming the carbon source and its isotopic signature are known. A simple isotopic mass balance equation often serves as a first order estimate for the mass of carbon input, but this approach ignores the effects of negative carbon cycle-climate feedbacks. Plus, translating the mass of carbon input into an estimate for atmospheric CO2 change is not straightforward due to intricate feedbacks related to ocean circulation and carbonate chemistry.

We present a framework of 432 carbon release experiments in an Earth system model that includes the impacts of ocean circulation, carbonate compensation, and terrestrial weathering on atmosphere-ocean carbonate chemistry. The framework is a tool to interpret geologic nCIEs with sizes ranging from 0.5 to 6.0‰ and onset durations between 12.5 and 225 kyr. In combination with other environmental constraints such as temperature or ocean pH, the mass and source of carbon release and the subsequent change in atmospheric CO2 can be reconstructed. For instance, a nCIE of 1.0‰ associated with an increase in sea surface temperature of 0.8°C with an onset duration of 12.5 kyr requires 1,250 Pg of organic (-22‰) carbon, resulting in a maximum rise of ~310 ppm CO2. On timescales greater than thousands of years, long-term negative carbon cycle feedbacks play a notable role in the removal of carbon from the atmosphere during CO2-release events. The relative rise in CO2 and the impact on global surface temperature, surface ocean pH and saturation state decrease with the nCIE onset duration. E.g. a 1.0‰ nCIE over 50 kyr requires 250 Pg more organic carbon but results in atmospheric CO2 90 ppm lower, and 0.3°C colder surface temperatures than the shorter nCIE. The framework can thus not only be utilized to estimate paleo-CO2 rise associated with a nCIE, but also to better constrain the duration of a geologic event with additional constrains on environmental changes.

**7. Are there past climate analogues for the future?**

## Using Temporal Scaling to Establish Paleoclimate Analogues

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It is commonly thought that one major barrier to establishing and using paleoclimate analogues for contemporary climate change is that the rate of contemporary climate change is unprecedentedly high. On this basis, many think that we need to restrict the use of paleoclimate analogues to drawing analogies independent of rates of change. However, others have argued that the conclusion that past and present rates are disanalogous is erroneous, as it does not take into consideration the dependence of rates on the durations over which they are measured. By using a process called "temporal scaling," we can adjust rates measured over vastly different durations to be comparable. If we do so, then past and present rates can be more adequately compared, and we may find that past rates are more similar to present rates than previously thought, as is suggested by some data.

This talk has two aims. First, I explain why temporal scaling is necessary for testing whether the rates of particular past episodes of climate change are analogous to rates in the present. In general, rates are not independent from the durations over which they are measured, but there is a precise inverse relationship between rates and durations (longer durations produce lower rates, and vice versa). This relationship applies in all cases where rates are nonconstant, including rates of climate change, as well as sedimentation, speciation/extinction, precipitation, and more. Luckily, we can use this relationship to extrapolate from measured rates to what the rate would have been if measured over a higher or lower duration. In the context of establishing paleoclimate episodes, this will either involve scaling paleoclimate rate data (necessarily measured over long durations due to the low temporal resolution of the historical record) to shorter durations, comparable with the durations over which contemporary data are measured, or scaling contemporary rate data to longer durations, comparable with the durations over which we collect paleodata.

Second, I give two recommendations for climate scientists who are interested in using paleoclimate analogues to draw conclusions about the trajectory or effects of contemporary climate change. Knowing that temporal scaling is necessary to compare rates, as will have been established in the first half of the talk, is not sufficient for telling us how to use temporal scaling in this way. Specifically, the particular duration over which rates should be compared is underdetermined. I will argue that choosing a duration primarily depends on our purposes; different sorts of climate projections are more or less useful over particular timescales. Consequently, I give two recommendations: (1) that researchers choose a useful time duration over which to establish analogy with paleoclimatic change, and (2) that researchers use this same time duration consistently when making projections. For example, if researchers determine that projections are useful only over fifty-year time scales, then they will need to first use temporal scaling to look for paleoclimatic episodes that are analogous over fifty-year time scales, and then use those paleoclimate analogues only to make projections over fifty-year time scales.