High resolution alkenone palaeobarometry indicates relatively stable pCO_2 during the Pliocene (3.3 to 2.8 Ma)

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Temperature reconstructions indicate that the Pliocene was ~ 3 °C warmer globally than today, and several recent reconstructions of Pliocene atmospheric CO_2 indicate that it was above pre-industrial levels and similar to those likely to be seen this century. However, many of these reconstructions have been of relatively low temporal resolution, meaning that these records may have failed to capture variations associated with the 41 Kyr glacial-interglacial cycles thought to operate in the Pliocene. Here we present a new, high temporal resolution alkenone carbon isotope based record of pCO_2 spanning 2.8 to 3.3 million years ago from ODP Site 999. Our record is of high enough resolution (~19 Kyrs) to resolve glacial-interglacial changes beyond the intrinsic uncertainty of the proxy method. The record suggests that Pliocene CO_2 levels were relatively stable, exhibiting variation less than 55 ppm. We discuss the potential influence of changing cell size or growth rate on the alkenone carbon isotopes. Although we cannot be precluded these, we have evidence for neither: lith sizes remain relatively constant and biomarker, benthic foraminiferal and bulk OM productivity indicators indicate low and stable biological productivity at the site. We perform sensitivity studies to investigate the possible effect of changing sea surface temperature, which highlights the importance of accurate and precise SST reconstructions for alkenone palaeobarometry, but demonstrate that these uncertainties do not affect our conclusions of relatively stable pCO_2 levels during this interval.

An alternative suggestion for the Pliocene onset of major northern hemisphere glaciation based on the geochemical provenance of North Atlantic Ocean ice-rafted debris

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The onset of abundant ice-rafted debris (IRD) deposition in the Nordic Seas and subpolar North Atlantic Ocean 2.72 millions of years ago (Ma) is thought to record the Pliocene onset of major northern hemisphere glaciation (NHG) due to a synchronous advance of North American Laurentide, Scandinavian and Greenland ice-sheets to their marine calving margins during marine isotope stage (MIS) G6. Numerous marine and terrestrial records from the Nordic Seas region indicate that extensive ice sheets on Greenland and Scandinavia increased IRD inputs to these seas from 2.72 Ma. The timing of ice-sheet expansion on North America as tracked by IRD deposition in the subpolar North Atlantic Ocean, however, is less clear because both Europe and North America are potential sources for icebergs in this region. Moreover, cosmogenic-dating of terrestrial tills on North America indicate that the Laurentide Ice Sheet did not extend to ~39˚N until 2.4 ± 0.14 Ma, at least 180 kyr after the onset of major IRD deposition at 2.72 Ma. To address this problem, we present the first detailed analysis of the geochemical provenance of individual sand-sized IRD deposited in the subpolar North Atlantic Ocean between MIS G6 to 100 (~2.72-2.52 Ma). IRD provenance is assessed using laser ablation lead (Pb) isotope analyses of single feldspar grains. To track when an ice-rafting setting consistent with major NHG first occurred in the North Atlantic Ocean during the late Pliocene, we investigate when the Pb-isotope composition ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$) of ice-rafted (>150μm) feldspars deposited at DSDP Site 611 first resembles that determined for IRD deposited at this site during MIS 100, 2.52 Ma, the oldest glacial during intensification of NHG for which there exists convincing evidence for widespread glaciation of North America (in the form of mid latitude glacial tills) and major global sea-level fall (of at least 60 m relative to the present). Whilst Quaternary-magnitude IRD fluxes exist at Site 611 during glacials from 2.72 Ma, we find that the provenance of this IRD is not constant. Instead, we find that the Pb-isotope composition of IRD at our study site is not consistent with major NHG until MIS G2 (2.64 Ma). We hypothesise that IRD deposition in the North Atlantic Ocean prior to MIS G2 was dominated by iceberg calving from Greenland and Scandinavia. We further suggest that the grounding line of continental ice on Northeast America may not have extended onto the continental shelf and calved significant numbers of icebergs to the North Atlantic Ocean during glacials until 2.64 Ma.

NORTH ATLANTIC OCEAN CIRCULATION AND THE ONSET OF NORTHERN HEMISPHERE GLACIATION

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The late Pliocene onset of major Northern Hemisphere glaciation is one of the most significant steps in the Cenozoic global cooling, leading to the glacial-interglacial cycles that have characterised the modern climate system. There are several possible causes of this phase of ice-sheet growth, including threshold changes in atmospheric CO_2[1] and changes in orbital cyclicity[2]. A change in North Atlantic ocean circulation or shift in the background state of the ocean, following the closure of the Central American Seaway (CAS) is also cited as a contributing factor.

We present new multispecies benthic foraminifera trace metal records (Li/Ca, B/Ca and Mg/Ca) from intermediate depth North Atlantic Ocean Drilling Program Site 982, located on the Rockall Plateau, encompassing the final closure of the CAS (~4.6 Ma) and the onset of Northern Hemisphere Glaciation (~2.7 Ma). These records trace the evolution of the bottom water mass in the North Atlantic across this tectonic and climatic transition.

Also presented is a ~10 kyr resolution record of the Sortable Silt mean grain size record of near bottom water flow speed variability spanning the same time interval (5.1 – 1.9 Ma). These flow speed changes are interpreted to record shifts in northern component water vigour, perhaps related to shifts in deep ventilation in the source regions of these waters.

The sortable silt and trace metal records are compared to existing stable isotope and ice rafted debris records for Site 982, and to records from sites in the North Atlantic and elsewhere in the world's oceans. Initial results show apparent shifts in the phase relationship between flow speed and benthic $\delta^{18}O$ at around 3.5 Ma. This may be related to the closed Central American Seaway changing the nature of circulation.

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MID-PLIOCENE CLIMATE MODELLED USING THE UK HADLEY CENTRE MODEL: PLIOMIP EXPERIMENTS 1 AND 2

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The mid-Piacenzian Warm Period (mPWP, 3.264-3.025Ma) is the last sustained and relatively stable interval of significantly greater warmth than pre-industrial period before the onset of significant Northern Hemisphere glaciation. It has therefore been chosen as the focus for the collection of the substantial PRISM3D dataset documenting the topography, ice sheets, ocean temperatures and vegetation of this interval of the late Pliocene As well as the insights these data give us into the climate system at this time, the dataset has been adopted to provide boundary conditions to PlioMIP, the Pliocene group of the Paleoclimate Modelling Intercomparison Project (PMIP). The PMIP process seeks to collect general circulation model (GCM) simulations from the widest possible range of models in order to improve understanding of the climate processes underlying the data and the model challenges inherent in simulating a warmer-than-modern climate system.

Here we present results of the standard PlioMIP atmosphere-only and coupled atmosphere-ocean experiments. As the proxy reconstructions of atmospheric CO_2 levels cover a significant range, we also investigate into the sensitivity of the model to a range of pCO_2 and attempt to formulate an algorithm to quantify the goodness of fit of each of the simulations to the relatively sparse and unevenly distributed temperature data and thus produce a model estimate of mPWP pCO_2.

Patterns of Early Pliocene Warmth: Testing Potential Mechanisms.

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Because the early Pliocene was the most recent interval of sustained warmth in Earth's history, with atmospheric carbon dioxide concentrations similar to those at present, it can provide insights into potential future climate conditions. Our synthesis of the ocean surface temperature field reveals that relative to today, the early Pliocene was characterized by substantially reduced meridional and zonal temperature gradients, but similar maximum ocean surface temperatures. These differences, considered together, amount to a **structural climate change** between the early Pliocene and present-day SST patterns as outlined in our recent study (Fedorov et. al. 2013, Nature 496). In an effort to understand the causes for this change, we have conducted a series of intercomparable sensitivity studies to test the currently proposed explanations. In particular, we have tested changes in ocean gateways (an open Central American Seaway, a closed Bering Strait, and a more southerly position of Indonesia), elevated CO_2 levels, and dynamical mechanisms that require modifications in the model physics to account for missing or underestimated feedbacks (ocean vertical mixing, changes in cloud albedo). All simulations are performed with the same model (the palaeoclimate version of the Community Earth System Model, CESM) and each potential mechanism is evaluated against the three conditions identified from the temperature synthesis. We find that plausible changes in low latitude ocean gateways or elevated levels of atmospheric CO_2 alone do not correspond with the observed conditions. A more promising answer is given by a combination of augmented CO_2 levels, and dynamical factors such as increased ocean mixing and reduced cloud albedo in the extra-tropics, which produces the right SST pattern, with a magnitude approaching the observations, as well as the ocean thermal structure that agrees with the observations. We conclude that simulating the early Pliocene may indeed require incorporating additional climate feedbacks into the models.

**Pliocene History from Lake El'gygytgyn, NE Russia:
Continuous terrestrial evidence of Pliocene climate variability**

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Evidence from Lake El'gygytgyn, NE Arctic Russia, some 100 km north of the Arctic Circle in western Beringia (67°30' N, 172 ° 05' E), provides the first continuous Pliocene paleoclimate record from the Arctic borderlands. We document that 3.6-3.4 million years ago, summer temperatures were ~8°C warmer than today and much wetter when others have suggested pCO2 was 340 to 400 ppm. Extreme warmth in the Mid Pliocene Arctic occurs at the same time ANDRILL results suggest the West Antarctic Ice Sheet was non-existent. Modeling sensitivity experiments using 300 and 400 ppm CO_2 are consistent with sustained forests at Lake El'gygytgyn during this interval and restricted glacial ice over Greenland in both cold and warm boreal summer orbits especially for the PRISM interval. This has implications for reinterpreting the M2 isotopic shift in the North Atlantic suggesting that most of the ice advance at that time was in Antarctica.

Pollen spectra and modern analog analysis show an unbroken persistence of summers much warmer and wetter than the Holocene until nearly 2.2 Ma, well into the early Pleistocene. Cross correlation of estimate mean July temperatures with the LR04 stack provides a rather good fit (R^2=0.41), illustrating the expected link between summer temperatures at Lake El'gygytgyn and obliquity via the isotopic stack. Several intervals of coniferous-dominated forests occurred during MIS 101, 93, 91 and 87 interglacials. Summers at Lake El'gygytgyn remain 1-3°C warmer than present for ~200,000 years after stratification of the North Pacific at 2.73 Ma, even during the coldest boreal summer orbits. Importantly, these data,

along with eustatic sea level reconstructions support the notion that Pleistocene cooling and intensification of Northern Hemisphere glaciation (NHG) was gradual, occurring in several steps but with warm Arctic summers persisting much later than previously documented. The climate record from Lake El'gygytgyn, provides a fresh means of testing the evolving magnitude of polar amplification over time, and the sensitivity of the Greenland Ice Sheet to extreme warmth in the rest of the Arctic.

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Simulating Pliocene warmth and a permanent El Niño-like state: the role of cloud albedo

Burls and Fedorov

Available evidence suggests that during the early Pliocene (4–5 Ma) the mean east-west sea surface temperature gradient in the equatorial Pacific Ocean was significantly smaller than today, reaching only 1-2^{o}C. The oceanic meridional temperature gradients were also substantially weaker, implying an expanded ocean warm pool in low latitudes. Subsequent global cooling led to the establishment of the stronger, modern meridional and zonal temperature gradients by some 1-2 Ma (for a review see Fedorov et al. 2013). Given our understanding of the physical processes that maintain the present-day cold tongue in the east, warm pool in the west, and hence sharp temperature contrasts, determining the physical processes that maintained early Pliocene climate still presents a challenge for climate theories and models. As a potential solution to this problem, it has been suggested that a key to the Pliocene puzzle may lie in different cloud properties (perhaps associated with a different aerosol composition in the Pliocene atmosphere). In this study we demonstrate how a different spatial distribution in cloud albedo could have been responsible for sustaining Pliocene climate. In particular, we show that a reduction in the meridional gradient in cloud albedo can sustain reduced meridional and zonal gradients in sea surface temperature, an expanded warm pool in the ocean, and weaker Hadley and Walker circulations in the atmosphere. Having conducted a range of modified cloud albedo experiments, we arrive at our Pliocene simulation, which shows good agreement with proxy sea surface temperature data from the major equatorial and coastal upwelling regions, mid and high latitudes, and the tropical warm pool. A good agreement is also achieved with available subsurface temperature data. Thus, our results demonstrate that cloud albedo may indeed be a critical element of Pliocene climate.

Relationships between sea surface temperature, Atlantic Meridional Overturning strength, vegetation type and hydrological variability in the Sahel during the Plio-Pleistocene (4.0-0.5 Ma)

Isla S. Castañeda, Ben Urann, Victoria Phu and David B. Finkelstein

A distinctive signature of Atlantic Meridional Overturning Circulation (AMOC) slowdown is anticorrelated variation between surface and subsurface water temperatures in the tropical N Atlantic [1,2]. AMOC slowdown leads to sea surface temperature (SST) cooling in the N Atlantic region, which in turn intensifies the NE trade winds [1,3]. Strengthened NE trade winds result in surface cooling of the tropical N Atlantic [1,2]. Simultaneously, shallow subsurface (< 30 m) waters warm due to reduced warm-water export to the north [1]. This distinctive pattern has been observed in coupled ocean-atmosphere climate models and observational data on decadal to multi-decadal timescales [1-2, 4]. Recently, Lopes dos Santos et al. [5] showed that the pattern of surface cooling and subsurface warming in response to AMOC slowdown also existed on longer, millennial to multi-millennial timescales. The authors reconstructed SST and thermocline temperatures using the $U^{k'}_{37}$ and TEX^{H}_{86} proxies, respectively.

In addition to producing the distinctive anticorrelated pattern between surface and subsurface water temperatures, AMOC slowdown also has a significant impact on N African climate. Strengthened NE trade winds, in combination with the advection of cold air from the high latitudes cause a southward displacement of the ITCZ and an intensification of the African Easterly Jet, leading to arid conditions in continental N Africa [3, 4]. Here, we examine sediments from ODP 660A (NE Atlantic), located near the site of [5], and use paired $U^{k'}_{37}$-TEX^{H}_{86} temperature measurements to investigate changes in AMOC strength over the past 4 Ma. We also examine the carbon ($\delta^{13}C$) and deuterium (δD) isotopic composition of plant leaf waxes, proxies for vegetation type (C_3 vs. C_4) and precipitation amount, respectively. Several studies have demonstrated close ties between AMOC variability and hydrological conditions in N Africa during the late Pleistocene and Holocene [e.g. 3, 5]. Results of this study further support a close link between SST and hydrological conditions in the Sahel during the past 4 Ma while also highlighting regional differences in aridity between Plio-Pleistocene records of western, eastern and southern Africa.

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Glacial- interglacial δ^{11}B-based atmospheric CO_2 records across the Plio-Pleistocene transition

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With warmer temperatures and higher sea level than today[1] – the Pliocene represents an important interval of study for predictions concerning the near future. Recent CO_2 measurements match those estimated from the Pliocene (2.6 million years ago, Ma), and so the world of tomorrow may share many characteristics with this epoch. Repeatedly highlighted is the importance of changing atmospheric CO_2 as a driver of climatic change from this interval towards the present bihemispheric ice sheet world[2,3,4].

Here we present pCO_2 records across the late Pliocene and early Pleistocene (1.5 to 3.6 Ma) measured from surface foraminiferal δ^{11}B at tropical sites in the Caribbean Sea and the Atlantic Ocean. The long-term decline in CO_2 helps to identify the drivers and responses of climate change in these conditions. In addition, we quantify the magnitude of glacial-interglacial CO_2 change seen throughout the Plio-Pleistocene transition to further characterize Pliocene glaciations in comparison to their better-studied Pleistocene counterparts.

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How to initiate and maintain a Greenland ice sheet during the late Pliocene warm period?

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The first major pulse of ice-rafted debris on Greenland continental margin is observed at 3.3 Ma, correlated with oxygen isotope signal, suggesting the first expansion in Greenland ice volume, with later increase occurring from 3 Ma (Kleiven et al., 2002). The extent of the Greenland Ice Sheet (GrIS) during the late Pliocene (3.3 to 3 Ma) remains largely unconstrained, but was fixed to 50% of its present-day volume for simulations of the late Pliocene climate (Dowsett et al., 1999; Hill et al., 2007). Reconstructed pCO_2 for this period vary during the time interval and among reconstructions. Seki et al. (2010) suggest values between 330 to 400 ppm, and Bartoli et al. (2011) propose minimal CO_2 estimates of 245 ppm.

Through a series of simulations with the IPSL-CM5A-LR coupled model used to force the GRISLI ice sheet model, we investigate the possibility of initiating and maintaining an ice sheet on Greenland during the late Pliocene warm period. First, starting from ice-free conditions on Greenland, we force the GCM with CO_2 levels of 405, 360 and 280 ppm and different orbital configurations (namely, a cold orbit leading to the minimum insolation at 65°N at summer solstice occurring between 3.8 and 3 Ma, and the preindustrial orbit). We find that even with a minimum insolation, CO_2 level has to be lowered to 280 ppm in order to build an ice sheet on the southeast mountainous regions of Greenland, with a volume of ~1 m sea-level equivalent. This ice sheet is then used as a boundary condition in the GCM which is forced with 360 and 405 ppm and preindustrial orbit or a warm orbit leading to a maximum of insolation at summer solstice. Results show that, unless combining a maximum insolation and 405 ppm of CO_2, which leads to a reduced and thin ice sheet less than 500 meters high, the ice sheet barely melts, because of strong ice-albedo feedbacks. Recoupling experiments using the GrIS simulated with low insolation and 360 or 280 ppm of CO_2 are currently carried out in order to investigate the strength of the ice-albedo feedback in a cold climate, which could lead to a larger glaciation. Nevertheless, GCM outputs show higher summer temperatures downwind of the GrIS when compared to the ice free experiments, possibly preventing its further growth because of a föhn effect, as in Langen et al. (2012).

Insights into the influence of sea surface temperature and iceberg flux on Pliocene Southern Ocean IRD provenance patterns

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The provenance of Southern Ocean iceberg-rafted detritus (IRD) can potentially reveal the past behaviour of the East Antarctic Ice Sheet (EAIS). For example, the Pliocene Epoch was characterised by a long-term global cooling trend preceded and punctuated by intervals of climatic warmth. Existing IRD records suggest that iceberg flux from the EAIS may have varied considerably during these changing climatic conditions.

Here we present a Pliocene IRD provenance dataset based on $^{40}Ar/^{39}Ar$ ages of hornblende grains from ODP Site 1165 (64°22'77" S, 67°13'14" E), Prydz Bay, East Antarctica. Prior to ~3.27 Ma, 70% of all ice-rafted hornblende grains are supplied from the local Prydz Bay region ($^{40}Ar/^{39}Ar$ ages of 455 to 575 Ma). Between ~2.65 and ~3.27 Ma, hornblende grains with $^{40}Ar/^{39}Ar$ ages of between 1050 and 1315 Ma become more abundant, making up ~50% of all grains. This $^{40}Ar/^{39}Ar$ age range matches outcrops and marine sediments along the distal Wilkes Land margin, at the mouth of the Aurora Subglacial Basin (ASB).

The lower amount of distally sourced Wilkes Land IRD in sediments deposited before 3.27 Ma point to warm sea surface temperatures (SSTs) and/or retreat of the EAIS into the ASB. The increase in Wilkes Land IRD we observe at ~3.27 Ma coincides with major ice sheet expansion in the local Prydz Bay area, regional SST cooling and a tenfold increase in IRD delivery to ODP Site 1165. To better constrain how changing Pliocene SSTs affected variable IRD provenance patterns, we developed a novel modelling framework by coupling the British Antarctic Survey ice sheet model (BASISM) with a model of iceberg transport and melting. Sensitivity simulations were run under hypothetical SSTs between 1°C and 8°C warmer than today. Results suggest that declining Pliocene SST's may have played a role driving the increase in Wilkes Land IRD after ~3.27 Ma. However, hornblende grains in samples deposited at ~3.1 Ma and ~3.2 Ma, and at ~4.6 Ma, are characterised by more Wilkes Land IRD (50-60%) than SST sensitivity tests can account for. This suggests that factors such as glacial-interglacial variations in SSTs and increased iceberg flux, driven by potential ice sheet retreat events, as well as variations in iceberg sediment loading, may also have effected Pliocene IRD provenance patterns on shorter timescales.

Glaciation in the Northern Hemisphere during the globally warm early Late Pliocene (marine isotope stage M2, ca. 3.3 Ma)

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The early Late Pliocene (3.6 to c. 3.0 Ma) world was characterised by a relatively stable global climate that was about 2–3˚C warmer than present and with atmospheric carbon dioxide concentrations comparable to today. Notwithstanding such warm and stable climate, a major glaciation within marine isotope stage (MIS) M2 occurred around 3.3 Ma. The processes behind this glaciation are unknown. We investigated the role of Central American Seaway through flow and North Atlantic surface ocean circulation in establishing this glaciation during MIS M2.
We used high-resolution geochemical proxy records for sea-surface temperature (Mg/Ca of different planktonic foraminifers and alkenones) and also analysed dinoflagellate cyst assemblages to reconstruct the surface circulation in the North Atlantic. Five ocean drilling sites along a transect from the Caribbean to the eastern North Atlantic allowed us to reconstruct variations in the Central American Seaway throughflow and in the Gulf Stream/North Atlantic Current system – a current system that transports warm surface waters to higher latitudes and influences present-day climate in NW Europe. Our results demonstrate that increased Pacific to Atlantic throughflow via the Central American Seaway had occurred already in the interglacial prior to MIS M2 and led to a weakening and southward shift of the North Atlantic Current. This resulted in reduced northward heat transport and cooling of the high latitude oceans, which was a crucial prerequisite for a major expansion of the Greenland ice sheet during MIS M2.

The Palynological record of the Pliocene in the Labrador Sea

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The palynological record of ODP Site 646 located on the southwest Greenland rise in the Labrador Sea permits to establish direct linkages between the terrestrial vegetation of Southern Greenland and regional sea-surface conditions (cf. de Vernal and Hillaire-Marcel, Science 2008). Low time resolution data from the Pliocene sediment suggest high pollen and spores inputs related to dense vegetation on southern Greenland. This vegetation was notably composed of coniferous trees (*Pinus*, *Picea*, *Tsuga* and *Sciadopitys*) and the development of *Sphagnum* peatland. Such vegetation type could be associated with boreal environments and cool temperate climate. Changes in taxa percentages and concentrations suggest, however, large amplitude variations in vegetation that might be related to climate change and/or ice growth and decay on Greenland. Pliocene dinocyst assemblages were dominated by cool temperate taxa (*Operculodinium centrocarpum*, *Nematosphaeropsis labyrinthus*, notably), which suggest similar temperature conditions than at present. The Pliocene assemblages also include abundant prasinophytes and acritarchs that suggest nutrient rich and low salinity surface waters. Large amplitude variation in taxa percentages and concentrations also indicate changes of sea-surface conditions with regard to productivity and temperatures. The overall palynological data suggest major transitions at about 4, 2.4 and 1.2 Ma with dinocyst taxa extinctions. The 2.4 Ma transition seems also to be marked by a drastic decrease of pollen input which might reflect significant ice growth on Greenland. Over the last million years, the only interval that might show similarities with >2.4 Ma conditions with coniferous woodland development on Greenland was the marine isotope stage 11. It is noteworthy that sea surface conditions were not very different from those of the late Holocene during this interval. Hence, dense boreal vegetation on Greenland seems to have characterized the Pliocene prior to 2.4 Ma and some subsequent episodic intervals, but sea surface conditions were not necessarily warmer in the Labrador Sea than during the present interglacial.

The response of the tropical Indo-Pacific warm-pool to conditions of global warmth

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The Indo-Pacific warm pool (IPWP) plays an important role in regional and global climate. Sea surface temperature (SST) records of the last 50 years show that IPWP SST warmed by ~0.1°C per decade; a faster rate compared to eastern equatorial Pacific and global SST. The early Pliocene is the most recent time in Earth history when greenhouse gas concentrations were similar to today and average global temperature was warmer. Climate models predict ~1˚C temperature rise in the IPWP when CO_2 concentrations increases by 100ppm (to ~400ppm), and a ~2˚C warming if CO_2 is doubled. If the IPWP was not warmer in the early Pliocene compared to today, then CO_2 was unlikely to be higher than ~400ppm. If IPWP SST was warmer in the early Pliocene, then it is possible that CO_2 reconstructions are underestimating greenhouse gas forcing in the early Pliocene.

We present a *G. sacculifer* Mg/Ca record in the Indian Ocean (ODP site 758: 5º23'N, 90º21'E, 2925 m water depth), which shows little variation through the last 5 Ma, agreeing with a previous Mg/Ca record in the western equatorial Pacific. IPWP SST stability has been called into question because SST records in the region are based on the Mg/Ca proxy, which may be biased by secular changes in Mg/Ca of seawater. However, Mg/Ca_{sw} is not well constrained; estimates of Mg/Ca_{sw} at 3-5 Ma range from 0.5-3 mol/mol lower than today. Adjusting Mg/Ca SST estimates at ODP site 847 in the eastern equatorial Pacific leads to early Pliocene SST estimates that largely disagree with $U^{K'}_{37}$ SST estimates. Adjusting Mg/Ca bottom water temperatures at ODP site 607 leads to unrealistic bottom water temperatures and $\delta^{18}O$ of seawater estimates that are implausible because they imply isotopically heavier seawater (higher ice volume) in the early Pliocene compared to today. Therefore, changes in Mg/Ca_{sw} were likely modest and had a minimal affect on the Mg/Ca paleotemperature proxy on these time scales, and our stable Mg/Ca record reflects little change in SST in the IPWP through the last 5 Ma. Stable SST in the IPWP supports records that show early Pliocene pCO_2 of ~400ppm. Given that climate models used to predict anthropogenic warming do not cause the 3-4ºC global warming observed in the early Pliocene when driven by such a modest change in pCO_2, it is likely that climate feedbacks played a large role in maintaining early Pliocene warmth.

First Global Climate Model Simulations of a Pliocene Glacial Event (Marine Isotope Stage M2: c. 3.3 Ma)

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The Pliocene Epoch (5.2 to 2.6 Ma) and specifically the PRISM interval (3.0 to 3.3 Ma) have often been targeted to investigate warm intervals in Earth history (e.g. Haywood et al., 2013). However, although not as dramatic as the glacial and interglacial cycles that typified the Pleistocene, the Pliocene also exhibited climate variability and periods which were apparently cooler than modern (Lisiecki and Raymo, 2005). Of particular interest is the major cooling event which occurred around 3.3 Ma during Marine Isotope Stage (MIS) M2. This "Pliocene glacial" punctuates an otherwise relatively warm background climate and has been referred to as a failed attempt of the climate to reach a full glacial state (De Schepper et al., 2009; Haug and Tiedemann, 1998). The onset of full Northern Hemisphere (NH) glaciation finally occurred at the end of the Pliocene (~ 2.75 Ma).

Although numerous temperature reconstructions from around the world's oceans tend to capture the MIS M2 cooling event, the exact nature of M2 remains enigmatic. Sea level records vary but suggest a maximum sea level drop of ~65 m compared to modern, which is significant enough to necessitate the growth of a NH ice sheet (Dwyer and Chandler, 2009). Previous ice sheet modelling suggests that ~8 m sea level equivalent (SLE) ice could be stored on Antarctica (Pollard and DeConto, 2009) and this larger ice sheet (compared to modern) is potentially supported by the increase in ice-rafted debris (IRD) found offshore of East Antarctica during this time (Passchier, 2011). IRD in the North Atlantic would suggest the presence of an ice sheet on Greenland (e.g. Kleiven et al., 2002), but the locations of other ice caps in the NH are not determined due to the destructive nature of subsequent Pleistocene ice sheet advances.

We present the first fully coupled atmosphere-ocean climate model simulations of the M2 glacial event in order to investigate the climate effect of potential ice sheet scenarios during this time. Our climate model, HadCM3 is run with dynamic vegetation, altered CO_2 and orbital configurations. Possible ice sheet configurations are based on Quaternary analogues. We compare our simulations with available terrestrial and marine reconstructions to provide guidance as to which experimental set-up might offer a more sensible reconstruction of global climate during the M2 glaciation.

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Land-sea correlation of the Pliocene-Pleistocene transition and early glacial - interglacial cycles in the southern North Sea

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A spliced Gelasian record from cored sections of North Sea boreholes for the first time portrays the detailed onset of Northern Hemisphere Glaciations from a shallow marine setting. The data is part of a multidisciplinary regional mapping of the Neogene Eridanos delta in NW Europe, which involves seismic, petrophysical, geochemical and biostratigrahical analyses. Uniquely, over 30 boreholes with detailed marine palynology records are available providing 3D grip on delta architecture. The palynological assemblages are rich in dinoflagellate cysts (dinocysts) and contain abundant pollen and spores resembling a transported assemblage of regional vegetation.
Paleomagnetic and palynological data provide a solid integrated timeframe that ties the obliquity cycles, expressed in the wireline logs, to Marine Isotope Stages (MIS) 103 to 94. Climate-forced grainsize variations show fining upward from coarse silt at the beginning of an interglacial, to clay at the top of each glaciation. Integrated palynological and organic geochemical records allow high resolution reconstructions of land- and Sea Surface Temperature (SST), vegetation, relative sea level, productivity, salinity, humidity and runoff. The palynological records indicates Late Pliocene gradual cooling followed by distinct warm-cold alterations and late Gelasian cool phase. During the prominent cold stages MIS 100, 98 and 96, the palynological record indicates stratification of the water column, increased herb domincance, and low SST and sea level indicators. During the warm stages MIS 99, 97 and 95 freshwater influx increases with higher tree percentages and. From the presence of outer neritic dinocyst taxa in the warm stages a relative high sea level is inferred. The terrestrial palynological record shows variations between dominantly open grassland and heath lands during glacials and more forested landscapes during interglacials. The freshwater algae Pediastrum peaks each time at the transition from glacial to interglacial, indicating increased run-off.
SST reconstructions based on palynomorphs show a clear coupling to the wireline log, total organic carbon, and a organic geochemical index for marine/terrestrial ratios (BIT), all showing increasing amplitude during MIS 103 to 94. The multi-disciplinary data obtained from the spliced record sets a regional stratigraphic standard for the Gelasian, and provides coupled land-sea climate evolution of the earliest Quaternary glaciations in NW Europe.

Keywords: marine palynology, Gelasian, cooling, Eridanos delta, The Netherlands

PRISM4 marine – terrestrial data-model synergism

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For twenty-five years the US Geological Survey PRISM Project has fostered a better understanding of the Pliocene as it represents an accessible warm world with relevance to future climate conditions. The PRISM (Pliocene Research, Interpretation and Synoptic Mapping) reconstruction has undergone a number of phases, generally adapting to the needs of the climate modeling community. With the success and knowledge gained from the first phase of the Pliocene Model Intercomparison Project (PlioMIP), PRISM now focuses research in two areas: (1) high-resolution time series from MIS M2 through KM5 at a number of localities in the mid to high latitude Atlantic and Pacific Oceans. We hope to provide confidence assessed constraints on temperature, productivity, salinity, surface and deep circulation, analysis of upwelling systems using both proxy data and simulation output, and reassessment of low latitude thermal stability, all areas of discord between the PlioMIP Phase I simulations and proxy data; (2) interface with PDIP (Palaeoclimate Data Integration Project), an international collaboration of workers whose goals include a better understanding of the integration of multiple environmental proxies, marine and terrestrial, applied to deep time sequences. We present a brief history of the PRISM work to date and preliminary PRISM4 and PDIP results.

2013 PLIOCENE ABSTRACT:

Evaluation of Proxies for Reconstructing Pliocene Southern Ocean Surface and Intermediate Water Hydrography

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The reconstruction of past surface (SST) and intermediate water temperatures (IWT) are critically important for understanding feedbacks within the ocean-climate system. Little is known of Southern Ocean dynamics through the Pliocene and Pleistocene, especially at intermediate water depths, however their reconstruction is particularly important since intermediate waters, including Antarctic Intermediate Water (AAIW), are proposed to be an important driver in high-low latitude teleconnections. Herein, we present preliminary data from a sediment core in the Southwest Pacific (DSDP site 593; 1068m water depth), in the core of modern AAIW, from the last 4 Myr, with a focus on the last 1.5 Myr.

Alkenone-derived U^{K}_{37}' SST data show a similar values and trends to previously published SST estimates from foraminiferal transfer function over the last 1 Myr (Hayward et al., 2001), confirming its utility as a SST proxy for examining the Pliocene. Pliocene SSTs are, on average, warmer than those estimated for the Mid- to Late- Pleistocene.

Benthic paleotemperature proxies have caveats, including the 'Carbonate Ion Effect' on the Magnesium to Calcium ratio (Mg/Ca) of benthic foraminifera. However, recent studies demonstrated that the infaunal species, *Uvigerina peregrina*, co-precipitates Mg independent of secondary effects, affording the use of $Mg/Ca_{U.peregrina}$ as a paleotemperature proxy (Elderfield et al., 2010). Here we examine the utility of the $Mg/Ca_{U.peregrina}$ at intermediate water depths by comparing the downcore record to records of $Mg/Ca_{P.\ wuellerstorfi}$ (controlled by bottom water temperature and carbonation ion effects; Elderfield et al., 2006) and $B/Ca_{P.\ wuellerstofi}$ (controlled mainly by carbonate ion effects; Rae et al., 2011) from the same time interval. Our preliminary results suggest that Southern Ocean IWT, like SST, was warmer during the Pliocene than during the Mid- to Late- Pleistocene.

Large changes in upwelling intensity, biological production and nutrient utilization in the Eastern Equatorial Pacific over the last 3.2 Ma

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The Plio-Pleistocene climate transition was initiated by high latitude cooling and extension of ice sheets around ~2.75 million years ago (Ma). The climate transition in the equatorial Pacific was manifested as significant changes in biological productivity and sea surface temperatures (SST). During this interval, the eastern equatorial Pacific (EEP) experienced huge variations in export productivity between ~2.2 and 1.6 Ma. The causes for such a large increase in biological production remain unknown and are considered in this study. Here, we reconstruct primary productivity, nutrient supply and hydrological conditions across the Pliocene-Pleistocene climate transition. We combine paleoproductivity proxies (alkenone (C_{37}), total nitrogen (TN) and organic carbon (TOC) concentrations), nitrogen isotope ($\delta^{15}N$) and alkenone-derived SST records from two EEP ODP Sites 1239 and 1240 spanning the last 3.2 Ma.

Between 3.2 and 2.2 Ma, during a cooling phase, the TN and TOC contents as well as the $\delta^{15}N$ values at both EEP Sites were low, while C_{37} concentration at Site 1239 displays variable values. From 2.2 to 1.6 Ma, during an interval of accentuated cooling, all the paleoproductivity indicators revealed extremely high values. This contrasts with the lowest and nearly invariable $\delta^{15}N$ values reconstructed in the EEP. During the last 1.6 Ma, this period of more stable SSTs corresponded to a decline in TN, TOC and C_{37} concentration values, while the $\delta^{15}N$ shifted towards increasing values. The SST record was mainly imprinted by the 100 ka signal through the Pleistocene, and in lesser extent by the 41 ka oscillations, more dominant during the late Pliocene/early Pleistocene cooling. During the first two periods, the C_{37} and TN records varied at 41 frequencies, while the late Pleistocene was characterized by the absence of any detectable frequency in these records. In contrast, the $\delta^{15}N$ records oscillated at both a 41 ka and 100 ka cycles through the Plio-Pleistocene.

Our results, combined to other records, suggest that the biological production maximum event occurring in the EEP between ~2.2 and 1.6 Ma was likely caused by both increased nutrient export sourced in polar oceans and the coeval establishment of a modern-like strong equatorial upwelling zone, driven by the intensification of both meridional and zonal atmospheric circulations. The enhanced utilization of nutrient in the high latitudes and increasing denitrification in the equatorial regions limited the nutrient supply and availability in the EEP, thus resulting in the termination of this high export production event ~1.6 Ma ago.

Persistent ENSO during the Pliocene?

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The El Niño - Southern Oscillation phenomenon (ENSO) is known to be the dominant mode of variability in the present-day climate. Likewise, growing evidence suggests that ENSO has been active over a vast geological epoch stretching millions of years from the Late Cretaceous to the Holocene. How ENSO persisted despite dramatic changes in global and tropical climates over this timeframe is a fundamental question of climate dynamics. Even more puzzling is that ENSO apparently persisted through the Pliocene when there occurred a strong reduction in the mean east-west temperature gradient in the equatorial Pacific - is a key element of the tropical ocean-atmosphere system (e.g. Fedorov *et al.* 2013, Nature 496). The mechanism of sustained ENSO activity in such a climate is not understood. Here we use a comprehensive climate model (CESM) to explore the dependence of ENSO on this mean temperature gradient. We find that in a broad range of climates El Niño remains surprisingly robust. When the mean east-west temperature gradient is reduced from 6^{o}C to 1^{o}C, the amplitude of ENSO decreases only by 30-40%, its dominant period remains between 3-4 years, and the spectral peak stays above red noise. To explain these findings we assess the magnitude of ocean-atmosphere feedbacks that control the stability of the natural mode of ENSO. Our computations show that due to reorganization of the atmospheric Walker circulation in response to changes in the mean temperature gradient, the growth/decay rates of the ENSO mode stay nearly constant throughout different climates. These results explain the persistence of the Southern Oscillation in past geological epochs and reconciles the seemingly contradictory findings of ENSO occurrence and the small east-west temperature gradient during the Pliocene.

Long-term stability and sensitivity of the Western Equatorial Pacific warm pool to radiative forcing

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The Western Equatorial Pacific (WEP) warm pool is an important source of heat for the global climate system, and small variations in its sea surface temperature (SST) can alter cloud cover and atmospheric circulation with global consequences. From orbital resolution SST reconstructions over Pleistocene glacial cycles, previous studies have inferred that the WEP warm pool largely responded to pCO_2-radiative forcing (Medina-Elizalde and Lea, 2005; Dyez and Ravelo, 2012). However, these reconstructions do not provide information on the thermocline, which is tightly coupled with SST, and were based on measurements of pooled foraminiferal shells, which do not resolve short-term SST variability. To investigate changes in the mean state, we combine published low-resolution SST records with a newly generated subsurface temperature record to monitor the thermocline. Additionally, to monitor high-resolution variability, populations of individual surface and subsurface dwelling foraminifera were analyzed from glacial-interglacial (G-IG) pairs from four intervals since the early Pliocene. Though pCO_2 values are estimated to be 350-400 ppm during the Pliocene (Seki et al., 2010; Pagani et al., 2010), throughout the last four million years long-term mean SSTs were similar to present day, and there were G-IG shifts of ~+0.6 to -2.0°C in the mean state relative to the Holocene. In contrast, subsurface temperatures in the early Pliocene were warm and gradually cooled to present day values, indicating a long-term shoaling or cooling of the tropical thermocline. Although the pairs show G-IG changes in mean surface and subsurface temperatures, the within-sample variability of single foramininfera measurements did not change since the early Pliocene. This implies that while the tropical long-term mean state (i.e. thermocline structure) and other boundary conditions (e.g. ice volume, pCO_2) have changed since the early Pliocene, the mechanism and feedbacks responsible for G-IG mean temperature changes are similar and consistent through time. We infer that changes in mean SST and subsurface temperatures on G-IG scales since the early Pliocene have responded largely to pCO_2 forcing and related feedbacks.

Modelling Pliocene warmth: how far have we come and what can we do next?

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Since the 2008 workshop, the number of climate model-based studies has increased. Most but not all of these new studies have focussed on modelling and understanding the mid-Pliocene Warm Period (mPWP). The mPWP is moving towards parity with other intervals such as the mid-Holocene and the LGM in terms of the attention it receives from modelling groups. There are numerous reasons why this is happening. For example, the continuing publication of new proxy records, the emerging paradigm of Earth System Sensitivity, and the developing role of the mPWP in the IPCC. Here we focus on another force behind the expansion of Pliocene model-based studies, the Pliocene Model Intercomparison Project.

In the pioneer days of Pliocene modelling it was common to perform experiments and sensitivity tests with a single climate model. In none of these studies was the *clear and present danger* of model dependency addressed (how different can model predictions be?). PlioMIP examines model-dependency and enables us to determine climate and environmental changes that are common across models.

PlioMIP has shown that whilst there are commonalities in model outputs, substantial variations exist in the sensitivity of models to the implementation of Pliocene boundary conditions. Models appear able to reproduce many changes in temperature and precipitation reconstructed from geological proxies. The spread in the PlioMIP ensemble for surface temperature change/precipitation can be large, and often encompasses the signal from proxy data. From a certain perspective this is encouraging. It implies that data/model comparison for the mPWP has the potential to determine which models do better than others. However, to attempt this with confidence limitations in currently available global syntheses of proxy data need to be addressed. It is difficult to use Pliocene proxy data to differentiate climate models if the ‘target’ is movable, i.e. the data does not reflect a single interval of geological time (i.e. time slice rather than a time slab).

PlioMIP indicates that ESS is greater than Climate Sensitivity (CS), and suggests that the ratio of ESS to CS is between 1 and 2, with a best estimate of 1.5. However, such estimates remain flawed due to the effects of orbital forcing during the mPWP producing changes in vegetation and ice sheets that were not responses to changing atmospheric CO_2 alone.

Palynological and geochemical analysis of North Atlantic circulation at the onset of late Cenozoic Northern Hemisphere Glaciation (ca. 2.78–2.52 Ma, MIS G9–100).

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Dinoflagellate cyst assemblages and foraminiferal geochemistry from a ca. 250 kyr time slab (2782–2520 ka) straddling the base of the Quaternary Period have been evaluated utilizing a same-sample methodology to assess the development of North Atlantic surface circulation during this critical interval. The 168 samples used in this study originate from two cores positioned to assess the North Atlantic Current (NAC): DSDP Hole 610A, in the path of the present NAC and IODP Hole U1313C in the subtropical gyre. Stable isotope analyses from both holes confirm the timing of the main phase of the onset of northern hemisphere glaciation near the marine isotope stage (MIS) G7–G6 transition (2.74 Ma). The palynological record, however, shows a continued dominance of the dinoflagellate cyst *Operculodinium centrocarpum* sensu Wall and Dale [1966], an NAC indicator, until MIS 104. During MIS 104 in Hole 610A this species is replaced rapidly by taxa reflecting much cooler conditions (e.g. *Pyxidinopsis braboi* and *Nematosphaeropsis labyrinthus*). These results indicate the high-latitude persistence of the NAC for about 110 ka beyond the recorded geochemical turnover at the inception of MIS G6, followed by a fundamental reorganization of North Atlantic surface circulation during MIS 104 (~2.6 Ma). The timing of the dinoflagellate cyst assemblage turnover supports the recent decision to lower the base of the Quaternary Period to 2588 ka.

A 100-kyr world in the Southern Hemisphere before Northern Hemisphere Glaciation?

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Very few records of southern hemisphere variability at the orbital timescale exist for the mid-Pliocene. We report here proxy records that monitor sea surface temperature (alkenone unsaturation), carbonate sedimentation (color reflectance), and intermediate water density and chemistry (stable isotopes) from ODP Site 1125 (Tasman Rise) from ~ 2.8-4 Ma. All data sets show prominent 100 kyr cyclicity, with a subordinate imprint of the 41 kyr obliquity cycle. SST and benthic $\delta^{18}O$ and $\delta^{13}C$ are tightly coupled and in phase. SST patterns strongly resemble a high latitude North Atlantic SST record from the same interval. What is more surprising is that the best match of the ODP 1125 proxies to an orbital template has warm, interglacial climates corresponding to minima in Eccentricity, the reverse of the late Pleistocene association. Our information therefore hints at a more striking difference in orbital pacing of climate before Northern Hemisphere glaciation than previously recognized.

Impact of palaeogeographic changes on simulations of the Pliocene North Atlantic

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The strong warming seen in records of sea surface temperature (SST) in the North Atlantic has proved difficult to reproduce in mid-Pliocene climate simulations. Direct comparisons between the data and models are hampered by differing techniques used in palaeoenvironmental reconstruction and physical climate simulations. However, even if current simulations are not directly comparable to the reconstructions of the North Atlantic, something must have forced these particularly high temperatures for at least parts of the mid-Pliocene warm period. Even transient simulations may struggle to get short-term warming of the observed magnitude, as SSTs are beyond those simulated by fixing the orbital solution to produce Northern Hemisphere maximum forcing.

Here we present a series of simulations exploring palaeogeographic changes in and around the North Atlantic region that have not been previously incorporated into climate simulations. Changes include river rerouting, reduced iceberg melt, lowering of North Atlantic sills and changes in the peripheral seas. We use the Hadley Centre coupled atmosphere-ocean HadCM3 to estimate the impact of these changes on SST in the North Atlantic. With simulations based on the PlioMIP Experiment 2 protocol, but with the changes applied individually and as a whole, we show that these palaeogeographic changes can produce changes in North Atlantic SST of a similar magnitude to data-model discrepancies. If firm conclusions are to be drawn about the ability of models to accurately reproduce past temperatures we need to ensure that the full range of possible palaeogeographic change has been incorporated into palaeoclimate simulations.

Speleothems as high-resolution archives of Pliocene climate.

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Speleothems (cave carbonates) have in recent decades become a major archive of terrestrial palaeoclimate in the Late Pleistocene, due to the combination of high resolution proxies and U-Th chronologies. New advances in the U-Pb dating of carbonates now enables speleothems of Pliocene age to be dated, and the application of well established speleothem research methods to the problems of Pliocene climate. I will outline approaches to the dating of Pliocene speleothems, including orbital tuning and the production of annual band chronologies, and the generation of high-resolution records of $\delta^{18}O_{rainfall}$. Examples of Pliocene ENSO variability, palaeotemperature proxies and data-model comparisons will be based on Southern African speleothems that span the late Miocene to the early Pleistocene.

Bristol Abstract

Tackling sea ice parameter uncertainties in GCM simulations of the mid-Pliocene

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Sea ice exerts a large influence over the climate in high latitudes in the Northern Hemisphere, so it is crucial that general circulation models (GCMs) represent sea ice processes proficiently. Important parameters in sea ice modelling include albedo and ice diffusivity. Recent studies of sea ice albedo hint that the standard minimum albedo values used in GCMs could be too high, and there is a wide range of uncertainty over the correct sea ice diffusivity value. Both minimum sea ice albedo and sea ice diffusivity paramters in GCMs are often used as tuning parameters, with the tuning typically for modern day climate, which may not be appropriate for a climate substantially different to the present.

Climatological reconstructions of the mid-Pliocene warm period (3.29 - 2.97 Ma) indicate that global mean temperatures were approximately 3°C higher than present day, with a warming of up to 10°C in the Arctic and North Atlantic. However, GCM simulations of this time period have failed to reproduce this high-latitude warming. An inappropriately high minimum sea ice albedo value, or insufficiently high diffusivity parameter could be preventing higher levels of polar amplification. In a warmer than present climate such as the mid-Pliocene, it is likely that a greater proportion of the ice in summer is first year ice, which has a lower average albedo than multi-year ice.

To investigate the full effects of changes to maximum and minimum albedo values on mid-Pliocene simulations, 24 different simulations with varying albedo settings were run using HadCM3. 5 simulations were run with altered sea ice diffusivity parameters, and these were also run in combination with four of the combinations of altered albedo limits.

For simulations with reduced minimum albedo, mean annual surface air temperatures north of 70°N show an average increase of $2-3$°C, with up to 6°C increase in some areas. This suggests that changes to the albedo in the models could make a contribution to achieving the polar amplification that mid-Pliocene simulations currently fail to obtain.

Results indicating the effects of changing the sea ice diffusivity parameter, on its own and in combination with changes to the sea ice albedo limit, will also be shown.

Long-term trend of stratification in the Bering Sea inferred from nitrogen isotopic compositions at IODP Sites U1341 and U1343

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The Bering Sea is one of the marginal seas in the North Pacific and though to be most enhanced marine productive surface water in the world due to enough nutrient supply from nutrient-rich subsurface water and continental shelf. It was reported that surface stratification in the subarctic North Pacific was enhanced during the Northern Hemisphere Glaciation (NHG) at 2.7 Ma (e.g. Haug et al., 1999). However, continuous records of nutrient condition and surface water structure in the Bering Sea were not revealed from Pliocene to Pleistocene. During the IODP Expedition 323, the continuous sediment sequences were drilled from the Bowers Ridge (Site U1341) in the central Bering Sea and the Beringian margin slope (Site U1343) back to late Pliocene. We analyzed nitrogen isotope ($\delta^{15}N$) of bulk sediments to reveal nutrient condition and surface stratification in the Bering Sea. The $\delta^{15}N$ values are relatively low, close to 2 ‰ from 4.3 Ma to ~1 Ma at Site U1341, indicating that there was an abundant supply of surface water nitrate and possibly less denitrification in the upwelling source waters. These records dose not support a drastic changes in the surface stratification in the central Bering Sea following the onset of the NHG. $\delta^{15}N$ values increased most dramatically just after the Mid-Pleistocene Transition (to a range of 4 to 6 ‰) reaching modern values indicative of water that carries a strong denitrification signature and nearly full nitrate utilization at the sea surface. These results indicate that the increasing stratification and/or decreasing ventilation (increasing denitrification) of intermediate water as climate cooled particularly in the Late Pleistocene. On the other hand, $\delta^{15}N$ records show continuously higher value about 7‰ at the U1343, suggesting the sedimentary nitrogen was significantly affected by strong denitrification in the intermediate water in the Bering Sea and/or on the continental shelf.

Benthic Foraminiferal Distribution and Diversity in Pliocene in the West Indian Ocean : Implications to Paleoecology

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Considerable amount of work has been done to understand Paleoecology, Paleoclimatic and Paleoocenographic evolution of the Indian Ocean during Pliocene using faunal data. Benthic foraminifera have substantial scope in paleoecological studies because of their wide distribution in all marine environments and the high fossilization potential of their tests. Faunal proxy data suggests major changes in the Cenozoic Earths climate forms relatively warm and equable climate in the Paleocene to cold conditions with nearly frizzing temperatures at the poles in the Pliocene. Deep-sea benthic foraminifera have been used to understand changes in deep water condition driven by climate forcing during the Pliocene. Deep sea-benthic foraminiferal species at different locations of South of West India Ocean (3150-4125 m water depth) is examined in terms of number of species (n) and diversity (d). The observed depth ranges of benthic foraminifera have been documented to recognize their distribution in Pliocene . Productivity continued in the Indo-Pacific Ocean (the biogenic boom) and the Oxygen minimumzone (OMZ) intensified over large parts of Indian Ocean continually . The diversity values show more abrupt trend as depth increases. Species like *Epistominella exigua* and *Pullenia bulloides* occur at both 3150 m & 3465 m depths indicating depth persistence. Further, *Oridorsalis umbonatus* and *Melonis sphaeroides* occur at both 3150 m & 3465 m depths. Species like *Gyroidina* sp an indicate of low oxygen environment and *Uvigerina hispida-costata* indicative of high organic carbon are found to occur at 3150 m & 3740 m respectively. Factor analysis and Pearson correlation matrix was performed on foraminiferal census data of 10 highest ranked species which are present in at least one sample. 3 factors were obtained accounting for 72.81% of the total variance. Thus the study suggests that fluctuations in species diversity at the locations of the present study were related to changes in productivity during the Pliocene . Further, the faunal data do indicate the early Pliocene Indian Ocean was influenced by increased ventilation perhaps by North Atlantic deep water and or circumpolar deep waters.

High-resolution topographic model for the Neogene Greenland-Scotland Ridge

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The Greenland-Scotland Ridge (GSR) is a vital element in global climate models because its elevation has strongly affected the strength of meridional overturning circulation through Neogene time. It has long been suspected that shallowing of the GSR since the mid-Pliocene could have promoted onset of the Northern Hemisphere Glaciation. Recent cross-disciplinary work on interaction between the Mid Atlantic Ridge and the Iceland Mantle Plume has yielded an improved history of GSR vertical motions. The most important control on GSR elevation during the Neogene has been temperature pulsing within the head of the Iceland Mantle Plume. Hotter/cooler rings of mantle travel rapidly outward from Iceland beneath the surrounding plates, like ripples on a pond. These cause periodic changes in GSR elevation close to Iceland of –100 to –200m (relative to present), with each phase of uplift or subsidence concentrated in <1 My. Relatively cool mantle lay beneath Denmark Strait and the Faroes region during the mid Pliocene, leading to a deeper GSR. The next most significant control on GSR elevation is oceanic plate cooling with age. Plate age does not increase monotonically away from the modern Mid Atlantic Ridge because of episodic relocations of the spreading axis at Iceland, themselves related to changes in the mantle plume beneath. Better plate age models are now available, based on improvements in understanding of Icelandic tectonics. The effect of plate cooling since the mid Pliocene is about +100m at Denmark Strait and the Faroe-Iceland Ridge and +10m in the Faroe-Shetland Channel. Eustatic sea-level change was about –25m. Sediment accumulation and compaction effects were less important still: up to –20m in the Faroe-Shetland Channel and –10m at Denmark Strait, with barely any effect on the Faroe-Iceland Ridge. The flexural effect of growth of the Greenland Icesheet since the mid Pliocene is negligible. These individual effects have been combined to produce a new vertical motion model for the GSR (and wider region). Denmark Strait and the Faroe Iceland Ridge were up to 200m deeper during the mid Pliocene than at present. Uncertainty comes mostly from combined uncertainies in plume pulsing and plate cooling effects. Recent climate modelling has shown that a 1 km deeper GSR produces a better simulation of the observed Pliocene meridional temperature gradient. Can more realistic representations of GSR deepening in higher resolution Pliocene climate models also reproduce Pliocene temperature proxies?

A benthic isotope record from the late Pliocene of IODP Site U1389 in the Gulf of Cadiz

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The precise mechanisms that drove the transition from a warm Pliocene to a cold Pleistocene, dominated by widespread Northern Hemisphere glaciations, are still poorly understood. Here, we present high resolution (~5 kyr) benthic isotope records from the lower core of the Mediterranean Outflow Water (MOW) for the late Pliocene – earliest Pleistocene transition (1.8-2.6 Ma). Data are compared to current records from the Mediterranean and open ocean to shed new light upon the evolution of the MOW during the onset of major Northern Hemisphere glaciations.

Synchronous cooling of mid-latitude oceans during the early Pliocene and its implications for the Panama hypothesis

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Based on paleoceanographic studies from either side of Panama it was assumed that the constriction of the CAS reached a critical threshold during ~4.8-4 Ma with distinct effects on the ocean circulation and climate. Through this tectonic closure model simulations predicted a significant increase of the Atlantic meridional overturning circulation leading to higher sea surface temperatures (SST) and sea surface salinities (SSS) of up to 7°C and 3 psu in the Northern Atlantic Ocean, while the entire Southern Hemisphere would experience cooling and freshening through "heat piracy" of the Northern Hemisphere. To test this "Panama hypothesis" during ~4.8-4 Ma we selected DSDP core sites 516A from the South Atlantic and 610A from the North Atlantic which are sensitive to the proposed interhemispheric changes in SST and SSS. We here used the combined measurement of Mg/Ca and $\delta^{18}O$ from planktic foraminifera *G. sacculifer* and *G. bulloides* to reconstruct sea surface temperatures and changes in salinities. However, our results are in contrast to the "Panama hypothesis": We find a sea surface freshening and a distinct cooling of up to ~4°C during ~4.6-4 Ma at both hemispheres in the Atlantic Ocean without any climatic effects from the constriction of the CAS. In combination with other SST reconstructions these data indicate a global cooling of the mid-latitude oceans of both hemispheres. We interprete this global cooling due to solar forcing with important implications for the depth of the thermocline in the equatorial eastern Pacific. Our data point to a mechanism that cooling of surface waters of the mid-latitude oceans led to a cooling/shoaling of the equatorial eastern Pacific thermocline (Harper, 2000) and presents for the first time an alternate interpretation for the cooling/shoaling of the East equatorial Pacific thermocline which started to terminate permanent El Niño-like conditions during the early Pliocene.

Reduced Atlantic circulation during the Pliocene warming?

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Changes in Atlantic meridional overturning circulation (AMOC) during the mid-Pliocene warm period (3.3–3.0 Ma) were studied at a suite of northeast Atlantic drill sites by using neodymium isotope (ε_{Nd}) and Mg/Ca-based temperature records of bottom water masses between 1135 and 5050 m water depth. The data were compared to new and published benthic foraminiferal $\delta^{13}C$ records. Results indicate ~2.5°C warmer and ~0.5‰ lesser ventilated water masses than today at all sites, which reflects a weak difference between water masses. The weak stratification is corroborated by ε_{Nd} values near –10 at all sites, which differs markedly from the clearly distinct modern ε_{Nd} signatures at each site. The lesser ventilated, warm, and weakly stratified water masses are most likely the result of the weaker AMOC during that time of global warming. Our study may provide a means of gaining insight into the effects of global warming on the Atlantic overturning circulation and climate in the near future.

NW African plant-wax signals during the Pliocene

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Climate conditions during the Mid-Pliocene Warm Period (MPWP) are often referred to as analogue scenario for future climate projections. Most findings derive, for instance, from dust, pollen and isotopic records, but allow for only indirect inferences about the continental paleo-hydrologic regime. Hence, one main purpose of this study is to decipher rainfall variability over NW Africa with a molecular isotopic approach by using hydrogen (δD) and carbon ($\delta^{13}C$) isotopes of terrestrial plant waxes obtained from deep-sea sediments (ODP Site 659). Furthermore, we compare conditions before (5-4.6 Ma) and during (3.6-3.0 Ma) the closure of the Central American Seaway (CAS) to investigate the impact of enhanced Atlantic Meridional Overturning Circulation (AMOC) on NW African biomes and climate. The general pattern of the Pliocene plant-wax isotopes is in good agreement with pollen and dust records and shows higher contributions of C_3 plants, interpreted as northward shifts of the Sahara-Sahel transition, under overall wetter conditions compared to the last glacial cycle. Nevertheless, there are almost no changes within the Pliocene, i.e., before and during the final CAS closure. Thus, humid conditions are a general attribute of the Pliocene and not only restricted to the MPWP. The glacial pattern of anti-correlating plant-wax δD and $\delta^{13}C$ is not observed in the Pliocene data, explained by the lack of glacial/interglacial modulations and generally weak North-East Trade Winds in the absence of large Northern Hemisphere ice sheets. Our Pliocene results do neither support a link to AMOC variations, nor to changes in sea surface temperatures. Instead, NW African paleo-hydrology and associated shifts in vegetation type are mainly controlled by low-latitude insolation intensity with highest climate variability during eccentricity maxima.

Indonesian Seaway Closure and Pliocene paleoclimatic changes in the eastern Indian Ocean: Benthic foraminiferal record

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Abstract

The deep sea benthic foraminifera of last 6.0 myr in the eastern Indian Ocean, offshore Western Australia were examined to understand the tectonically/climatically induced paleoceanographic changes in this region. Characteristic faunal assemblages and increased faunal diversity along with low values of benthic $\delta^{18}O$ suggest relatively oligotrophic and warm bottom water conditions during most of the early Pliocene. Prior to the final closing of the Indonesian Seaway at about 4-3 Ma (Cane and Molnar, 2001) a permanent El Nino like condition was existing due to continuous exchange of warm water mass from the south Pacific to the eastern Indian Ocean. At the beginning of the late Pliocene (i.e. ~3.5 Ma) relative abundances of *Uvigerina proboscidea* (an upwelling and high productivity species), infaunal taxa and high productivity taxa increased, whereas faunal diversity showed a distinct decline along with higher $\delta^{18}O$ values suggesting the development of pronounced upwelling resulting in higher surface water productivity. The strongly reduced inflow of warm and oligotrophic water masses as the South Equatorial Current (SEC) from the South Pacific to the eastern Indian Ocean due to the effective closure of the Indonesian seaway increased the surface water productivity. The closing of the Indonesian seaway during the late Pliocene was also responsible for the cessation of the warm, southward-flowing Leeuwin Current (LC) and the greater influence of the cold, deep and northward-flowing Western Australian Current (WAC) in the eastern Indian Ocean. It was probably during this period that westerly equatorial winds also became stronger, which started to impinge on the west coast of Australia, and were accompanied by stronger tropical easterlies blowing off the Australian landmass. These stronger offshore winds are responsible for intense offshore Ekman transport, causing potential upwelling of cold and nutrient-rich water and development of higher surface water productivity at low latitudes off the west coast of Australia. The flow of northern cold Pacific waters into the Indian Ocean may have lowered SSTs in upwelling regions, which caused the cooling of northern America through teleconnections and also initiated the late Pliocene Northern Hemisphere glaciations. These changes in the circulation pattern are the major controlling factors for upwelling, surface water productivity and deep sea ventilation, which ultimately influence the benthic foraminiferal distribution in this region.

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Neogene Dinoflagellates and Global Change

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Proxies are an essential tool to enhance our understanding of climate change and ocean circulation. Dinoflagellate cysts make excellent proxies because their cysts preserve well and temperature, salinity, ice cover, and nutrient content limit their abundance and diversity. They will be used as a proxy to infer the ocean circulation at a global level during the Neogene and have the potential to help predict future changes. The evolution of Neogene climate is important to study, as modern climate conditions are a direct result of the changes that took place during the last 20 million years. This allows for a better understanding of how and why the natural systems change and what the potential effects of future changes might be. I intend to research how the circulation of the Neogene oceans evolved and use this information to predict future alterations to circulation patterns and determine possible impacts on the global climate. The research involves collecting and collating all the previously published data on dinoflagellate cysts during the Neogene into a database which I will then analyse and enhance by collecting further data to help fill in geographical gaps in the existing data set. Multiple palaeontological climate proxies are important for building reliable climate models, as they are essential to producing the most dependable boundary conditions. With a view to understanding the large scale changes, I will look in finer detail at the Piacenzian, 3.6Ma to 2.588Ma. This period contains a relatively stable warm period, known as the Mid-Pliocene Global warmth (MPGW), compared to the generally cooling climate and was the last sustained warm period found in the geological record. I will specifically be researching the North Atlantic Ocean, looking at samples gathered from IODP sites U1313 and U1308 and DSDP site 610 amongst others in order to gather information as to the changes that took place such as the position of the Gulf Stream, the closing of the Central American Sea way as well as the build-up of ice in the northern regions.

The evolution of Atlantic Overturning Circulation during the Plio-Pleistocene intensification of northern hemisphere glaciation

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The ocean, through its ability to globally redistribute heat and partition carbon dioxide, is believed to play a key role in driving and amplifying climate change during Quaternary glaciations on orbital to millennial timescales. Little is known, however, about the changes in the Atlantic Meridional Overturning Circulation (AMOC) associated with the culmination of Earth's most recent major climate transition, the intensification of northern hemisphere glaciation (iNHG) by ~2.5Ma. Evidence for a long-term weakening of AMOC (e.g. Ravelo and Andreason, 2000), and suggestions of sub-orbital deep ocean circulation changes (Becker et al., 2006), during iNHG are primarily based on benthic carbon isotope records. Carbon isotopes may be biased, however, by changes in carbon cycling and associated changes in the isotopic composition of northern and southern deepwater sources during this interval of major global change. New proxy records of ocean circulation, independent of the carbon cycle, such as Nd-isotopes measured on fish debris, are therefore needed to evaluate the evolution of ocean circulation during iNHG. To this end I present new, sub-orbital resolution, records from the deep (IODP Site U1313, 3,426m) and intermediate (ODP Site 981, 2,157m) North Atlantic Ocean for the late Pliocene and earliest Pleistocene to assess AMOC dynamics as major northern hemisphere ice sheets first developed.

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Patterns of Early Pliocene Warmth: Synthesizing Ocean Surface Temperature Records

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Because the early Pliocene was the most recent interval of sustained warmth in Earth's history, with atmospheric carbon dioxide concentrations similar to those at present, it has been used as an analog for potential future climate conditions. Here, we synthesize existing Plio-Pleistocene sea surface temperature (SST) records derived from alkenone and Mg/Ca paleothermometry to characterize the spatial pattern of the ocean surface temperature field. Our synthesis includes nearly 30 time series, most of them continuous and extending from the Holocene to 5 million years ago. We find that relative to today, the early Pliocene was characterized by substantially reduced meridional and zonal temperature gradients, but similar maximum ocean surface temperatures. Mid to high latitude regions were 3-8ºC warmer, subtropical coastal upwelling regions were 4-11ºC warmer, cold tongue regions in the tropics were 3-5ºC warmer, even though warm pool regions had temperature similar to today. These differences, considered together, amount to a structural climate change between the early Pliocene and present-day SST patterns (Fedorov et. al. 2013, Nature 496). Beyond existing published Plio-Pleistocene SST records, here we also present novel SST datasets from the southern hemisphere. These datasets derived from sediments at ODP Sites 1125 (42ºS, 178ºW) and 1088 (40ºS, 15ºE), indicate that SSTs in these mid-latitude localities in the southern hemisphere were ~3-4ºC warmer than modern, confirming that augmented mid-latitude warmth during the early Pliocene was a bi-hemispheric phenomenon. Collectively, existing published and novel SST datasets from the early Pliocene support previous inferences that the tropical warm pool was significantly expanded during the early Pliocene and that despite having boundary conditions that are fairly similar to today's the spatial distribution of temperature during the early Pliocene was markedly different than modern. These observations suggest that either in its current state the Earth's climate is fairly sensitive to modest changes in forcing, or the present-day and early Pliocene climates represent two different stable states of the system.

Environmental reconstruction in the South Caspian Sea Basin using statistical analyses of a palynological dataset from the Pliocene Productive Series in Azerbaijan

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The South Caspian Sea Basin (SCSB) has been a very important oil and gas producing region since the late 19th century. The Early Pliocene strata, part of the Neogene Productive Series, are the principal reservoirs. The onset of the deposition of the Productive Series is correlated as approximately synchronous with the Messinian salinity crisis, which meant a water-level drop and the disconnection of the Caspian Sea from the general oceanic system. From a palynological point of view, the Pliocene in the SCSB has been the focus of detailed studies during the last decade (Lowe & Richards 2001, Richards 2010, Vincent *et al.* 2010). However, the published data is fragmented and does not show a continuous environmental reconstruction for the Productive Series. To fill this gap we present sixteen palynological records located onshore and offshore of the Apsheron Peninsula, covering the intervals from the Pontian (Late Miocene) to the Sabunchi Suites (Late Pliocene). Owing to a high volume of data (1376 samples, 79 taxa) we have used Principal Components Analysis (PCA) to reduce the dimensionality and to describe the main features of the palynological record. PCA analysis has been applied to: 1) the regional dataset (hinterland pollen) that has been a valuable tool for inferring temperature changes, and is in broad agreement with the oxygen stable isotopic record of the global ocean; and 2) the local dataset (aquatic pollen, spores, dinocysts and algae) that has been helpful for inferring lake level changes and other processes such as erosion, river input and water salinity changes. All these results combine to offer an exceptional opportunity to infer the environmental conditions in which the Productive Series was deposited and understand the complex system of the Caspian Sea during the Pliocene.

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δ^{11}B-based atmospheric CO_2 records during the Pliocene at orbital resolution

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The Mid-Pliocene is the most recent time in Earth's history when mean global temperatures were substantially warmer and sea level higher than they are today [Haywood *et al.*, 2000]. The subsequent intensification of the Northern Hemisphere Glaciation (iNHG) represents the key final step in the climatic transition from the warm Pliocene to the current "icehouse" climate. Recent modeling and proxy-based results [Lunt *et al.*, 2008; Pagani *et al.*, 2010; Seki *et al.*, 2010] suggest that this climate shift was forced by a reduction in atmospheric CO_2 concentrations (pCO_2), which highlights the relationship between climate and this important greenhouse gas. Hence, there is significant potential in the use of the Pliocene as an analogue for future global warming in modeling studies and as a key period to study the role of CO_2 in driving major climatic shifts. Despite recent advances in the reconstruction of pCO_2 change during this important period [Pagani *et al.*, 2010; Seki *et al.*, 2010], detail at the orbital scale is currently lacking.

Boron isotopes (δ^{11}B) in planktic foraminifera are a proven proxy for past surface oceanic pH [Sanyal *et al.*, 2001; Foster, 2008], which has provided valuable insights into past changes in the ocean carbonate system, and ultimately into past atmospheric pCO_2. Here we will present new planktic foraminiferal δ^{11}B-based pCO_2 records to determine the temporal evolution of pCO_2 for an interval spanning the Pliocene Warm Period and the iNGH at orbital scale temporal resolution. Our record provides insights into the causes and consequences of the changes in the atmospheric concentration of this important greenhouse gas.

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Southern hemisphere perspectives on Pliocene sea surface and intermediate water temperature

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The mechanisms driving the evolution of the global climate system over the last 4 million years continue to be debated, as does the nature of the feedbacks that translated such forcing into global climate change. As a consequence, our understanding of the sensitivity of some key climate feedbacks to warmer (Pliocene) and cooler (Pleistocene) global climate states has been limited. Here, we assess the timing and spatial patterns of ocean temperature change since the middle Pliocene in two regions of the southern hemisphere, the SE Atlantic and the SW Pacific. We reconstruct sea surface temperatures (SSTs) using alkenones (the UK37' index) and use benthic Mg/Ca analyses in the shallow infaunal species, Uvigerina peregrina, to reconstruct temperatures in the most extensive intermediate water mass in the present ocean, Antarctic Intermediate Water (AAIW). Although AAIW provides a key pathway linking low and high latitudes, its temperature evolution since the Pliocene is unclear.

We show that in the SE Atlantic (ODP 1087) Pliocene SSTs were 2-3°C warmer than present, but that a southward shift of the Benguela upwelling system had occurred, leading to higher levels of productivity at the site. In the SW Pacific, both SSTs and intermediate waters were warmer than present, consistent with a southward displacement of the Subtropical Front, warmer polar waters and reduced sea ice extent. Superimposed upon the long term signal of warmer Pliocene ocean temperatures, our data sets also indicate orbital and sub-orbital scale variability in the order of 2°C, with more pronounced cooling occurring during glacial stages such as M2 and KM2 (SSTs up to 5°C cooler than the mid Pliocene maxima). We assess here whether these events indicate an early development of glacial-interglacial cycles comparable to those which characterise the Pleistocene epoch

Changes in the North Atlantic deep circulation at the Eirik Drift during the Pliocene

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The global climate and its changes are coupled to the ocean circulation. The surface ocean stores and transports heat and freshwater, interacts with the overlying atmosphere and thereby impacts the climate. The global Termohaline circulation (THC) is described as a conveyor belt for heat and freshwater within the world's oceans. Deep-water formation in high latitudes is the driving mechanism of the THC. It connects the surface circulation with the reversed deep circulation. The Eirik Drift, located offshore southern Greenland, lies closely downstream of the deep-water formation regions of the Nordic Seas and is built under the influence of the deep branch of the North Atlantic THC. The sedimentary packages and structures of the Eirik Drift therefore bear information about the strength and direction of the North Atlantic deep-water circulation in a changing climate. High-resolution seismic reflection data were correlated with geological information of ODP Leg 105 Site 646 and IODP Expedition 303 Sites 1305-1307 to decipher the changes of the deep current system at the Eirik Drift. For the Pliocene epoch we observed an intensification of the deep currents at the Eirik Drift along with the climate reversal to the early Pliocene warm period (~5.6 Ma, horizon R2). The maximum deep current intensity at the Eirik Drift is documented in an erosional unconformity at ~4.5 Ma. The deep currents at the Eirik Drift remained strong during the transition to Pliocene cooling (~3.2 Ma) until ~2.5 Ma (horizon R1), when the onset of ice rafting evidences the intensification of Northern Hemisphere glaciation. The observation of intensified deep circulation during warm climate conditions and a weakening during the cooling phase is in conflict to our expectations. We suggest a southward shift of the deep-water formation region along with a shift of the deep current system during cool phases. This implies that the main North Atlantic deep-water route just affected the Eirik Drift during warm phases and that during cool phases solely weak branches of the circulation system overflowed the Eirik Drift.

Strengthening of North American dust sources during the late Pliocene (2.7 Ma)

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Here we present orbitally-resolved records of terrestrial higher plant leaf wax input to the North Atlantic over the last 3.5 million years, based on the accumulation of long-chain *n*-alkanes and *n*-alkanl-1-ols at IODP Site U1313. These lipids are a major component of dust, even in remote ocean areas, and have a predominantly aeolian origin in distal marine sediments. Our results demonstrate that around 2.7 million years ago (Ma), coinciding with the intensification of the Northern Hemisphere glaciation (NHG), the aeolian input of terrestrial material to the North Atlantic increased drastically. Since then, during every glacial the aeolian input of higher plant material was up to 30 times higher than during interglacials. The close correspondence between aeolian input to the North Atlantic and other dust records indicates a globally uniform response of dust sources to Quaternary climate variability, although the amplitude of variation differs among areas. We argue that the increased aeolian input at Site U1313 during glacials is predominantly related to the episodic appearance of continental ice sheets in North America and the associated strengthening of glaciogenic dust sources. Evolutional spectral analyses of the *n*-alkane records were therefore used to determine the dominant astronomical forcing in North American ice sheet advances. These results demonstrate that during the early Pleistocene North American ice sheet dynamics responded predominantly to variations in obliquity (41 ka), which argues against previous suggestions of precession-related variations in Northern Hemisphere ice sheets during the early Pleistocene.

Pliocene-Pleistocene sea surface temperature reconstructions: Comparisons and implications arising from a multiple proxy approach

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The tropical oceans are thought to have played a major role in the evolution of the Earth's climate since the Pliocene, such that accurately reconstructing tropical sea surface temperatures (SSTs) and SST gradients is an essential part of investigating how the global climate system has evolved over the past 5 Myr. Marine sediments from the tropical South China Sea (SCS) have yielded numerous palaeotemperature records, however disagreement among different proxies and the potential causes of these differences may be hindering our understanding of the climate system. Using sediments from ODP Site 1143 located in the southern SCS within the western Pacific warm pool, we have applied three independent paleo-proxies to examine variations in SST for the past 5 Myr. Specifically, we have generated comparable SST records using the TEX_{86} index and Mg/Ca ratios in planktic foraminifer, *G. sacculifer.*

Our SCS TEX_{86}- and foraminiferal Mg/Ca-derived temperatures, together with published alkenone $U^{K'}_{37}$-SST estimates, give good agreement in both absolute values and variability for the Pleistocene. In contrast, during the Pliocene SCS TEX_{86}-SSTs are offset to warmer values by ~0.5 °C relative to $U^{K'}_{37}$-SST estimates, whilst Mg/Ca-derived temperatures are offset to lower values by ~2.2 °C. Comparison of Mg/Ca SST estimates versus alkenone SST estimates for other localities including the Caribbean Sea and the Eastern Pacific reveals a similar magnitude of offset, ~2 °C, to what we observe for the southern SCS. The offset of Pliocene TEX_{86}-SSTs to higher values relative to $U^{K'}_{37}$-SST values likely reflects the inability of the $U^{K'}_{37}$ index to accurately record SST estimates above the limits of the $U^{K'}_{37}$ proxy (27-29 °C) and suggests warm, >27 °C, conditions in the Pliocene southern SCS. It is thus surprising that foraminiferal Mg/Ca ratios predict much cooler (>2 °C) SST estimates for the Pliocene SCS. After considering various environmental parameters including depth of habit, seasonality and salinity, both for the SCS and in other locations where this offset is observed, we propose that this offset reflects a lower ratio of Mg/Ca in seawater during the Pliocene. Having demonstrated that foramininferal Mg/Ca-SSTs are biased to lower values in the Pliocene we present our southern SCS TEX_{86}-SST estimates as a record of the evolutionary history of western Pacific warm pool SSTs during the past 5 Myr.

Pliocene paleoceanography in the Bering Sea: results from IODP Expedition 323

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During IODP Expedition 323, cores with high sedimentation rates were collected at 7 sites in the Bering Sea. Among them, a hemipelagic site drilled to 600 mbsf on Bowers Ridge provided records back to 4.3 Ma at U1341. Multi-proxy records revealed Pliocene paleoceanography in the Bering Sea. Alkenone paleothermometry indicate that averaged sea-surface temperature (SST) ranged from 10 to 14°C before 3 Ma, which was warmer than the present Bering Sea. Abundant %*Stephanopyxis* spp., warm water diatoms, supports the idea of warmer Bering Sea during the early Pliocene. Alkenone-SST ranged from 8 to 10°C between 3 and 2.5 Ma. Sea-ice related diatoms such as *Fragilariopsis cylindrus* and *F. oceanica* were present with low abundance since 2.9 Ma. Initial dominance of *Distephanus medianoctisol*, a polar silicoflagellate species, was observed at 2.7 Ma. The changes in microfossil assemblages coincide with those observed in alkenone-SST data. Although siliceous microfossil assemblages showed similar patterns to the pelagic subarctic Pacific (ODP 882), no drastic drops in both biogenic opal and number of diatom valves were observed in the Bering Sea with the intensification of the Northern Hemisphere Glaciation at 2.75 Ma.

Strengthening of Intermediate Water circulation in the Caribbean during the final stages of Central American Seaway closure

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Abstract

Shoaling of the Central American Seaway (CAS) brought about a major reorganization of ocean circulation and has been controversially reported as contributing to both a warming and a cooling of global climate. An increase in moisture supply to the northern hemisphere, through the strengthening of the Gulf Stream, may have been an important precondition for Northern Hemisphere Glaciation (NHG). The timing of CAS closure in comparison to changes in Atlantic Meridional Overturning Circulation (AMOC) is key to interpretations. Here we use the authigenic coatings of sediments in the eastern equatorial Pacific (ODP Site 1241) and the Caribbean (ODP Sites 999 and 1000) to reconstruct seawater Nd and Pb isotope compositions during the final stages of CAS closure between 5 and 2 Ma. Nd isotopic data for the Pacific site fall within a small range for the entire period of time investigated and indicate there was no influence from the Atlantic or Caribbean. Contrastingly, data from the intermediate depth Caribbean show a pronounced trend towards less radiogenic ε_{Nd} values from 3.9-3.1 Ma, which we attribute to a strengthened flow of Atlantic waters through a basin already isolated from all but shallow Pacific inflow. This provides further evidence for strong AMOC between 4 and 3 Ma [*Steph et al*., 2010] and a close relationship between a shoaling CAS and the strength of the AMOC. The ε_{Nd} signature of the intermediate Caribbean stabilized after 3.1 Ma, indicating that the onset of NHG did not further increase the strength of the Atlantic inflow.

Reference

Steph, S., R. Tiedemann, M. Prange, J. Groeneveld, M. Schulz, A. Timmermann, D. Nuernberg, C. Ruehlemann, C. Saukel, and G. H. Haug (2010), Early Pliocene increase in thermohaline overturning: A precondition for the development of the modern equatorial Pacific cold tongue, *Paleoceanography*, *25*, doi:Pa2202/2210.1029/2008pa001645.

Bette Otto-Bliesner

Why Modeling the Mid-Pliocene is Important for the Next IPCC Climate Change Assessment Report in 2019

Bette L. Otto-Bliesner[1], Alan M. Haywood[2], Ayako Abe-Ouchi[3], Mark Chandler[4], Aisling Dolan[2], Harry Dowsett[5], Daniel Lunt[6], Ulrich Salzmann[7], and PlioMIP participants

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"The Pliocene has entered the political mainstream of palaeoclimate and climate change science." This quote from Alan Haywood's keynote lecture at the 1st Pliocene Workshop in 2009 still very much holds today. Phase I of the Pliocene Model Intercomparison Project (PlioMIP), which examined the climates and environments of a time slab during the mid-Pliocene warm period (3.264 to 3.025 Ma), successfully incorporated climate model simulations, ice sheet model simulations and data into its assessment of this period. The model-data intercomparisons have primarily focused on surface temperature changes. Evaluations have also made of the regional changes in monsoons, the Atlantic meridional overturning circulation, and sensitivity of the ice sheets.

The extensive research publications on the Pliocene since the IPCC AR4 in 2007 allowed this period to be highlighted in the soon-to-be-released IPCC AR5 report. Chapter 5, Information from Paleoclimate Archives, includes, from a forcing perspective, an assessment of our knowledge on the atmospheric CO_2 and mineral dust aerosol concentrations from geological proxy data. The report also considers, from a response perspective, the Mid-Pliocene temperature changes and polar amplification, sea level, and climate variability as seen in the proxy record and simulated by climate models.

Planning for the modeling experiments, CMIP6, which will contribute to the IPCC AR6 in 2019 are underway. PlioMIP Phase II proposes to adopt a time-slice centered at 3.205 Ma (3.204 to 3.207 Ma) to better constrain the comparisons between models and data and help reduce uncertainties associated with forcings incorporated into the model designs. The model experiments included in PlioMIP Phase II will be important not only for Pliocene4Future but also Pliocene4Pliocene, thus advancing our knowledge of this period in its own right. In this talk, we provide an update from the 1st Pliocene Workshop on the progress, uncertainties, and future opportunities in Mid-Pliocene research from both a modeling and data perspective.

Multi-Proxy Reconstruction of Pliocene pCO_2: Implications for Climate Sensitivity

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Of the many motivations to investigate Pliocene palaeoclimate, one of the most prominent is its contribution to constraining climate sensitivity. The Pliocene, and especially the Mid-Pliocene, is the most recent time in Earth's history when mean global temperatures were substantially warmer than today. Given the relatively similar vegetation, geography and orography, it appears that this is largely due to elevated pCO_2 levels, and constraining those has been a focus of substantial recent research. Our previous work (Seki et al., 2010) applied a multi-proxy, planktic foraminiferal $\delta^{11}B$ and alkenone $\delta^{13}C$, approach at ODP Site 999 in the Caribbean. Although this work revealed broad agreement between the two approaches (350 to 400 ppm during the Mid-Pliocene), the temporal resolution of the record was low and insufficient to resolve glacial-interglacial cycles. Moreover, proxy agreement was attained only by adjusting the alkenone record for a putative decrease in coccolithophorid lith size. In the current work, we have dramatically increased the resolution of the Site 999 alkenone $\delta^{13}C$ and planktic foraminiferal $\delta^{11}B$ pCO_2 records, added the first Pliocene $\delta^{11}B$ records from additional sites, and directly interrogated proxies for growth rate and lith size that could influence the alkenone- pCO_2 record.

The major findings from foraminiferal $\delta^{11}B$ analyses are presented by Martinez-Boti et al. elsewhere at this meeting. In summary, the new Site 999 $\delta^{11}B$ records exhibit the same pronounced pCO_2 decrease from 3.0 to 2.6 Ma, a trend that we have now reproduced at lower resolution at other sites. However, the higher resolution analyses at Site 999 reveal profound (50-100 ppm) variability both before and after the intensification of Northern Hemisphere glaciation (INHG) and the concomitant initiation of strong glacial-interglacial cycles. In contrast, alkenone-derived pCO_2 records at Site 999 are similar to other sites and exhibit only a gradual decrease over the past 3 Myr; moreover, the magnitude of the change, as well as the magnitude of Pliocene G-IG variations, is much lower. In previous work, we have discussed the influence of changing cell size or growth rate on the alkenone record. Although such mechanisms cannot be precluded, we have evidence for neither: lith sizes remain relatively constant and biomarker, benthic foraminiferal and bulk OM productivity indicators indicate low and stable production. Thus, differences between the two proxies remain unresolved. Crucially, foraminiferal $\delta^{11}B$ suggests Mid-Pliocene pCO_2 levels of 320 to 420 ppm, whereas alkenone $\delta^{13}C$ values suggest levels of only 270 to 320 ppm (Badger et al., 2013).

These two different estimates have markedly different implications for climate sensitivity. As has been argued by Pagani et al (2009), the alkenone-derived pCO_2 levels indicate very high climate sensitivity, one that is markedly higher than that of the Pleistocene. In contrast, the $\delta^{11}B$ pCO_2 estimates suggest a climate sensitivity, at least across the INHG, that is similar to that of the Pleistocene.

Ocean circulation in the South-east Atlantic Ocean in the Pliocene

. ***Benjamin Petrick***[1], Erin L. McClymont[2], Sonja Felder[1], Melanie J. Leng[3]

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The Southeast Atlantic Ocean is an important ocean gateway because major oceanic systems interact with each other in a relatively small geographic area. However, there remain questions about circulation change in this region during the Pliocene, including whether there was more or less Agulhas Leakage, which transfers heat and salt to the Atlantic from the Indian Ocean and plays an important part in the global thermohaline circulation. ODP site 1087 (31º28’S, 15º19’E, 1374m water depth) is located outside the Benguela upwelling region but is affected by Agulhas leakage in the modern ocean. Sea-surface temperatures (SSTs) are thus sensitive to the influence of Agulhas Leakage at this site, whereas foraminifera species and pigment concentrations help to isolate the influences of the highly productive Benguela Upwelling system to ODP 1087.

Our approach is to apply several organic geochemistry proxies and foraminiferal analyses to reconstruct the Pliocene history of ODP 1087, including the U^{K}_{37}’ index (SSTs), pigments (primary productivity) and foraminifera (water mass changes). Our results indicate that the Benguela upwelling system had intensified and/or shifted south during the Pliocene. We find no evidence of Agulhas leakage, meaning that either Agulhas Leakage was severely reduced or displaced during the mid Pliocene. Finally there is dynamism during major cold periods characterised by SST decreases in the absence of changes in foraminifera species or pigment concentrations which may relate to changes in ice build up in Antarctica. Therefore there were displacements of the major oceanic systems in the Southeast Atlantic during the Pliocene.

Is it possible to reconcile models and data? An intra-model assessment of Pliocene climate.

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Uncertainty in model simulations arises due to the construction of the model (structural uncertainty), the representation of sub-grid scale processes (parameter uncertainty) or the input boundary conditions. Model intercomparison projects (e.g. PlioMIP) have been used to tackle structural uncertainty by assessing climate simulations from a range of different climate models given a standardised experimental design. Perturbed physics ensembles (PPEs) produce an ensemble of simulations using a single climate model. A PPE produces different representations of climate by altering the tuning of parameterisations representing processes occurring on sub-grid scales, such as clouds and radiation.

We present results from a PPE investigating model and boundary condition uncertainty for the mid-Pliocene Warm Period. Through the use of a PPE, 14 versions (13 perturbed members and the standard version) of the UK Met Office atmosphere-ocean general circulation model HadCM3 were created. The ensemble was run for different boundary conditions to assess the impact of simultaneously changing boundary conditions for orography, ice sheets and vegetation in combination with perturbed physics. Finally the effect of the potential range in reconstructed mid-Pliocene CO_2 was investigated through a sub-ensemble of the PPE.

Site to site data-model comparisons (DMCs) were performed on sea surface temperature (SST), surface air temperature (SAT) and biomes. For the SSTs, well established regions of large data-model mismatch (i.e. a model cold bias through the North Atlantic) in these comparisons were maintained. However, the magnitude of the mismatch was reduced in ensemble members with parameterisations resulting in warmer simulated climates. A similar response was observed in the terrestrial SATs, with warmer ensemble members reducing the model colder than data mismatch through Eurasia. Cohen's Kappa statistics showed that only one member performed better than the standard version in comparison to the biome reconstruction.

Ensemble member zonal means show a strong relationship with zonal means derived from proxy data in the mid-latitudes with models too warm in the tropics and too cool in the highest latitudes, however, the data-model zonal mismatch is small. Ensemble members run with lower CO_2 concentrations reconcile tropical data-model mismatches, however these ensemble members produce a weaker high latitude data-model comparison than their 400 ppm CO_2 equivalents.

Late Pliocene lakes and soils: A global data set for the analysis of climate feedbacks in a warmer world

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Albedo-related soil and vegetation feedbacks are key uncertainties and climate models differ considerably in estimating their strength. For the terrestrial realm, large inland water bodies and wetlands have also been shown to significantly affect surface temperatures and energy balance in past and present climate systems.

Based on a synthesis of geological data we have reconstructed the global distribution of Late Pliocene soils and lakes which are then used as boundary conditions in a series of model experiments using the Hadley Centre General Circulation Model (HadCM3) and the BIOME4 mechanistic vegetation model. By combining our novel soil and lake reconstructions with a fully coupled climate model we are able to explore the feedbacks of soils and lakes on the climate of the Late Pliocene. Our experiments reveal regionally confined changes of local climate and vegetation in response to the new boundary conditions. The addition of Late Pliocene soils has the largest influence on surface air temperatures, with notable increases in Australia, southern North Africa and Asia. The inclusion of Late Pliocene lakes generates a significant increase in precipitation in central Africa, as well as seasonal increases in the northern hemisphere. When combined, the feedbacks on climate from Late Pliocene lakes and soils improve the data to model fit in western North America and southern North Africa.

Responses of the West Antarctic Ice Sheet due to obliquity-paced climate change during the Pliocene

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Response of ice sheets, especially the marine-based West Antarctic Ice Sheet (WAIS), is recognized as a significant unknown in predicting future consequences of global warming. ANDRILL's AND-1B sedimentary rock core has in its upper 600m a Plio-Pleistocene proxy record of the WAIS history that can be used to assess past ice sheet dynamics and its responses to Milankovitch forcing under pCO_2 values equal to or greater than present. The core shows WAIS changed from being a cold ice sheet prior to 10.5Ma, to being warmer until 7.6Ma with significant channelized subglacial meltwater during glacials and local rivers flowed to McMurdo Sound during interglacials. Between 5-3Ma meltwater decreased and interglacial periods were cooler but still 4^{o}C warmer than present, with diatoms dominating the nearshore marine environment rather than muds from local meltwater. Volumes of sub-ice-sheet meltwater during glacials and local interglacial meltwater continued to decline through to 0.8Ma indicating WAIS was cooling. However, WAIS remained more dynamic than after 0.8Ma when it reached its present cold state, inferred from thicker diamictite packages and thin to absent interglacial mudstones. Most importantly during the Pliocene WAIS responded at different tempos to changing amplitude (and to some degree frequency) in its obliquity-paced dynamics. Glacial advance facies are locally preserved under till, indicating little erosion occurred during some ice sheet advances that were rapid and short-lived. During other slower and probably more massive ice sheet advances significant erosion occurred, removing many glacial-interglacial cycles. G-I facies transitions are also locally condensed with little to no glacial retreat packages, indicating ice sheet retreat was rapid in response to interglacial warming events. Other interglacial transitions show a slower ice sheet response with thicker ice-proximal successions deposited. Some extended intervals of orbital cycles show minimal response of the WAIS to cooling in that it did not advance through the Ross Sea during glacials, and in some, even iceberg rafting was minimal. The sum indicates a complexity of ice sheet responses to orbitally-paced climate change at higher pCO_2 levels.

Climate response to changes in orbital forcing around the first Pliocene time slice

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Existing data/model comparisons for the mid-Pliocene have identified specific regions of concordance and discord between climate models and proxy data. One reason for site-specific disagreement is likely related to the time (warm peak) averaged nature of the mid-Pliocene ocean temperatures provided within existing proxy syntheses. To facilitate improved data/model comparisons in the future new proxy sea surface temperature reconstructions could focus on specific time slices within the Pliocene epoch. Haywood et al. (2013) have identified an initial time slice for environmental reconstruction and climate and environmental modelling centred on Marine Isotope Stage KM5c (3.205 Ma). Critically, this interval displays a very near to modern orbital configuration simplifying the interpretation of proxy data and the experimental design used within climate models. It is also within a warmer period as identified by a negative benthic oxygen isotope excursion of significant duration (thousands of years) in the LR04 stack. Nevertheless, current limitations of chronology and correlation make it likely that new proxy records will be attributable to a time range around the time slice, and may not always represent the time slice specifically. This introduces an element of uncertainty through orbital forcing around the time slice which can be investigated and quantified within a numerical climate modelling framework.

The Hadley Centre Coupled Climate Model Version 3 (HadCM3) has been used to perform a series of orbital forcing sensitivity tests around the identified time slice at MIS KM5c. Simulations every 2 Kyr either side of the time slice to a range +/- 20 kyr have been performed. The model results indicate that +/- 10 kyr either side of the time slice, orbital forcing exerts a less than 1°C change on global MAT. Seasonally, temperature variations exceed this value locally. Simulations have also been undertaken at 8 kyr intervals 20 Kyr either side of the 3.060 Kyr PlioMAX peak (or super interglacial event) which is characterised by one of the lightest benthic oxygen isotope excursions evident in the entire PRISM time slab (Marine Isotope Stage K1; Raymo et al.) in order to compare these results to the orbital forcing sensitivity tests around the MIS KM5c time slice.

Title: MID-PLIOCENE climate an anologue for near future climate?

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ABSTRACT

We choose the opportunity of the comparison exercises CMIP5 and PMIP3 (PLIOMIP) to compare Mid Pliocene equilibrium climate simulations obtained with IPSL, OAGCM with PLIOMIP boundary conditions and RCP4.5 future scenario using the same model.

We focus mainly on the tropical response atmospheric dynamics in terms of Hadley and Walker cells. As it is very often claimed that Mid-Pliocene is a good analogue for future climate, we investigate this issue through a comparison of both runs, and checking the robustness of our conclusions in comparison with other model results from PLIOMIP and CMIP5.

In this presentation, we shall explain the dynamics of the Hadley and Walker cells, and show that, despite minor discrepancy, mid-Pliocene is certainly an interesting analogue for future climate changes.

A comparison of sea surface temperature patterns in the late Miocene, Pliocene and Pleistocene

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The spatial pattern of sea surface temperature (SST) of the global ocean is indicative of, and has an influence on, atmospheric circulation and climate conditions. Over the last ~10 myrs, a major climate transition from warm Late Miocene and Early Pliocene epochs to the Late Pleistocene ice ages occurred; to effectively diagnose climate change mechanisms during this transition, there is a fundamental need to reconstruct changes in spatial SST patterns. We combined newly generated geochemical SST estimates from the North Pacific with previously published data in order to map the SST patterns of two time slices during warm periods (the late Miocene at ~9 Ma, and the early Pliocene at ~4.15 Ma) prior to Northern Hemisphere Glaciation (NHG), and three time slices (at ~0.55 Ma, 1.45 Ma, 2.55 Ma) after NHG. The SST estimates come from alkenone and Mg/Ca paleothermometry. Alkenone-SST estimates utilized the same calibrations, and thus were incorporated into our database as published. However, to ensure internally consistent Mg/Ca-SST estimates, we recalculated SST values by applying consistent dissolution corrections and calibrations to the raw Mg/Ca data; these new SST estimates were then incorporated into our database. A kriging approach was then used to produce SST maps for each timeslice. The basin-wide SST patterns of the earliest time slices are distinctly different from the time slices that follow glaciation. The late Miocene and early Pliocene time slices show the presence of warm subtropical eastern boundary current (EBC) regions, zonally uniform SSTs in the tropics and mid-latitudes, poleward expansion of tropical warmth, and poleward offsets of the subarctic/subtropical transition zones prior to the onset of NHG. The time slice for 2.7-2.4 Ma shows a meridional temperature gradient in the western Pacific that is similar to the gradient of the early Pliocene, though the EBCs were cooler relative to the early Pliocene. The two most recent time slices show EBCs with SSTs that were similar-to or cooler than modern SSTs and meridional temperature gradients in the western pacific that are steeper than those of the Miocene and Pliocene. The observed strengthening of Pacific SST gradients since the late Miocene may support the hypothesis that changes in basin-wide SST distributions were instrumental in determining the atmospheric circulation (including Hadley cell dimensions and strength), regional precipitation patterns, and, through cloud and water-vapor feedbacks, the global temperatures that resulted in the onset of NHG.

Sea Level in a 400 ppm world: field evidence, modeling results, and new investigative strategies

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Determining maximum eustatic sea level (ESL), or equivalently minimum ice volume, during the Mid-Pliocene warm period (MPWP, ~3.3 to 2.9 Ma) has been a central but elusive goal in the study of past warm climates. Estimates of ESL based on geologic field data span a broad range, variation we now recognize is due in part to geographically varying post-depositional displacement caused by glacial isostatic adjustment (GIA) and dynamic topography (DT). By mapping shorelines at numerous localities around the world and modeling the effects of subsequent GIA and DT on their current position, we can narrow the range of possible sea level scenarios. We show that dynamic topography, supported by convectively maintained stresses generated by viscous flow in the mantle and associated buoyancy variations in the lithosphere, plays a significant role in the post-depositional displacement of Pliocene and even much younger Pleistocene shorelines. We will discuss how we are using predicted global patterns of GIA and dynamic topography to guide field efforts aimed at extracting the eustatic component of sea level change during past warm climates.

Plio-Pleistocene foraminifera-bound $\delta^{15}N$ records of the Western Pacific and its global and regional implications

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The long term cooling trend, from the warm Pliocene period to the Pleistocene ice ages, was accompanied by decreasing atmospheric CO_2. Temporal changes in the global inventory of fixed nitrogen (N), a critical nutrient for marine primary productivity, could have generated changes in the strength of the biological pump driving variations in atmospheric CO_2. N_2 fixation (N source) and denitrification (N sink), are the two microbial processes that govern the inventory of marine fixed nitrogen. In the modern ocean, these flux terms have unique stable nitrogen isotopic ($\delta^{15}N$) signatures: the addition of nitrogen through N_2 fixation produces fixed N of ca. $\delta^{15}N$ = -1‰, removal of N through water-column denitrification fractionates the fixed N pool up to ca. ~15 - 25‰, and removal of N through sedimentary denitrification has small or zero isotope effect.

Establishing widely distributed paleoceanographic records of sedimentary $\delta^{15}N$ is a promising approach to quantify changes in the sinks, sources and budget of fixed N through time. Existing sedimentary $\delta^{15}N_{bulk}$ records for the past 4 Ma are primarily from regions of high productivity, and are thus strongly influenced by denitrification, or changes in nutrient utilization at the surface. To test the stability of the isotopic composition of the marine fixed N inventory during the Pliocene to Pleistocene transition, and determine the evolution of N_2 fixation relative to existing records of denitrification, we produced two foraminifera-bound $\delta^{15}N$ (FB-$\delta^{15}N$) records for the last ~5 Ma in the western Pacific: one at site ODP 806 in the western equatorial Pacific, which is currently influenced by water column denitrification and the other at site DSDP 451 in the western subtropical north Pacific (WSNP), which is host to high N_2 fixation rates in the modern ocean. At ODP 806, FB-$\delta^{15}N$ increases from ~5‰ to ~8‰ over the last 5 Ma, which may reflect an increase in water column denitrification of the source waters. At DSDP 451, FB-$\delta^{15}N$ values are relatively stable at ~3‰ and consistently lower than the present mean ocean nitrate $\delta^{15}N$, which suggests that (1) the WSNP is a stable supply of fixed N, and (2) mean ocean nitrate $\delta^{15}N$ is constant over the last 5 Ma. These FB-$\delta^{15}N$ results, together with existing $\delta^{15}N_{bulk}$ records suggests that denitrification and N_2 fixation are coupled throughout the Plio-Pliestocene.

Characterizing conditions of the Nordic Seas water column through the Pliocene

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The Nordic Seas is one of the world's ocean areas with least data available to constrain Pliocene temperatures. Nevertheless, the Nordic Seas is considered to be the hot spot of the worlds oceans in terms of temperature anomalies between the Pliocene and preindustrial times. In this study a multi proxy approach is used to characterize the conditions of the Pliocene water column of the Nordic Seas. The study site is ODP Site 642B, located in the eastern Nordic Seas (67°13.5´N, 2°55.7´E, 1286 m water depth), a site presently under influence of the warm Norwegian Atlantic Current.

Temperature estimates based on alkenone indicate 1-2°C warmer SSTs compared to the Holocene, probably reflecting the effect of higher radiation on summer mixed layer temperatures. In contrast to the slight warming recorded by the alkenones, planktic oxygen isotopes document colder (and/or saltier) conditions than through the Holocene. Temperature estimates based on relative abundance of planktic foraminifera supports an interpretation of colder subsurface conditions, as indicated by the oxygen isotopes. Hence, the results from ODP Site 642B shows that the eastern Nordic Seas was less warm than previously suggested. Benthic isotopes record saltier (and/or colder) bottom water than what is seen for the Holocene in the same area. Together, the planktic and benthic oxygen isotopes show that stratification and density structure of the water column was different during the Pliocene. The planktic carbon isotope record document a well ventilated upper water column, with the exception of the period ca. 4-3.7 Ma BP when the ocean atmosphere gas exchange was hindered by a fresh water lid. Even though the upper part of the water column was well ventilated, the benthic carbon isotopes document that the bottom water was less well ventilated during the Pliocene than through the Holocene, implying that no strong deep convection took place. Our results that the ocean circulation and northern limb of the AMOC may operate differently from today under climate boundary conditions close to modern.

Multiproxy approach to the reconstruction of climate in time slices of the Pliocene: proposal for a community initiative

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The Pliocene has often been proposed as climate analogue for a future climate conditions. However, despite relatively small difference in climate control factors, including CO_2 concentrations, the Pliocene climate was markedly different from modern. This has thus made the Pliocene a relevant climate interval to validate climate models, which requires, however, confidence in the paleoestimates to be able to ascertain confidently model strengths and weaknesses. In addition, as it is scientifically and technically not possible at present to reconstruct a continuous record in space and time of past climate variations, instead, a discrete and distinct time interval is needed to focus research efforts of the scientific community.

A first pioneering effort was undertaken by the Pliocene Research, Interpretation and Synoptic Mapping group (PRISM) through the reconstruction of sea surface temperatures (SST) and vegetation in a time slab spanning 3.3 to 3.0 Ma, before the intensification of large-scale Northern Hemisphere glaciation.

We propose a new concerted effort of the international community to go a step further than PRISM in order to reduce current uncertainties on Pliocene climate. Following on the model set by of initiatives such as CLIMAP (Climate long-range investigation, mapping, and prediction) and MARGO (Multiproxy approach for the reconstruction of the glacial ocean surface), our aim is to bring together leading experts and younger scientists studying Pliocene climate to

- provide consensus agreements on priority time slices to focus research efforts
- appraise performance of available proxies on temperature (marine and continental) and CO2
- compile all the available information on the cryosphere, sea level and vegetation
- collate and harmonise all the available proxy data and place them into a common framework for a multi-proxy climate reconstruction
- Undertake data-modelling comparisons to ascertain strengths and weaknesses of models to incorporate on future assessments of the IPCC

A key aim of the initiative is to generate quantitative data for the past to decipher the climate forcings that explain the warm climate of the Pliocene. The data would allow improving on current capacity to estimate climate sensitivity and the role of CO_2 in driving Pliocene warmth. The reconstruction of multiple climate parameters would also allow gauging the interaction between the components of the Earth System, and the changes at regional and global scales in the atmosphere, biosphere, cryosphere and hydrosphere. This will be possible thanks to a international community effort to compile and synthesize data at regional scales in a fashion that it is relevant for data modeling comparisons.

Refining alkenone pCO_2 estimates in the Plio-Pleistocene

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Atmospheric pCO_2 has been thought to be a primal driver of global temperature change and thus better understanding the relationship between pCO_2 and climate is a key to improve the accuracy of prediction of future climate change. Paleoclimate responses to pCO_2 change are important components in resolving climate sensitivity and related relationships - but only if we have reliable information on past atmospheric pCO_2. Alkenone $\delta^{13}C$ and carbonate $\delta^{11}B$ pCO_2 proxies (Seki et al., 2010; Pagani et al., 2010; Bartoli et al., 2011) were applied to reconstruct pCO_2 level in the warm Pliocene (3-4.5 Ma), which is considered as possible analogue of the future global warming. However, the both methods yield large differences in estimates (>200 ppm) among sites (Pagani et al., 2010). Therefore, absolute pCO_2 values in warm Pliocene and long-term pCO_2 trends are still ambiguous. In this study, I have refined alkenone pCO_2 barometry and revised published Pliocene pCO_2 data from the Pacific Ocean (ODP 806 1012, 1208, and 1241), Atlantic Ocean (ODP 925 and 982) and Caribbean Sea (ODP 999) (Pagani et al., 2010; Seki et al., 2010) in order to better constrain pCO_2 level in the Pliocene warmth.

The pCO_2 estimates based on the conventional method exhibit profound variability amongst sites, but the difference is significantly reduced by the refined method with better constraint on physiological factor. Moreover, the revised Pleistocene pCO_2 values (220 to 300 ppmv) fall within the range of pCO_2 levels documented from Antarctic ice cores (Lüthi et al., 2008). This suggests that although our pCO_2 reconstruction still relies on various assumptions (e.g., constant growth rate, production depth and sea-air CO_2 equilibrium), refining the b-term for alkenone production depth appears to resolve the profound variations in previously published datasets. The revised data indicate that pCO_2 levels in the Pliocene warmth are lower (270-340 ppm) than the previous estimates (330-380 ppm).

U-Pb-dated speleothem records of Pliocene vegetation and climate from the southern Australian semi-arid zone

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The nature of terrestrial environments in the Southern Hemisphere (SH) during the warm Pliocene is poorly known. This is not only because there are few published fossil records, but also because most of the existing records have very limited age control. For example, in Australia, the ages of most putative "mid-Pliocene" fossil pollen records are based solely on biostratigraphic correlation. These correlations for the most part do not have the resolution to differentiate late Miocene from early Pliocene environments, let alone to pinpoint a <1 million year long interval. Hence it remains unclear whether fossil records attributed to the "Pliocene" are actually representative of a period of peak Pliocene warmth (whether Dowsett's PRISM 3.0-3.3 Ma interval, or Fedorov et al's [2013, *Nature* 496:43] 4.0-4.4 Ma interval). Additionally, this lack of age control means these records provide little basis for evaluating whether there was a distinctive vegetation response to peak Pliocene warmth, or whether vegetation remained unchanging throughout the Pliocene.

Here, we present new fossil pollen records recovered from individual U-Pb dated speleothems (cave deposits) from the Nullarbor Plain, a 200,000 km^2 limestone karst plateau in southern Australia with a semi-arid mediterranean-type climate (annual rainfall c. 200 mm), which today is dominated by Chenopodiaceae shrubland. The U-Pb ages have errors of approximately 1%, allowing placement of each individual pollen record within the Pliocene with an error of no more than 30-50 kyr. The pollen records indicate that Pliocene vegetation in this region was substantially different from today, and that the earliest Pliocene (at c. 5 Ma) vegetation differed remarkably from that at 4-3 Ma. At c. 5 Ma, the pollen record is dominated by the woody taxa Casuarinaceae and Gyrostemonaceae, but between 4-3 Ma, is dominated by *Eucalyptus* and a number of other Myrtaceae, and by *Banksia* (Proteaceae). This change is tentatively interpreted as representing an increase in community productivity, from very open woodland in the earliest Pliocene, to open forest during the 4-3 Ma interval. Hence Early and Late Pliocene climates differed enough to force complete biome turnover. Explanations of the mechanisms that drove Pliocene warmth may thus need to explain not only why the Pliocene warm interval was terminated by Pleistocene cooling, but also why the warm interval differed from the earlier Pliocene.

Deglaciation history of Dronning Maud Land, East Antarctica deduced by ^{10}Be exposure dating and geomorphology of Sør Rondane Mountains coupled with GIA modeling

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Abstract

A reconstruction of past variability of the Antarctic ice sheet is essential to understand its stability and anticipate its contribution to sea level change with future climate change. Recent studies have reported a significant decrease in thickness of the East Antarctic Ice Sheet (EAIS) during the last several million years. However, the geographical extent of this decrease and subsequent isostatic rebound remain uncertain and topic of debate. In this study, we reconstruct the precise magnitude and timing of ice sheet retreat at the Sør Rondane Mountains in Dronning Maud Land, East Antarctica, based on detailed geomorphological survey, cosmogenic exposure dating, and glacial isostatic adjustment (GIA) modeling. Our data show ~570 m of ice sheet thinning in this region since Pliocene. To better understand ice sheet dynamics and its relationship with sea-level change, further investigations and application of more accurate dating are needed.

Modelling oxygen isotopes in seawater for the mid-Pliocene using the Hadley Centre GCM: a model-data comparison study.

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One of the most widely used palaeoproxies for temperature reconstruction of past climates is the ratio of different isotopes of oxygen in archives such as ocean dwelling foraminifera and corals. Palaeotemperatures are reflected in these archives because, as the organisms incorporated water throughout their lifecycle, a temperature dependent isotope fractionation process occurred. However, to accurately utilise these archives, knowledge of the oxygen isotope ratio of the seawater which these organisms incorporated is needed. Unfortunately there is no independent evidence of the oxygen isotope ratio of sea water for the past.

Isotope enabled General Circulation Models (GCMs) can be used to estimate oxygen isotope ratios throughout the hydrological cycle in a way that is consistent with GCM physics and prescribed climate forcings.   Here we present simulations of the mid Pliocene (~3.2ma) using the isotope enabled version of the Hadley Centre GCM (HadCM3). We show how modelled water isotope ratios in the ocean have changed between the mid Pliocene and the preindustrial, and use these results to facilitate an accurate data-model comparison for the mid Pliocene.

We show there is excellent agreement between the model and coral data in the Western Pacific (Wantanbe et al 2011), in both the mean state and temporal variability.   There is also good model-data agreement when comparing variability in the model with variability in planktonic foraminifera, however the mean temperatures derived from the planktonic foraminifera are usually cooler than the model. A comparison of the sites which show good model-data agreement and sites where model and data disagree will be discussed - providing insights into the interpretation of paleodata for the Pliocene climate.

The Pliocene Permanent El Nino and Atmospheric Superrotation

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A mechanism for maintaining a weaker Pliocene equatorial temperature gradient (i.e., a mechanism for the Pliocene permanent El Nino) is proposed that borrows from theories of atmospheric superrotation. The mechanism is based on enhanced or rearranged tropical convective activity during the warmer Pliocene climate exciting atmospheric Rossby waves that propagated poleward from the equator. These waves can produce an equatorward flux of westerly momentum that weakens the surface easterlies and therefore the east-west thermocline slope and SST gradient, leading to a permanent El Nino state. Three main related threads will be presented, including (1) a positive feedback leading to superrotation based on an equatorial Rossby Wave resonance that occurs in a westerly background flow; (2) evidence for enhanced Madden-Julian Oscillations in warm climate that can lead to the enhanced excitation of atmospheric Rossby waves and hence to superrotation; (3) a related mechanism that may lead to the observed warming of upwelling sites. The main challenge facing this idea is the tendency of superrotation to occur in atmospheric models in the upper atmosphere rather than near the surface where it can impact the ocean, and possible limitations of present models that may lead to this difficulty will be discussed.

Pliocene climate changes and vegetation development in northwest Africa

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The climate variability in northwest Africa during the Pliocene is characterized by fluctuations from wetter to drier conditions as it is shown in the oxygen isotopes records and in dust flux records, obtained from marine sediment cores. Although many studies have been published about the climate variability in northwest Africa and its driving forces, data which could link the vegetation development, the different hydrological conditions and the oceanic changes, are scarce. It has been suggested that during the Quaternary, aridity/humidity cycles in West Africa are driven by changes in the Atlantic meridional overturning circulation (AMOC). To test this hypothesis for the Pliocene, we are investigating the vegetation and climate changes occurring in West Africa and in the eastern Atlantic Ocean for two time slices, from 3.6 to 2.5 Ma (including the mid-Pliocene warm period) and from 4.9 to 4.6 Ma. These two intervals experienced different oceanographic conditions relatively the strength of the AMOC, which was enhanced during the younger and reduced in the older interval. We use marine palynology (pollen, spores and dinoflagellate cysts) to reconstruct the changes in vegetation and climate of the African continent and to analyse the different conditions of the surface waters of the east Atlantic. Moreover, we use elemental ratios of the major elements (Ti, Fe, Si, Al, K, Ca) as indicators of terrestrial input, continental humidity and dust source areas. Here, we present the palynological results, element ratios obtained for ODP Site 659 (offshore Mauritania) and the comparison between our records and other published proxies from the same core (dust flux, oxygen isotopes). The more abundant pollen taxa in the mid-Pliocene sediments of ODP Site 659 are Poaceae, represented by an average percentage value of 43 % and CCA with an average value of 20 %. Between 3.3 and 3 Ma, the relative abundances of the different taxa show a higher degree of variability, compared to the interval of 3.6 -3.4 Ma. Also the dust record is highly variable. Only between 3.25 and 3.2 Ma an extended humid phase occurred with increased chemical weathering indicated by the Fe/K ratios. Low dust input and low pollen concentration during this period of ca. 50 ka probably indicate decreased windiness. Similar large climate variability has been recorded at ODP Site 658 offshore Cape Blanc. These records challenge the idea of a stable warm climate during the mid-Pliocene warm period.

North Pacific origins of Northern Hemisphere glaciations

Nicholas L. Venti, Katharina Billups, Timothy D. Herbert

A suite of proxy records generated in the Kuroshio Extension (Ocean Drilling Program Site 1208) suggest regularly increased interaction of westerly winds augmented by the East Asian winter monsoon (EAWM) and the North Pacific Ocean prior to obliquity-paced Northern Hemisphere glaciations (NHG). In modern climate, these powerful winds cause sensible ocean-atmosphere heat flux in excess of 100 Wm^{-2} and provide the primary source of iron to the micronutrient-limited North Pacific Ocean. In the Pleistocene, obliquity-paced intensification of these westerlies may have caused NHG by 1) advecting heat and moisture to the atmosphere for snow fall over North America and 2) delivering iron via dust to fertilize the basin, thereby increasing primary productivity and drawing down atmospheric carbon dioxide concentrations. To examine mechanism 1, we reconstructed sea surface temperature (SST) seasonality by comparing summer hydrography (salinity and temperature), as reflected in the $\delta^{18}O$ values of an exclusively warm-water-dwelling planktic foraminifer, *Globigerinoides ruber*, to an alkenone-based mean annual SST estimate, which includes winter cooling from EAWM-enhanced westerlies. With NHG onset at 2.73 Ma, summer SST increased, while mean annual SST decreased, suggesting increased heat transfer from the subtropical ocean to the mid-latitude atmosphere. On the orbital scale, summer hydrography varies with summer/fall overhead insolation at the 19-kyr precessional band, but not with obliquity. In contrast, mean annual SST varies primarily at the 41-kyr period and SST decreases lead glaciations, as recorded by benthic foraminifer $\delta^{18}O$ values. This consistent relationship implies that increased ocean-atmosphere heat transfer contributed to rather than resulted from the glaciations. Alkenone mass accumulation rate (MAR), because the recalcitrant compounds are produced by certain species of haptophyte algae, reflect primary productivity. Similarly, sediment reflectance values (L*), which at the Kuroshio Extension correlate strongly to carbonate versus opal flux, decrease with increasing opal content and macronutrient (Si, P, N) availability. Together these provide insight into mechanism 2. Increased productivity and macronutrient availability with NHG onset are inferred from increased mean alkenone MAR and decreased sediment reflectance values after 2.73 Ma. Like sea surface cooling, the primary productivity and macronutrient proxies vary primarily at 41-kyr periodicity, their phasing with respect to benthic $\delta^{18}O$ suggesting increased nutrients and productivity ahead of glaciations. Thus, the North Pacific Ocean may have drawn down atmospheric carbon dioxide concentrations ahead of the glaciations. Finally, magnetic susceptibility/accumulation reflects eolian deposition of magnetic iron oxides from Asia. As predicted, increased magnetic accumulation (westerly intensity) leads glaciations.

The amplification of Arctic terrestrial surface temperatures by reduced sea-ice extent during the Pliocene

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The Pliocene remains a paradox in that atmospheric CO_2 level were at approximately 400 ppm and yet temperatures, especially in the Arctic were significantly warmer than present. This amplification of temperatures has proven very difficult for model simulations. Here we describe an atmospheric general circulation model experiment assessing the response of terrestrial temperatures in the mid-Pliocene (3.02 to 3.26 Ma) to an ice-free Arctic, and we compare model results with a compilation of proxy-based Pliocene paleotemperature reconstructions. Our experiments indicate that the amplification of Arctic surface temperatures is much more sensitive to the extent of sea ice than continental ice. The removal of Arctic sea ice results in simulated mean annual surface temperatures that better match terrestrial proxy data (RMSE = 2.9°C) than experimental conditions that included seasonal sea ice (RMSE = 4.5°C). Our simulations also show a decrease in the seasonal amplitude of temperatures in the absence of sea-ice, which is consistent with theory predicting more equable climates in the Arctic during warmer intervals in Earth's history. Our results demonstrate that sea-ice removal leads to latent heat loss from the ocean to the atmosphere as water vapor is advected over continental interiors resulting in enhanced surface warming. Although our sensitivity experiment does not help to identify the full array of feedback mechanisms that may mediate the ice-free versus ice-covered state, it does demonstrate that Arctic terrestrial surface temperatures are extremely sensitive to the spatial and seasonal extent of sea-ice.

Late Miocene – Pliocene Tropical Pacific Temperatures, Equatorial Upwelling, and the Ancient El Niño

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The western Pacific warm pool is the warmest sea surface water body on Earth, whereas the eastern equatorial Pacific (EEP) is characterized by strong upwelling of cold, nutrient and CO_2-rich deep-waters, termed the cold tongue. The warm pool and cold tongue control the circum-Pacific climate and impact the globe through El Niño – Southern Oscillation (ENSO) teleconnections. Sea surface temperature (SST) reconstructions of the Pliocene epoch, a time period characterized by sustained global warmth and CO_2 levels similar to today, appear that the temperature gradient between the west and east equatorial Pacific was negligible, giving rise to the supposition of conditions similar to a "permanent El Niño". However, recent studies reveal interannual climate variability during the Pliocene that resemble ENSO events, challenging the notion of a permanent El Niño. Here we show a temperature history of equatorial Pacific since the late Miocene (~12 Ma). Our results demonstrate that both the Pacific warm pool and cold tongue continuously cooled since ~12 Ma, with persistent zonal temperature gradient of ~3°C that increased during the latest Miocene towards the modern value of 5-6°C. Our results stand in contrast to previous observations that cooling in the warm pool was negligible during long-term global cooling. Further, we argue that the smaller meridional temperature gradient during the late Miocene to Pliocene contributed to warmer upwelled waters in the EEP, which in turn helped to lower the zonal gradient. The presence of a large and dynamic cold tongue in the late Miocene – Pliocene may have fueled ENSO-type of climate variability associated with thermocline depth fluctuations.

If temperature is not a faithful recorder of upwelling intensity, one alternative tracer for deep-water outcropping is the disequilibrium of CO_2 between surface seawater and the atmosphere. Using modern shipboard data, we show that seawater CO_2 in the modern EEP varies from 145% of atmospheric value during La Niña events, to only ~80% during El Niño. Excess CO_2 in this region is strongly related to the Niño 4 index. We further present our preliminary results on CO_{2sw} reconstruction across equatorial Pacific using the alkenone-CO_2 method, which potentially provides a way for quantitatively estimate the Pacific ENSO climate state in the late Miocene – Pliocene.

Increased ventilation of Antarctic deep water during the warm mid-Pliocene

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Abstract

The mid-Pliocene warm period (mPWP) is a recent warm geological period that shares similarities with predictions of future climate. It is generally held the mPWP Atlantic Meridional Overturning Circulation (AMOC) must have been stronger, to explain a weak Atlantic meridional $\delta^{13}C$ gradient and large northern high latitude warming. However, climate models do not simulate such stronger AMOC when forced with mid-Pliocene boundary conditions. Proxy reconstructions allow for an alternative scenario that the weak $\delta^{13}C$ gradient can be explained by increased ventilation and reduced stratification in the Southern Ocean. Here this alternative scenario is supported by simulations with the Norwegian Earth System Model (NorESM-L), which simulate an intensified and slightly poleward shifted wind field off Antarctica giving enhanced ventilation and reduced stratification in the Southern Ocean. Our findings challenge the prevailing theory, and show how increased Southern Ocean ventilation can reconcile existing model-data discrepancies about AMOC while explaining fundamental ocean features.