Session: 07 - Informing the Future by Understanding the Past

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Since the 1960s, scientific understanding of our global environment and its climate has undergone a remarkable transformation. We are now increasingly aware that the world around us is dynamic, and quasi-stable only in the short-term. Recognizing the challenge of human-induced climate change, the World Meteorological Organization and the United Nations Environment Program established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to assess our understanding of the scientific basis of risk of climate change and opportunities for adaptation and mitigation. Since this time, the IPCC has reported a scientific consensus of the latest findings; the most recent Fourth Assessment Report (AR4) was released through 2007. The conclusions in AR4 are startling: by 2100 global temperatures are estimated to increase between 1˚ and 6.5˚C compared to 1990, accompanied by a sea level rise of 20 to 60 centimeters (IPCC, 2007). Worryingly, the AR4 estimates already appear conservative (Rahmstorf et al., 2007; Pfeffer et al., 2008), largely because of increasing greenhouse gas emissions and uncertainties in the sensitivity of the Earth system to changes in radiative forcing. The AR4, however, identifies a number of areas where significant improvements can be made, many of which are the result of short (historical) records. Palaeoclimate data can address this issue, extending historical records and providing critical insights into the climate system, thereby reducing uncertainty of future change (Schrag and Alley, 2004). Our session **'Informing the Future by Understanding the Past'** was developed to report the latest findings in palaeo research and how it might best inform the future.

Past periods may not be complete analogues for anthropogenic-driven climate change, but the mechanisms that operated at different times can provide analogues of climate processes ('process analogues') for the future and provide excellent tests of climate models. By the end of this century, the Earth will experience radiative forcing not seen for tens of millions of years. The rate of warming is unprecedented, with past gradual warming often triggering more rapid warming. Past warm climates are often linked to significant disruptions to the biosphere.

Past Greenhouse Gas Forcing

Two major periods are often identified in the palaeo record for characterizing the impacts of future greenhouse gas levels: the Palocene-Eocene Thermal Maximum (or PETM; 56 million years ago) and the Pliocene (centred on 3 million years ago).

The Palocene-Eocene Thermal Maximum (56 million years ago)

Somewhere on the order of half of the historical emissions of CO_2 to the atmosphere have been absorbed by the ocean. Unfortunately, there is a price to pay: ocean acidification. The geological record contains evidence of the response of marine ecosystems to past ocean acidification events. The largest known 'greenhouse warming' event in the past 65 million years took place during the Paleocene-Eocene Thermal Maximum. This event was associated with a dramatic loss in benthic calcifiers (Kennett and Stott, 1991) but is not related to any significant extinction of planktic calcifiers.

Paired Earth system model simulations predict that a future release of about 1000 PgC will drive a magnitude and rate of ocean acidification in the deep ocean comparable to the PETM (Panchuk et al., 2008). 2000 PgC will create a comparable rate of warming in the deep ocean. Hence, at 1000-2000 PgC cumulative fossil fuel CO_2 release we would expect global extinctions of deep-sea organisms to start to occur. At the surface, we expect the future rate of surface ocean acidification and environmental pressure on marine calcifiers to be unprecedented in the past 65 million years (Ridgwell et al., in prep.).

The Pliocene (3 million years ago)

The Pliocene enables us to examine the equilibrium temperature response to current or near future atmospheric CO_2 levels (Haywood et al., 2009). As a global average, of the total mid-Pliocene 3.3˚C temperature change, climate models estimate that 1.6˚C was derived from the CO_2 forcing, 0.7˚C is from the orography forcing, 0.7˚C from the vegetation feedback, and 0.4˚C was from the ice feedback. The long-term response of the Earth System to elevated CO_2 including slow feedbacks (the Earth System sensitivity) is about 50% greater than the more traditional short term response (the 'Charney' sensitivity).

Importantly, temperature changes were amplified at higher latitudes. Ice sheets models from this period indicate complete loss of the WAIS, loss of ~65% of Greenland and ~20% of the EAIS. Lunt et al. (2008) model-simulated the mid-Pliocene Greenland ice sheet and found it was substantially smaller than that of modern, mostly due to the higher mid-Pliocene CO_2 (estimated to be of the order of 400 ppm). The Pliocene also provides an assessment of 25 m sea level rise for near present CO_2 level over the long term. A crucial research question is whether the Pliocene can help us identify a dangerous level of climate change? Simulations of short-term future climate change, however, indicate that the same increase in CO_2 is not sufficient to melt the modern ice sheet substantially - care must be taken when interpreting the mid-Pliocene as an exact future analogue due to vegetation and ice-sheet feedbacks.

Furthermore, there appears to have been reduced meridional and zonal sea surface temperature (SST) gradients. Altered zonal gradient in tropics (Pacific) could have been driven by changes to El Niño-Southern Oscillation (ENSO) though this is unproven from a data perspective due to the relatively low temporal resolution of the proxy data). Models show ENSO variability (in fact enhanced variability for the Pliocene, more and stronger El Nino’s). Proxies indicate enhanced ventilation in the North Atlantic and North Pacific but OAGCM results predicts the opposite.

A Future ‘Super-Interglacial’

Future projections of climate change imply our planet is moving into a ‘super-interglacial’ (Overpeck et al., 2005). Within the late Pleistocene, there are previous interglacials that are known to have been warmer than present, therefore providing a natural analogue for what the future might hold. Arguably one of the best periods for this purpose is the last interglacial (otherwise known as OIS-5e); climate modelling appears to demonstrate that this was a result of an orbitally-driven excess of Northern

Hemisphere summer insolation (Otto-Bliesner et al., 2006).

Climate during the Last Interglacial (130,000 to 116,000 years ago) provides an excellent analogue for future change. Last interglacial proxy-records of sea ice conditions from the Arctic Ocean north of Greenland and Ellesmere Island reveal much reduced (summer) sea ice concentrations (CAPE Last Interglacial Project Members, 2006). A comprehensive restudy of a number of key sediment records from the interior Arctic Ocean support a near-to ice-free Last Interglacial Arctic Ocean (Nørgaard-Pedersen et al., 2007). These results confirm the vulnerable nature of the Arctic Ocean sea ice cover, and how rapidly it can react to regional changes in insolation and/or atmospheric and oceanographic conditions.

Alongside high latitude warming and sea ice cover reductions were significant changes in sea level. It is important to note, however, that local sea level and Global Sea Level (GSL) are not identical. It is therefore important to take into regional variability when attempting to assess GSL from local proxies. Kopp et al (in prep.) have used a novel statistical approach that combines Gaussian process regression to account for spatial variability with Markov Chain Monte Carlo modeling of geochronological errors in order to analyze a new database of Last Interglacial sea level indicators from 47 localities. These authors found global sea level was higher than today during the Last Interglacial, likely peaking at 6-9 m above the current level. During the interval when sea level was within 10 m of its present value, the 1000-year average rate of sea level change reached 8-11 m per 1000 years. This rate estimate is consistent with post-AR4 empirical estimates of rates of sea level rise for the next century.

Abrupt Climate Change

The past has repeatedly undergone climate changes where the climate has changed dramatically over a period of decades on at least regional scale, representing rates of change many times higher than those projected for the future. Studies of the anatomy of these changes show that some parts of the climate system change even faster than this, so that the main shift in dynamics from glacial to interglacial conditions happened in 1-3 years (Steffensen et al., 2008). It is not clear which mechanisms were responsible for these abrupt changes, but the data document the existence of tipping points not yet fully understood or captured by climate models. Past gradual warming has been observed for trigger rapid warming. The documented threshold crossings occurred in a period of significantly different climate conditions than today and are thus therefore not direct analogies to future climate scenarios. However, projected climate changes will soon bring us into an uncharted regime where similar thresholds may exist. Further work on quantifying the precise details of past climate change and identifying the underlying mechanisms is needed to fully assess the risk of future abrupt climate change.

Tropical Changes

The globe has shown coherent shifts in precipitation patterns as the climate warmed from the last ice age. In the tropics, home to some 40 % of the world’s population, Sachs et al. (in prep) presented evidence from lake and ocean sediments in the western, central and eastern tropical Pacific that the last millennium was a time of marked change in rainfall patterns. Crucially, the Intertropical Convergence Zone (ITCZ) was located south of its present position for most of the last 1000 years. Its most southern position was 5° closer to the equator, occurring from 1450-1630 A.D. (during the north European climatic period known as the Little Ice Age). The ITCZ has since migrated north at an average rate of 1.4 km/yr. This trend may be a response to global warming, both natural (following the Little Ice Age) and anthropogenic forcing.

In many low-latitude regions, glaciers provide a crucial source of water during summer months. In tropical east Africa, glacier shrinkage on Kilimanjaro (4500-6000 metres above sea level) between the 1880s and present can be definitely linked to a drier regional climate than before. The combination of high-altitude measurements and glacier mass balance modelling reveals that precipitation has dropped by 30 to 45 %, accompanied by reductions in cloud cover and air humidity. Similar moisture reductions occurred in the lowlands (Mölg et al., 2009). The initial moisture drop in the late 19th century was most probably caused by a decrease in the Indian Ocean dipole dynamics, while the most recent drying since the 1980s is likely due to global warming implications (i.e., due to a warming Indian Ocean and/or a convective margin shift) (Mölg et al., 2009). If global warming in the 21st century starts to also affect dipole dynamics and increases them, as suggested by the IPCC AR4 simulations (Vecchi and Soden, 2007), precipitation in tropical East Africa is expected to decrease.

Climate change of the recent past, as revealed by glacier-climate interactions on Kilimanjaro, suggests for the future that: (a) tropical east Africa, and most likely other tropical regions (e.g., Held and Soden, 2006), will experience significant moisture changes in a warming world. As tropical societies strongly depend on rainfall seasons, such changes are more critical than local and regional air temperature changes; (b) Moisture changes will be manifested particularly strong at high elevation of mountainous tropical regions.

Human Responses to Past Climate Change

Archaeological research is essential if we are to understand how human communities have dealt with the impacts of climate change in the past; particularly the impacts of relative sea level rise, variation in precipitation patterns and changes in the frequency and intensity of extreme weather events.

It is essential to correlate and compare archaeological and paleoclimatic datasets from different spatial and temporal scales in order to model and predict how short-term local impacts on human communities arise from long term patterns of global climate change. Over the long-term, exploratory behaviour and the coincident exposure to new environmental conditions, and all the evolutionary consequences associated, depends on a reliable, stable physiological state (Hetherington and Reid, in press). Humans possess the ultimate independence from the vicissitudes of the external environment because we can complement physiological self-maintenance with intelligent behaviour. In the past human generalists combined their innovative behaviour with intelligence and education to explore and improve their conditions of life. When rapid environmental changes were imposed on early hominins *in situ*, for example when climate rapidly changed and altered the vegetation and reduced the number of food species available to early *Homo* species in Africa, they epigenetically developed, and became more physiologically and behaviourally adaptable. These changes then permitted early humans to explore new environments. For example, they moved out of Africa at the beginning of the last glacial cycle. The exploration of new environments likely induced novel responses and as a result additional new environments were occupied. As a consequence modern humans subsequently dispersed around the world.

Global climate simulations of the past 135,000 years indicate climate variability, water availability, and changing vegetation placed significant demands on early humans. Humans sought options and congregated in the most congenial conditions where environmental effects were minimized and where human interaction was amplified. It is just these types of environmental influences that can typically impact species development, both behavioural and epigenetic. Social evolution of humans was the result of a three "c"s syndrome: catastrophe, communication and cooperation. In our past, rapidly changing circumstances stimulated the emergence of bright ideas and revolutionary change.[i]

Archaeology can inform modern day mitigation strategies for climate change; specifically improved resilience through household architecture, food procurement strategies and settlement location.

Though anthropogenically-induced climate change on a global scale is a phenomenon of the present, dramatic climate variability has occurred throughout human history, and human societies have reaced in a variety of ways (e.g. Rosen 2007; Crumley, 2001; McIntosh et al., 2001). Surveying the ways in which past societies have reacted to these changes provides us with insights into adaptation to modern-day climate change.

A relatively recent global shift in climate occurred at the Pleistocene-Holocene transition (11,700 years ago; Walker et al., 2009). In southwestern France, people in the Dordogne Valley seem to have adapted to changing environments by exploiting newly available resources in a new way. At the site of Pont d'Ambon, it appears that the inhabitants began warren-based hunting of the wild European rabbit (*Oryctolagus cuniculus*), a species that was unavailable in the Dordogne prior to the onset of the Allerød (Jones 2006). In so doing, they moved into the realm of food production, rather than straightforward hunting and gathering, even though domestication in the area was 3000 years in the future.

A more modern example can be seen in the American Southwest, around the 15th century AD. The American Southwest is a region of constant small-scale climate variability; precipitation is highly variable from year to year, with occasional intervals of relative stability (Dean 1996). As a wet stable interval came to an end in the late 14th century, agriculturally-oriented Ancestral Puebloans aggregated along major waterways, abandoning the Four Corners region (Adams and Duff, 2004). Migration is a key cultural value to Puebloans today, and seems to have been equally important in the past (e.g. Bernardini, 2005).

Soon after the Four Corners region was abandoned by the Puebloans, Navajo peoples moved into this area (Towner and Dean, 1996), where they remained (Barring a period of forced relocation by the U.S. Government in the 19th century) ever since. Navajo culture is characterized by subsistence flexibility; by changing their lifeways in response to climate, the Navajo adapted to this environment characterized by climate variability.

Looking at the ways in which human cultures have reacted to past instances of climate variability suggests that in these instances, two options arise: migration (such as the Puebloans) or change (as the Pleisticene-Holocene transition foragers did by making use of the new resources, or as the Navajo have by making change a way of life). The details of how these adaptations play out, however, are highly particular to location. Because the environmental impacts of climate change are local, adaptations are also local, suggesting that as we plan for climate change today, we must look for local solutions as well as global ones.

In the future, it is unlikely that humans will undergo further genetic adaptational specializations, unless we are catastrophically subjected in small, isolated populations to extended periods of confinement in stressful conditions. Any changes will appear instead as epigenetic, physiological, and behavioural developments. These factors operate above the gene level.

It is now becoming clear that changing human behaviour is not simply a matter of asking people to do things differently. There is a great reluctance to change behaviour that has worked in the past. For real change to occur humans must typically experience significant environmental stress. Future climate change will bring environmental stress and so may encourage behavioural change. However, we must be very cautious in our development and implementation of behaviours and technologies that control or dominate nature, individuals or sectors of human society. This is because human dominance and control is responsible for significantly contributing to climate change, environmental destruction, and biodiversity loss. Repeating past mistakes and behaviours will not resolve future climate change or economic instability.

An enormous opportunity exists. If the Hetherington and Reid (2010) are correct, that much of our past development arose in response to changing environmental conditions combined with the concentration of human populations and resulted in the stimulation of revolutionary ideas, then there exists hope for our future. Within the overarching *H. sapiens* family there are individuals and groups that are more flexible and open to novelty and diversity than others. This is generally because they have had to be just to survive. It seems like our capacity to adjust to future climate change will be better in those groups and societies that are open and willing to accept difference and change. This is what makes modern complex societies vulnerable to collapse during times of rapid environmental (and economic). The degree of acceptable change depends on how sensitive the organism, group or society is to change and how well change is recognized and understood. If it is not recognized or understood, or if the change required is too great for the individual, organism, or society to manage, or alternatively if they are not willing to adjust, then decline and even extinction prevails. As such humans are not invulnerable to extinction. The ability to innovate, think outside the box, adjust to change at a moment’s notice, and choose cooperation rather than conflict when circumstances become trying are skills that are imperative if we are to successfully adjust to future climate change. Also imperative will be a capacity for natural and social scientists to communicate complex scientific information and ideas to the public. This is particularly important because our behaviour must change immediately, before the stresses associated with present and future climate change provide the impetus for behavioural change (Hetherington and Reid, in press).

Implications for Modelling

Climate models provide important assessments of climate sensitivity. Uncertainty in historical radiative forcing has not been sufficiently considered in previous studies – including these uncertainties in the analysis implies that climate sensitivity is less constrained at the high end than previously thought (Tanaka, 2008; Tanaka et al., 2008). How we learn about climate sensitivity is significantly influenced by how we account for the uncertainty in radiative forcing (Tanaka and O'Neill, 2009). It has recently been proposed that greenhouse gas changes preserved in the Antarctic ice cores shows a clear response to cooling during the period known as the Little Ice Age (Cox and Jones, 2008). Unfortunately, however, the inferred climate sensitivity remains relatively large because of the uncertainties in extrapolating northern hemisphere records to the globe. In addition, modeling of the Pliocene indicates that the long-term response of the Earth System to elevated CO_2 including slow feedbacks (the Earth System sensitivity) is about 50% greater than the more traditional short term response (the 'Charney' sensitivity).

Palaeo data provides important tests of climate models. Proxy records for the Pliocene and earlier warm periods indicate that temperature changes are amplified at high latitudes. It is of concern that current models can't seem to capture warming in polar regions at time of high warming though they can capture tropical change (Schrag and Alley, 2004). For past global warm periods, there also appears to have been reduced meridional and zonal sea surface temperature (SST) gradients, although more data is needed to fully understand the implications. Climate models do not reproduce these changed gradients.

Reconstruction can also be integrated into modeling endeavors to examine processes and sensitivities. A quantitative Danish climate reconstruction has been incorporated into the national hydrological model to assess water resource sensitivity to changes in climate. Furthermore, models of palaeo data allow us to undertake formal detection studies. For instance, Tett et al. (2007) recently reported a modeling study which suggests anthropogenic-driven warming may have been significant in the tropics from AD 1830. At present, the paucity of sites analyzed for temperature in the region cannot test this hypothesis.

Past climate changes provide comparisons to the future and allow tests of climate models to elucidate controls in the earth-ocean-atmosphere system. It is anticipated the palaeo reconstructions will show current climate models are conservative in their magnitude and rate of future change. **The session on 'Informing the Future by Understanding the Past' helped bring together some of the latest thinking on our understanding of the mechanisms of climate change as well as constraining model uncertainty for predicting future variability and its impacts.**

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