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PAST GLOBAL CHANGES
MAGAZINE

DUST

EDITORS

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PAGES

GLOBAL IGBP CHANGE

News

PAGES funding update
The US National Science Foundation has confirmed it will support PAGES' activities until mid-2018, and the Swiss NSF, until the end of 2015 with an invitation to re-submit a proposal under Future Earth. We thank the NSFs for their vote of confidence that means we can continue to work with the paleoscience-community over the coming years.

New PAGES Working Groups
Three new PAGES working groups have recently been launched:
• C-PEAT – Carbon in Peat on EArth through Time
• DICE – Dust Impact on Climate and Environment
• OC3 - Ocean circulation and carbon cycling.
You can read more about the plans of C-PEAT and DICE in their Program News articles in this issue, and there's more about all of our new, ongoing, and former groups on the PAGES website.
Three more new working groups on transitions in aquatic systems; soil and sediment transfers in the Anthropocene; and anthropogenic land cover change were also accepted at the last EXCOM meeting and are now in the process of being set up.
The next deadline for working group proposals is 5 January 2015. See PAGES website > Working Groups for more information.

Future Earth update
The Future Earth program's permanent secretariat, operational in 2015, will span three continents with five global hubs in Montreal, Paris, Tokyo, Stockholm and Boulder. This will be complemented by regional hubs representing Latin America, Europe, and North Africa and the Middle East.
Future Earth also recently announced funding for eight new Fast Track Initiatives and Cluster Activities intended to kick-start integrated activities and strengthen interdisciplinary collaboration. PAGES, designated to join Future Earth in 2015, is involved in two Fast Track Initiatives: one organizing scientific support to the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES), and another, investigating extreme events and environments and the impact on climate and society.

Supported workshops
At its most recent meeting in June 2014, the PAGES Executive Committee granted support for four scientific meetings. View the list of successful meetings at: PAGES website > People > Scientific Steering Committee > Meeting Minutes. The next deadline for meeting support proposals is 5 January 2015. See PAGES website > My PAGES.

Nominate for the PAGES SSC
PAGES is calling for nominations of scientists to serve on its Scientific Steering Committee (SSC) from 2016 onwards. The SSC is the body responsible for overseeing PAGES activities. At the end of 2015, four members will rotate off the SSC (See PAGES website > People > Scientific Steering Committee > SSC membership history). Scientists serve on the SSC initially for a period of 3 years, with the potential of renewing for an additional 3-year term.
By 2015, it is envisioned PAGES will be operating as part of Future Earth with active collaborations with the World Climate Research Program. Nominees should be familiar with the development of these programmes and be able to contribute positively to strengthening PAGES' position within this environment.
In seeking nominations, not only are we looking for scientific excellence and a high level of commitment to PAGES' goals, but we are also aiming to achieve a disciplinary, nationality, gender and age balance. The deadline for nominations is 5 January 2015. The guidelines are available at: PAGES website > People > Scientific Steering Committee > Nominate

Contribute to the PAGES 2k Global Temperature Database
The PAGES 2k Project invites anyone with an interest in and knowledge of climate change during the past two millennia to join a worldwide effort to update and publish the next generation database of temperature-sensitive proxy climate records of the last two millennia. The updated database will be the basis for reconstructing global temperature changes and addressing a range of research questions. More details about the plan, goals, guidelines, and timeline can be found at: PAGES website > Working Groups > 2k Network

Paleoclimate documentary featuring 2k Network
Taking Earth's Temperature: Delving into Climate's Past is an hour-long documentary showcasing scientific discoveries in climate change research. Made by filmmakers at Northern Arizona University's IDEA Lab, it features contributions from many PAGES-affiliated scientists, including the PAGES 2k Network. The broadcast schedule and DVD are available at: www.takingearthstemperature.org. Teachers can also register on this website for free access to the film and a lesson plan.

Calendar

4th Asia2k Workshop
19-20 March 2015 - Kyoto, Japan

Large-scale climate variability in Antarctica
24-26 March 2015 - La Jolla, USA

Forest insect and pathogen disturbances in time
30-31 March 2015 - Taos, USA

Conference on Volcanoes, Climate, and Society
07-11 April 2015 - Bern, Switzerland

Arctic2k working group meeting
12 April 2015 - Vienna, Austria

Climate and human impacts in central Europe
17-19 June 2015 - Gdansk, Poland

PALSEA 2015 Sea Level Workshop
22-25 July 2015 - Tokyo, Japan

http://pages-igbp.org/calendar

Featured products

Special issues
• Members of the C-PEAT working group published a special issue on peatland carbon dynamics in the circum-Arctic region during the Holocene (Yu Z et al., 2014, *The Holocene* 24).
• The International Partnerships in Ice Core Sciences (IPICS) group has published a joint special issue (Barbante et al., 2014, *Clim Past* & *The Cryosphere*) which emerged from their First Open Science Conference in 2012.
• The special issue, Progress in paleoclimate modelling (Kageyama et al., 2014, *Clim Past*), emerged out of a 2012 PAGES-supported meeting: PMIP3 - Towards IPCC AR5.

Papers
• The Regional Integration Theme proposes a paleodata-based framework that integrates social and environmental impacts at the regional scale (Dearing et al., 2014, *Global Env Chg* 28).
• A study on East Antarctic climate variability by Pol et al. features contributions from PAGES' Past Interglacials Working Group (2014; *Geophys Res Lett* 41).
• PAGES' Arctic2k working group has published an extended and revised Arctic proxy temperature database for the past 2,000 years (McKay & Kaufman, *Scientific Data* 1).
• A *New Phytologist* paper (Gavin et al., 204), compares three methods for studying past climate refugia (locations where taxa survive periods of regionally adverse climate).

Online resource
The Varve Image Portal provides a summary of varve images around the world. See: PAGES website > Working Groups > Varves WG > Varve Image Portal

Cover

Layers of desert dust in the accumulated snow on Mt Elbrus, Caucasus Mountains, Russia.
The majority of the dust deposited on Mt Elbrus was traced back to the Syrian Desert and northern Mesopotamia. This study was supported by the European FP7 DIOGENES project. Picture by Vladimir Mikhalenko.

Present and past mineral dust variations – a cross-disciplinary challenge for research

Ute Merkel[1], D.-D. Rousseau[2,3], J.-B. W. Stuut[1,4] and G. Winckler[3,5]

In its recently published report, the Intergovernmental Panel on Climate Change identified the role of mineral dust in the Earth system and the uncertainties it introduces to the total aerosol radiative forcing and climate projections as key topics for future research (WG 1, chapters 5, 7 and 9). Achieving a thorough understanding of feedbacks associated with eolian dust is a challenge for a number of Earth science disciplines as mineral dust processes operate on a wide range of spatial and temporal scales. On the other hand, studies of mineral dust contribute significantly to research on past climatic and environmental conditions enabled by dust preservation in different kinds of depositional paleoclimate archives.

Such work has been the focus of PAGES' recently concluded ADOM (Atmospheric Dust during the last glacial cycle: Observations and Modeling) working group, which was established in 2008 with the goal of combining reconstructions of climate and atmospheric circulation from terrestrial, marine and ice-core records with modern dust evidence and model simulations of past and present atmospheric circulation. To this end, ADOM considered processes ranging from the regional to (inter-) hemispheric scales and focused on fostering more detailed knowledge on dust-related dynamics. The idea of editing a dedicated PAGES Magazine on mineral dust was born during the 2nd ADOM workshop held at MARUM in Bremen, Germany, in November 2011. This issue with contributions from workshop participants and colleagues from the ADOM community provides an overview of the science ADOM has focused on during recent years and highlights challenges to state-of-the-art dust research.

Modern dust

From a meteorological perspective the conditions governing the mobilization and entrainment of dust into the atmosphere (Fig. 1) and its long-range transport operate on daily to seasonal timescales. Schepanski et al. (p. 62) present an introduction to the modern mineral dust cycle and discuss on the basis of recent observational results how conditions for dust mobilization depend on daily meteorological conditions and on prevailing seasonal patterns. Lelli et al. (p. 64) show how seasonality impacts atmospheric aerosol content. Remote sensing of atmospheric aerosol content from satellites has now been carried out for more than three decades, which is sufficiently long to analyze interannual aerosol variations. However, developing algorithms to retrieve dust deposition information from the remotely sensed mineral dust content in the atmosphere is still a challenge (Lelli et al. p. 64). This is particularly relevant over the oceans where in-situ measurements of dust deposition are scarce (Fig. 2) but nevertheless required to put the dust deposition recorded in marine sediment into a quantitative perspective.

Seasonal dust fluctuations are also superimposed by longer-term variations on interannual-to-decadal timescales. Shao (p. 66) sheds light on the links between dust fluctuations and climate variability modes and trends, and presents recent regional dust modeling results for Asia and Australia. Altogether, these results emphasize the need for long-term monitoring of dust deposition. To that effect, the most striking long-term effort discussed in this issue is the dust recordings from J. Prospero's Barbados observatory. The observations now cover half a century and provide a deep insight into West African dust source variations and trans-Atlantic dust transport (Prospero p. 68). This record revealed for example a less pronounced correlation between precipitation in the Sahel region and dust deposited on Barbados than suggested previously.

Figure 1: Dust storm in Iwik, Mauritania (photo by Jutta Leyrer).

Figure 2: Dust collection at sea (photo by Jan-Berend Stuut).

In addition to analyses of the total amount of dust deposited such as those discussed above, understanding the evolution of particle-size distributions along the transport path is another important target of dust research. It requires that sectoral observational studies are coordinated towards a holistic source-to-sink approach, connecting research on near-source dynamics of surface dust emission, on size-selective transport processes in the atmosphere, and on depositional processes including the sinking behavior of dust particles through the atmosphere and (ocean or lake) water column, and finally sediment formation. To achieve this, the different communities studying the dust cycle need to collaborate. Ideally, correlations between source area information and paleoclimatic records would emerge, taking into account the dust particle interactions and transformations on their way to the deposition site (Stuut et al. p. 70).

Paleo archives of dust

Looking into the past enables us to detect amplitudes, ranges, and timescales unseen in modern observational records. In spite of the many challenges associated with understanding atmospheric processes and dust particle dynamics on their source-to-sink pathway, paleo-dust reconstructions have provided elucidating insights into the global dust cycle and its variations in the past. Paleoclimatic archives such as ice cores, terrestrial loess deposits, peat bogs, and marine sediments reveal direct information about variations of dust deposition processes over time. In addition they provide hints about dust-related facets of the Earth system, such as changes in vegetation cover, atmospheric circulation patterns and wind strength.

A central issue of paleo-dust studies is the question of provenance, i.e. what was the origin of the dust that eventually got deposited and preserved as sediment. The question becomes especially intriguing when paleo-dust archives are remote from established source areas such as it is the case for polar ice cores. These provide highly detailed information about gradual and abrupt climate change due to their high temporal resolution, but their interpretation requires assumptions about the long-range dust transport pathways. Based on the mineralogical and isotopic signatures of the dust, the Taklamakan desert of western China was recently identified as the main dust provenance region for Greenland ice cores (Bory p. 72). Mineral dust in East Antarctic ice cores has largely been attributed to Patagonian sources, in particular during glacial times. However, for the late Holocene, Australia and also Antarctica itself have now been identified as secondary dust sources to Antarctica (Vallelonga p. 74). Furthermore, dust signatures at West and East Antarctic deposition sites have been shown to be impacted by topographic elevation effects (Koffman and Kreutz p. 76). Similarities detected recently in the geochemical fingerprint of Australian and Southern South American dust (Gili and Gaiero p. 78) further complicate the interpretation of dust in Antarctica.

A large amount of mineral dust is deposited over the open ocean and leaves an imprint in marine sediments. Recent methodological developments have added non-destructive fine-scale elemental scanning and geochemical fingerprinting methods to the portfolio of sediment core analysis. The gain in information detail reveals new insight into dust provenance and transport mechanisms, as demonstrated with a marine sediment core off southern Australia (De Deckker p. 80). Reconstructing dust deposition over the ocean is of particular interest because of the potential role of dust input in fertilizing high-nutrient, low-chlorophyll regions of the surface ocean with the micronutrient iron, thereby stimulating phytoplankton growth and organic carbon export to the deep ocean. Iron fertilization as traced in marine sediments from the Southern Ocean (Martínez-García and Winckler p. 82) may help explain variations in atmospheric CO_2 over past glacial climate cycles, and help to asses the potential of artificial iron fertilization as geo-engineering strategy.

Understanding the variability of the dust cycle in the past is closely tied to knowledge about past atmospheric circulation. The continental loess deposits at mid-latitudes around the world provide information about paleowind direction and intensity. Recent examples demonstrate that loess properties such as coarse-to-fine particle ratios and alterations in paleosol-loess sequences can provide insight into glacial-interglacial variations in eolian particle transport (Muhs et al. p. 84). Furthermore, an overview of global loess deposits and a comparison between climate model results and loess records in Europe highlights the potential for studying the role of changes in the seasonal cycle for the millennial-scale abrupt changes of Marine Isotope Stages 2 and 3 (Rousseau and Sima p. 86). During the past decade, peat bogs and the mineral dust they contain have turned out to be a new valuable natural archive for reconstructing the role of dust in climate change and during abrupt events, in particular during the Holocene (De Vleeschouwer et al. p. 88).

Encouraging collaboration

As emphasized by the contributions in this dust issue of PAGES Magazine, the evidence from proxies and model simulations about dust variations in the past is increasing rapidly. These are good conditions to foster cross-disciplinary approaches that combine more advanced characterizations of dust sources with the dust signatures at deposition sites. Concerted efforts are needed to produce quantitative proxy records and a synopsis of available records. Such an improved data basis would not only benefit the paleo-dust reconstruction community but climate modelers, who require quality-controlled globally gridded datasets as model input or for meaningful model-data comparisons. As an example of such concerted efforts, this issue provides news from the DIRTMAP initiative (Maher and Leedal, p. 90) and the new PAGES working group, DICE (Dust Impacts on Climate and Environment; Winckler and Mahowald, p. 61). DICE will build on the successful legacy of ADOM and provide a collaborative platform to build a tight and well-coordinated link from (paleo) observations to (paleo) climate modeling.

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DICE: Dust impact on climate and environment

Gisela Winckler[1,2] and Natalie Mahowald[3]

Natural and human contributions of aerosols and dust are critically important components of climate and Earth system dynamics. Mineral dust aerosols, emitted through wind erosion, affect the radiative budget of the planet, precipitation patterns, biogeochemical cycles, the chemistry of the atmosphere, air pollution and human health. Emission patterns, transport and impact of aerosols on societies are almost certain to change under ongoing climate and environmental change, and it is thus increasingly important to improve our understanding of the impact of dust on climate and environment.

Dust influences the radiative balance of the planet in two different ways: either directly by reflecting and absorbing solar radiation, or indirectly by affecting cloud formation and precipitation patterns (Fig. 1). Mineral dust containing iron can impact marine biological productivity and ecosystem structure by supplying micronutrients to regions of the ocean where iron-scarcity limits primary productivity, and thereby affect the efficiency of the biological pump, a mechanism that could be important in driving ice age cycles.

Dust not only affects climate, but is also influenced by it: its production, atmospheric transport and deposition are sensitive to climatic conditions. Therefore, dust aerosols can act as a tracer of continental conditions and atmospheric circulation.

Since aerosol interactions with climate are a major uncertainty in climate model simulations and predictions (e.g. Myhre et al. 2013), improved understanding of the role of aerosols in past climates represents an important contribution from paleoscience to projections of future climate.

Building on the success of PAGES' Atmospheric Dust: Observations and Modeling (ADOM) working group, the new DICE working group seeks to provide a collaborative platform to build a tight and well coordinated link from paleo-data observations to paleoclimate modeling. This will be achieved by fostering direct interaction between observationalists and theorists, between climatologists and the dust modeling community, and between paleoclimatologists and geochemists.

DICE will convene workshops providing interactions between these communities, drawing input from observationalists and modelers, as well as from scientists focusing on modern times and paleo-perspectives. The goal of this working group will be to develop new databases of dust fluctuations, including deriving more detail from existing data, and to assist in the assessment and development of new proxies for desert dust in paleo-environments.

Specifically, DICE aims to facilitate the compilation of a next-generation global observational dataset for dust deposition from sedimentary archives for the Late Quaternary, synthesizing spatially and temporally resolved proxy datasets from marine sediments, sediment traps, corals, ice cores, terrestrial deposits and lake sediments. The new compilation will build and extend on the success of DIRTMAP (Dust Indicators and Records of Terrestrial and Marine Paleoenvironments; Kohfeld and Harrison 2001, and Maher and Leedal, this issue) by providing time-series data. The DICE database thus aims to meet the demands created by recent developments in Earth system models, which are now able to run transient simulations and to include more complex interactions between dust and climate. Datasets with high temporal resolution and grain size information will serve as a reference for time-transient studies, e.g. of millennial scale variability or variability associated with abrupt climate change, such as Dansgaard/Oeschger and Heinrich events, or the last glacial transition.

The DICE working group will interact with other paleoscience working groups, such as the International Partnerships in Ice Core Sciences (IPICS), and seek interaction with Earth system science projects rooted in modern observations, such as the International Global Atmospheric Chemistry (IGAC) Project, with the goal of strengthening the links between the paleo community and the modern atmosphere community.

Visit the DICE working group webpage at: www.pages-igbp.org/workinggroups/dice

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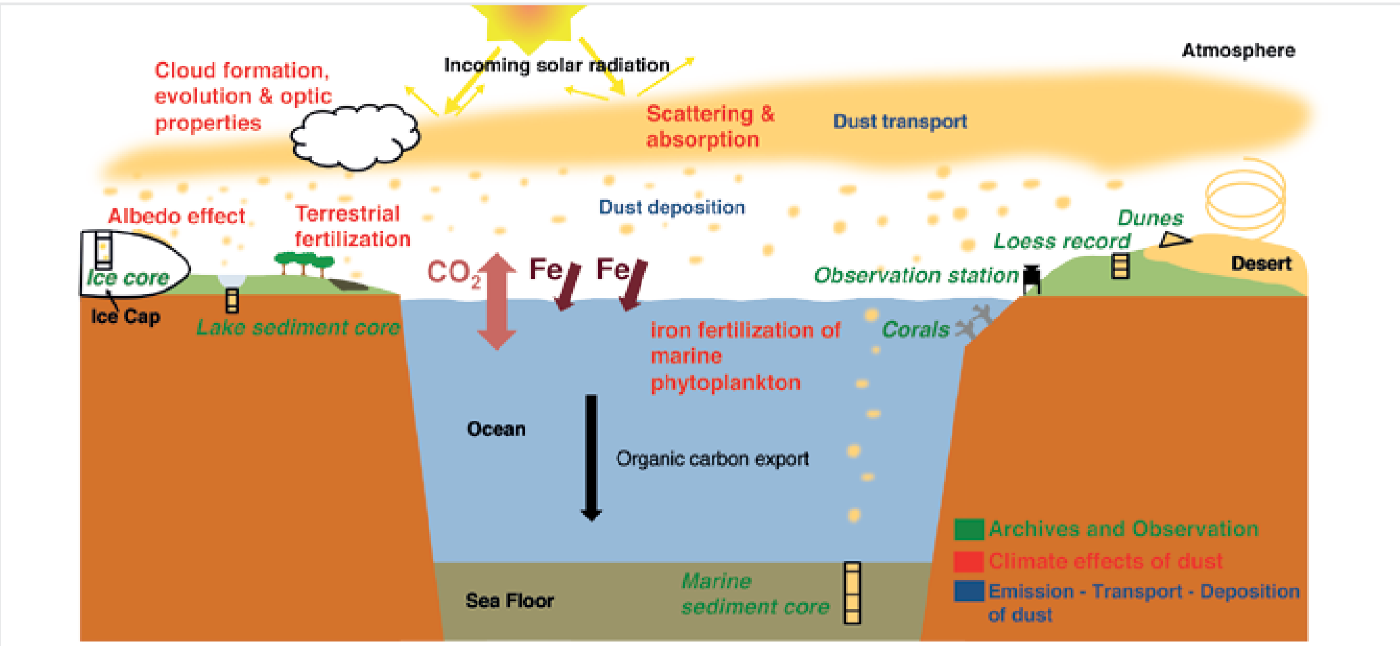

Figure 1: Schematic showing the interactions between mineral aerosols and climate.

Mineral dust: Meteorological controls and climate impacts

Kerstin Schepanski[1], U. Merkel[2] and I. Tegen[1]

Dust contributes substantially to the aerosol load of the atmosphere, but lifting dust high above the ground requires specific meteorological conditions. Once mobilized, dust interacts with components of the Earth system in multifaceted ways, which causes modifications to the energy budget and ecosystems.

Bare land surfaces are the main sources for mineral dust. The most active and strongest dust sources are predominantly situated in semi-arid and arid regions at sub-tropical latitudes where subsiding air masses stabilize the atmosphere and dry climates prevail. In terms of dust emission flux and frequency of emission events, the Sahara Desert is considered the world's largest dust source, although the spatio-temporal variability and characteristics of its dust production are yet not fully understood.

Dust uplift and entrainment into the atmosphere are determined by surface wind speeds and local land surface characteristics such as soil texture, soil moisture, and vegetation (Fig. 1). Dust emission is often described as a threshold problem, where particles are only entrained when wind speeds rise above a certain threshold transferring momentum from the atmosphere to the dust particles. The wind speed required for entrainment depends on soil characteristics (e.g. Marticorena and Bergametti 1995) such as particle shape, size and density, and inter-particle binding energy.

In addition to the atmospheric control on dust emission, land surface characteristics also play a role by determining the dust source's erodibility. Relative to atmospheric conditions, the land surface characteristics of dust sources remain fairly constant. Thus, the predominance of specific land surface conditions, such as smooth surfaces and the presence of fine and loose soil particles, is an important aspect in determining its erodibility. In particular, alluvial sediments are prone to wind erosion and play a significant role in many dust sources today and in the past (Reheis and Kihl 1995). As fresh layers of fluvial sediment deposits tend to occur in response to strong precipitation events such as flash floods, dust emission from this source type are characterized by more pronounced interannual variability.

Meteorological settings for dust emission

The processes contributing to dust source activation vary between seasons due to seasonal changes in atmospheric circulation patterns. Besides land surface characteristics, understanding the meteorological aspects of atmospheric conditions which provide sufficient wind (momentum) for dust uplift is crucial when discussing the dust cycle today, but also during ancient times and for future scenarios.

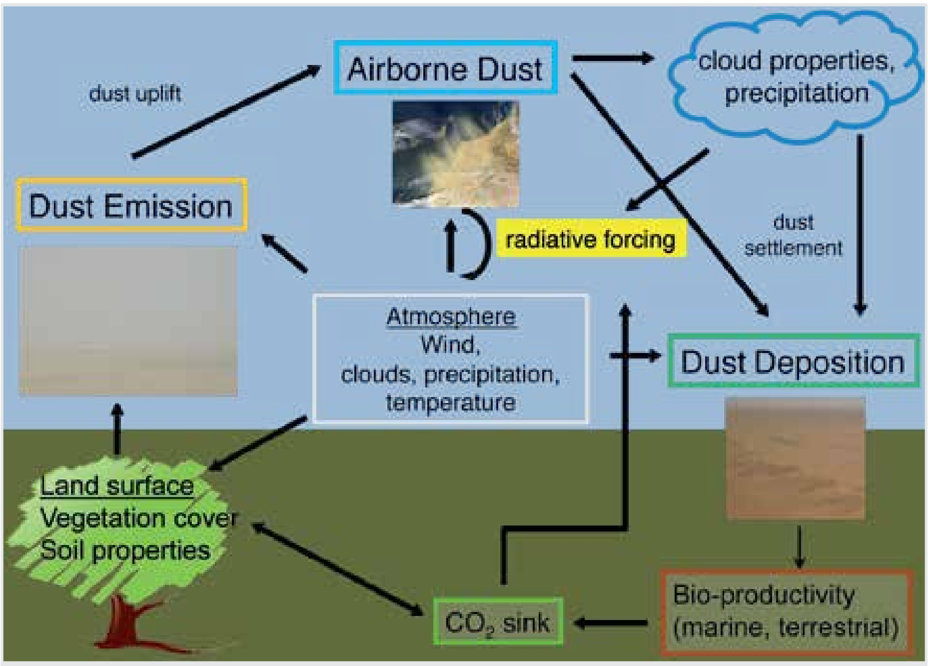

Figure 1: The atmospheric dust cycle and related feedback mechanisms.

Recent studies analyzing satellite data and model simulations have identified different meteorological settings that play a key role in creating suitable atmospheric conditions for dust uplift (Schepanski et al. 2009). Satellite observations at 15-minute resolution revealed a strong diurnal cycle in the onset of dust emission and, integrated over months, synoptic climate patterns that result in dust uplift (Fig. 2). In terms of frequency and associated dust emission fluxes, the following meteorological processes are suggested: (1) downward mixing of the nocturnal low-level jet (LLJ), (2) cold pools induced by moist convection, and (3) baroclinicity and cyclogenesis.

A sudden and strong increase in surface wind speed occurs in the vicinity of a decaying nocturnal LLJ. LLJs are characterized by a low-level (~200-700 m above ground) wind speed maximum that forms due to the frictional decoupling of upper air layers from the surface air layers at night. These preconditions are frequently fulfilled during calm nights. Nocturnal LLJs usually begin to form before midnight and accelerate during the second half of the night. After sunrise, convective turbulence increases due to solar heating and erodes the nocturnal temperature inversion. Consequently, the LLJ layer is frictionally coupled to the surface layer and momentum from the LLJ is mixed downward leading to wind gusts and increased surface wind speeds, ultimately uplifting dust particles after sunrise when the resulting winds are strong enough. Nocturnal LLJs are a frequent phenomenon over North Africa and can explain a major fraction of observed dust source activations in space and time.

Cold pools, also described as downdrafts or gravity (density) currents, are initiated by deep convection. Evaporative cooling creates pools of cold air that subsides due to its higher density compared with the surrounding air. At the ground, the downward motion is transformed into a horizontal motion and the air mass spreads out horizontally forming a gust front. High surface wind speeds following the front can uplift dust and build an arcus-like dust front, a so-called Haboob. Although high dust emission fluxes are achieved during the passage of such a gust front, such dust emission events are less frequent than that from LLJs due to the rare occurrence of cold pools.

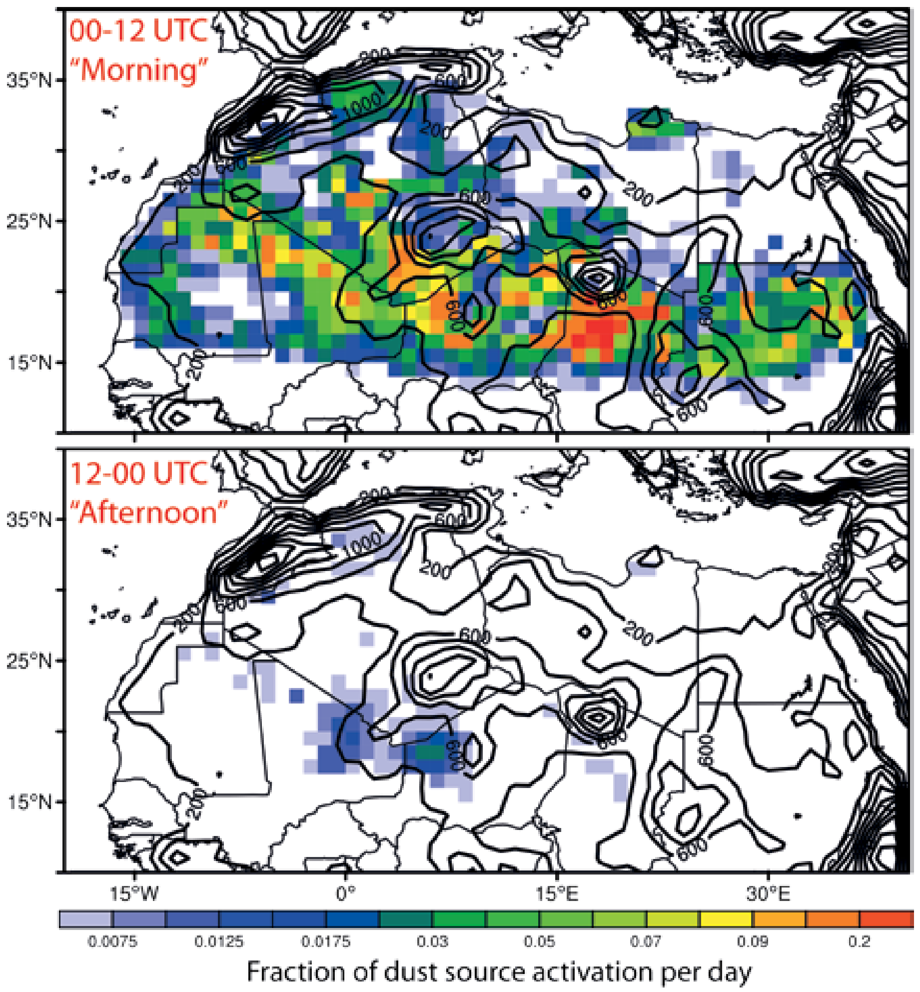

Figure 2: Diurnal variability of dust source activations over North Africa inferred from MSG-SEVIRI IR dust imagery for 2006-2010 following Schepanski et al. (2009). Figures shows the occurrence frequency of dust source activations in the first (top panel) and second (bottom panel) half of the day. Orography is given by contour lines.

Strong surface wind fields also form in association with baroclinic disturbances and cyclonic systems, predominantly during boreal spring. Prominent examples are the cold outbreaks of Arctic air masses over China that result in dust fronts originating from the Gobi Desert, and Mediterranean cyclones which form dust fronts over Mediterranean North Africa and the Middle East.

Climate impacts of dust

The relevance of mineral dust for the modern climate system has been widely studied, most often from an atmospheric perspective through its impact on the radiative balance and on clouds. Dust impacts the radiation balance of the Earth by scattering and absorbing incoming solar radiation, and by absorbing and emitting terrestrial radiation. Net radiative forcing by dust depends on the optical properties of the particles, which in turn depend on their size distribution and mineral composition. The magnitudes and even the sign of the net radiative forcing at the top of the atmosphere by dust from both natural desert sources and anthropogenic (agricultural) land surfaces are highly uncertain. The uncertainty of estimates of global annual average forcing is in the order of 1-2 Wm^{-2} at the Earth surface (Carslaw et al. 2010).

Dust also provides nuclei for ice particle formation in the atmosphere and thus impacts the microphysical properties and the lifetimes of mixed-phase and ice clouds, and the kind and frequency of precipitation.

Dust now receives increasing attention from an Earth system perspective (Shao et al. 2011) since mineral dust interacts with different components of the Earth system (Fig. 1). For instance, the deposition of mineral dust on glaciers has the potential to lower their surface albedo, enhance their melt rates, and speed up their retreat (Oerlemans et al. 2009). This process and positive feedback mechanism may also have played an important role during Pleistocene deglaciations (Ganopolski et al. 2010).

The marine realm is also affected by mineral dust deposition. Downstream of major west African dust sources, tropospheric mineral dust cools the Atlantic ocean surface and mixed layer by 0.5-2°C in response to an increase in the aerosol optical depth (Evan et al. 2009; Martínez Avellaneda et al. 2010). Furthermore, Atlantic hurricane formation, could be reduced in response to two effects: (1) The dust's cooling effect on the surface ocean reduces the energy for strong atmospheric convection and (2) increased wind shear due to heating of air layers containing dust might impede the development of cyclonic cells. However, an unambiguous causal relationship has not yet been proven with sufficiently good data.

Through its impact on ocean surface temperatures and its modification of land-sea contrasts, dust may also feed back on the hydrological cycle, and thus on vegetation dynamics. In turn, associated changes in land surface conditions modify the dust mobilization potential of source areas. Superimposed on the natural dust variations, current and future anthropogenic land is altering the geographical distribution of preferential dust mobilization, although quantitative estimates of projected human-induced dust changes are highly uncertain (Mahowald et al. 2009).

Dust also impacts biogeochemical cycles. Over land, desert dust influences soil conditions in various ecosystems through phosphorous deposition. In the ocean, dust has been found to enhance marine productivity by iron fertilization (Jickells et al. 2005; Martínez-García and Winckler, this issue) and has been argued to increase particle settling rates through ballasting, i.e. the adhesion of organic matter to sinking mineral particles. This affects the ocean carbon cycle by enhancing organic carbon export from the surface to the deep ocean (Iversen et al. 2010; Ternon et al. 2010).

Perspectives

Geological records from ice cores, ocean sediments and loess deposits provide information about dust deposition in past climates. However, from a paleo-perspective, dust-relevant processes operate on extremely short timescales and relatively small spatial scales. Nevertheless, these processes are embedded in the large-scale background climatic state and low-frequent variations of the climate system, in addition to playing an important role through various feedbacks, e.g. the dust-snow-albedo effect, or the link to the ocean biological pump. Therefore, the geologic dust research should be flanked by modeling efforts which realistically implement the processes controlling dust emission, transport and deposition into global Earth system models to provide the required spatio-temporal context for the interpretation of the proxy evidence.

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Dust deposition rates derived from optical satellite observations

Luca Lelli, W. von Hoyningen-Huene, M. Vountas, M. Jäger and J.P. Burrows

Satellite retrievals of aerosol optical thickness over the Atlantic Ocean have been used to estimate the rates of dust deposition. The results reveal higher dust deposition in summer than in winter and give insights into the location of desertic dust source areas.

Desert dust (or dust aerosol) outflows off the West African coast impact offshore biogeochemical processes and can be regarded as natural hazards to human activities and ecosystems. For example, dust storms affect aviation operations reducing flight visibility, causing engine mechanical damages and flight path reassessments. On the other hand, dust input adds nutrients to the surface of the seas which stimulate phytoplankton production, and higher particle flux can increase export fluxes of biomass from the surface waters to the sea floor and hence increase accumulation rates in the underlying sediments.

Dust is collected on land only at few observation sites, like at Cape Blanc (Mauritania) or Barbados (Fischer and Karakas 2009; Prospero 1999). Conversely, remote satellite monitoring of dust transport covers the entire Atlantic Ocean and is therefore an invaluable complement to in-situ measurements.

Standard remote sensing techniques of dust are based on the physical principle of extraterrestial sunlight travelling through the Earth's atmosphere and being attenuated by suspended dust particles. Nadir-looking spectral satellite radiometers (e.g. SeaWiFS, MERIS, MISR, MODIS) measure

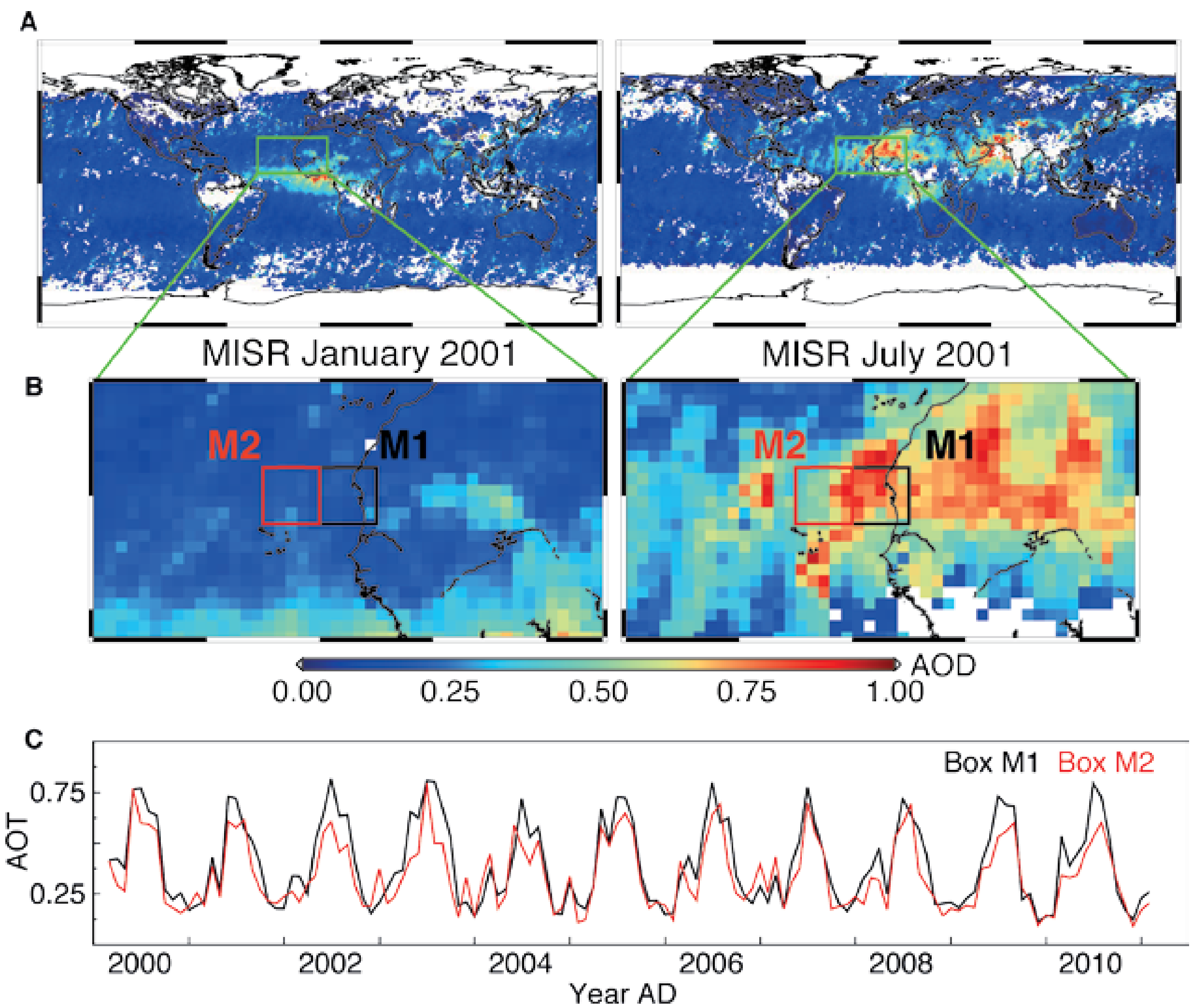

Figure 1: Monthly averages of Aerosol Optical Thickness (AOT; dimensionless) retrieved from MISR satellite data for the determination of dust sedimentation rate. Maps of AOT for January and July 2001 on a global scale **(A)** and zoomed in to the example region around Cape Blanc **(B)**, where sediment traps are deployed across West Africa and the Atlantic Ocean. The time series in **(C)** portrays the AOT signal extracted for the adjacent boxes M1 and M2. The oscillations of both curves indicate that dust activity is more frequent in summer than in winter. Dust deposition is reflected by the difference between the red and black curves during the respective months.

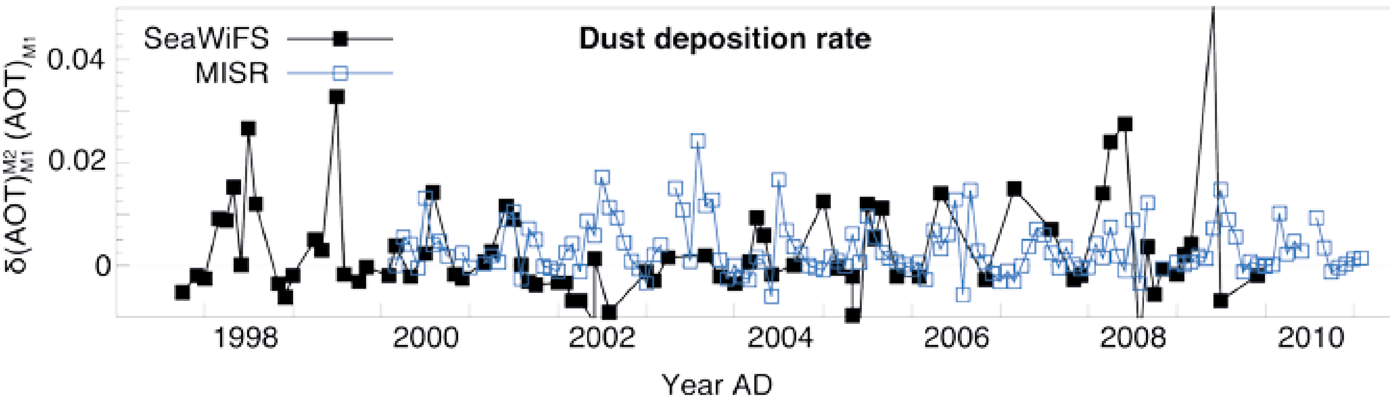

Figure 2: Time series of AOT changes between boxes M1 and M2 (see Fig.1), derived from satellite retrievals from SeaWiFS (black curve) and MISR (blue curve) instruments. The curves can be considered as approximations for the rate of dust deposition at the site of Cape Blanc.

the amount of sunlight reflected back to space and allow us to determine the degree of sunlight attenuation. The latter is described by Aerosol Optical Thickness (AOT), which is defined as the extinction coefficient of light integrated over a vertical column through the atmosphere. AOT can be calculated from data of reflected light with algorithms like the Bremen AErosol Retrieval (BAER; von Hoyningen-Huene et al. 2003, 2011) and monitored both in space and time. However, such algorithms are challenged not only by missing a-priori information on the specific optical properties of dust (Dinter et al. 2006), but also by local reflectivity of the ground. Radiant surfaces (such as the bright Sahara) may reduce the contrast between suspended dust and the ground beneath, hence degrading the overall algorithmic performance and accuracy.

Figure 1 shows seasonal variations in satellite-derived AOT in dust-laden regions worldwide. Off West Africa, for example, AOT is about three times as high in summer than in winter.

From optical thickness to dust deposition

Comparisons of satellite-derived AOT and data from sediment traps over West Africa and the Northern Atlantic do not show a direct relationship between atmospheric dust loading and dust accumulation. However, the spatio-temporal change of dust AOT can be used as an indicator for the fallout of aerosol along the transport path. The method described in the following, has been developed to determine dust deposition from satellite data.

The deposition rate of aerosol particles is reflected by the decrease of AOT along the transport path rather than AOT itself. Driven by this idea, a method has been developed to determine the relative change of AOT along an estimated transport path. This requires that the aerosol loading is determined from AOT for the region of interest, i.e. the AOT needs to be transferred quantitatively into aerosol mass load. The algorithm for this is based on assumptions on the dust grain size and dust particle density in the air.

Mass loss (or sedimentation rate) which can be directly compared to ground measurements can be derived from lateral dust transport in two ways: (i) using a transport model with a sedimentation module or (ii) estimating the mass loss from the change in the aerosol columnar mass along the trajectory. Here, the latter approach is followed.

The sedimentation rate is inferred from the mass difference along the main aerosol transport path. If one takes the temporally averaged AOT of two adjacent regional boxes (see boxes M1 and M2 in Fig. 1) along the main trajectory, a sedimentation rate can be estimated from the difference between the red and black AOT curves (Fig. 1C). Our new method allowed us to produce estimates of dust deposition from monthly averages of AOT on a regional grid.

Testing the method

Preliminary qualitative comparisons have been made for Cape Blanc on the coast of Mauretania, using deposition data by Fischer and Karakas (2009). First, AOT values were calculated with the BAER algorithm using SeaWiFS data. Then, two grid boxes over the site and offshore Cape Blanc were selected. The two neighboring boxes are located between 20°N and 22°N (see M1 and M2, Fig. 1). We assume that both boxes are located along the main westward oriented dust transport path. Even though this assumption is only of limited validity and the time series of the difference between AOT in both boxes shows some negative values (Fig. 2), the analysis of the time series reveals a potentially promising correlation ($r > 0.6$) between the AOT derived from remote sensing and in-situ sedimentation data from Cape Blanc (unpublished, not shown). Figure 2 also shows that the method is sensitive to the satellite radiometers used. The pictured values of AOT changes, derived from SeaWiFS and MISR measurements, exhibit differences that can be attributed to distinct instrumental characteristics.

These preliminary results are a first step towards a systematic application of this method. However, the approach needs significant improvements in terms of the consideration of dust transport trajectories, the injection height of dust, its mixing with surrounding air and optical parameters used for determining the local dust type.

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Including dust dynamics in paleoclimate modeling

Yaping Shao

Knowledge about today's climate-dust dynamics is the basis for the interpretation of dust deposition records. Regional climate models with built-in dust modules provide insights into dust transport out of the major source regions and facilitate direct comparison with sediment sequences.

Atmospheric dust loads have varied substantially over time (Maher et al. 2010), as revealed in dust records in ice cores (Lambert et al. 2008), deep-sea sediments (Winckler et al. 2008) and loess sequences (Ding et al. 2001). A key feature of Greenland and Antarctic ice cores is the pronounced dust load variations between glacials and interglacials, with more dust during glacials than during interglacials (Fischer et al. 2007). Deep-sea sediments also indicate high dust loads during glacial stadials; for example Moreno et al. (2002) found higher dust transport from the Sahara to the western Mediterranean during the cold stadial periods of the Dansgaard-Oeschger cycles.

Modern dust variability

Dust records reflect past climate changes in the form of varying deposition rates, particle size and dust mineralogy, but their interpretation is not straightforward. It is therefore important to understand the present-day climatic drivers of dust processes and their variability on different time scales. Using synoptic dust-weather and visibility data for the period 1974-2012, Shao et al. (2013) analyze recent dust trends and their link to climatic drivers. Figure 1a shows a series of the global monthly-mean dust concentration. For the period 1974-1983, the uncertainty in the dust concentration estimates is larger due to the smaller sample size (~20,000 month^{-1}) relative to 1984-2012 (~300,000 month^{-1}). The data analysis shows that dust concentration was in the order of 10-100 μgm^{-3} and decreased by about 0.2-0.5 μgm^{-3} per year over the past four decades. This trend is attributed primarily to decreasing dust production in North Africa and Northeast Asia.

Correlations have been examined between dust variability and key indices that affect climate variability in North Africa, including the Multivariate El Niño Southern Oscillation (ENSO) index (MEI), the North Atlantic Oscillation (NAO), and the Atlantic Multi-decadal Oscillation (AMO). The AMO is the main cause of tropical Atlantic sea surface temperature fluctuations and oscillates with a period of ~70 years (Goldenberg et al. 2001). A positive AMO phase corresponds to enhanced rainfall in the Sahel and above-normal hurricane activity over the Atlantic. Wang et al. (2012) used a dataset with records extending back to the 1950s and found multi-decadal co-variability between North Atlantic sea surface temperatures, African dust and Sahel rainfall (as well as Atlantic hurricanes). Low North Atlantic temperatures were accompanied by more African dust and less Sahel rain; high temperatures by less dust and more rain. The dust concentration time series for North Africa is significantly negatively correlated with the AMO index. This negative correlation has also been detected in several previous studies (Foltz and McPhaden 2008; Evan et al. 2012). No significant correlations were found between dust and MEI or NAO. This indicates that the present day global dust trend might be determined by the climate systems that govern variability in the Atlantic-North African region, i.e. mainly by the AMO. Regionally, the dominant drivers can however be different. Dust in Northeast Asia is more related to the Arctic Oscillation, while dust in Australia is primarily related to ENSO. Currently, there is not enough evidence to directly attribute the decreasing trend in dustiness over the last decades to global warming.

Dust modeling

Increased interest in dust has prompted rapid progress in dust modeling since the late 1980s. It began primarily with modeling dust transport, but has since grown to the point that comprehensive dust models have been developed and applied to all major dust regions around the world, in particular North Africa, Northeast Asia and Australia. Since the 1990s dust components were included in global climate models (e.g. Tanaka and Chiba 2006) by building dust modules into the model's atmospheric component. The central task of dust modeling in this context is to solve the dust budget equation for various particle size groups, including the computation of dust emission, transport and deposition.

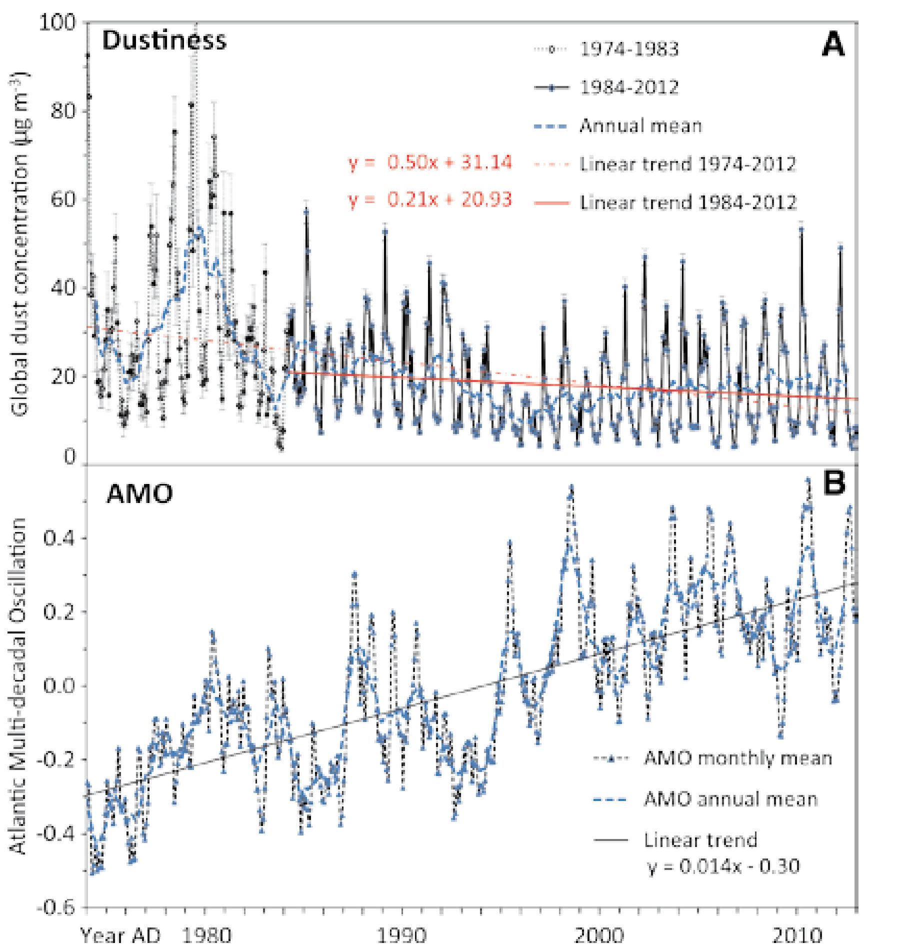

Figure 1: (A) Time series of global monthly-mean dust concentration, and the corresponding 95% confidence interval (in error bars), for the period 1974-2012, together with the yearly running mean and the linear trends. The trend for the full is shown by the dashed red line, for the period 1984-2012 by the solid red line. **(B)** Time series of the AMO index as monthly and yearly running mean, and showing the linear trend.

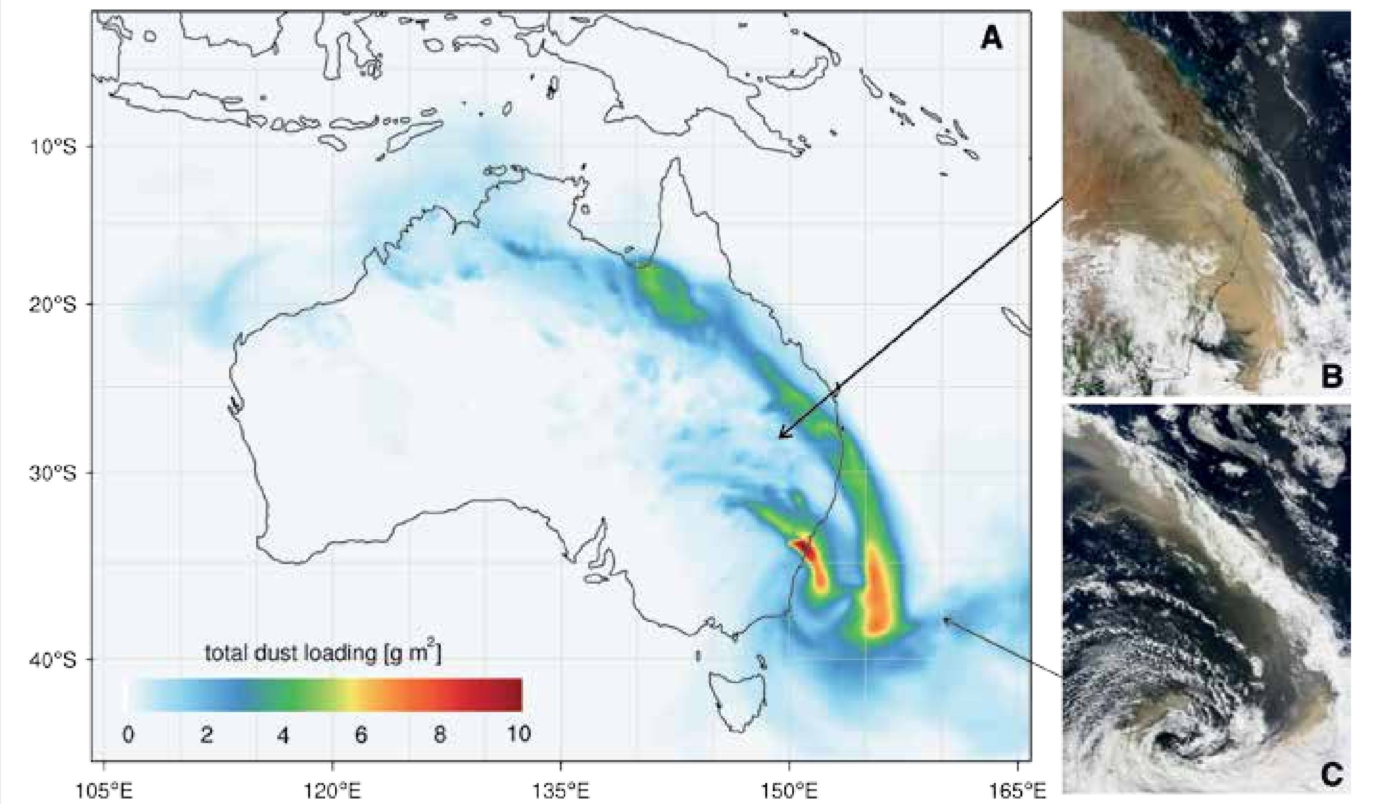

Figure 2: (A) Simulated dust load for the Australian dust event on 23 September 2009, using the WRF-CHEM/D model with a spatial resolution of 40 km. Australian dust is transported across the continent along two major routes: the southeast route along which dust is transported to the southern Pacific Ocean and the northwest route to the Indian Ocean. **(B)** MODIS satellite image from the morning of 23 September 2009. **(C)** As (B), but from 24 September 2009. The satellite images confirm the good performance of the model.

Early dust models were not equipped with adequate dust emission and deposition schemes. In the late 1980s, dust emission schemes were developed based on wind erosion physics (e.g. Alfaro and Gomes 2001; Kok 2011) and more recently, measurements of size-resolved dust fluxes have become available for scheme validations (Ishizuka et al. 2014). Using these methods, dust simulations on continental scales have been quite successful. Figure 2 shows an example of the WRF-CHEM/D simulation of the Australian dust event of 23 September 2009, the strongest dust strom event on meteorological record, which swept over almost the entire Australian continent. Comparison with satellite observations shows that the simulation captured features of the dust event development and the dust distribution patterns well.

Present-day dust transport modeling provides information about dust dynamics as a basis for the interpretation of paleo-dust records. The particular example shown in Figure 2 suggests that Australian dust is transported across the continent along two major routes: the southeast route along which dust is transported to the southern Pacific Ocean and the north-west route to over the Indian Ocean.

Simulations of modern dust transport in North Africa revealed that Saharan dust is primarily transported towards the monsoon region in Western Africa by the northeasterly wind and then westward by the easterlies in the tropics (Klose et al., 2010). In winter, dust is transported mainly along a southerly route, while in summer a more westerly route dominates. The simulation of a typical dust event suggests that much of the dust transported to the tropical Atlantic originated from the northeastern part of North Africa (Libya, Egypt and Sudan). Dust emitted there was advected toward the Sahel dust zone and then transported westwards over the Atlantic. The Sahel dust zone exists in a climatic sense in terms of dust event frequency. It is located between 10 and 16°N, stretching several thousand kilometers over the Sahel from west to east, reaching the western boundary of the Ethiopian Highlands.

Finally, simulations in Northeast Asia revealed that the motion of the Mongolian cyclones and the cold air generally follow the East Asian trough. Dust from the Taklimakan and Gobi deserts is primarily transported toward the southeast and then the northeast. The Tarim Basin, in the Taklimakan desert, is no more than 1000 m a.s.l., but is surrounded by mountains of ca. 3000 m altitude. Dust is first lifted vertically by convection and basin-scale mountain-valley circulation to 8-10 km a.s.l. (see also Bory, this issue). Due to the strong westerlies in the upper atmosphere, the uplifted dust can travel more than once round the Earth (Uno et al. 2009).

Perspectives on paleo-dust modeling

Efforts are now being made to model dust in paleoclimate scenarios using Earth System Models (ESMs), such as those participating in the Paleoclimate Modeling Intercomparison Project Phase 3 (PMIP3; Otto-Bliesner et al. 2009). Within PMIP3, more than 20 GCMs/ESMs are run over 100 to 500 year periods centering on the Holocene, the Last Glacial Maximum and the Eemian Interglacial.

Regional climate models with built-in dust modules, such as the WRF-CHEM/D (Kang et al. 2011), were nested within the PMIP3 simulations to regionalize paleo-dust information and make comparison with sediment sequences easier. This should allow investigation of the dust patterns in North Africa during the Holocene and LGM. The outcomes of such model simulations are expected to strengthen the paleoclimatic interpretation contained in dust records. At present, this effort is confronted with the need for reconstruction of land-surface and regional climate and weather conditions. Our understanding of paleo land-surface conditions (e.g. soil type and vegetation cover), which ultimately determine the distribution and strength of paleo dust sources, is rather low. PMIP3 simulations generally have coarse spatial and temporal resolutions, which are insufficient for reliable paleo dust modeling. However, some progress has been made by use of techniques such as statistic-dynamic downscaling and ensemble simulations to reproduce paleo weather patterns for potential paleo dust regions.

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Characterizing the temporal and spatial variability of African dust over the Atlantic

Joseph M. Prospero

Mineral dust in sediments and ice cores is often used as a proxy for changes in aridity and large-scale wind systems. Long-term dust measurements on Barbados and other Atlantic sites show a close but complex relationship between hydroclimate and dustiness.

Mineral dust plays a role in many aspects of climate through atmospheric processes by absorbing and scattering solar radiation and by impacting cloud microphysical processes (Shao et al. 2011). Also, dust deposited to the ocean yields nutrients that can modulate marine biogeochemical processes and the global carbon cycle and, hence, climate (Shao et al. 2011). The climate-dust relationship is complicated by the fact that dust generation and transport are themselves modulated by climate.

Dust records in sediments and ice cores show that transport has varied greatly over glacial-interglacial (Maher et al. 2010) and shorter timescales. In order to use dust as a proxy in paleoclimate studies, we need to understand the role that climate plays in modulating dust transport today. This information is also important to understanding how dust can itself affect climate. Here we present the results of long-term network studies in the North Atlantic that characterize the great variability in transport over the region. These studies yield insights into some of these processes that affect variability and give direction for further research on the link to climate.

The Barbados record

North Africa is the focus of much dust research because it is the world's largest persistently active source, accounting for about 70% of total dust emissions (Huneeus et al. 2011). Much of this dust is carried to the west over the Atlantic in large-scale plumes, some of which can be tracked by satellites all the way to the southern United States (Bozlaker et al. 2013), the Caribbean and South America (Chin et al. 2014; Yu et al. 2013).

Our understanding of long-term trends in dust transport to these regions rests largely on aerosol monitoring studies on Barbados that began in 1965 (Delany et al. 1967; Prospero and Lamb 2003) and which continue to this day at the University of Miami atmospheric chemistry field site located on the east coast of Barbados (13.17°N; 59.43°W; Prospero and Mayol-Bracero 2013).

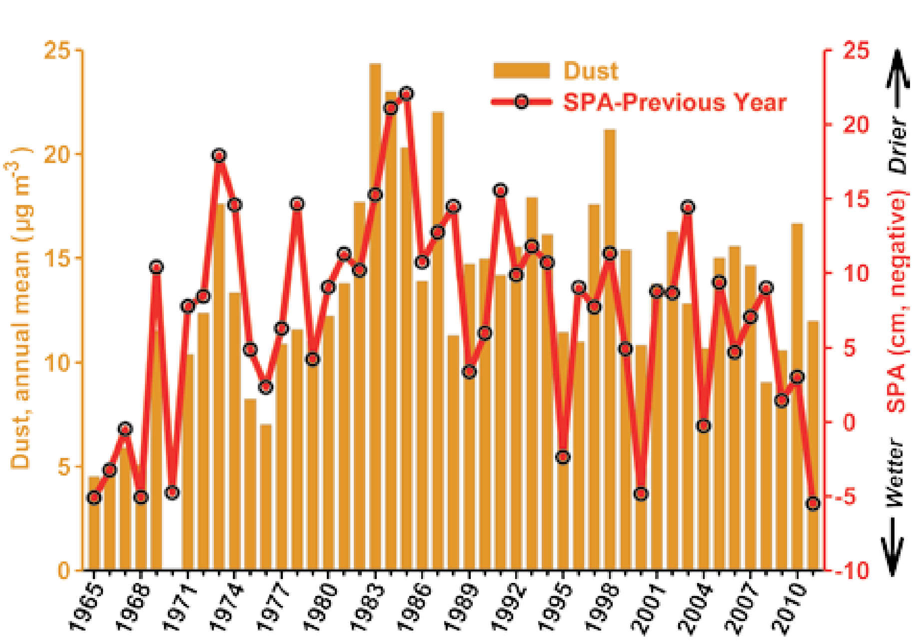

Figure 1: Barbados annual mean dust concentrations and Sahel June-October Precipitation Anomalies (SPA) from 1965-2011. To more easily compare dust concentrations with rainfall metrics, the SPA values are plotted as the arithmetic negative. SPA data are taken from www.jisao.washington.edu/data_sets/sahel/ with anomalies calculated from data over the period 1950 to 2011.

Barbados dust concentrations show great variability on a broad range of time scales ranging from days, to seasons, to decades (Prospero and Lamb 2003). Of particular interest is the long-term variability seen in the annual mean concentrations over 1965-2011 (Fig. 1). Dust transport increased sharply in the early 1970s with the onset of severe long-term drought in West Africa and peaked in the mid-1980s coincident with the most intense phase of the drought.

This increase focused attention on the role of rainfall in the dust cycle particularly in the Sahel, a region that depends greatly on the seasonal progression of the West African monsoon to provide rainfall (Marticorena et al. 2010; Doherty et al. 2012). In the first half of the record, increased transport is clearly associated with markedly drier conditions in the Sahel as seen in the close relationship between rainfall variations (expressed as Sahel Precipitation Anomalies; SPA) and dust concentration (Fig. 1). SPA is based on precipitation departures from the mean over the period 1950-2011. This association fits our general expectation that drier climate results in dustier conditions.

However, beginning in the early 1990s, this relationship appears to weaken. Dust concentrations remain relatively high despite increased rainfall and evidence of "greening" in the Sahel (de Jong et al. 2011). Although there is considerable year-to-year variability in dust transport and rainfall there is no strong relationship between the two. Note, for example, that dust concentrations in 1987, 1997-1998, and 2010 were comparable to those at the peak of the drought; in contrast, the SPAs, although moderately positive (i.e. relatively dry) were generally closer to the long-term mean. It is notable that over the period 1989 to 2005 most SPA annual means fall within a narrow range and show no evidence of a trend. However, after

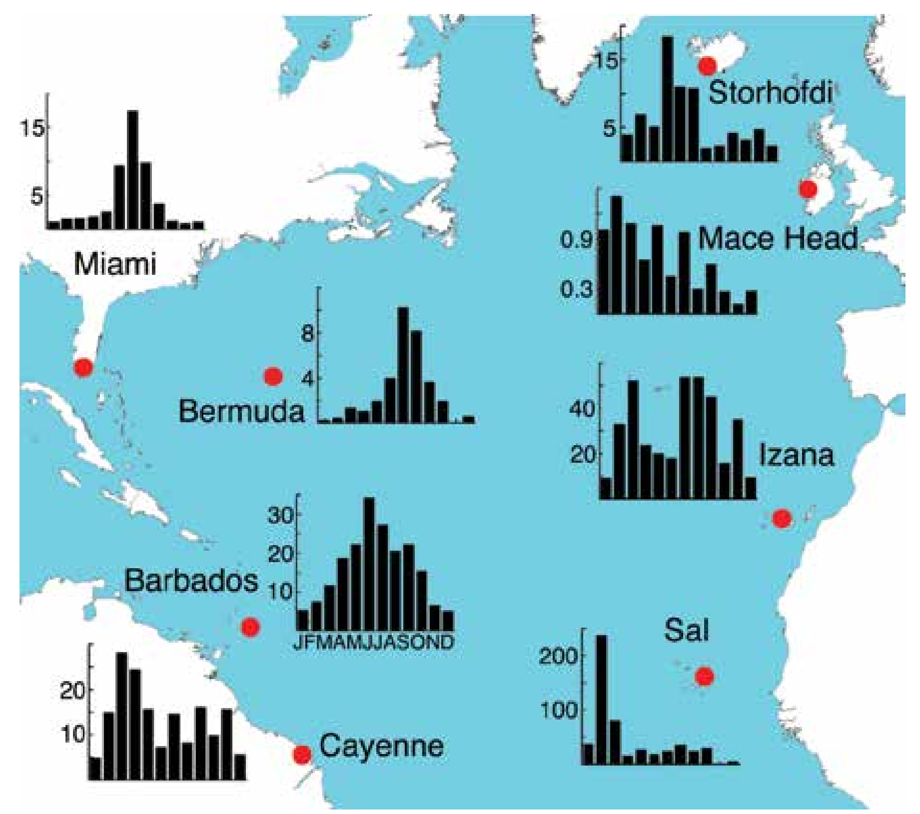

Figure 2: The annual cycles of monthly mean dust concentrations at University of Miami network sites in the North Atlantic. The means at each site are based on multi-year data but they are not necessarily measured concurrently. Note the difference in the ordinate scales in each inset figure. Figure adapted from Prospero et al. (2012).

2007 rainfall was close to normal yet dust concentrations remain moderately high, especially in 2010.

Dust transport to South America

The annual mean values on Barbados (Fig. 1) are strongly weighted by the high dust concentrations that prevail during boreal summers. Although dust concentrations are low in winter and spring on Barbados, we know that there is intense dust activity in North Africa in the Sahel region, most prominently in the Bodele Depression in northern Chad (Ben-Ami et al. 2012). Bodele sediments, deposited during the Holocene in what was Lake Mega Chad, are now being mobilized in huge quantities (Washington et al. 2009). Almost daily in spring, satellites show immense plumes being carried westward across the Atlantic, many eventually reaching South America in the region of French Guiana, 8000 km from the source. Ten years of recent air-quality aerosol measurements from Cayenne, a coastal town in French Guiana (04.95°N; 52.31°W), show a strong annual cycle with a spring maximum (Prospero et al. 2014). The magnitude and persistence of dust transport has had a significant impact on the supply of minerals and nutrients to the soils and sediments to the Caribbean and South America (including the Amazon; Ben-Ami et al. 2012; Muhs et al. 2007) and to the tropical and subtropical Atlantic (Baker et al. 2013).

Dust transport to the North Atlantic

The Barbados and Cayenne measurements and those made at other sites in the Miami Atlantic network (Fig. 2) document the widespread impact of mineral dust over the North Atlantic. Dust concentrations at all sites except Mace Head (Ireland) and Storhofdi (Iceland) are dominated by African dust, most notably in the subtropical and tropical regions. Iceland dust is transported by winds from paraglacial deposits in southeast Iceland and deposited to the North Atlantic where it might serve as an important source of nutrient iron (Prospero et al. 2012).

The summer maximum observed at Barbados, Miami, and Bermuda contrasts greatly with the spring maximum at Cayenne, which reflects the combined effects of the seasonal shifts in African dust sources and in the transporting wind systems. The records closest to Africa at Izaña (Tenerife) and Sal Island (Cape Verde Islands) differ greatly in seasonality and in concentrations from those observed at the western sites (Fig. 2). This contrast shows that dust transport processes to the eastern Atlantic differ from those that carry dust to the western Atlantic (Stuut et al. 2005) and complicates attempts to relate the composition of sediments in the eastern Atlantic to the more westerly regions.

In order to more fully understand the various factors affecting dust mobilization we need a better understanding of the most active source areas (Prospero et al. 2002), the factors affecting source activity (Formenti et al. 2011; Ginoux et al. 2012) and the relationship between source soil properties and those of the emitted aerosol, such as particle size (Mahowald et al. in press) and composition (Scheuvens et al. 2013). This knowledge is important to interpreting dust-climate relationships and decoding the paleo-dust records from sediments and ice cores.

Understanding dust and climate

While rainfall is a critically important factor for dust emission, we know that other factors also play a role (Okin et al. 2011), most notably wind speed and gustiness (Ridley et al. 2014) and terrain features, especially vegetation cover (Bullard et al. 2011). In the future, land use and land disturbance will become increasingly important (Ginoux et al. 2012) as populations shift and grow. The complexity of these relationships presents a challenge to the modeling community (Huneeus et al. 2011).

Africa, as the world's largest present-day dust source, presents a special challenge when anticipating the changes in dust emissions in coming decades. It is notable that in the recent IPCC assessment, models forecast that large areas of North Africa will become drier (Seneviratne et al. 2012). However, the models could not agree on the future trends in large areas of North Africa that today are the most active dust sources, most notably those in the Sahara and the Sahel. Thus, it is important that we continue to monitor transport from Africa to the Atlantic in a systematic manner so as to track changes over this region and to test the ability of dust-climate models to characterize long-range transport to the oceans (Schulz et al. 2012).

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The significance of particle size of long-range transported mineral dust

Jan-Berend W. Stuut[1,2] and Maarten A. Prins[3]

The physical properties of mineral-dust particles turn out to be more important than hitherto recognized; their composition, radiative properties, and fertilizing and ballasting potential fluctuate on various spatial and temporal scales. Especially the impact of large dust particles is often underestimated.

The role of aeolian dust for the radiation balance of the Earth is size-dependent. Dust has a direct cooling effect when small particles (< 2 µm) elevated into the high atmosphere block incoming sunlight (e.g. Claquin et al. 2003), but it can also act like a greenhouse gas when larger particles (> 10 µm) remaining in the lower atmosphere absorb and re-emit energy reflected from the Earth's surface (e.g. Otto et al. 2007). Therefore, to account for the climatic effect of mineral dust it is critical to have a good understanding of the size distribution of suspended particles in space and time.

However, until now, the scientific community has not considered the fact that dust particles suspended in the atmosphere and transported over large distances (>1000's km) can easily be of sizes >10µm. Specific set-up of air-monitoring programs, which are designed to measure air quality for human health studies and follow the guidelines of the World Health Organization (WHO), which do not consider particles larger than 10 µm. For this reason, these large dust particles are often simply not measured. As a consequence, they do not show up in the records and therefore seem non-existent.

Grain size sorting during transport

The particle-size distribution of mineral dust is not only a function of lateral but also vertical transport distance (e.g. Torres-Padrón et al. 2002). This observation had already been put into a conceptual model by Pye and Zhou (1989; Fig. 1). As wind is a very size-selective transport mechanism, the sediments it had carried typically a well-sorted particle-size distribution, which gradually gets finer from proximal to distal deposition sites. This fact has been used in numerous paleo-environmental studies to both determine source-to-sink changes in the particle size of aeolian dust (e.g. Sarnthein et al. 1981; Prins and Vriend 2007) and to quantify accumulation rates of aeolian dust (e.g. Prins and Weltje 1999; Moreno et al. 2005). Obviously, at proximal locations (where aeolian dust is deposited relatively close to its source), particles are coarser grained and mass accumulation rates are larger than at more distal locations (where aeolian dust is deposited relatively far from its source). This observation was first prominently described by Sarnthein et al. (1981; Fig. 2).

Evidence for large aeolian particles

Despite the availability of these conceptual models and many grain-size related studies, there are still many unresolved questions related to the physical properties of wind-blown particles, particularly their particle size and shape. Most of the mineral-dust particles that are suspended in air and collected further than 100 km away from their source are smaller than 20 µm (e.g. Middleton et al. 2001, and references therein). This particle-size constraint can be explained by the physical laws of entrainment and settling velocities (e.g. Gillette 1979). However, various aeolian-dust records from loess and marine sediments contain considerable amounts of coarse-silt and fine-sand grains, i.e. particles well above the theoretical 20 µm size limit.

Moreover, there are many examples of so-called "giant" sand-sized (> 63 µm) mineral particles collected more than 5,000 km away from their source. For example, quartz particles originating from the Asian

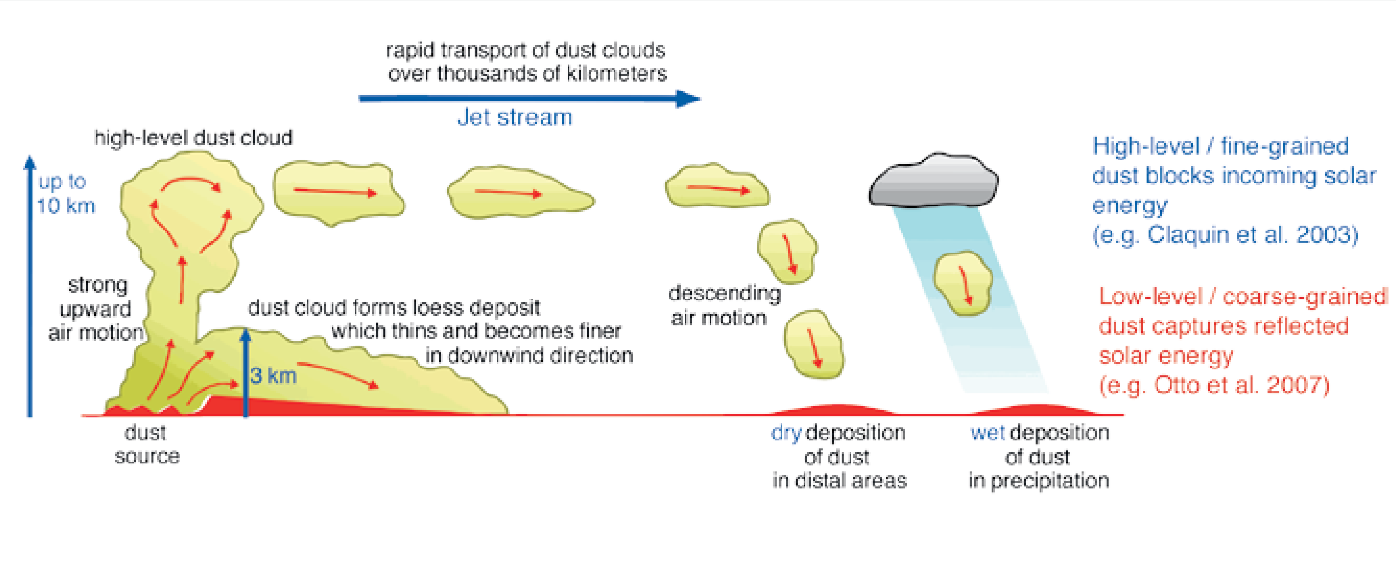

Figure 1: Schematic diagram showing different dust-transport mechanisms in the high- and low-level atmosphere (redrawn from Pye and Zhou 1989).

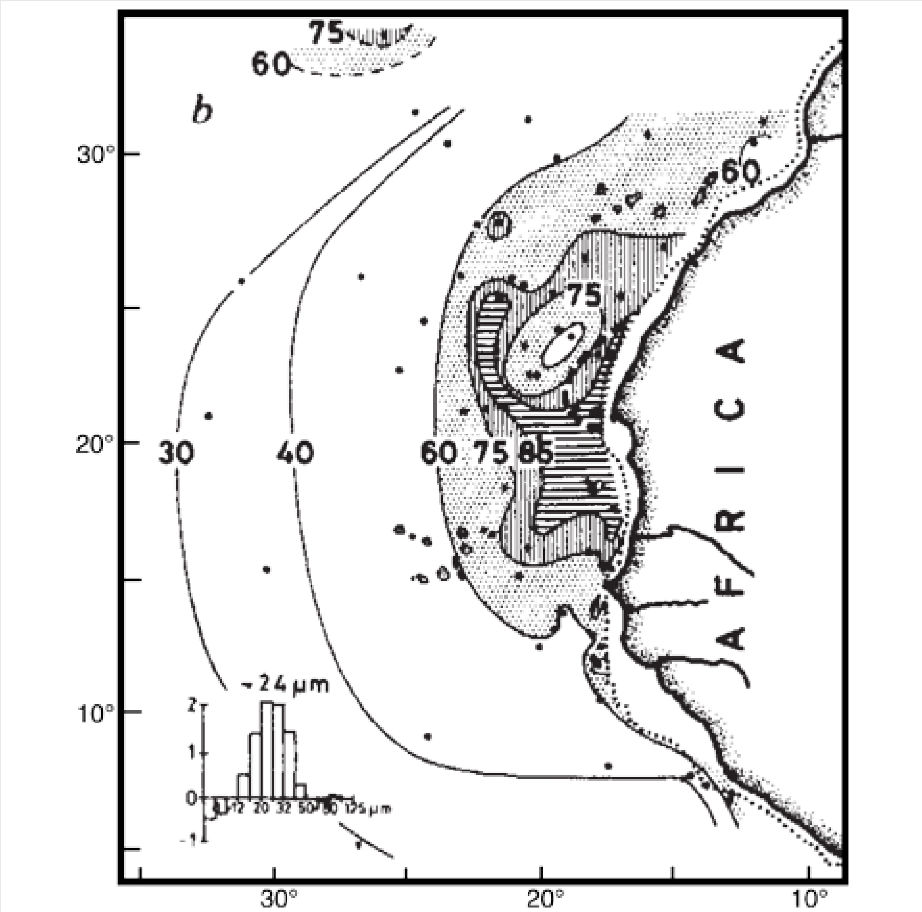

Figure 2: Map of the subtropical northeastern Atlantic, showing the decrease in both particle size and dust flux as measured in surface sediments by Sarnthein et al. (1981).

deserts were collected on Hawaii (Betzer et al. 1988), Asian-dust particles were collected in free-drifting sediment traps in the north Pacific (Middleton et al. 2001), volcanic particles were found in Greenland ice (Ram and Gayley 1991), and Saharan-dust particles were observed in high-volume dust collectors over the distal Atlantic ocean (Stuut et al. 2005). New unpublished results from transatlantic Saharan dust-monitoring projects (e.g. SALTRACE and DUSTTRAFFIC) show how large (>20 µm) Saharan-dust particles are observed suspended in the atmosphere, as well as deposited in moored marine sediment traps at thousands of kilometers from the African coast.

These observations suggest that the assumptions regarding the transport capacity of individual dust outbreaks need to be revised (e.g. Menéndez et al. 2014). Such revisions would have consequences not only for the interpretation of the proxy records, but also for the quantification of the climate-forcing effect of wind-blown particles in the atmosphere (e.g. Boucher et al. 2013).

Marine production and export

The size and shape of aeolian particles and dust-transport processes may also have affected past atmospheric CO_2 changes, due to the role that sinking dust particles may play in the biological carbon pump in the oceans. Martin and Fitzwater's (1988) famous Fe hypothesis predicts that during glacial periods more micro-nutrients were transported to the ocean by mineral-dust, which boosted the growth of marine phytoplankton and zooplankton. The increased primary productivity and its downward export sequestered additional CO_2 from the atmosphere (see also Martinez-Garcia and Winckler, this issue). A crucial step in this process is the export of organic matter from the surface ocean to the sea floor. Many Fe-fertilization experiments were carried out as a consequence of the postulated Fe hypothesis (e.g. de Baar et al. 2005). They demonstrated that it is indeed possible to boost marine life with artificially added dissolved micro-nutrients, but that most of the generated organic tissue containing the sequestered CO_2 is being recycled in the surface ocean layer. Here, the dust particles may play a crucial role by providing mineral ballast for the aggregation and sinking of the organic tissue. If this ballasting process is fast enough, there is less time for the organic tissue to be recycled and the export of organic matter becomes more efficient. The speed of the downward transport from surface to the deep ocean is directly related to the size of the dust particles that act as anchors for organic matter.

Intuitively, one would think there is an upper limit to size and potential scavenging; a brick would be too large and sink too fast to have a significant scavenging effect. However, given that the largest dust particles observed near the African coast are smaller than 200 µm (e.g. Ratmeyer et al. 1999; Skonieczny et al. 2013; Stuut, unpublished data from a dust monitoring station in Iwik, Mauritania) and thus still have a relatively slow sinking speed, we assume that there are no dust particles too large to have a ballasting effect.

From the above, we infer that the largest ballasting and scavenging effect will take place at proximal deposition sites. Thus, even without adding nutrients to the ocean, mineral dust may increase the C-cycle by speeding up the export of organic material to the sea floor.

On the other hand, particle size and associated sinking speed also impacts the bio-availability of the dust-borne micro-nutrients; the faster the particles sink, the less time remains to mobilize the nutrients they carry. Therefore, at distal locations, where dust particles are small and the size-dependent specific surface area of the particles is high, the amount of nutrients per mass is much higher than at proximal sites. We speculate that there is an ideal source-to-sink distance where dust particles are large enough to have an optimal ballasting effect, but also small enough to have an optimal fertilizing effect.

Outlook

The aforementioned role of mineral-dust particles assumed all deposition to be the result of gravitational settling from the atmosphere. However, hardly anything is known about wet deposition of mineral dust. New observations (Prospero, pers. comm.) seem to indicate that fluxes of wet-deposited dust not only are larger than those of dry deposition but that these "wet" mineral-dust particles are also coarser grained. Transatlantic observation projects have been set up to shed light at source-to-sink variability at high temporal resolution. Next to the physical and chemical properties, also the temporal and spatial (micro-)biological effects on nutrient availability and scavenging need to be studied, as they may play a dominant role on the aforementioned physical processes.

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A 10,000 km dust highway between the Taklamakan Desert and Greenland

Aloys J-M Bory

Mineralogical, elemental and isotopic measurements point to Eastern Asia as the main source of dust reaching Greenland, both in the present and during the last glacial period. Data suggest that the bulk of the dust derives from the Taklamakan Desert of western China.

Determining the provenance of ice core dust is key to our understanding of the prominent variability in the dust concentration observed in the Greenland and Antarctic ice core records (see also Vallelonga et al. and Gili-Gaiero et al., this issue). Greenland dust provenance was a matter of speculation until the mid 90s. Some studies based on modern aerosol elemental composition suggested the Saharan region as a possible source (Mosher et al. 1993) while back trajectory calculations favored East Asian or North American provenances (Kahl et al. 1997).

The Eastern Asian signature of Greenland ice core dust

A major breakthrough came with the analysis of dust extracted from the Greenland Ice Sheet Project (GISP2) ice core record obtained at Summit in central Greenland. Based mainly on the clay mineralogy of the dust, Biscaye et al. (1997) were able to rule out the Sahara and North American deserts as significant contributors to the dust deposited in Greenland during the Last Glacial Maximum. They showed that instead it closely resembled the fine material deposited in the Chinese Loess Plateau region and must therefore have derived from adjacent deserts. An Eastern Asian provenance was also supported by radiogenic isotope ratios (Sr, Nd and Pb), which were consistent with a Chinese Loess Plateau signature, taking into account the fact that ice core samples unavoidably contain variable amounts of volcanogenic particles mixed with the dust. These findings were confirmed by evidence from rare earth element patterns and extended through several levels of the Greenland Ice Core Project (GRIP) record spanning over 30 ka across MIS-3 and MIS-2 up to the Younger Dryas (Svensson et al. 2000).

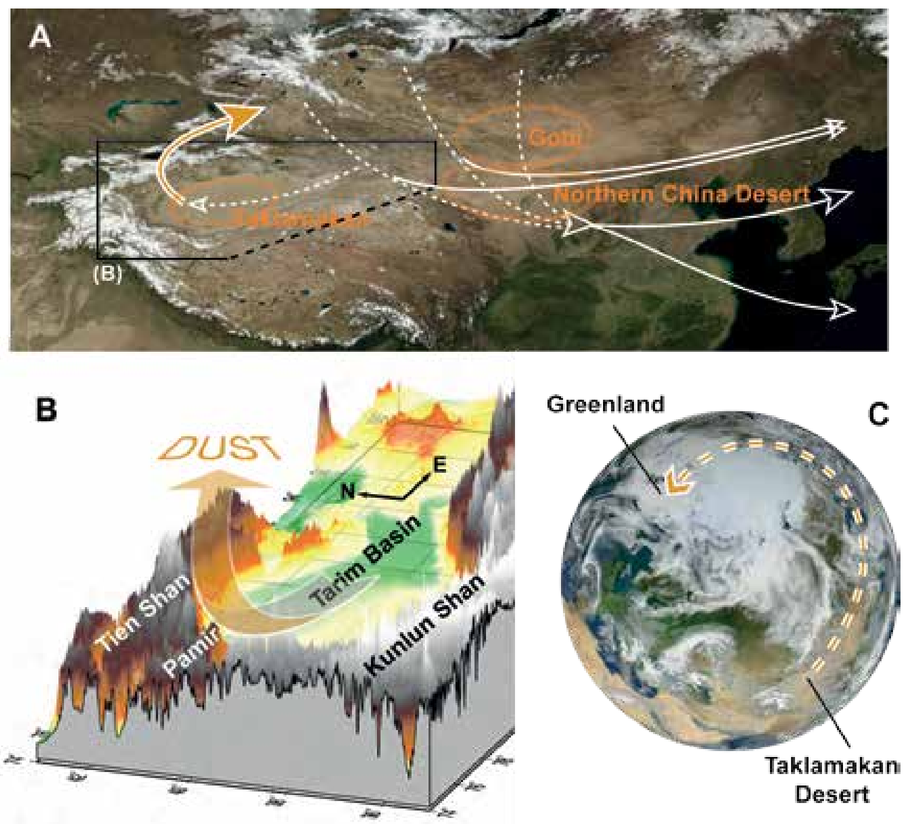

Figure 1: (A) April view of Eastern Asia (Terra MODIS sensor). Locations of the main deserts. Taklamakan and Northern China deserts are indicated together with the main winds (dotted lines) and dust transport pathways (solid lines) in the spring (adapted from Sun et al. 2001). **(B)** 3D-topographic modeling (NASA SRTM30 data) of the Tarim Basin and surrounding mountain chains (5x vertical exaggeration) and schematic illustration the dust's typical pathway in the spring. **(C)** Full disk of the Earth from space, showing both the Taklamakan desert of Western China and the Greenland ice sheet (background images in (A) and (C) courtesy of NASA).

Little change over time

Only minor variability was observed in the mineralogical and isotopic characteristics of these ice core dust samples (Biscaye et al. 1997; Svensson et al. 2000). Slight changes in clay mineralogy, correlated to some degree with the climate $\delta^{18}O$ record, suggested a possible shift in latitude or altitude of the provenance region over time; however, these changes remained small compared with the contrasting mineralogical signatures of the Northern Hemisphere's potential source areas (Bory et al. 2002). Also, the mineralogical and isotopic characteristics of dust extracted from Holocene ice core sections at various elevated sites across central Greenland did not depart significantly from glacial dust signatures (Svensson 1998; Bory et al. 2003a). So, overall, the mineralogical and isotopic signatures of dust in ice-cores all point to Eastern Asia as the overriding supplier of the dust to the top of the Greenland ice cap, both under glacial and inter-glacial climate conditions.

Clues from snow deposits in Greenland

In order to gain further insights into the contributing source region(s), especially in Eastern Asia, the provenance of modern-day Greenland dust was investigated. Large snow pit samples were excavated at the NorthGRIP site, permitting mineralogical and isotopic characterization at a seasonal or even better resolution (Bory et al. 2014). The clay mineralogy of these samples confirmed the eastern Asian source for Greenland dust in the current climate system (Bory et al. 2002), as also observed at Summit by Drab et al. (2002). Furthermore, radiogenic isotopes, Nd in particular, revealed a seasonal shift in provenance within the Eastern Asian region (Bory et al. 2002, 2003b).

Isotopic fingerprints of Eastern Asian deserts

An important effort was thus dedicated to the sampling of Eastern Asian potential source areas and to their mineralogical and isotopic signatures characterization. In order to make source samples comparable with the dust transported to Greenland (whose diameter never exceeds a few micrometers), measurements were carried out on the fine fraction (<5 µm) of the source material, following identical analytical protocols (including carbonate removal) as for Greenland ice-core dust (Biscaye et al. 1997).

These investigations revealed that significant differences exist in fact between the isotopic signatures of the three main source regions in Eastern Asia, i.e. the Mongolian Gobi desert, the deserts of Northern China (e.g. Tengger, Mu Us), and the Taklamakan desert of Western China (Fig. 1A), highlighting the interest of radiogenic isotopes for provenance discrimination in this region (Bory et al. 2003b).

Gobi dust across the Pacific but not in Greenland

One of the most unexpected outcomes was the fact that, although the Gobi area is clearly an active dust source in the region at present (Prospero et al. 2002), no obvious evidence for Gobi dust was found in the Greenland snow pit samples. This was even more surprising since there is indication from satellite data that Gobi dust can be transported across the Pacific Ocean (Husar et al. 2001). Trans-Pacific Gobi dust transport was confirmed using mineralogical and isotopic tracers during one of the most striking Asian dust events ever recorded on satellite images in April 2001, when dust deposited on Mount Logan, the highest mountain in Canada on the Canadian-Alaskan border, revealed a pure Gobi isotopic fingerprint (Zdanovicz et al. 2006). This massive event, however, was not detected in Greenland. The signature of the dust reaching the top of the ice cap during the major spring dust peak in Greenland points instead to the Taklamakan desert as the most important source. Yet, isotopes show that other sources of dust (likely located in Northern China) contribute to the signal, especially during the low dust seasons in Greenland (Bory et al. 2002, 2003b). However,

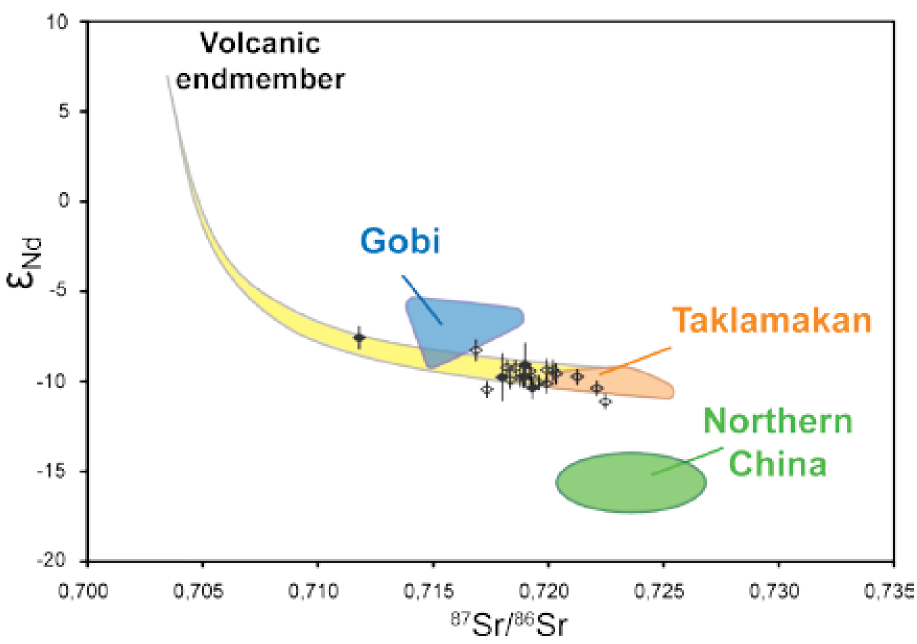

Figure 2: εNd versus $^{87}Sr/^{86}Sr$ signature of Greenland dust extracted from late glacial sections of the GISP2 (closed diamonds) and GRIP (open diamonds) ice core records (Biscaye et al. 1997; Svensson et al. 2000) and of potential source area samples from China and Mongolia (Bory et al. 2003b). The isotopic mixing domain between the Taklamakan desert and a circum-Pacific volcanic end-member is also shown.

considering the weight of the spring peak in the yearly dust deposition flux, all other contributions must clearly be minor compared to those from the Taklamakan.

A perfect launch pad for a 10,000 km flight to Greenland

When ice-core dust is compared to the Eastern Asia potential source areas database, it becomes apparent that almost the entire Greenland Sr and Nd isotopic composition range might actually be accounted for by inputs from the Taklamakan alone, assuming some mixing with minor amounts of volcanogenic material (Fig. 2).

Three main factors may make the Taklamakan so effective at delivering dust to Greenland. (1) The Taklamakan is the major dust source in the region at present and the second most important worldwide after the Sahara (Prospero et al. 2002). (2) The Taklamakan lies within the Tarim Basin, a large topographical depression in Eastern Asia; due to the elevated mountain ranges surrounding the basin, Taklamakan dust is already entrained to elevations >5000 m when it escapes the basin, whereas dust from the Gobi and Northern Chinese deserts are generally transported below 3000 m. (3) Wind systems in the basin often carry Taklamakan dust across the northern hedge of the Tarim, while dust originating from the Gobi and Northern Chinese deserts are initially transported eastward and south-eastward (Sun et al. 2001; Fig. 1b). The higher altitude and latitude at which Taklamakan dust is injected into the Westerlies likely represent a key precondition for long-range transport to Greenland (Fig. 1c). If confirmed (additional data from potential source areas should be generated to complete and refine the fingerprinting of all Asian contributing sources), the fact that most of the dust extracted from Greenland ice originates from a single spot in Western China represents useful clues for our interpretation of the Greenland dust signal and its close correlation to the rapid climate changes identified in the Greenland ice core records (e.g. Steffensen et al. 2008).

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The enigma of dust provenance: where else does Antarctic dust come from?

Paul Vallelonga

It has been shown that most, but not all, of the dust in Antarctica originates from Southern South America. Where else does dust come from? I review the evidence for dust provenance from Australia and within Antarctica.

Since the 1990's, there has been clear and increasingly unequivocal evidence that the majority of dust in Antarctica originates from Southern South America (SSA), particularly Patagonia and likely also the Puna/Altiplano region. The key method for attributing dust sources is radiogenic isotope geochemistry: the identification of characteristic isotopic ratios of Strontium (Sr), Neodymium (Nd) and Lead (Pb) (Delmonte et al. 2008; Vallelonga et al. 2010), which vary due to the different ages and geochemical compositions of their source rock material on each continent. There is a clear match between the isotopic signatures of Antarctic ice from the dust-rich Last Glacial Maximum (LGM) and loess samples taken from SSA dust deflation zones as well as lofted dust collected from the atmosphere.

Multiple isotopic fingerprints

Although the precise number and locations of the contributing dust sources are still debated, it is clear that most LGM dust in Antarctic ice strata originates from South America. It is much more difficult, however, to identify dust sources during the interglacials. One difficulty is that interglacial Antarctic dust fluxes are up to 25 times lower than LGM fluxes (Lambert et al. 2008), so much larger sample sizes are needed to analyze the dust.

Another problem lies in the difficulty of distinguishing minor isotopic source signatures. Sr and Nd isotopic signatures found in ice reflect a mixture between multiple sources – the more significant the major source is, the more difficult it is to distinguish any minor source. In the case of an equal-ratio mixture of two sources, the Sr and Nd signature will be midway on a mixing line between the endmember source signatures. Also, there is evidence that Sr isotope signatures are subtly influenced by particle size fractionation processes, which occur during the long range transport of dust particles (Gaiero 2007).

In the case of Sr and Nd isotopes in interglacial Antarctic ice, there are indications of dust arriving from SSA, Antarctica and Australia. As shown in Figure 1A, the Sr and Nd signatures of interglacial dust have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios compared to signatures in glacial dust. Two potential source areas of dust deflation with compatible isotopic signatures include the Puna/Altiplano region in South America (Delmonte et al. 2010; Gaiero 2007), which is also considered the most likely

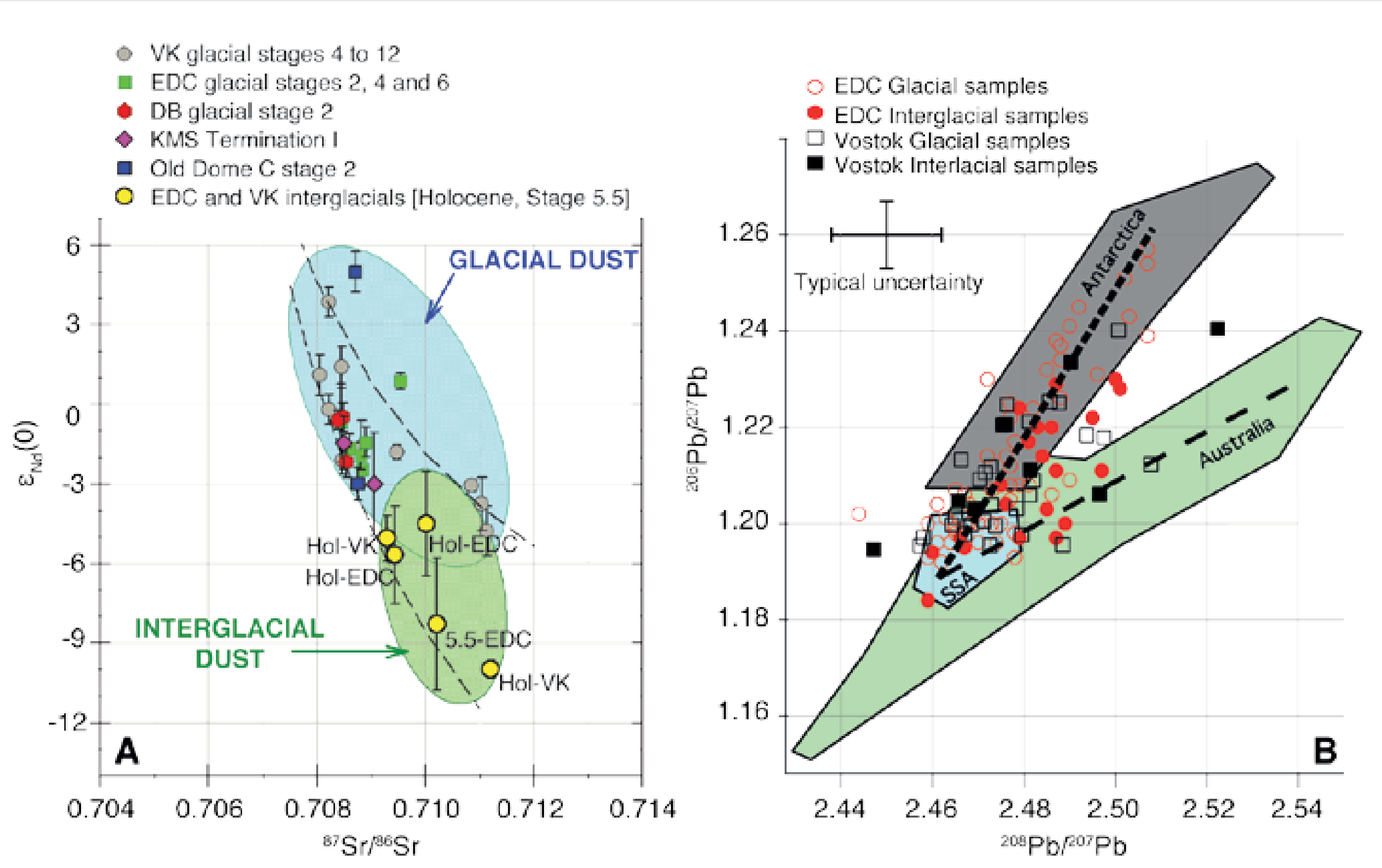

Figure 1: Strontium and Neodymium isotopes **(A)** and Lead isotopes **(B)** demonstrate changes in isotopic signature from glacial to interglacial periods. The identification of dust sources other than those of Southern South America is limited by measurement precision and the overlapping signatures of potential secondary dust source areas. Panel A modified from Delmonte et al. (2007). VK: Vostok; EDC: Epica Dome C; DB: Dome B; KMS: Komsomolskaya.

secondary source during glacials, as well as the ephemerally watered basins of central (Lake Eyre) and southeast (Darling basin) Australia (De Deckker et al. 2010; and this issue). Bory et al. (2010) sampled large volumes of surface snow at Berkner Island, in the Atlantic sector of coastal Antarctica, for seasonal resolution of Sr and Nd isotopic compositions. The results confirmed SSA to be the dominant dust source but also suggested a variety of dust sources occurring without seasonal regularity. While the possibility of springtime dust inputs from Australia could not be excluded, the relatively high proportion of large (>5 µm) dust particles found in the snow was indicative of dust from proximal deflation sources within Antarctica (see also Gili and Gaiero, this issue).

For Pb isotopes, the situation is complicated because volcanoes also emit Pb, and hence in Antarctic ice, the Pb isotope data usually fall along a mixing line between the dominant dust source in SSA and the dominant volcanic Pb source attributed to Mt Erebus in Antarctica. Figure 1B shows Pb isotope data from the EPICA Dome C (Vallelonga et al. 2010) and Vostok (unpublished data) ice cores. Rather than a random scattering around the mixing line between SSA Pb and Antarctic Pb, the data tend to have signatures indicative of a third source which matches the signature of dust samples from Australia and Antarctica. The improved identification of secondary dust sources in central Antarctica by Pb isotopes is also due, among other factors, to recent advances in instrumentation that now offers isotope ratio measurements with higher precision. For an even better result, it would be advantageous to apply such measurements to an ice core from a location where the interference of Pb from local Antarctic volcanism is minimized.

Changes in the dust mix

Despite the difficulties of identifying secondary sources of dust to Antarctica, indications are strong that the composition of dust deposited in Antarctic ice has varied, particularly during the LGM-Holocene transition 20 to 10 ka ago. Indications of dust composition changes are found in a variety of indicators, particularly in trace element compositions, geochemistry and physical properties such as magnetic susceptibility and solubility. Siggaard-Andersen (2007) identified changes in the solubility of Lithium in EPICA Dome C (EDC) ice over the deglaciation, suggestive of a change of dust source(s) over that time. Marino et al. (2008) confirmed such indications by geochemical characterization of EDC dust, as well as suggesting an Australian dust source during interglacials. Albani et al. (2012) identified a deglacial change in dust particle size distributions at Talos Dome, in Northern Victoria Land. The shift toward larger dust particles at Talos Dome indicated that local dust sources in the Transantarctic Mountains were activated in the early Holocene.

Wegner and colleagues have reported the concentrations of Rare Earth Elements (REEs) in various Antarctic ice cores (Gabrielli et al. 2010; Wegner et al. 2012). Comparable to the Sr, Nd and Pb isotopes, REEs are subject to fractionation as they have similar chemical properties but range in atomic weight from 139 (Lanthanum) to 175 (Lutetium). Consequently, the REE compositions differ between dust deflation zones due to their specific geochemical histories. Wegner and colleagues identified a "glacial" REE signature in the EDML ice core: In addition, they differentiated four other REE types, which were observed only during the deglaciation after ~15 ka ago (Fig. 2) and were attributed to dust from Antarctica, Australia and New Zealand.

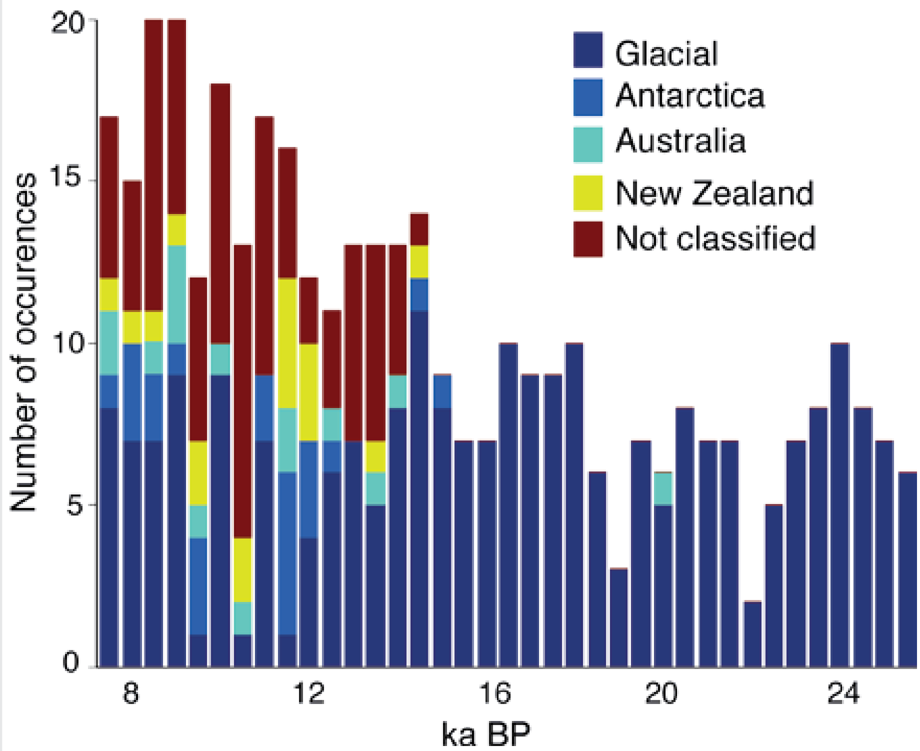

Figure 2: Histogram of REE patterns found in the EPICA Dronning Maud Land ice core over the last deglaciation, clearly demonstrating the appearance of non-glacial dust types after ~15 ka BP. REE patterns were statistically attributed to dust from Antarctica, Australia and New Zealand. Modified after Wegner et al. (2012).

Known unknowns of intercontinental dust transport

While there is only indirect evidence of early Holocene transport of Australian dust to Antarctica, unequivocal evidence of intercontinental dust transport in the late Holocene has been observed. Lead isotopic compositions in Law Dome ice show that anthropogenic Pb contamination of Antarctica began late in the 1880's (Vallelonga et al. 2002). Lead isotopes showed the pollution source to be the Broken Hill mine in Southeastern Australia – one of the known dust deflation zones of Australia. Broken Hill Pb was released in the process of smelting Silver-Lead ores, first at Broken Hill (1887-1889) and later at Port Pirie in South Australia (1889 onwards). This demonstrates that aerosols can in principle be transported from Southeastern Australia to Antarctica, but the question remains as to whether anthropogenically-emitted Pb can be considered representative of naturally deflated mineral dust.

Some ways forward

Resolving the question of secondary dust sources in Antarctica is possible, but requires a cross-disciplinary approach, with further investigation of dust deflation zones, more precise analyses of dust in Antarctic ice, and enhanced understanding of the transport processes involved. Improved characterization of dust deflation zones will ensure that the source areas characterized accurately represent the deflated dust. Dust traps and airborne collection techniques can help with such efforts. Satellite observations can help understanding the dynamics of dust transport by tracking dust plumes from their continental sources all the way to Antarctica. New or improved analytical techniques may also enable better studies of the dust deposited in ice. Some techniques, such as REE or Pb isotope analysis, require larger datasets or more sensitive instrumentation, respectively. Finally, completely new approaches, such as Optically Stimulated Luminescence may offer a fresh approach to distinguish and apportion inputs of feldspar-rich SSA dust from quartz-rich Australian dust (Lepper et al. 2001).

DATA

Data presented in this article are available from the PANGAEA (www.pangaea.de) and NOAA paleoclimate (www.ncdc.noaa.gov/paleo) databases, except for the Vostok Pb isotope data (available from the author).

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Evidence that local dust sources supply low-elevation Antarctic regions

Bess G. Koffman[1,2] and Karl J. Kreutz[1]

Dust flux and size distribution measurements from the West Antarctic Ice Sheet (WAIS) Divide and other non-East Antarctic plateau ice core sites suggest that local dust sources supply a significant amount of dust to the high-latitude atmosphere and ocean.

Polar ice is an important high-latitude archive of past environmental and atmospheric changes. The physical measurement of dust particles trapped in well-dated ice cores provides independent information, in the form of dust flux and particle size distribution (PSD) parameters, about past environmental changes in dust source regions, the proximity of dust sources, and variability in atmospheric circulation intensity. Much effort has gone into understanding the sources and transport of dust to the high-elevation sites (~3200-3500 m a.s.l.) Vostok and Dome C on the East Antarctic Ice Sheet (EAIS) plateau (Fig. 1). These records together provide a climatic history spanning the past eight glacial cycles (Lambert et al. 2008; Petit et al, 1999; Wolff et al. 2006). The East Antarctic plateau predominantly receives far-traveled dust, as evidenced by its lognormal distribution, small size (mode of 2 µm) and geochemical signature (e.g. Basile et al. 1997; Delmonte et al. 2004). The ice cores from this region provide invaluable information about hemispheric-scale changes in dust emissions and transport, but due to their high altitude, they do not capture dust carried in the lower-to-middle troposphere, and thus do not represent dust delivery to about half the Antarctic continent.

In order to assess changes in dust supply and transport to the lower-elevation regions of Antarctica, we must look to ice core records from West Antarctica and around the margins of the EAIS. Dust flux and particle size distribution measurements from WAIS Divide and other lower-elevation and coastal cores show that these sites receive both higher dust fluxes and coarser PSDs than the East Antarctic plateau cores. Accordingly, we infer that local dust sources supply a significant amount of dust to the atmosphere and ocean around Antarctica.

Higher dust fluxes near the Antarctic coast

Dust flux is measured in units of mass per area and time. It takes into account the possible dilution effects of the snow accumulation rate on aerosol deposition, and thus can be compared readily among sites and across time intervals. Changes in dust flux are considered to represent changes in atmospheric dust concentrations (Fischer et al. 2007; Wolff et al. 2006); therefore, flux measurements offer insight into the atmospheric dust burden and its potential impacts on climate.

During the late Holocene, dust fluxes measured at sites near the margins of the Antarctic ice sheet and at elevations below ~2500 m a.s.l. range from about 1-12 mg m^{-2} yr^{-1} (Fig. 2). This contrasts with the significantly lower fluxes well below 1 mg m^{-2} yr^{-1} measured at high-elevation East Antarctic sites. At WAIS Divide a background dust flux of ~3-5 mg m^{-2} yr^{-1} is punctuated by several particularly dusty intervals during the last two millennia, reaching peak fluxes of ~15-25 mg m^{-2} yr^{-1} (Koffman et al. 2014). At James Ross Island near the tip of the Antarctic Peninsula (1540 m a.s.l.), dust flux (calculated using aluminum concentrations) was found to be 12 mg m^{-2} yr^{-1} ca. 150 years ago, prior to the effects of land-use changes in Patagonia (McConnell et al. 2007). Near the Transantarctic Mountains at 2315 m a.s.l., the Talos Dome ice core yields a late Holocene dust flux of about 1 mg m^{-2} yr^{-1} (Albani et al. 2012). While these records come from different sectors of the Antarctic continent and are almost undoubtedly influenced by different dust sources, they consistently show dust fluxes substantially higher than those seen on the East Antarctic plateau, where the interglacial dust flux is 0.2-0.6 mg m^{-2} yr^{-1} (Lambert et al. 2012). Corroborating these observations, Bory et al. (2010) report that the dust flux measured in modern snow at Berkner Island (899 m a.s.l.) in the Weddell Sea is about three times higher than at Kohnen Station in Dronning Maud Land (DML; 2890 m a.s.l.) for particles in the 5-10 µm range. Similarly, *nss*Ca^{2+} fluxes (a common proxy for mineral dust in ice cores) measured in the EPICA (European Project for Ice Coring in Antarctica) DML ice core at Kohnen Station were found to be three times higher than those measured at Dome C, which is about 300 m higher and several thousand km further from Patagonian dust sources (Fischer et al. 2007). In short, during the late Holocene, sites from Antarctica show an inverse relationship between elevation and dust flux (Fig. 2).

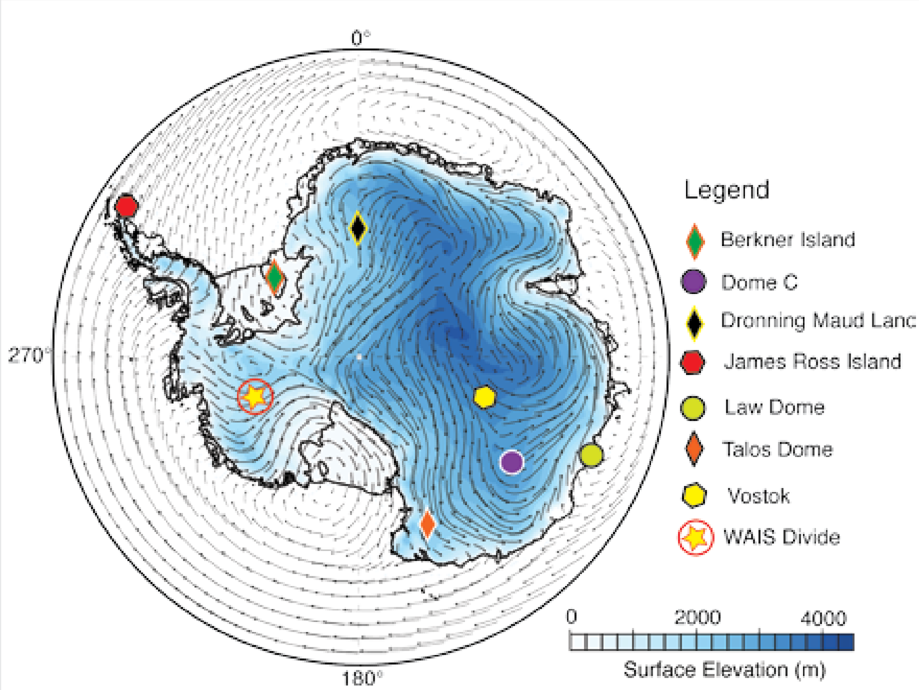

Figure 1: Surface elevation map of Antarctica showing sites discussed in the text and annual average winds at 700 hPa (ERA-Interim climate reanalysis). Image obtained using Climate Reanalyzer (http://cci-reanalyzer.org).

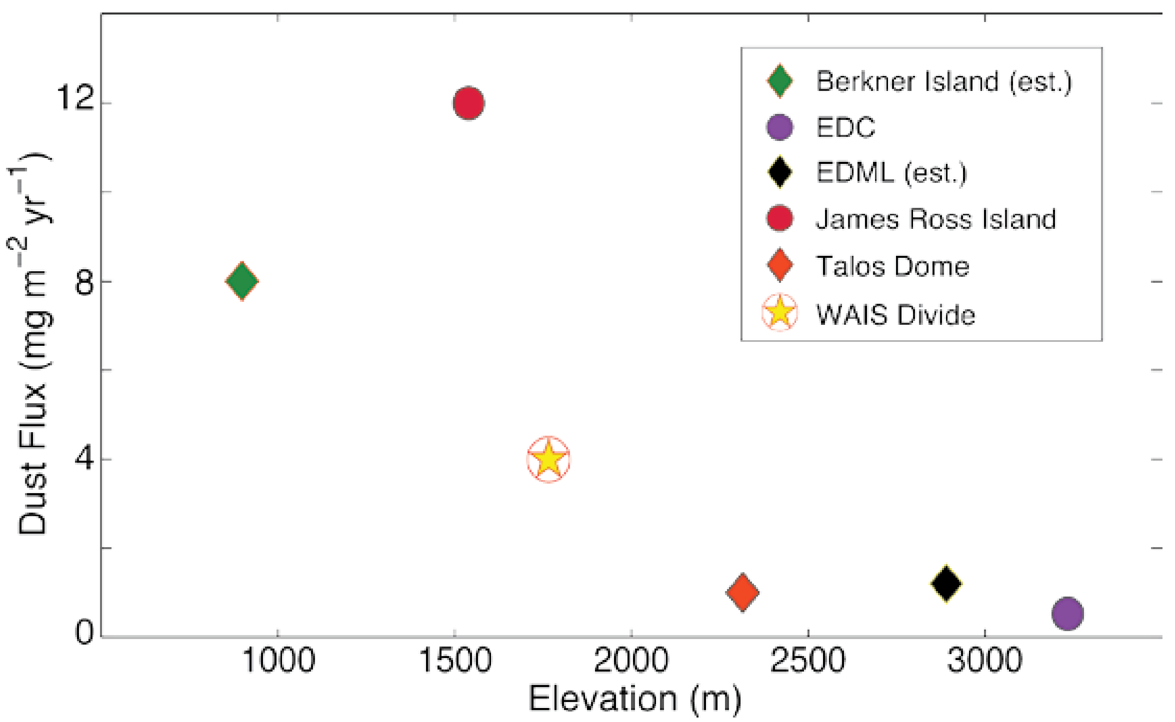

Figure 2: Dust flux versus elevation for: Berkner Island (Bory et al. 2010), EPICA Dome C (EDC; Lambert et al. 2012), EPICA Dronning Maud Land (EDML; Fischer et al. 2007), James Ross Island (McConnell et al. 2007), Talos Dome (Albani et al. 2012) and WAIS Divide (Koffman et al. 2014). Flux values for EDML and Berkner Island are estimated based on published flux ratios to other sites and available particle size information.

These observations imply an elevational gradient in the atmospheric dust burden over Antarctica, with the ice sheet margins receiving about 1-2 orders of magnitude more dust than the East Antarctic plateau. Further supporting evidence comes from high and low iron flux measurements from coastal Law Dome and high-elevation Dome C in East Antarctica, respectively (Edwards et al. 2006). Observation of an elevational dust flux gradient within the EAIS confirms that observed flux differences across Antarctica do not relate to regional (e.g. WAIS vs. EAIS) differences. Instead, it seems likely that the higher fluxes at coastal sites and below ~2500 m elevation reflect greater proximal dust emissions activity, and possibly also higher deposition of far-traveled dust (e.g. from Patagonia and Australia). Today, about 2% of Antarctica is ice-free, comprising an area roughly the size of New Zealand (Campbell and Claridge 1987). Although much of this area consists of exposed bedrock, several regions with available fine-grained material could serve as dust sources.

Coarse particles imply local sources

Coarser particle sizes near the margin of the Antarctic ice sheet and at elevations below 2500 m a.s.l. further support that proximal dust sources play an important role. At WAIS Divide, the dust flux is dominated by particles in the 5-10 µm range, and the long-term (100 year average) mode size of the volume-weighted distribution is 5-8 µm diameter (Koffman et al. 2013). From the few sites in Antarctica where mode sizes have been reported, it appears that relatively coarse PSDs are a common feature of lower-elevation regions. For example, late Holocene dust deposited at Berkner Island and at Talos Dome is dominated by particles > 5 µm diameter (Albani et al. 2012; Bory et al. 2010). The high proportion of coarse particles contrasts with observations from the East Antarctic plateau, where the volume-weighted mode size is close to 2 µm diameter for both glacial and interglacial periods (Delmonte et al. 2002). Although very coarse (> 75 µm diameter) particles have been observed to travel distances greater than 10,000 km (Betzer et al. 1988), particles larger than 5 µm diameter generally are associated with short transport distances (e.g. Mahowald et al. 2013; Tegen and Lacis 1996), implying local sources of dust.

Conclusions

The observed differences in dust fluxes and PSDs between lower- and higher-elevation sites in Antarctica (e.g. below or above ~2500 m a.s.l.) indicate that locally sourced dust is transported too low to reach the East Antarctic plateau. Climate models suggest that dust originating from southern South America and Australia is transported at altitudes greater than 4000 m (Krinner et al. 2010), i.e. well above the Vostok and Dome C ice core sites (e.g. Basile et al. 1997; Delmonte et al. 2004; Revel-Rolland et al. 2006). In contrast, based on existing particle size measurements, we infer that dust from Antarctic ice-free areas is transported below ~2500 m. Additional PSD measurements from a range of elevations are needed to confirm this interpretation.

The relatively coarse PSDs at WAIS Divide and other sites below 2500 m a.s.l. are good evidence that Antarctic ice-free areas comprise active dust sources for the high-latitude atmosphere and ocean. While some areas, such as the McMurdo Dry Valleys, are known to be dusty (e.g. Bory et al. 2010), additional work is needed to understand the emissions activity and importance of Antarctic potential dust source areas, including the relative contributions of glacier-derived sediments and material of volcanic origin.

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DATA

The WAIS Divide ice core dust record can be obtained from the Global Change Master Directory (GCMD) public database.

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South American dust signature in geological archives of the Southern Hemisphere

Stefania Gili and Diego M. Gaiero

Patagonian dust is the darling of researchers of paleoclimatic variability of southern South America. However, new chemical data from yet unexplored dust source areas allows for deeper investigation of the geological archives in the region.

In present-day southern South America (SSA) the major dust source areas are located in a continuous N-S band of arid and semi-arid terrains extending from the coastal regions of Peru to Patagonia. Three main persistent source areas stand out: Patagonia, Central-Western Argentina (CWA) and the Puna/Altiplano Plateau (Fig. 1). Multiple evidence indicates that these areas were continuously active over the last several glacial cycles.

Aeolian transport from Patagonia was often employed to explain the accumulation of the Pampean loess, the geochemical composition of sediment from the Southern Ocean and dust contained in Antarctic ice. However, chemical and isotopic fingerprinting methods has led to acceptance that Patagonian sediments can explain only part but not the entire range of compositions found in those archives. Other until now less considered but nevertheless important Southern Hemisphere regions were also important suppliers of dust during glacial-interglacial cycles. Current international efforts are dedicated to better characterize these non-Patagonian dust sources (e.g. De Deckker, this issue). Here, we present new geochemical data of sediments from potential source areas (PSAs) in SSA north of Patagonia.

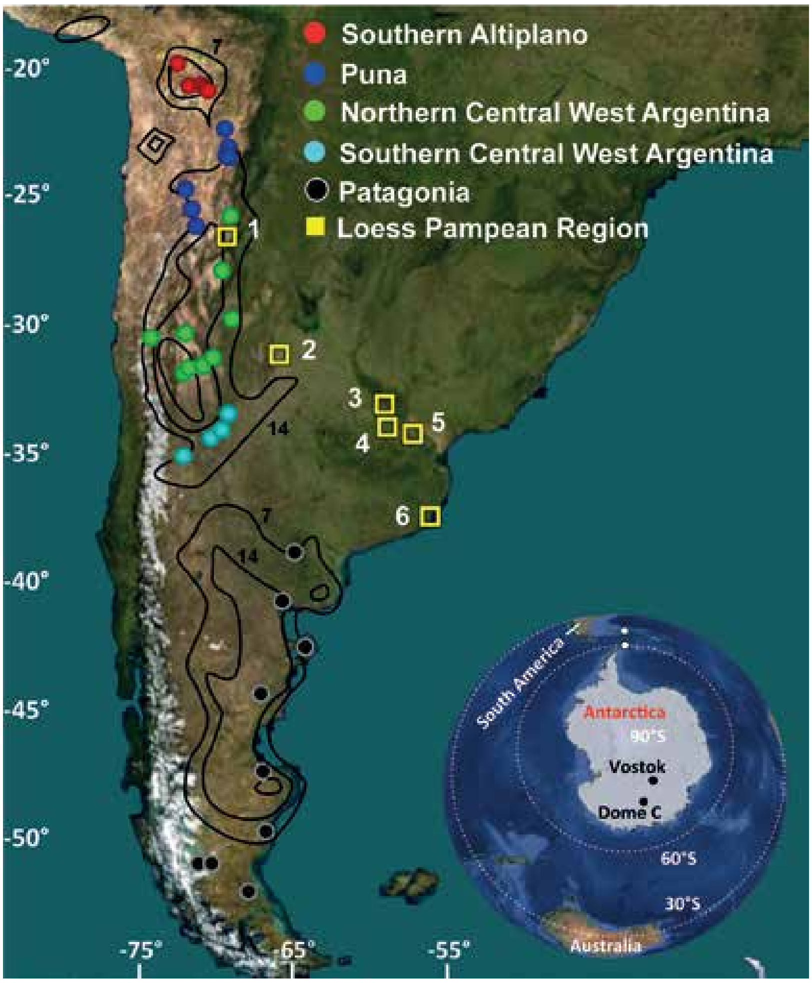

Figure 1: Location of the main present-day dust sources in southern South America (black lines show the number of days with dust activity during a year; adapted from Prospero et al. 2002). Color dots indicate the position of collected surface sediments used to define the rare earth elements signature regions as shown in Figure 2. Yellow squares show the position of proximal aeolian (loess) records across the Pampas (Smith et al. 2003; Gallet et al. 1998). Inset: Distal aeolian records. Scotia Sea (white dots; Diekmann et al. 2000), and Vostock and Epica Dome C (black dots; EPICA community members 2006).

Environmental setting of the PSAs

A climatic transition at ~38-39°S differentiates between regions dominated by summer rains to the north and winter rains to the south. South of this boundary lies Patagonia, a ~700,000 km^2 area of drylands that extend down to Tierra del Fuego (~54°S). The atmospheric circulation there is dominated by strong meridional pressure gradients that promote strong Westerlies and high wind speeds year round. The Westerlies are associated with cold frontal systems that are capable of lifting dust high into the atmosphere. During glacial times these fronts were probably even stronger than today.

North of ~37°S the altitude of the Andes increases notably, disrupting the dominant zonal flow. East of the Andes lies the CWA region, a N-S oriented strip of drylands (36° to 26°S) encompassing the geomorphological domains of the Andean piedmont and the western Pampean ranges. Meridional surface winds dominate present and quaternary atmospheric circulation over the north and central sectors of this area. In the south (~34°S to 38°S), SW winds prevail today and also dominated in the quaternary as reconstructed in loess and sand fields studied in the western Pampean region (Muhs and Zárate 2001). The area is cut by several ephemeral streams that form extensive sand flats, saline marshes, and saline lakes. The whole sector is drained to the south by the hydrographic system of the Bermejo-Desaguadero-Salado River (~250,000 km^2). A large volume of Andean sediments formed during the last glacial were transported by this hydrologic system to the south and then, once settled down, picked up by SW winds and transported to the northeast (Iriondo 1997).

The PAP area (~15°S to 26°S) is a high plateau (~4,000 m a.s.l). It consists of extensive, internally drained depocenters that contain large quantities of silt eroded from the surrounding N-S oriented mountain ranges. The region is influenced by the subtropical jet stream, which intensifies during the austral winter and can

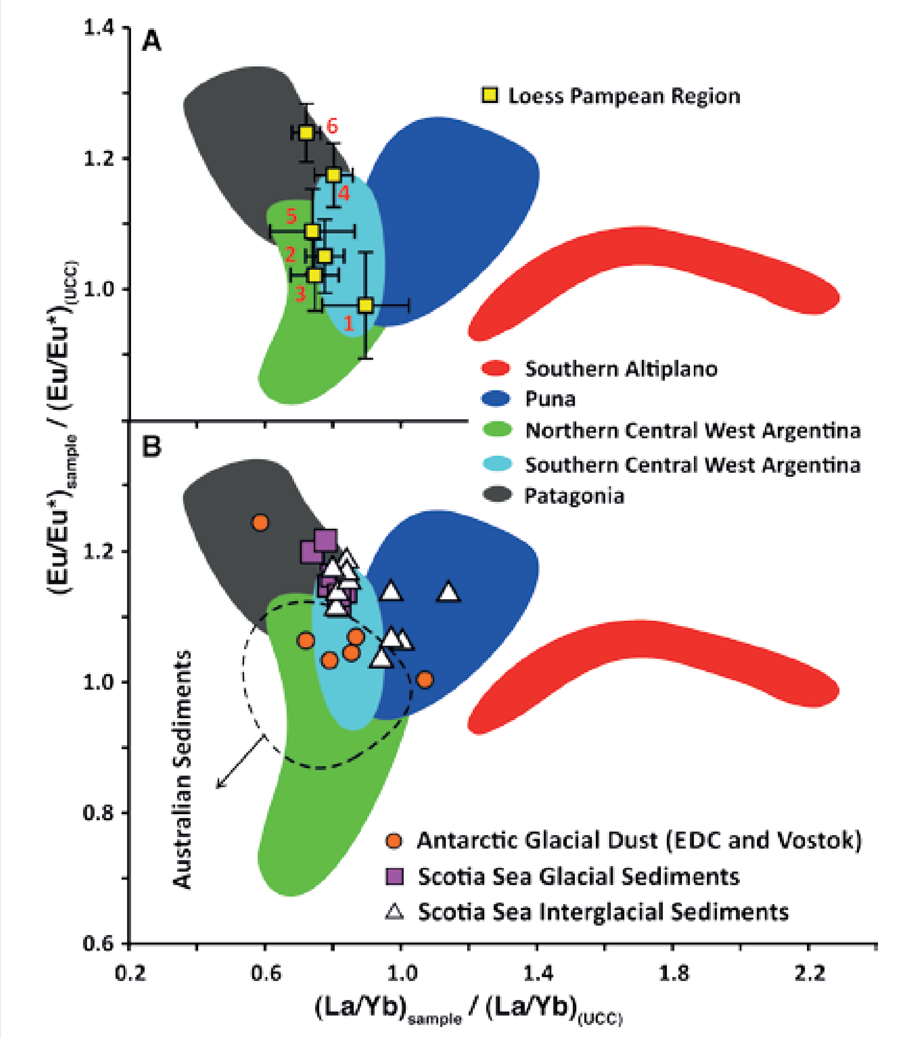

Figure 2: (A) Colored areas represent the rare earth elements (REEs) signature of the main potential dust sources in southern South America as inferred from surface sediments (Fig. 1). The yellow squares show the chemical composition of Pampean loess sequences (1, 2, 3, 5 and 6 from Smith et al. 2003; 4 from Gallet et al. 1998). **(B)** Comparison with distal geological records: sediments from the Scotia Sea and dust from East Antarctica (Basile et al. 1997; Diekmann et al. 2000). Autstralian sediments data from Gingele et al. 2007.

result in very strong winds that lead to sizable dust storms (Gaiero et al. 2013). Moreover, most of the Altiplano was repeatedly covered with paleolakes during the Late Quaternary, indicating alternating cycles of dry and wet conditions. In the Puna, evidence indicates large depressions of primary aeolian origin of likely Pliocene and early Quaternary age. From about 18°S to 26°S, sand dunes and wind-scoured ignimbrite ridges indicate a prevailing NW-SE wind direction during the late Pliocene and Pleistocene.

Chemical fingerprint of the PSAs

Figure 1a shows the locations where we collected surface sediment from arid and semi-arid terrains (colored dots). Sampling locations were selected based on direct field evidence of dust activity and dust storms identified on satellite images. Sediment samples were taken from intermountain closed basins from a range of desiccated lake edges, fluvial-alluvial fans and enclosed basins.

Rare earth elements (REEs) analyses were run on <63 and <5 µm grain-size fractions of sediments. This group of elements is a very useful tool in sediment provenance studies because REEs inherit the composition of their sources. La_N/Yb_N ratios and Eu/Eu* anomalies turned out to be particularly sensitive parameters for the recognition of PSAs. Based on these parameters it was possible to single out five PSAs (Fig. 2).

SSA dust in geological archives

The Pampean region is a large area (~10^6 km^2) covered with a 20-50 m thick loess cover. It represents the proximal geological record of dust activity in SSA to the sources to the West. The chemical composition of loess sequences collected from sections 1-5 (Fig. 1), can be reconciled with the chemical composition of the non-Patagonian PSAs (Fig. 2A). The southernmost section (6) has a clear Patagonian signature, while the chemical fingerprint of the southern CWA prevails over the loess sections located further north (2, 3 and 5). The provenance of aeolian materials in section 1 (~2,000 m a.s.l) is contentious; for this area chemical data have the largest variability. From a mechanistic perspective, the Puna sector seems to be the most likely source because dust can be transported from there by upper tropospheric air masses. Unexpectedly, loess samples from section 4 are chemically different from samples from the nearby sections 3 and 5.

The chemical signature of dust from SSA can also be recognized in distal geological archives. Figure 2B shows that the chemical composition of glacial-interglacial sediments deposited in the Scotia Sea, to the south-east of SSA, match well with the Patagonian signature and, to a lesser extent, with materials derived from the southern CWA. Notably, an important number of interglacial samples from the Scotia Sea fall within the compositional area corresponding to Puna surface sediments. The interpretation of the source of dust deposited in East Antarctica is more ambiguous as the chemical composition of four of the six samples also match the chemical composition of some surface sediments from Australia.

Implications for further research

The sediments from the PSAs of SSA have relatively distinct REE chemical compositions, which is a good prerequisite for a reliable paleo-climatic interpretation of the dust records of the SH. Our new data set from surface sediments suggests that most of the continental sediments deposited during glacial-interglacial periods in the Scotia Sea and the Pampas have REE comprised mostly of a mix of Patagonian, southern CWA and Puna origin. Contrary to other evidence, chemical data suggest that southern Altiplano sediments play a minor role in the composition of these materials. The provenance of dust in East Antarctica is ambiguous, because the chemical REE composition is similar to Australian sediments as well as some of the PSAs in SSA. Therefore, other methods are required to unambiguously attribute East Antarctic dust to a provenance.

The possibility of distinguishing all these signatures in paleo-dust archives could be important to improving our understanding of the major atmospheric circulation patterns during the last glacial-interglacial cycles, such as understanding the equatorward and poleward displacements of the Westerlies and the subtropical westerly jet stream during the past climatic cycle. To achieve this, higher temporal resolution studies with appropriate age controls of Pampean loess sequences are required. Moreover and in addition to the REEs approach, more detailed analysis of the geochemistry (e.g. Sr, Nd, Pb isotopes) and mineralogy of surface sediments from SSA and Australia are needed.

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Fingerprinting aeolian dust in marine sediment: examples from Australia

Patrick De Deckker

Methods to identify airborne material in deep-sea sediment cores and track dust provenance are reviewed here. An example from Australia demonstrates how evidence from Sr and Nd isotopes and rare earth elements can reveal the climatic history with sub-regional detail.

The quest to identify the aeolian component among the terrigenous material deposited at sea relies on a whole suite of techniques that can be applied to determine the presence of airborne dust in deep-sea sediment cores and to track its origin:

(1) *The percentage of the quartz fraction* in sediment cores from the deep ocean and the continental shelves gives an indication of the airborne fraction, based on the assumption that the quartz particles were wind blown. This approach was first applied by Thiede (1979) in the Tasman Sea, east of Australia.

(2) *The size of quartz grains and their texture*, i.e. the pitted depressions of desert sand grains from collisions during saltation, contain information on wind speed, the degree of storminess, and the distance traveled from land. Rea and colleagues used such an approach in sediment cores from the northwestern and central Pacific Ocean (Janecek 1985; Rea 1990, 1994).

(3) *The proportion of different clay species* can reflect the mode of sediment transport. Comparison of the clay composition in deep-sea sediment cores with clays from nearby rivers and dune fields can provide a quantitative measure for the relative importance of fluvial and aeolian transport. Such an approach was performed by Gingele et al. (2001) who differentiated riverine from airborne clays offshore northern Australia.

(4) Using the same approach and samples as Gingele et al. (2001), Ehlert et al. (2011) were able to consolidate the previous findings using a combination of *Pb, Nd and Sr isotopes*. In this latter study, Ehlert et al. (2011) were able to identify the origin of fluvial clays and define patterns of oceanic currents at the sea surface during and after the Last Glacial Maximum.

(5) *Rare earth elements (REE)* in deep-sea core sediments. The REE composition and geochemistry is specific to each ablation area. This REE signature can help identify the origin of the material deposited at sea. (See example below on the use of Yttrium).

(6) *Sr and Nd isotopes* from regolith samples such as in Australia can help constrain the origin of the deep-sea sediments provided there is sufficient information on the composition of the regolith that can potentially supply material at sea, either airborne or by fluvial discharge.

(7) X-ray fluorescence scanning of soft marine sediments at a centimeter to sub-millimeter scale for a variety of elements (see Weltje and Tjallingii 2008) can be used to estimate the relative contributions of fluvial and aeolian material. *Some elemental ratios* such as K/Ca and Rb/Ca relate to continental weathering whereas others such as Ti/Ca,

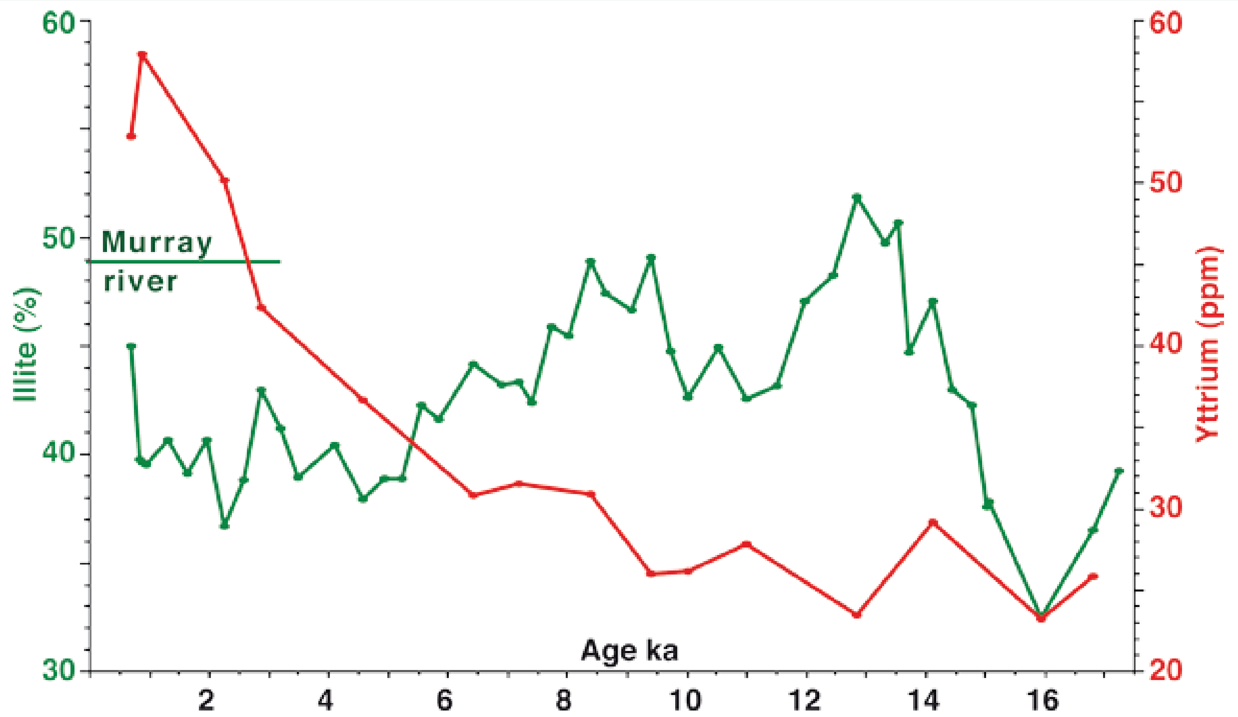

Figure 1: Illite and yttrium concentrations in sediment core MD03-2611 offshore Kangaroo Island for the last 17 ka. The horizontal line shows the illite percentage at the mouth of the Murray River today. The two illite peaks around 14-12 ka and 10-8 ka represent significant water discharge from the eastern highlands of SE Australia. The yttrium increase shows a change to predominantly aeolian sediment supply after 6 ka.

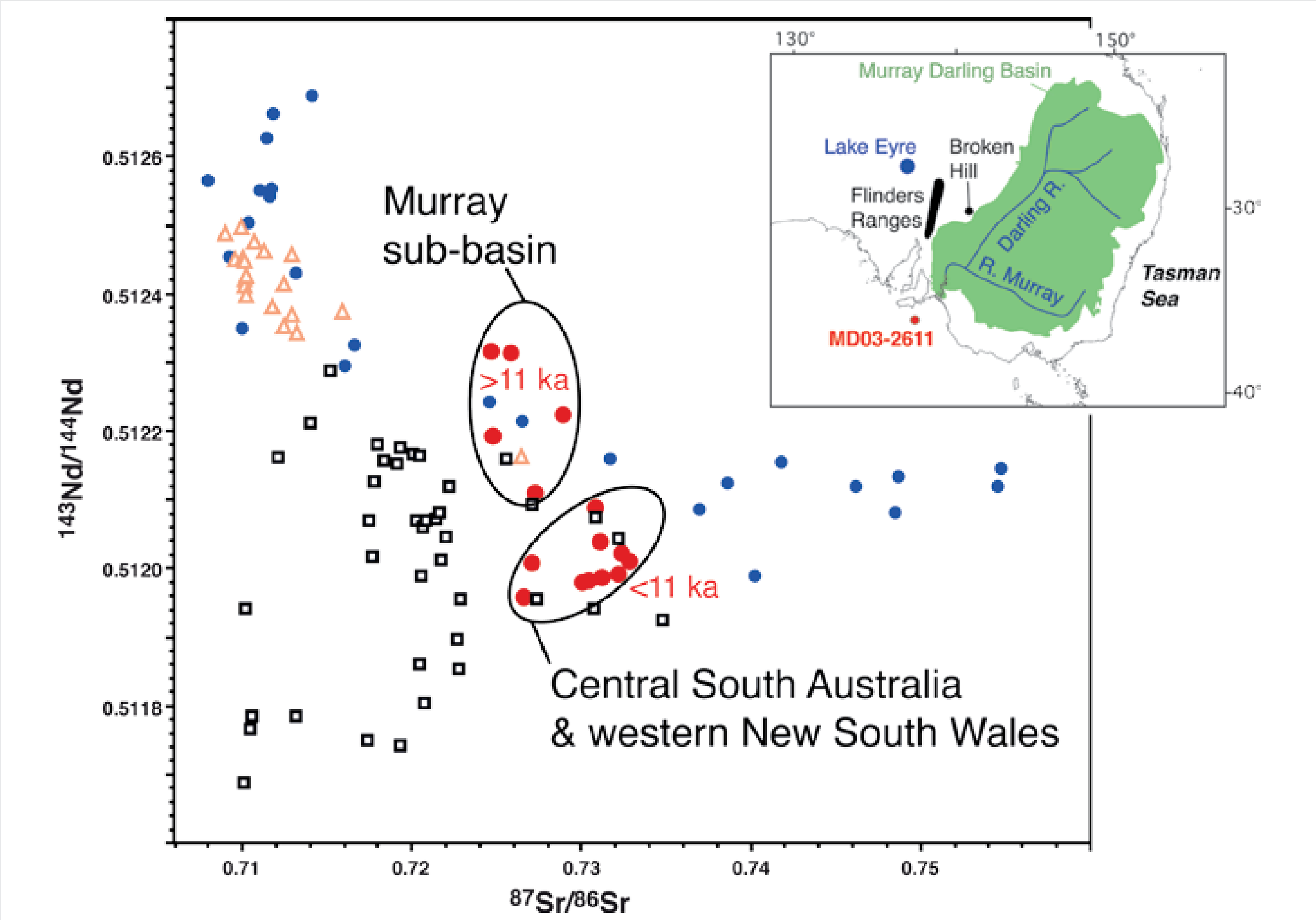

Figure 2: Plot of Sr and Nd isotopes for sediment core MD03-2611 (red dots) and from regolith samples in eastern and central Australia that are considered potential sources of airborne dust. Blue dots represent tributaries of the River Murray and Darling River. The Nd isotopic ratios above 0.51255 pertain to Darling River tributaries that share similarities with samples from the Lake Eyre region (orange triangles). Black squares represent samples from west and east of the Flinders Ranges and from western New South Wales near Broken Hill. The samples aged >11 ka BP come from the Murray sub-basin and would have been transported to the core site by water (thus being river borne), whereas the younger samples come from central South Australia and western New South Wales, and are considered to have been airborne, being from outside the Murray Darling Basin.

Si/Ca and Zr/Ca relate to an aeolian component. This was recently demonstrated for a core taken offshore northwestern Western Australia by Stuut et al. (2014).

Application to marine sediments off Australia

Deep-sea sediment core MD03-2611 was taken offshore South Australia, opposite the mouth of the Murray River that together with the Darling River system drains the extensive (1.10^6 km^2) Murray Darling Basin (map in Fig. 1). De Deckker et al. (in press) analyzed selected samples from that core with several of the methods listed above to constrain the chemical signature of various parts of the Australian regolith.

The relative abundance of the clay species illite, smectite, and kaolinite, combined with Sr and Nd isotope ratios of the clay fraction (Gingele et al. (2007) revealed the flooding history of the Murray Darling Basin. Clay speciation (Fig. 1) varied substantially over the last 17 ka. The surprise was to find a drop in illite content during the Holocene, which indicates prevalence of an aeolian component from a remote source during the last 6 ka, since what was recognized as the clay sediments did not pertain to the Murray Darling Basin. This period of aeolian activity is also recognized in the Sr and Nd isotope records (Fig. 2). The history of increasing supply of airborne sediment paralleled a progressive sea-surface cooling determined by alkenone chemistry carried out on the same sediment core (Calvo et al. 2007).

The increase in the concentration of the REE yttrium following 6 ka BP also points to a fundamental change in the supply source of terrigenous material to the core site (Fig. 1). Furthermore, Sr and Nd isotopes compared to the Australian regolith constrain the origin of the sediments in core MD03-2611. Figure 2 shows the spread of Sr and Nd isotopes for different regions in the southeastern sector of Australia, all of which are considered potential dust sources (De Deckker et al., in press). Sr and Nd ratios in core MD03-2611 suggest that prior to 10 ka BP the sediment originated from the Murray sub-basin, after that from regions outside the Murray Darling Basin. Likely distal sources are central South Australia and western New South Wales, implying an aeolian transport mechanism to the sediment core site.

Conclusion

An array of traditional and new approaches for studying sediments in marine sediment cores can fingerprint the origin and indicate the transport mechanism of the terrigenous material deposited at sea. Methods include clay speciation and the chemical composition of the clay fraction such as Sr and Nd isotopes and REE. Core scanning that allows us to determine various elements at high resolution (but not in a quantitative way) also provides a new tool for distinguishing aeolian from fluvial components. The scanning method is non-destructive, relatively inexpensive and rapid and, therefore, can inform us which analytical techniques are best applied to identify the airborne fraction of marine and other sediments.

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Iron fertilization in the glacial ocean

Alfredo Martínez-García[1] and Gisela Winckler[2]

We review the hypothesis that the increased supply of iron-bearing dust to high-nutrient, low-chlorophyll regions of the ocean stimulated phytoplankton blooms that sequestered climatically relevant amounts of carbon and contributed to lowering atmospheric CO_2 during ice ages.

The concentration of major inorganic nutrients nitrate and phosphate is perennially high in one quarter of the surface ocean. However, despite this excess in macronutrients available for phytoplankton growth, biomass production still remains fairly low in the Southern Ocean, the equatorial Pacific and the subarctic North Pacific.

The causes of the incomplete use of macronutrients by marine organisms and hence of the existence of these high-nutrient, low-chlorophyll (HNLC) regions have been subject to intense oceanographic research in the past decades. In the late eighties John H. Martin and his team reported evidence suggesting that phytoplankton growth in these regions was chronically limited by iron deficiency (Martin and Fitzwater 1988; Martin et al. 1990). Martin immediately realized that one important consequence of this discovery was that changes in the availability of Fe in HNLC regions could have large effects on marine phytoplankton productivity and organic carbon export to the subsurface ocean, and therefore could influence the efficiency of the global biological pump in sequestering atmospheric CO_2 (Martin and Fitzwater 1988).

Iron fertilization in the Southern Ocean

The Southern Ocean is the largest HNLC region (Fig. 1) and represents the area of the ocean where variations in iron availability can have the largest impact on Earth's carbon cycle through its fertilizing effect on marine ecosystems. In 1984, several years before Martin's discovery of iron limitation, a series of papers postulated the potential role of the Southern Ocean in driving changes in atmospheric CO_2 concentrations during ice ages (Knox and McElroy 1984; Sarmiento and Toggweiler 1984; Siegenthaler and Wenk 1984). Combining these ideas with his discovery of iron limitation in the modern Southern Ocean, and the first observations of increased glacial dust deposition recorded in Antarctic ice cores, Martin proposed that the enhanced supply of Fe from dust could have stimulated marine productivity during ice ages, increasing carbon sequestration in the deep ocean and leading to a decrease in atmospheric CO_2 levels (Martin 1990).

Iron enrichment experiments

Since the seminal work of Martin, the effect of iron on marine ecosystem structure and productivity has been extensively studied through a series of short-term in situ iron enrichment experiments performed in the different HNLC regions of the ocean, but also by observing phytoplankton blooms induced by natural iron fertilization (Fig. 1).

Artificial iron fertilization experiments have provided unambiguous evidence that iron addition generates phytoplankton blooms in HNLC regions (Boyd et al. 2007; Smetacek et al. 2012). These findings are consistent with the observations of natural phytoplankton blooms in these regions stimulated by Fe

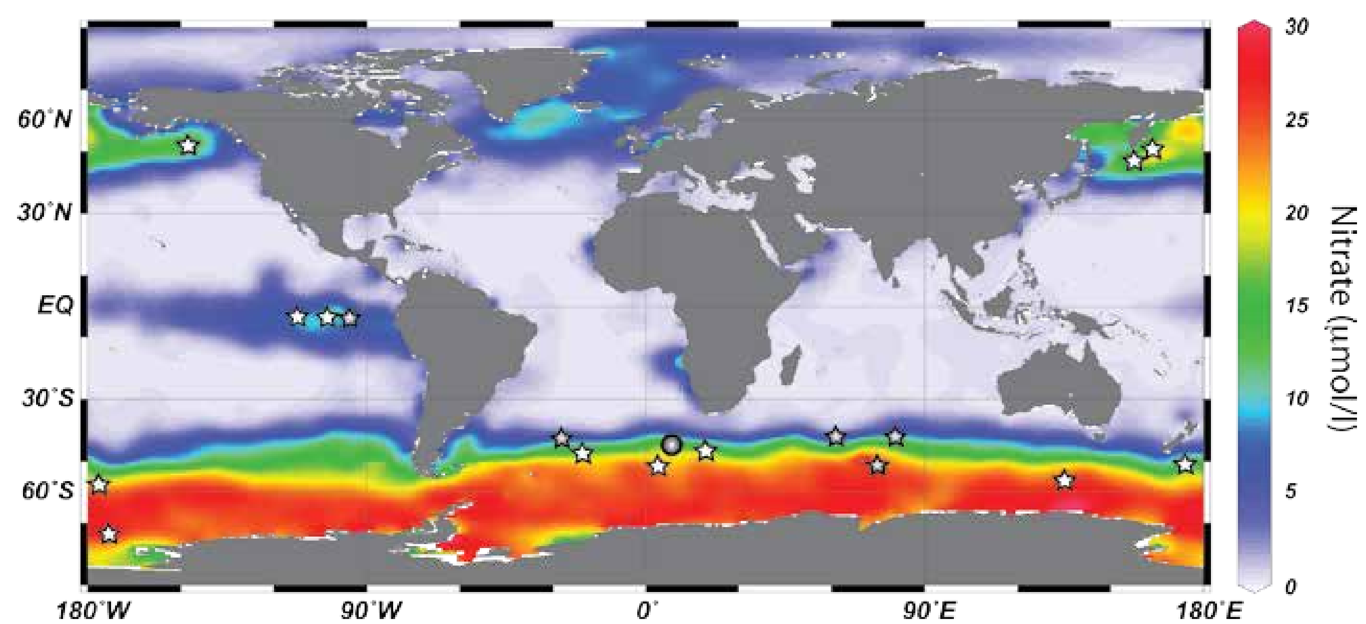

Figure 1: World ocean surface nitrate concentrations from the World Ocean Atlas (Garcia et al. 2010) indicating the three high-nutrient, low-chlorophyll (HNLC) areas (Southern Ocean, equatorial Pacific, Subarctic North Pacific). The gray circle marks the location of ODP Site 1090 and the stars mark locations where iron fertilization experiments (white stars) and iron enrichment experiments (gray stars) have been performed (Blain et al. 2007; Boyd et al. 2007; Smetacek et al. 2012).

input from different sources including continental dust (Cassar et al. 2007), volcanic ash (Hamme et al. 2010), free-drifting icebergs (Smith et al. 2007) and the upwelling of iron-rich deep waters (Blain et al. 2007). However, the efficiency of the iron fertilization process in removing CO_2 from the atmosphere ultimately depends on the depth at which sinking organic matter is remineralized. For example, in the Southern Ocean, the fraction of carbon retained within the deep winter mixed layer (upper 200 m) would return to the atmosphere within months, but organic matter sinking to the deep ocean and sediments, could be sequestered for centuries, millennia or longer (Smetacek et al. 2012). Unfortunately, the results of iron fertilization studies in the modern ocean with respect to the efficiency of organic carbon export to the deep ocean are still ambiguous, limiting our understanding of the potential efficiency of large-scale iron fertilization for atmospheric CO_2 sequestration.

Paleoceanographic records

Paleoceanographic studies provide an excellent opportunity to directly test the influence of continued large-scale iron fertilization on marine phytoplankton production and downward export of biomass, and its potential effect on atmospheric CO_2 levels.

Paleoceanographic reconstructions attempting to test the iron hypothesis have mainly focused on the Southern Ocean. Data indicate a heterogeneous response of Southern Ocean productivity during ice ages, characterized by an increase in productivity in the Subantarctic zone and a decrease in the Antarctic zone (Kohfeld et al. 2005). The decrease in Antarctic zone productivity was first interpreted as a challenge to the iron hypothesis raising doubts about the sensitivity of marine ecosystems to atmospheric iron supply (Mortlock et al. 1991). However, subsequent studies have proposed that the Antarctic Ocean was more strongly stratified during ice ages, reducing major nutrient supply from upwelling waters, and consequently explaining the lower glacial marine productivity in the Antarctic zone of the Southern Ocean (Francois et al. 1997).

In addition, in the Subantarctic zone, which is located downwind of major Southern Hemisphere dust sources, several studies have indeed found a remarkable correlation between iron deposition and marine productivity as predicted by the iron fertilization hypothesis (Kohfeld et al. 2005; Kumar et al. 1995; Martínez-García et al. 2009). The productivity increase occurred consistently in the later part of the glacial cycle, when atmospheric CO_2 concentrations were below a threshold of about 225 ppm and dust fluxes peaked (Kohfeld et al. 2005; Martínez-García et al. 2009). In addition, a recent study has shown that in the Subantarctic Atlantic (ODP Site 1090; Fig. 1) the high dust and productivity intervals of the last ice age are also characterized by an increase in the degree of nitrate consumption by marine phytoplancton, a combination that is only consistent with iron fertilization (Martínez-García et al. 2014).

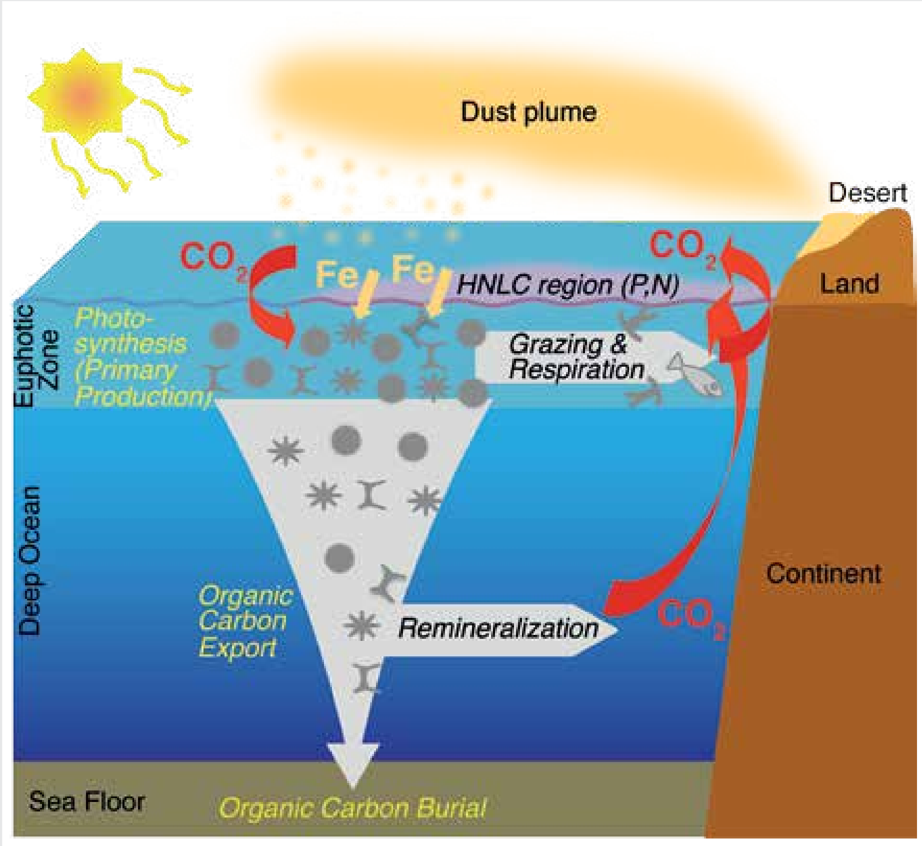

Figure 2: Schematic representation of the iron fertilization process.

These findings suggest that the iron fertilization process in the Subantarctic Southern Ocean may have been particularly important to explain the last 40 ppmv of the atmospheric CO_2 decrease observed during the ice age cycles of the last million of years (e.g. Martínez-García et al. 2011; Martínez-García et al. 2014). In fact, a CO_2 drawdown of up to 40 ppmv from Subantarctic iron fertilization is consistent with estimates obtained using geochemical box models and Earth system models, which in most cases range between 20 and 40 ppmv (e.g. Hain et al. 2010; Brovkin et al. 2007). In addition, recent studies suggest that dust flux, productivity and nutrient consumption also increased during the Antarctic millennial-scale cold events that characterize the last ice age (Martínez-García et al. 2014; Anderson et al 2014). These findings indicate that iron fertilization can also contribute to explain the millennial-scale CO_2 oscillations associated with these Antarctic cold events.

Although reconstructions of the effect of iron fertilization in the Southern Ocean have, so far, been largely limited to the Atlantic sector of the Southern Ocean, new sediment cores and dust flux reconstructions from the Pacific sector of the Southern Ocean (Lamy et al. 2014) will soon allow the hypothesis to be tested also in the South Pacific, the largest subbasin of the southern Ocean.

Implications for the future

Paleoceanographic data and models suggest that iron fertilization of the Subantarctic zone of the Southern Ocean stimulated marine export production and that this process increased carbon sequestration into the deep ocean, contributing to explain part of the atmospheric CO_2 decrease observed during ice age cycles. However, its potential application as a geoengineering strategy to mitigate anthropogenic CO_2 emissions is highly controversial, not only due to doubts about the limited efficiency of artificial iron fertilization for long-term atmospheric CO_2 sequestration, but also because of the potentially dangerous side-effects of large scale iron addition such as deoxygenation of intermediate waters or changes in phytoplankton community composition that may cause toxic blooms or promote changes further along the marine food chain (e.g. Buesseler et al. 2004; Johnson and Karl 2002).

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Loess as a Quaternary paleoenvironmental indicator

Daniel R. Muhs[1], M.A. Prins[2] and B. Machalett[3]

Loess (aeolian silt) is widespread in Eurasia and the Americas. Paleowind direction and wind strength can be reconstructed from spatial and temporal trends of loess thickness and particle size. Fossil land snails in loess can reveal much about past climate and vegetation.

Loess is aeolian sediment that is dominated by silt-sized particles. Unlike either coarser dune sand or finer-grained, long-range-transported dust, loess is relatively poorly sorted, reflecting a combination of transport processes, including saltation, low suspension, and high suspension. Loess can be readily identified in the field; deposits range in thickness from a few centimeters to many tens of meters, and are found over large areas of Eurasia, South and North America (Fig. 1), and smaller areas of New Zealand, Australia, Africa and the Middle East. Loess covers approximately 10% of the Earth's land surface and is therefore one of the most important terrestrial archives of paleoenvironmental change during the Quaternary. In many regions, loess sections consist of deposits of mostly unaltered sediment with intercalated paleosols. Paleosols represent periods of landscape stability when loess deposition ceased altogether, or at least slowed significantly. Loess can be dated directly using luminescence, radiocarbon, and amino acid geochronology methods.

Paleoclimatic interpretation

Loess property changes yield clues about the prevailing paleowinds during deposition. Thickness, particle size, and carbonate content, in general, decrease away from sources (e.g. Muhs 2013; Muhs et al. 2014). Thus, reduction in sediment load downwind from a source can be inferred from decreases in loess thickness. Paleowind direction and intensity can also be determined from the decrease in mean particle size away from a source, reflecting a winnowing of the coarse load in regions proximal to the dust source. Here we present some recent examples where paleoclimatic conditions in the Quaternary were inferred from loess deposits.

Determining source areas

A good example of the spatial variability of loess properties that can be used to infer paleowinds comes from the Chinese Loess Plateau region (Fig. 1a). Prins and Vriend (2007) conducted detailed measurements of loess stratigraphy, loess unit thicknesses, and particle size in a transect of loess sections across this region. Their results indicate that loess dating to the last glacial period, ~25-12 ka, referred to as the "L1-1" unit, shows a systematic decrease in thickness and an increase in the abundance of fine silt (modal size of ~22 µm) from north to south (Fig. 2a). This implies that loess source areas during the last glacial period lay to the north of the Chinese Loess Plateau, in the desert basins situated to the north and northwest of the region, which is consistent with various previous findings (see Muhs 2013; Muhs et al. 2014). Northerly or northwesterly paleowinds inferred from these observations indicate longer residence of the Siberian and Mongolian high-pressure systems (dominant in winter today) during the last glacial period and a shorter East Asian and Indian summer monsoon season.

Changes in wind strength

Changes in wind strength over time can be inferred from the particle size spectrum through a loess section. A number of researchers have used the ratio of coarse-to-fine silt as an indicator of wind strength at single sites over time in loess sections of Asia, Europe, and North America. Higher abundances of coarse silt imply stronger winds, which are capable of entraining and transporting coarser particles. Machalett et al. (2008) provide an example from a thick loess section in Kazakhstan, Central Asia (Fig. 2b). Glacial periods are recorded as thick, relatively unaltered sections of loess, whereas interglacial and interstadial periods are recorded as paleosols. The loess of Kazakhstan is, however, an excellent example of the kind of depositional system where aeolian particle transport and deposition do not "turn off" completely during interglacial and interstadial periods. Instead, deposition of the very fine-grained loess particles continued throughout the interglacials, but pedogenesis proceeded at rates greater than the loess sedimentation. The continued loess accumulation implies that loess source areas still existed during interglacial or interstadial periods, but wind strength was too low to transport coarse-silt-sized

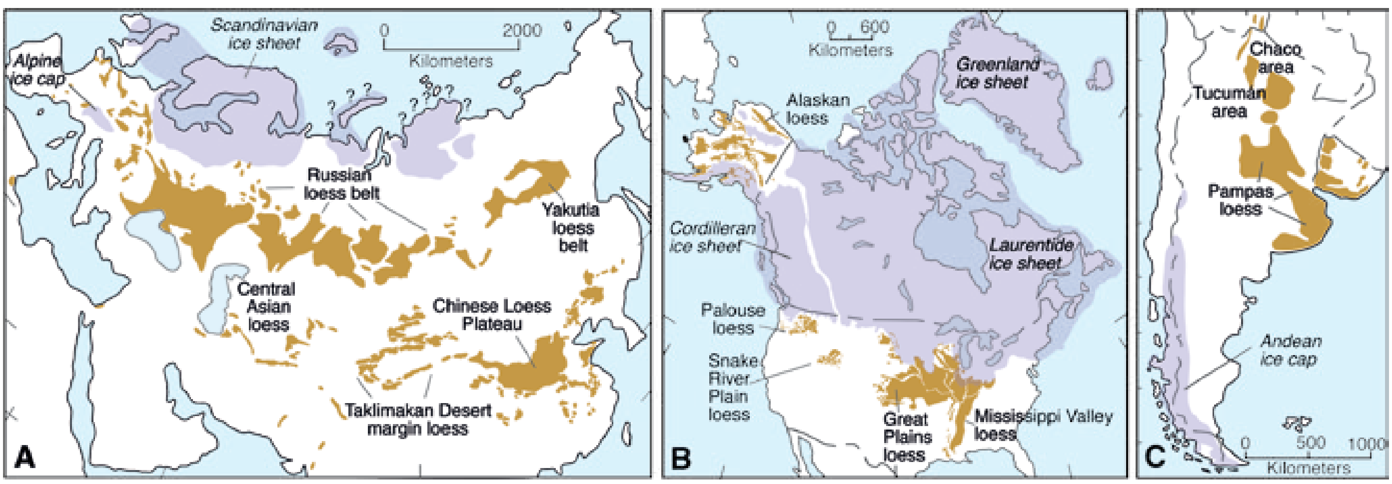

Figure 1: Distribution of loess in **(A)** Eurasia, **(B)** North America and **(C)** South America. Redrawn from Muhs (2013) and Muhs et al. (2014), and sources therein.

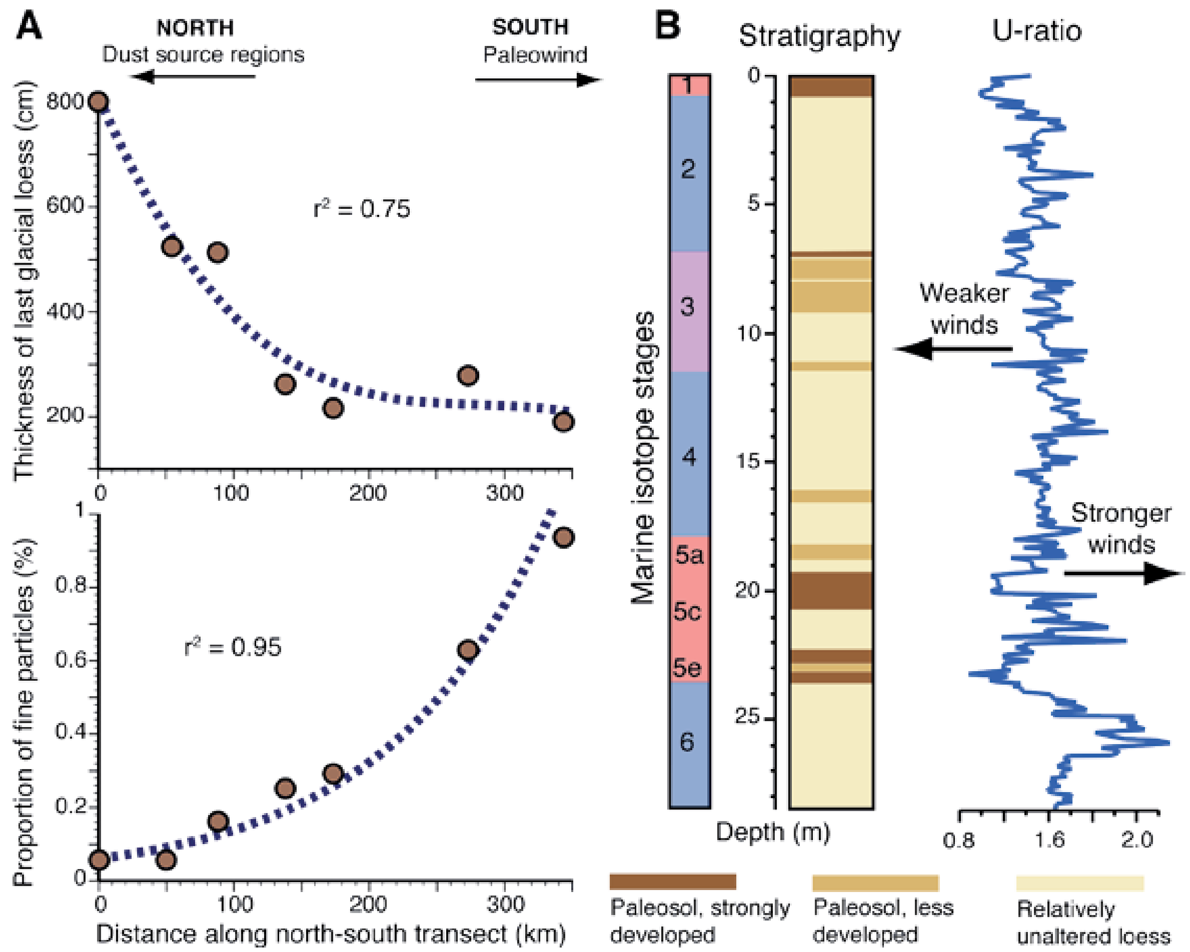

Figure 2: (A) Trends in thickness (upper plot) and abundance of fine silt particles (modal size of ~22 µm; lower plot) shown as a function of distance along a north-south transect in the Loess Plateau region of China, for last-glacial-aged loess (unit L1-1 in the Chinese loess stratigraphic system). Redrawn from data in Prins and Vriend (2007). **(B)** Stratigraphy of loess deposited during the past two glacial periods and ratio of coarse-plus-medium silt to fine silt (the "U-ratio") at a thick loess section at Remisowka, Kazakhstan. Note that while loess sedimentation occurs at a greatly diminished rate during interglacial or interstadial periods, allowing soil formation, it does not cease completely. Redrawn from data in Machalett et al. (2008).

particles. This variation in wind strength over time is documented by changes in the "U-ratio", a measure of coarse-plus-medium silt to fine silt (Fig. 2b). During the last glacial period (marine isotope stage or MIS 2 and 4) and the penultimate glacial period (MIS 6), high U-ratios indicate strong winds capable of transporting coarse particles, similar to modern winters. Conversely, in interglacial and interstadial periods (MIS 1, 3, and 5) aeolian silt was deposited concurrently with pedogenesis, but was dominated by fine-silt-sized particles, resulting in lower U-ratios. This interglacial pattern is due to weaker winds under a different synoptic-scale atmospheric circulation pattern, much more like that during modern summers.

Land snail fossils

Loess lacks many of the Quaternary paleoecological indicators commonly used in lacustrine or marine sediments, such as pollen, diatoms, ostracodes, radiolaria, or foraminifera. Furthermore, it is rare for mammalian fossils to be preserved in loess, although the deposits in Alaska (USA) and Siberia (Russia) are important exceptions to this generalization. Fortunately, it is common for the shells of land snails to be preserved in-situ in loess, most abundantly in China, Europe, and North America. Most of these snails are extant species, and their modern zoogeography is reasonably well established. Thus, it is possible to infer past climates during the times of loess deposition through the identification of extralimital taxa, i.e. those species that do not currently live in a locality but can be found there as fossils. Many of the land snail shells can be radiocarbon dated (Pigati et al. 2013). In North America, loess deposited during the last glacial period revealed a number of extralimital species of land snail fossils. For example, in the Great Plains region, the upper part of last-glacial loess contains several boreal (extralimital northern) or Cordilleran (western mountain) species of snails that do not live in the region today. The presence of these northern-forest and mountain-forest species implies a much cooler glacial climate with forest vegetation, as opposed to the temperate grassland dominating the region today.

Conclusions

Loess is found over large areas of Europe, Asia, South America, and North America. Loess has the distinct advantages over other Quaternary sediments for documenting climate change in that it provides a direct record of atmospheric circulation. It can be dated directly by luminescence, radiocarbon, and amino acid geochronology methods. The direction and strength of paleowinds can be reconstructed from spatial and temporal trends of loess thickness and particle size. Paleosols are common in loess and represent periods of little or no loess deposition. Fossil land snails that are often well-preserved in loess can provide paleontological information on past climate and vegetation.

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Abrupt climate changes recorded in loess sequences

Denis-Didier Rousseau[1,2] and Adriana Sima[1]

The glacial-interglacial and orbital-timescale oscillations imprinted in loess records have been studied for a long time. Researchers have recently started to investigate millennial and sub-millennial variations by means of high-resolution field studies and data analyses combined with modeling experiments.

The terrestrial sediments known as "loess" represent an important archive of paleoclimatic variability. Mineral material mobilized by wind at the ground surface was transported over distances from a few hundred to thousands of kilometers and deposited back on the ground where it underwent a gradual transformation into loess sediment. The largest loess deposits are found in the Northern Hemisphere, primarily because the continental surface is much larger than in the Southern Hemisphere. Depending on their location on the globe (Fig. 1), the deposits have formed under the influence of different climate factors, and contain more or less detailed records of regional climate change. Here we review the current knowledge about the three main loess regions of the Northern Hemisphere. The many underlying references are provided in an extensive online archive of references, listed by regions.

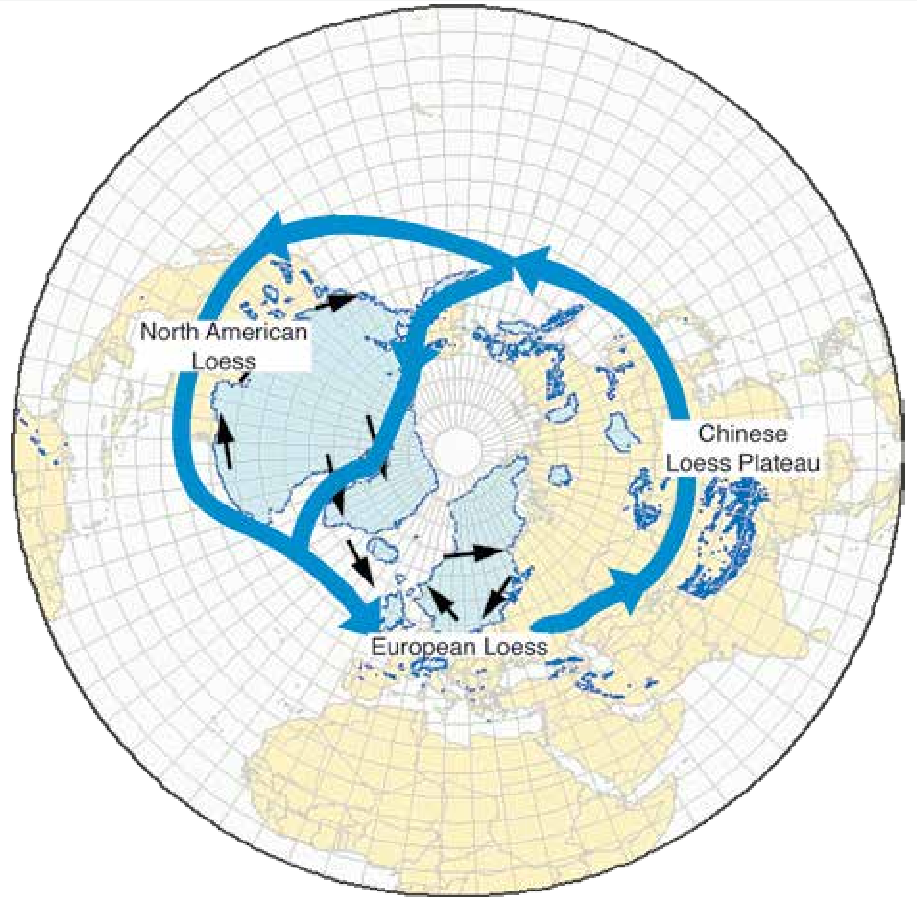

Figure 1: The Northern Hemisphere ice-sheets (in light blue) and glaciers (dark blue dots) at the Last Glacial Maximum (map compiled by Jürgen Ehlers, available at www.qpg.geog.cam.ac.uk/lgmextent.html), the schematic location of the polar jet stream (blue arrows), wind patterns (black arrows) generated by the presence of the ice sheets (Kutzbach 1987), and (labeled) the loess regions discussed in the text.

European loess

An almost continuous loess band stretches, along approximately 50°N, from western Europe to the Dnieper valley in Ukraine. In this band, loess sequences mainly record the North-Atlantic millennial-scale climate changes of the last glaciation (between ca. 110-15 ka BP): the Dansgaard-Oeschger (DO) events and Heinrich stadials (Rousseau et al. 2007, 2011). The DO events correspond in the Northern Hemisphere to abrupt warmings, of about 10°C in Greenland within 50-100 years, and are followed by a more gradual return to cold (stadial) conditions. The Heinrich stadials represent particularly cold climate episodes caused by massive iceberg discharges from the Northern Hemisphere ice sheets known as Heinrich events.

Multidisciplinary loess studies and detailed chronological analyses indicate a strong correlation between these climate variations and European loess sedimentation. In the 50°N European loess band, the alternating warm and cold episodes are clearly imprinted in the stratigraphy as a succession of doublets of paleosol-loess units, in particular during marine isotope stages 3 and 2 (between approx. 60-15 ka BP). The soils were formed during the relatively warm North-Atlantic phases (Greenland interstadials) associated with DO events, when the eolian sedimentation was reduced or even absent. The degree of development of each soil depended on the duration of the corresponding warm episode. The loess units correspond to the cold North-Atlantic phases (Greenland stadials and Heinrich stadials), when the dust cycle was very active and the sedimentation rates were high. Other loess deposits can be found in Europe at lower latitudes, but the millennial climate variations represented by the alternation of paleosols and loess units are absent in the stratigraphy, suggesting drier conditions than in the 50°N loess band.

Recent studies have employed numerical modeling to investigate the mechanistic link between the North-Atlantic millennial climate signal and the loess sedimentation variations in Europe around 50°N (Sima et al. 2009, 2013). These studies focused on variations in dust mobilization, reasonably assuming that the deposition fluxes strongly depended on the emission fluxes. An important aspect of modeling the formation of loess deposits in Europe is to identify the geographical areas that were potentially subject to deflation during glacial times, but are not anymore under present-day climate conditions.

For Western Europe, data-based studies have shown that the continental shelf that emerged during glacials (when sea-level dropped), especially in the English Channel and the

North Sea, used to be a strong dust deflation area. Transported from there by westerly winds, fine material must have reached loess deposits located many hundreds of kilometers away, together with coarser material from nearer sources, such as large river valleys or periglacial outwash plains. Modeling results (Sima et al. 2009) point to vegetation changes in response to the millennial climate variations as a key factor in modulating dust emission, and hence ultimately also in controlling loess sedimentation (Fig. 2). They also show the strong seasonality of the dust cycle. Dust emission was mainly active in springtime when the snow cover had melted, the topsoil layer had begun to thaw, the surface winds were still strong (even though weaker than in winter), and the vegetation had not yet developed enough to completely protect the surface from wind erosion. The colder the climate, the later the emission season started, and the later it ended. Numerical experiments generated about one month of delay for a given region between the warmest ("Greenland interstadial") and the coldest ("H stadial") simulated climate state.

For Eastern Europe, previous data-based studies only suggested the general direction in which the source areas should have been located with respect to the investigated loess deposits. Numerical modeling results (Sima et al. 2013) now show the likely dust source areas (Fig. 2). They also suggest that Heinrich stadials, even though generally colder and drier than the other stadials, were not necessarily dustier. Dust storms appeared to be generally less frequent during Heinrich stadials, but individual events could become stronger than during non-Heinrich stadials. These modeling results are in agreement with findings of relatively coarser-grained layers in loess sequences interpreted as Heinrich-Stadial signature.

Asian loess

In the eastern part of Eurasia, the sedimentation in the Chinese Loess Plateau (Fig. 1), which commenced about 22 Ma ago, strongly depended on fluctuations of the Southeast Asian monsoon. Initial investigations on loess sequences from this area have identified orbital timescale variations related to changes in the three astronomical parameters: eccentricity, obliquity, and precession. Some series from the north of the Chinese Loess Plateau also exhibit particle-size variations with millennial frequency, similar to the DO oscillations observed in North Atlantic records. A correlation, mainly based on luminescence dates, has been established between intervals of coarse loess layers and Greenland stadials (without particularly distinguishing the Heinrich stadials), while intervals of fine-grained loess were associated with the DO warming events. The grain size changes are interpreted as reflecting variations in the strength of the atmospheric circulation during the SE Asian winter monsoon over the deserts of Mongolia and northern China, the main dust suppliers to the Chinese Loess Plateau.

The Chinese loess sequences do not contain any paleosols related to DO events, because the corresponding climate is too dry to allow pedogenesis. Alternating paleosol-loess units similar to those observed in Europe along 50°N can, however, be found in Siberian loess deposits north of Lake Baikal. The available radiocarbon dates allow the Siberian paleosols to be correlated with the DO events and suggest that the impact of the North-Atlantic millennial climate variations reached at least as far east as Lake Baikal.

North American loess

The North American loess deposits have recorded various influences, mostly related to climate changes originating in the North Atlantic and Pacific regions. According to climate simulations run with an Earth system model of intermediate complexity, the eastern part of North America should have been affected by the DO and Heinrich abrupt climate changes, but very few loess deposits can be found there to verify this model result. On the other hand, modeling results indicate that much of the Great Plains, where the thickest North American loess deposits are located, and the western part of the continent were not influenced by DO and Heinrich events. Indeed, the succession of paleosol-loess units in sediments in the state of Illinois, 120 km south of the Laurentide ice sheet margin at its maximum extent, is interpreted (using radiocarbon dates) as reflecting sub-millennial timescale inflow of air from the Gulf of Mexico, with a periodicity of about 450±100 yr. Loess sequences located further west, mainly in the state of Nebraska, show bedded mineral layers corresponding to even finer timescales. These were formed as a result of the transport of material during the Last Glacial Termination (~23-12 ka BP) from nearby areas, including the outwash areas of the southwest margin of the Laurentide ice sheet and the east margin of the Cordilleran ice sheet.

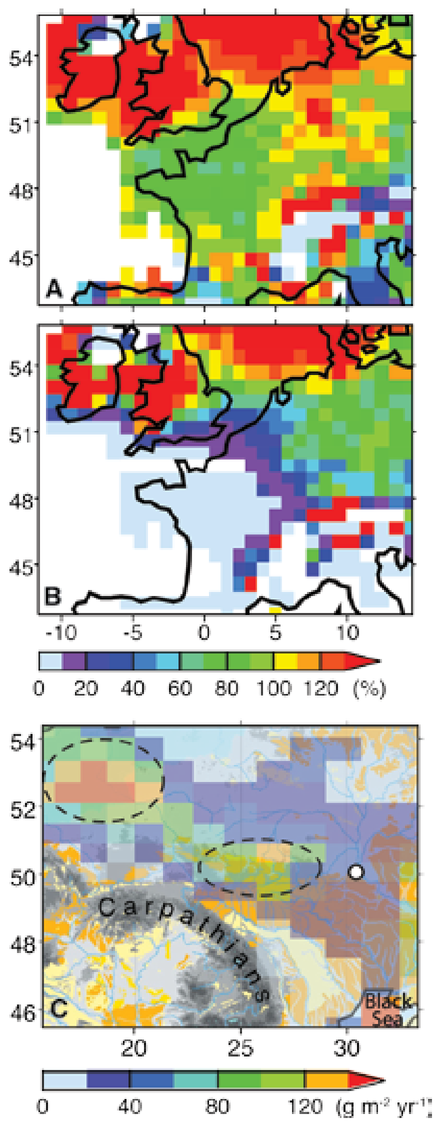

Figure 2: (A) Simulated dust emission fluxes for Western Europe for a "Greenland interstadial" (GIS) are relatively close to those for a "Greenland stadial" (GS) when the GIS and GS fluxes are computed without taking the vegetation effect into account (GIS/GS flux ratio between 70-130%); **(B)** the flux ratio GIS/GS strongly decreases when the vegetation effect of inhibiting eolian erosion is taken into account (modified from Sima et al. 2009). **(C)** Simulated dust emission fluxes for Eastern Europe for a GIS, superimposed on a topographic map; the most active spots (indicated with dotted lines) have probably been important sources for some Eastern European loess deposits (in yellow, in background), such as those around Stayky (white dot) in NW Ukraine (modified from Sima et al. 2013).

Outlook

Many loess deposits, especially across the Northern Hemisphere, have recorded past climate changes at millennial and sub-millennial timescales. Some loess sequences also contain evidence of particularly strong dust events with a much shorter characteristic timescale. Thus, during Marine Isotopic Stage 5, European sequences (especially from Central Europe) have recorded dust storms of continental magnitude in response to atmospheric blocking episodes (Rousseau et al. 2013). More effort is needed, on the data side, to better quantify the past dust-cycle variations at these different timescales, and on the modeling side, to more realistically simulate them.

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Extracting paleodust information from peat geochemistry

François De Vleeschouwer[1,2], M. Ferrat[3], H. McGowan[4], H. Vanneste[1,2] and D. Weiss[3]

Peatlands are formidable geochemical archives of atmospheric dust and are increasingly being used to address major paleoclimatic questions. Here, we provide an insight into the recent advances.

Peatlands are increasingly used as terrestrial archives of atmospheric dust deposition. Peat records mostly cover the Holocene, although some may extend beyond 10 ka (e.g. Kylander et al. 2007). The global occurrence of peatlands makes them a good alternative for making inter-hemispheric comparisons of paleoclimate when other terrestrial records are not available. Europe, for example, lacks long Holocene atmospheric archives such as ice cores, but it contains widespread peat deposits. Similarly, in the Southern Hemisphere, peatlands provide an opportunity to probe the entire Holocene, a period for which dust records from polar ice and marine cores are generally absent or offer lower resolution.

Peatlands have two key advantages over many other paleoenvironmental archives: they are relatively easy to access and sample and their high accumulation rates allow records of sub-decadal scale to be developed. Ombrotrophic (i.e. atmosphere-fed) peatlands, or bogs, offer the greatest insights into past climate as they only receive input through the atmosphere, such as aerosols and rain, and thus truly reflect local to regional-scale atmospheric conditions (Le Roux et al. 2010; Marx et al. 2009). Minerotrophic (i.e. stream-fed) peatlands, or fens, can also provide valuable information in terms of dust sources (e.g. Kylander et al. 2007; Muller et al. 2008a,b).

Earlier studies on peatland chemistry focused on atmospheric trace metal contamination to reconstruct pollution histories (e.g. Lee and Tallis 1973; Shotyk et al.1998). Today, studies focus more on the paleoclimatic and paleoenvironmental information of the dust trapped in peat. This includes developing tools to assess the integrity of the record (i.e. effects of post depositional element movements or groundwater input), to identify the origin of mineral dust particles and to quantifying flux changes through time.

Flux calculation

Atmospheric dust fluxes in bogs are reconstructed from the vertical distribution of lithogenic trace elements such as Ti, Sc, Zr, Y or REE (Rare Earth Elements) in bulk peat samples. These elements are not affected by post-depositional processes and do not have a significant anthropogenic source. In addition, it is essential to develop robust chronologies for the peat profiles based, for example, on ^{14}C and ^{210}Pb dating, and on age modeling that takes into account dating and accumulation rate uncertainties (Blaauw and Christen 2011). Robust chronologies allow dust fluxes to be calculated accurately, and to establish specific tie-points and correlate them to known climate events. Dust flux records have been successfully used to pinpoint abrupt events such as the Younger Dryas (Shotyk et al. 2002; Weiss et al. 2002), the 8.2 ka event (Shotyk et al. 2002; Le Roux et al. 2012), and the Little Ice Age (De Vleeschouwer et al. 2009). Furthermore, with good knowledge of the geochemical properties of potential dust source areas it is possible to distinguish distal from local (sub-)catchment sources, and apportion their contributions through time, thereby providing insight into regional scale environmental change (Marx et al. 2009, 2010).

Using dust records in modeling

The deposition rates determined from peat records offer a tool for validating atmospheric circulation model simulations, which in turn provide a platform for investigating the interactions between the atmospheric dust cycle and environmental change. Model validation of aerosol components is, however, still limited by the scarcity of past dust flux records.

A regional atmosphere-chemistry/aerosol climate model (REMOTE) has recently been successfully applied to simulate dust emissions and transport from the major Chinese deserts to its subsequent deposition over the Central Tibetan Plateau (Ferrat el al. 2013). This study showed that numerical modeling has the potential to reveal more about past and present dust cycles. The study also concluded, however, that further refinement of the dust and soil surface property parameterization is in particular needed in order to improve the climate model.

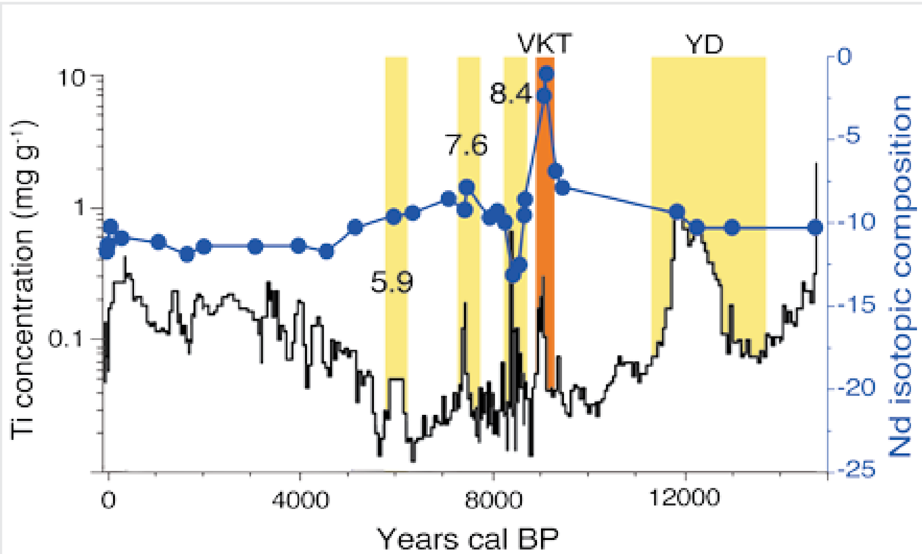

Figure 1: Ti concentration and Nd isotopic composition (εNd) in a bog profile in Switzerland. The Younger Dryas (YD) is characterized by an increase in local dust input, reflected by high Ti concentrations. Early Holocene Vasset-Kilian eruptions (VKT) in the French Massif Central result in high εNd. Saharan dust input is identified by negative εNd around 8.4 ka. The progressive desertification of the Sahara during the Holocene decreases εNd progressively from 7.5 to 3.5 ka cal BP, when local erosion becomes dominant. The two dust peaks (yellow bars) at 5.9 and 7.6 ka remain unexplained. Modified from Le Roux et al. 2012.

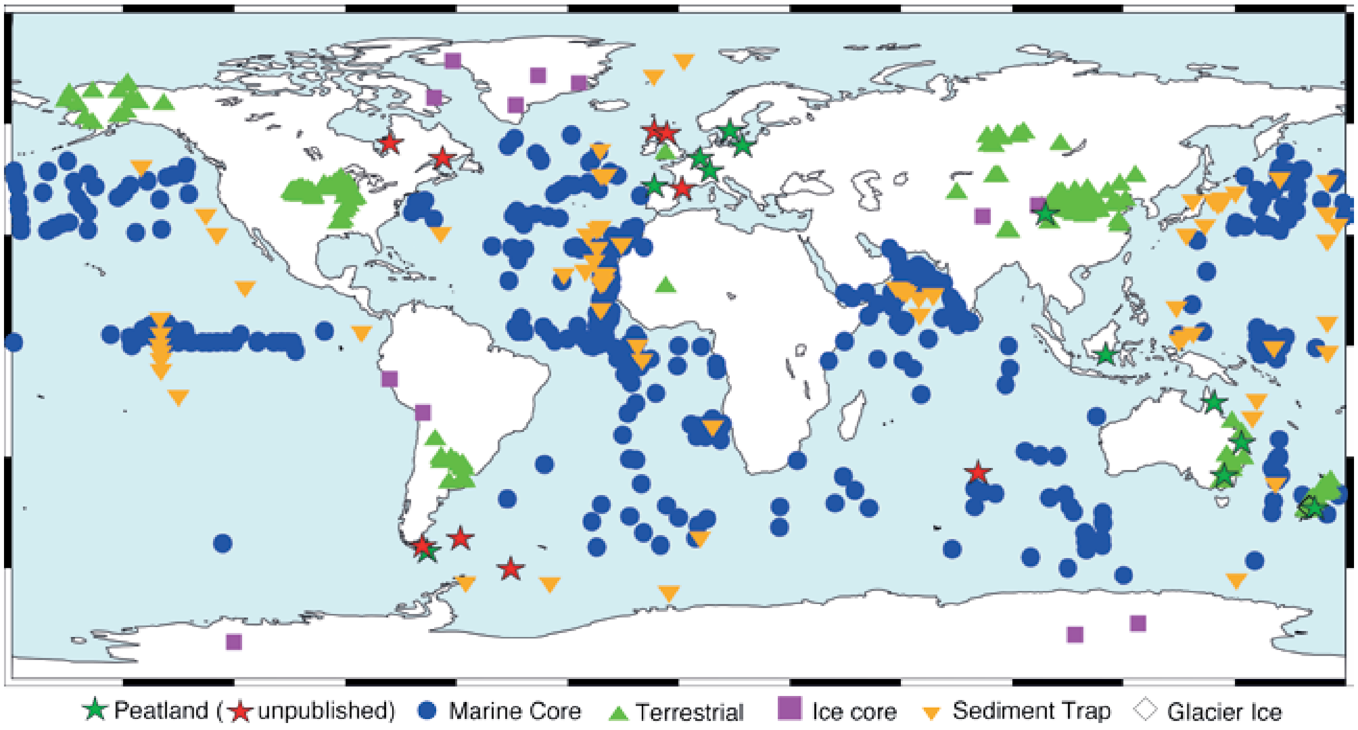

Figure 2: World coverage of dust records in peat, including already published peatland records (green stars) and ongoing works (red stars). Map drawn from Kohfeld and Tegen (2007), Mahowald et al. (2006) and Kohfeld and Harrison (2001).

Another opportunity of data-model symbiosis lies in quantifying abrupt changes (or change points). The dust deposition record is normally represented as a function of depth or time. Trans-dimensional Markov chain Monte Carlo analysis has recently been explored to infer probability distributions on the number, position and age of change points, the mean distance between change points, and the noise variance associated with each dust record (Gallagher et al. 2011; Kylander et al. 2013). Simulating noise in dust records from bogs or ice cores can complement the observational information. Noise estimates of proxy records are normally limited to the measurement uncertainty, and in most cases it is not practical to repeat sampling and measurements to experimentally assess noise. Gallagher et al. (2011) analyzed several sets of geochemical dust data from peat cores taken from Australia, Sweden and Tibet. They showed that their model-based analyses are consistent with those previously inferred qualitatively from independent data and interpretations. Moreover, this approach provides quantitative estimates of the relative probability of the inferred change points, allowing an objective assessment of the significance of each change.

Sources

Lead isotopes were first used to identify sources of anthropogenic and natural dust in bogs (Shotyk et al. 1998). This opened a field of investigation aimed at developing proxies that better constrain the relative contributions of local and regional dust sources to peat deposits. However, lead has been emitted by anthropogenic activities for more than 5000 years (Nriagu 1983). This has limited the potential of lead as a natural dust tracer for the Holocene and has resulted in uncertainty in dust provenance reconstructions (Kamber et al. 2010).

In order to define the provenance of dust with greater certainty, other geochemical tracers are increasingly used. Coupling REE and Pb isotopes or lithogenic elements allows us to determine shifts between wet and dry climate (Kylander et al. 2007), to discriminate local from distal dust (Marx et al. 2009), and to reconstruct wind strength and changes in atmospheric circulation (Marx et al. 2011). In Europe, where Holocene atmospheric archives are rare, Le Roux et al. (2012) combined lithogenic elements, REE and Nd isotopes to reconstruct the dust flux and sources over the last 14 ka from a bog in Switzerland (Fig. 1). In this study, the interplay between climate and natural dust draws a complex picture of the Holocene dust sources, which are the Sahara desert, volcanism in France, and local erosion. Dust during the Younger Dryas dominantly originated from strong local erosion and mineral input, while during early Holocene volcanic eruptions and abrupt Saharan dust input around 8.4 ka BP were the main sources. In addition, the progressive desertification of the Sahara, already suggested by Kylander et al. (2005) using lead isotopes in a Spanish peat core, was identified through a progressive increase in Ti and a shift in εNd from 8 to 4 ka BP. With the same approach using REE and Nd isotopes, Allan et al. (2013) identified increased dust fluxes during cold periods and large supplies from distal (Saharan dust and Icelandic volcanism), regional (European Loess) and local sources during the Holocene.

Outlook

As an increasing number of studies have shown, the geochemical separation of dusts in peat and their provenance offers the prospect of unmatched insight into paleo-atmospheric circulation, its variability and the environmental consequences, primarily from synoptic to macro-scales, and associated environmental changes (McGowan et al 2008; Petherick et al. 2009). Accordingly, using dusts as tracers of paleoclimate provides an opportunity to calibrate and validate climate models. Efforts are now being made to refine the spatial coverage of peat dust records from the high latitudes to the tropics (Fig. 2) and extend the records back into the Quaternary. Peat researchers are now focusing on covering areas where dust records are lacking such as Canada, India and the Southern Hemisphere (Patagonia, Tierra del Fuego, South Africa, Falkland Islands, Amsterdam Island).

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DIRTMAP: development of a web-based dust archive

Barbara A. Maher and David T. Leedal

The influence of airborne dust on climate, through changes in the radiative properties of the atmosphere and through iron fertilization of oceans, remains a poorly quantified element of the Earth's climate system, both in the present and in the past. Key dust properties include fluxes, mineralogy, and particle size and shape. However, dust-cycle models presently employ a relatively simple representation of dust properties (e.g. assuming spherical particles); these simplifications severely limit the realism of simulations of the impact of changes in dust loading on radiative forcing and biogeochemical cycling. One way to overcome this limitation and complement and validate these modeling efforts is to use records of dust deposition to assess what effects dust had in the past under different climatic conditions. This is where DIRTMAP, a dust database tailored for such interdisciplinary mineral dust research, could prove a valuable resource. Recently, the original DIRTMAP database (Kohfeld and Harrison 2001) was re-developed into a readily accessible web-based archive which allows interactive interrogation and visualization of the data.

DIRTMAP's evolution

The Dust Indicators and Records of Terrestrial and MArine Palaeoenvironments (DIRTMAP1) database was originally developed in Lund, Sweden in 1997, as a product of the Mineral aerosols and glacial-interglacial cycles project, led by Sandy Harrison, Colin Prentice and Henning Rodhe. It was designed to enable mapping of mass accumulation rates (MARs) of dust at the Last Glacial Maximum compared with the late Holocene.

DIRTMAP2, subsequently developed by Karen Kohfeld and colleagues at Jena, Germany, included dust information from more sites, encompassing dust fluxes in ice cores, marine sediments, marine sediment traps, and loess sediments. Archived at the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/loess/dirtmap/), it also provided information on site age models (e.g. layer counting, radiocarbon, oxygen isotope stratigraphy), methods used for calculation of aeolian accumulation rate (e.g. isolation of terrigenous components, Al concentration measurements, number or mass concentrations), and marine sites with non-aeolian sedimentary contributions (e.g. IRD, sediment redistribution).

Other than the incorporation of some additional loess data, the underlying database for the next version, DIRTMAP3 (Maher et al. 2010), underwent relatively little change, as the multi- and inter-disciplinary dust research communities debated their future aims, methodologies, time-slices, dynamics and environments of enquiry. It became clear that any new version of DIRTMAP had to be not only more easily accessible but also more flexible in order to accommodate more diverse research objectives.

DIRTMAP4

Funded through the International Union for Quaternary Research (INQUA), the "Dust and Climate Working Group", led by Lancaster University (www.lancaster.ac.uk/lec/sites/dirtmap/INQU), is currently developing a new website for the development of DIRTMAP4. The aim is to provide the opportunity for rapid updating and quality control of data, and the subsequent development of a new data archiving and access protocol, e.g. enabling archiving of data for additional time slices, and new meta-data fields (e.g. proxy data; particle mineralogy, size distribution, particle shape; bioavailable elements).

As part of this work on DIRTMAP4, we created a web interface to access the database and take advantage of the power of modern browsers and Asynchronous JavaScript and XML (AJAX) technology, thereby eliminating the need for users to install additional software to access the database. The aim is to provide the dust research community with instant access to the data and allow interactive interrogation and visualization (Fig. 1). A prototype version of the website is presently online at www.lancaster.ac.uk/lec/sites/dirtmap/hw.html.

The design has intentionally been kept simple to make it easy for other researchers to get involved. Indeed, extension of the database is actively encouraged under the terms of the MIT license (a permissive, free software license which originated at the Massachusetts Institute of Technology). We hope that the user interface and functionality is intuitive and self-explanatory.

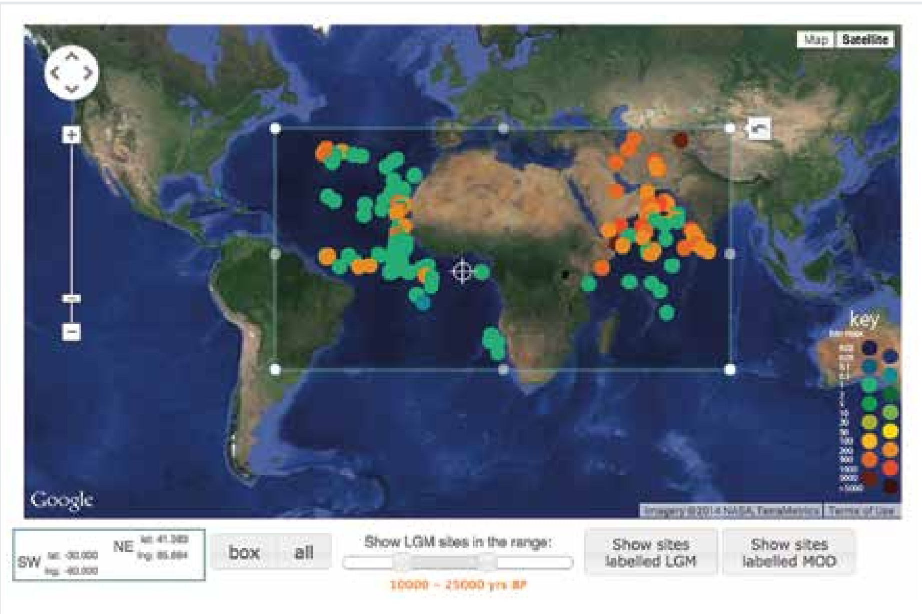

Figure 1: Detail from DIRTMAP4 website showing map and querying controls.

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Share your geoscience resources in EarthCube's Paleogeoscience Catalog

David Anderson, K. Horlick and R. Lingo

Your input is needed to produce a new, comprehensive, and openly accessible catalog of paleogeoscience resources, including databases, sample repositories, and shared software.

Imagine a world where the global community of Earth scientists are well-connected, where resources such as data, software, sample repositories, journal articles, and social networking combine efficiently to accelerate the pace of discovery, where the infrastructure enables new approaches, where the time needed to manage data is reduced enabling more time to do science. This is the world envisioned by EarthCube, a US National Science Foundation sponsored long-term effort to develop cyber-infrastructure, bridge disciplines, and unlock the power of sharing tools, data, and information.

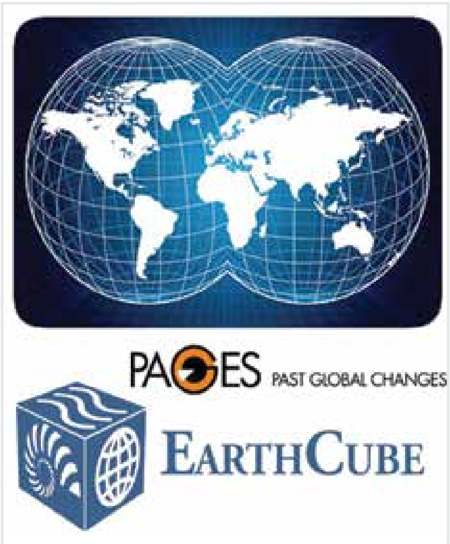
EarthCube was launched in 2011. Over 2500 scientists have contributed to the current structure and program development (Richard et al. 2014). EarthCube hopes the planned changes to Earth Science will be comparable in speed and breadth to the spread of the Internet or other basic Infrastructures. The EarthCube system will enable data intensive science, become an integral part of everyday research, and provide access to people, tools, and data.

The data management component will improve the availability and documentation of scientific data, enabling synthesis and re-use. Resource catalogs will put lists of software, data, and sample repositories on your desktop. Data and software will be integrated to simplify access, analysis, and visualization. Results will be piped between processes in reproducible workflows. Stovepipes constraining narrow disciplines will be removed enabling data and tools originating in one discipline to be applied in another.

One of the first steps to create this new world is to develop a catalog of resources. So the World Data Center for Paleoclimatology is now reaching out to PAGES scientists and educators, to help you add information about databases, software, and repositories to a central and comprehensive catalog of paleogeoscience resources.

Project history

The National Oceanic and Atmospheric Administration (NOAA) is spearheading the catalog development for the EarthCube project titled "C4P: Research Coordination Network for Paleogeosciences". The C4P



project connects with an Earth-Science-wide cataloging effort titled CINERGI that has the goal to build a comprehensive system linking geoscience resources, users, publications, usage information, and cyberinfrastructure components. The initial CINERGI catalog, with some paleoclimate entries, can be found at http://hydro10.sdsc.edu. A pivot table view exists at http://hydro10.sdsc.edu/c4pviewer/CommunityPivot.html. Both C4P and CINERGI produce resources that can be shared worldwide beyond the Earth Science discipline, for example through resource sharing platforms such as SciCrunch (scicrunch.com). In the future, informatics experts hope to create a catalog of resources that embraces all scientific disciplines.

The catalog idea

The guiding idea of the cataloguing effort is to help scientists discover samples, software, and data and use these resources in new and creative ways. Some PAGES-relevant resources are well known, for example the IMAGES and IODP marine sediment core collections, the PANGAEA and NOAA databases, and various radiocarbon calibration software packages. However, many resources that could be shared to the benefit of providers and users are instead hidden or hardly traceable. Cores and sample collections sometimes remain in the laboratories of individual investigators long after projects have been completed. Software that could be shared is used only by one team of investigators. Sharing resources accomplishes several goals that accelerate the pace of science and advance discovery. One goal is to identify best practices and unusually significant samples and data sets. Pilot studies made on already-existing samples can provide crucial evidence needed to secure research funding. Another goal is to enable resources used in one field, or for one scientific question, to be applied to other problems. For example, mosquitos collected and preserved by entomologists years ago, their skeletons affixed with pins to a board, have been sampled by epidemiologists to understand the spread of the West Nile virus using the DNA found in the mosquito's bodies (Kaufmann et al. 2003).

Feed the catalog

We need your input and suggestions to produce the catalog of paleogeoscience resources. Input from scientists in the PAGES community is vital to make the catalog a comprehensive and truly international resource. We want your suggestions of software and databases focused on or relevant to paleogeosciences.

- Software should be non-commercial, and should be paleogeoscience-specific, such as radiocarbon calibration code or CoreWall (corewall.org).
- Databases for the catalog are defined as having an online searchable interface.

Paleogeosciences encompasses both paleoenvironmental and paleobiological research, including paleoclimatology, paleoecology, paleogeography, geochronology, and geochemistry. Conceptually these topics focus on past Earth and life processes.

To contribute a resource, email paleo@noaa.gov with the name of the software or database resource, the URL, and a two-sentence description, with "EarthCube" in the subject line.

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Carbon in Peat on EArth through Time (C-PEAT)

Zicheng Yu[1], D. Charman[2], D.W. Beilman[3], V. Brovkin[4] and D.J. Large[5]

Peatlands represent the largest carbon (C) pool in the terrestrial biosphere. In the form of peat (organic soils) they store at present ~600 Pg C, accumulated mostly since the Last Glacial Maximum. We know that peatlands played an important role in the global C cycle during the Holocene as also recognized by the IPCC AR5 (Ciais et al. 2013); however, we still lack a full understanding of how sensitive these C-rich ecosystems are in responding to climatic changes. Also, the lack of data and understanding on some fundamental processes, such as peatland lateral expansion, hinders large-scale synthesis and global modeling efforts. Furthermore, we have little idea about the C pool size and dynamics of peat deposits further back in time, such as during previous interglacials, the Pliocene and beyond, and their sensitivity to climate conditions outside the range of the Holocene.

C-PEAT's goals

The formation of the PAGES' C-PEAT working group follows on the success of community-wide efforts sponsored by PAGES, INQUA, US NSF and UK NERC over the last five years. The effort was initiated with two workshops in 2009 (Jackson and Charman 2010) that resulted in a synthesis paper on northern peatland C during the last millennium (Charman et al. 2013). A recent workshop at Lehigh University in October 2013 (Yu and Loisel 2014) focused on synthesizing our knowledge on northern peatland C dynamics during the entire Holocene. This ongoing effort is built on an expanded database of Holocene peat C records described in Loisel et al. (2014), as part of a special issue in *The Holocene* on Holocene circum-Arctic peatland carbon dynamics guest-edited by Yu et al. (2014).

C-PEAT aims to synthesize data and knowledge on the evolution of peat C stocks through Earth's history through collaborations between international peat C researchers working on peat of all locations and ages. We will continue to focus on Holocene peatlands because of abundant information being available, but we will also extend our attention to timeframes beyond the Holocene.

The ultimate goal of the working group is to understand the climatic sensitivity and contribution of peat deposits to the global C cycle by looking at peat dynamics in the past. Paleo peat data are essential not only for documenting C sequestration histories but also for evaluating global climate-carbon cycle models and for projecting future changes.

Planned activities during Phase 1

In the next three years, the working group proposes the following synthesis activities that will allow us to approach a first comprehensive assessment of peat C stocks on Earth through time.

(1) Antarctica and southern peatlands. A workshop held in England in October 2014 was focusing on the processes of peat inception and preservation in Antarctica, and comparisons of waterlogged peatlands versus aerobic peatbanks. This process understanding is critical to projecting future dynamics of peat-forming systems in Antarctica as more ice-free land becomes available in a warming climate. We also plan to synthesize peat C accumulation records in and around Antarctica, including sub-Antarctic islands, Patagonia and other southern high-latitude regions.

(2) Tropical peatlands. We encourage researchers working on tropical peat C history to lead and participate in the effort to synthesize peatland records to reconstruct peatland initiation and C accumulation histories.

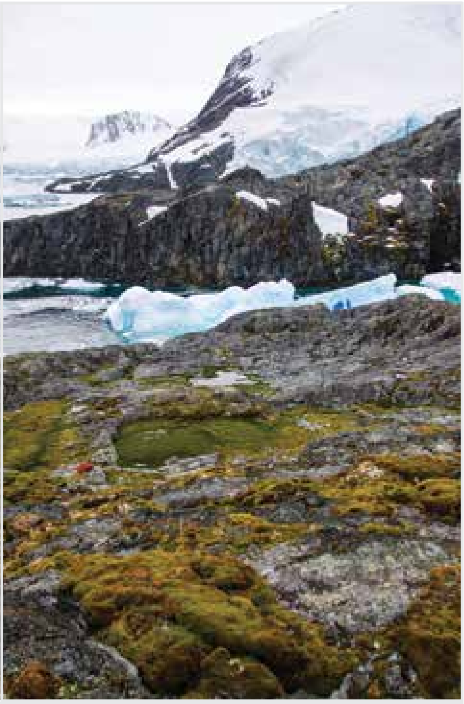

Figure 1: Peat-accumulating systems in Antarctica. Two waterlogged "peatlands" (center left) and aerobic moss peatbanks (foreground) at Rasmussen Hut on mainland Antarctic Peninsula around 65°S (photo by Zicheng Yu, February 2014).

That effort would contribute to a unified understanding of processes controlling C accumulation.

(3) Pre-Holocene peat and coal. What were peat C stocks before the Holocene? How do the pre-Holocene and Holocene peat C accumulation rates compare? What switched global peat formation on and off in the past? What are the implications of extending peat growth models over time periods that greatly exceed those of the Holocene? What were the impacts of peat C on Earth's carbon cycle and climate?

(4) Process understanding and modeling. There is an ongoing effort to understand the peatland lateral expansion process, especially for data-rich northern peatlands. This understanding will provide more robust estimates of peatland area change over time and of regional and global peatland C stocks. Also, understanding long-term decomposition is essential for reconstructing peat net C balance and its impact on the global C cycle in the past and in the future. Gaining a better understanding of these processes will contribute to global peat C modeling efforts as well as reconstructions of C sequestration history.

We welcome and invite anyone who is interested in peat C to get in touch with us to lead, contribute to and participate in these community-wide synthesis efforts. Visit the C-PEAT website: www.pages-igbp.org/workinggroups/peat-carbon

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The quest for temperature and hydroclimate records

Anne Hormes[1] and Jostein Bakke[2]

The Arctic is characterized by a high diversity of paleoclimate archives, resulting in reconstructions that integrate multiple proxy evidence. At a workshop in San Francisco, USA, on 8 December 2013, Arctic2k took stock of its status and discussed scientific objectives and organizational structures for the coming phase of the project.

Phase I: Mission completed

In 2013, Arctic2k reached a milestone by contributing a data collection and 2000-year long temperature reconstruction to the benchmark paper by the PAGES2k Consortium (2013). Since then, the Arctic2k temperature reconstruction has been revised based on updates and corrections to the dataset. The revisions result in more pronounced decadal-scale variability and in amplification of the pre-20$^{\text{th}}$ century cooling trend (McKay and Kaufman 2014). The dataset now also includes the geochronologic data for the sedimentary records and age models based on a uniform approach for all records.

Here we would like to thank Atte Korhola and Sami Hanhijärvi (Helsinki, Finland) for their leadership, data management and analysis during Phase I, as well Nalân Koç (Tromsø, Norway) for initiating Arctic2k back in 2008.

Phase II: Hydroclimate and temperature

Jostein Bakke and Anne Hormes, the co-authors of this article, were designated as the new co-leaders of Arctic2k. They are supported by the data managers and proxy-specific coordinators helping with the inclusion of new records. For activities beyond the data collection, points of contact were established for specific methods and regions (see Arctic2k website).

The goal for Phase II is to produce multi-proxy based spatial reconstructions for temperature, precipitation and humidity for comparison with the model output of PMIP3 simulations. The first step towards this goal is to expand the Arctic proxy data collection with precipitation and humidity records.

The following goals and timeline were defined:

- Arctic2k meeting in April 2015 at EGU in Vienna
- Final version of the T and P database by 2015
- Regional temperature field reconstructions in 2015
- Comparison of spatial sea ice and climate reconstructions in 2015
- Hydroclimate reconstructions in 2015-2016
- Atmospheric pressure field reconstructions in 2015-2016
- Forcing vs climate signal analysis in 2015-2016

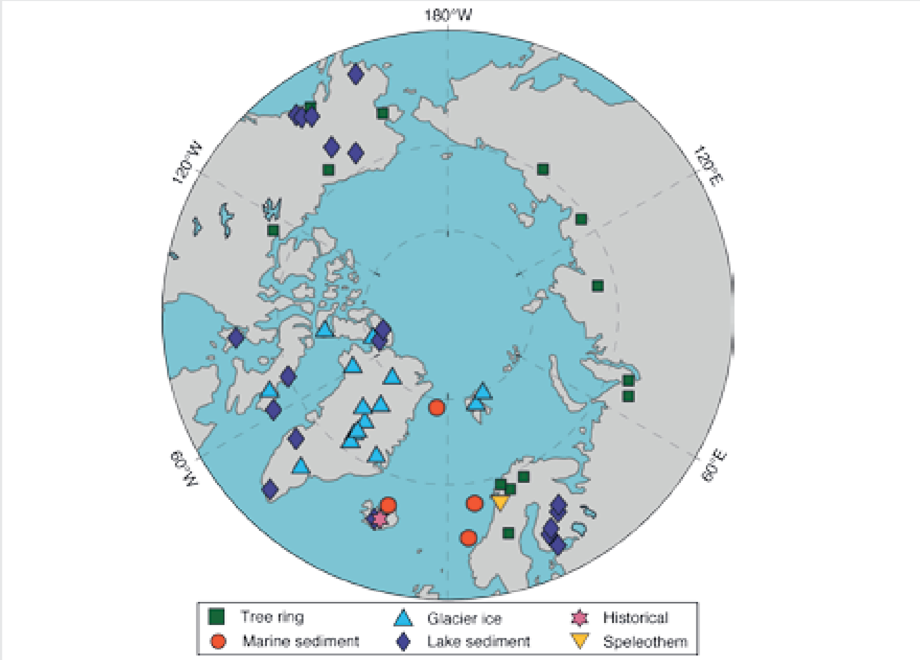

Figure 1: Map of the Arctic showing the location and type of temperature proxy records in the PAGES Arctic2k database. Modified from McKay and Kaufman (2014).

Three papers focusing on the following topics are in preparation:
1. Temperature field reconstruction using annually resolved records in the North-Atlantic region (J. Werner, M. Debret, H. Linderholm et al.).
2. Methods for hydro-climate reconstruction in the Arctic (A. Hormes, J. Bakke, W. d'Andrea, F. Lundqvist, J. Werner, H. Linderholm et al.).
3. Integration of marine and terrestrial paleoclimate records from the Svalbard-Barents Sea (E. Isaksson, D. Divine, K. Husum, J. Werner, M. Debret, A. Hormes, A. Miettinen et al.).

Please let us know if you would like to contribute to these publications or if you are planning additional papers using the Arctic2k database.

Arctic2k needs your input!

Temperature records currently in the Arctic2k database are shown in Figure 1. Some regions, such as the Russian or Canadian Arctic still yield few temperature records, while precipitation and humidity records still need to be collected for all regions. The task for the community of Arctic paleo-researchers over the coming months is therefore to complete the database with temperature or hydroclimate records fulfilling the following criteria:

- Demonstrated plausible mechanistic relation to climate
- At least one numerical age per 500-year interval
- At least one analysis every 200 years
- Must span at least 500 years during the past 2k
- Must be published in a peer-reviewed journal
- Must be made available once used for a PAGES2k publication

If you are aware of records that fulfill these criteria, please contact the Artic2k data managers Dmitri Divine or Johannes Werner. All new data will first be used internally by the PAGES 2k Network and be archived publicly once a product is published.

Finally, if you would like to participate in Arctic2k and contribute to our scientific objectives and publications, please contact us. You can also subscribe to the Arctic2k mailing list. Visit www.pages-igbp.org/workinggroups/arctic2k for more information. The updated Arctic2k database is available here: www.ncdc.noaa.gov/paleo/pages2k/pages-arctic-2k.html

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Millennial-scale climate variability in the American tropics and subtropics

Dunia H. Urrego[1,2], J.P. Bernal[3], C.M. Chiessi[4], F.W. Cruz[5], M.F. Sanchez-Goñi[2], M. Power[6], H. Hooghiemstra[7] and LaACER participants[8]

The Latin American Abrupt Climate Changes and Environmental Responses (LaACER) initiative aims to assess the geographical extent and climatic signature of millennial-scale climate variability in the American tropics and subtropics by combining atmospheric, vegetation and oceanic records, and model simulations.

Millennial-scale climate variability such as Dansgaard-Oeschger cycles (Dansgaard et al. 1993) and Heinrich Events (Heinrich 1988) are characterized by a rapid onset and a duration ranging between 200 and 2500 years (Wolff et al. 2010). Open questions relate to the expression of these events in the tropics, the oceanic and atmospheric mechanisms involved, and the interaction with other forcings (e.g. ice volume, greenhouse gases and insolation changes). Modeling these rapid changes in the tropics has proven difficult, partly because modeling targets and constraints from well-documented paleoenvironmental observations of vegetation, fire, precipitation, oceanic processes and biogeochemical cycles remain scarce. Understanding how tropical systems have been affected by, or may have triggered, rapid climate variability in the past is valuable, as the impacts recorded in natural archives might offer some insights into anthropogenic climate change.

Figure 1: Sampling sites and schematic representation of a Heinrich event. White spots depict iceberg discharge in the Ruddiman belt (Ruddiman 2001). Gray areas represent the boreal-winter configuration of the ITCZ and the SASM based on average January rainfall measured between 1998-2009 (NASA TRMM). Locations of records mentioned in the text are numbered as follows: **1.** Peten-Itza (Correa-Metrio et al. 2012; Escobar et al. 2012), **2.** Fúquene (Bogotá et al. 2011; Groot et al. 2011; Hooghiemstra 1984), **3.** Cariaco (González and Dupont 2009; Peterson et al. 2000), **4.** M772-059 (Mollier-Vogel et al. 2013), **5.** Junin (Hansen et al. 1994), **6.** Titicaca (Baker et al. 2001; Fritz et al. 2010; Paduano et al. 2003), **7.** Consuelo (Urrego et al. 2010), **8.** La Gaiba (Whitney et al. 2011), **9.** Lapa Sem Fim, and **10.** Paixão (Strikis et al., pers. comm.), **11.** Botuverá (Cruz et al. 2005), **12.** GeoB6211-2 (Chiessi et al. 2008, 2009), **13.** Chaplin (Mayle et al. 2000), **14.** Cueva del Diamante (Cheng et al. 2013), **15.** Santiago (Mosblech et al. 2012), **16.** GeoB 3104-1 (Arz et al. 1998).

The LaACER initiative

The INQUA International Focus Group, ACER (Abrupt Climate Changes and Environmental Responses), has promoted considerable advances in the understanding of millennial-scale climate variability and environmental responses. However, in its global synthesis, ACER also emphasized the scarcity of millennial-scale paleoclimatic records from the tropical regions (Harrison and Sanchez-Goñi 2010). The Latin American ACER (LaACER) project was conceived to fill this gap. LaACER sits within the Palaeoclimate Commission of INQUA, and has held two workshops to date, both co-supported by PAGES (www.ephe-paleoclimat.com/acer/LaACER.htm).

LaACER's main objective is to improve our understanding of millennial-scale climate variability by investigating its geographical extent and environmental signature in the American tropics and subtropics. Climate in these two regions is influenced by both the Pacific and Atlantic oceans, and by several atmospheric features including the Intertropical Convergence Zone (ITCZ), the North American Monsoon (NAM), the South American Summer Monsoon (SASM), and El Niño-Southern Oscillation (ENSO; Garreaud et al. 2009). The convergence of multiple climatic features in the focus region of LaACER makes it essential for our understanding of the whole climate system.

A consistent chronology

Understanding the signature of millennial-scale events requires a tight chronological framework that not only permits consistent identification of the events, but also the accurate determination of leads and lags. In their review paper, Sanchez-Goñi and Harrison (2010) define a Heinrich Stadial (HS) as the cold interval triggered by a Heinrich Event (HE). HEs are defined as the periods when large amounts of ice-rafted debris (IRD) were deposited in the Ruddiman belt, a region in the North Atlantic influenced by the Laurentide and Scandinavian ice-sheets (Fig. 1). In absence of the characteristic IRD layers, defining the timing of climate phases related to HEs in the American tropics and subtropics is challenging, but nevertheless critical for advancing our understanding of the processes underlying abrupt climate changes.

As an example, the various chronological approaches used to date the onset of HS1 in the LaACER region result in age discrepancies of up to 800 years. In marine records off the coast of Brazil (GeoB6211-2; Chiessi et al. 2008, 2009; Fig. 1) HS1 is correlated with the chronostratigraphy of HE1 in the North Atlantic (McManus et al. 2004), whereas in the eastern Equatorial Pacific (M772-059; Mollier-Vogel et al. 2013) HS1 is tied to Iberian Peninsula records (Bard et al. 2000). Pollen records are correlated with the

HS chronozones as defined in Sanchez-Goñi and Harrison (2010), others with the interstadials of the North Greenland Ice Core Project or from the Iberian Margin (Martrat et al. 2007). Finally, speleothem records are U-Th dated, but the HS are identified via abrupt stratigraphic changes in the $\delta^{18}O$ record (Botuverá, Cruz et al. 2005; Santiago, Mosblech et al. 2012; Fig. 1).

Speleothem records show clear abrupt $\delta^{18}O$ stratigraphic changes that coincide, within age uncertainty, with the timing of radiocarbon-dated Heinrich layers from the Ruddiman belt. These changes can be directly dated with U/Th, avoiding radiocarbon calibration uncertainties and reservoir corrections. Outside the Ruddiman belt, and specifically in the tropics, the timing of abrupt stratigraphic changes in speleothem records can probably provide the most accurate ages for HS. However, it is important to note that ages derived from speleothem records cannot provide a direct age for HE, as the definition of these climatic events is based on the identification of IRD layers in marine records from the Ruddiman belt. Additionally, assuming synchronicity between high and low latitude records invalidates any analysis of leads and lags.

State of the art

The LaACER workshops have highlighted well-documented climatic intervals in the American tropics and subtropics, available terrestrial and marine records, and spatial and temporal priorities for future research. The importance of high-resolution records has been illustrated through the development of new speleothem and pollen records that provide some of the best paleoclimate archives from the region. These records reach back to Marine Isotope Stage (MIS) 5 in Botuverá, MIS7 in Lake Fúquene, and MIS8 in the Cueva del Diamante (Fig. 1). Modeling efforts have focused on transient climate simulations and data-model comparisons (Groot et al. 2011; Nace et al. in press). Available paleovegetation records with decadal to centennial resolution are concentrated in the Northern Hemisphere (e.g. Fúquene, Peten Itza, Cariaco). In the Southern Hemisphere, paleovegetation records have centennial to millennial resolution (e.g. Junin), and only a handful reach back to MIS 3 (e.g. Consuelo, Titicaca, Chaplin, La Gaiba).

The structure of millennial-scale events in the American tropics and subtropics is one of the main foci of LaACER for the coming years (Fig. 2). A multi-phased structure of HSs in the region is becoming apparent from available records. HS1 in particular has been the focus of paleoceanographic research in the Atlantic (Chiessi et al. 2008) and the Pacific (Mollier-Vogel et al. 2013), and was studied in a series of yet-to-be-published speleothem records from the Lapa Sem Fim and Paixão caves in eastern Brazil (Fig. 1). Overall, records consistently indicate reduced precipitation in the northern American tropics and enhanced precipitation in the southern American tropics during HSs, with two sub-events identified mostly in eastern Brazil (Fig. 2). High-resolution speleothem records from Brazil also reveal two discrete peaks in monsoon activity forming a "double-plunge" structure during the 8.2-ka event (Cheng et al. 2009).

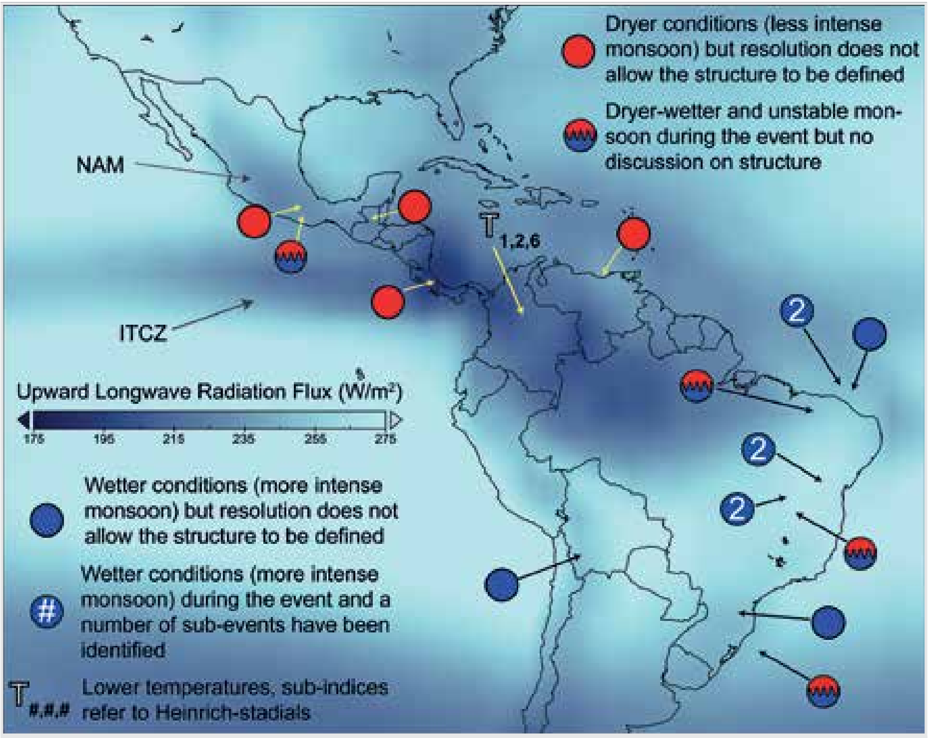

Figure 2: Average outgoing long-wave radiation for the period 1950-2008 (May-November) for the American tropics and subtropics as an indicator for convective activity (NCEP Reanalysis) showing the average position of the ITCZ and the NAM. Circles indicate the structure and signature of millennial-scale North Atlantic cooling stadials at different sites.

Ways forward

To gain an improved understanding of millennial-scale events in the American tropics and subtropics, LaACER has identified the following research priorities.

- Modeling efforts should prioritize transient and snapshot simulations not only of ocean and atmospheric processes, but also integrate changes in vegetation and fire activity.
- More data-model comparisons will help disentangle the physical processes driving millennial-scale climate variability.
- High-resolution records of vegetation change and fire activity are needed to discern abrupt shifts in environmental conditions.
- The lack of independent proxy records from sedimentary archives for which pollen sequences already exist has been recognized as a limitation, and future work should focus on the generation and integration of such records.
- Existing marine records could possibly be used to extend the sea surface temperature evolution of the Brazil Current beyond HS1.
- New marine records could help characterize the North Brazil Current and its direction during other HSs.
- Marine records with well-preserved terrestrial markers could allow us to directly relate continental and marine changes without chronological ambiguity.
- Future work should also aim to understand ENSO dynamics during HS in the eastern tropical Pacific.
- A priority in the area of atmospheric research is to extend the spatial coverage of paleoclimate data with new high-resolution records that can reveal the dynamics of NAM and SASM.
- Finally, combining speleothem records with vegetation and fire records will reveal more about the dynamics of the ITCZ, NAM and SASM, and enable us to identify the environmental consequences of millennial-scale variability.

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Ice Core Young Scientists

Pascal Bohleber[1], M. Cavitte[2], B. Koffman[3], B. Markle[4], P. Pavlova[5], M. Winstrup[4] and H. Winton[6]

Following the International Partnerships in Ice Core Sciences (IPICS) 2012 conference in Giens, France, a small group of passionate early-career ice core researchers from Australia, Europe and the United States joined to form Ice Core Young Scientists (ICYS).

ICYS is intended to be an informal, international network of early-career scientists dedicated to the study of polar and alpine ice cores and ice core-related sciences. Our purpose is to foster personal connections among young scientists from around the world, in order to build a supportive ice core science community and to inspire future collaborations.

We are entirely self-organized and have been meeting on a regular basis since Giens to prepare for embracing new members to extend the network. One of our key tools is our LinkedIn page, an online environment where members can connect and exchange scientific ideas or advertise upcoming meetings. We also have an ICYS webpage on the PAGES website and a Facebook group.

Some informal networking events have taken place at recent conferences. The first was held during the 2013 AGU Fall Meeting where we organized an ice core dinner. Similar events took place during the recent SCAR Open Sciences conference in August and EGU General Assembly in April 2014 and were highly successful, with a turnout of more than 30 ice-core scientists of all ages.

In light of these successes, ICYS will continue organizing social events to facilitate networking among young ice core scientists, making them a regular tradition at future EGU and AGU annual meetings as well as at a number of other international conferences. We are also envisioning a series of early-career scientist workshops.

We are planning ICYS early-career events at AGU Fall Meeting (San Francisco, USA, 15-19 December 2014) and EGU General Assembly (Vienna, Austria, 12-17 April 2015). These will be great opportunities to meet fellow ice core young scientists from around the world. Stay tuned for details of these events.

Figure 1: Lana Cohen (Victoria University of Wellington, New Zealand) examining storm layers in a snow pit on Roosevelt Island, Antarctica, 2010. Photo by Bradley Markle.

We are aiming to build an online community for young ice core scientists to share ideas, ask questions, and collaborate with each other across the globe - a resource we all can share - so we encourage you to join us on LinkedIn and Facebook and subscribe to our email list by writing to: icecoreys@gmail.com.

Website: www.pages-igbp.org/icys

LinkedIn: www.linkedin.com/groups?home=&gid=5053409&trk=anet_ug_hm

Facebook: https://www.facebook.com/groups/751731074891138/?fref=ts

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Past sea ice reconstruction - proxy data and modeling

Rainer Gersonde[1], A. de Vernal[2] and E. W. Wolff[3]

3rd Sea Ice Proxies (SIP) Working Group workshop – Bremerhaven, Germany 23-25 July 2014

The distinct contrast between recent trends in Arctic and Antarctic sea ice calls for sea ice records extending beyond instrumental observations. Such estimates must rely on well-established sea ice proxy data obtained from marine, ice core and coastal materials and should ideally be supported by sea ice modeling.

A primary goal of the PAGES Sea Ice Proxies (SIP) Working Group is to critically assess different sea ice proxies. This issue was central to the first SIP workshop in 2012 and resulted in the publication of 18 papers. Further proxy development, comparisons and applications in time-series and time-slice reconstructions were stimulated and discussed at the second SIP workshop in 2013.

The third workshop focused on sea ice data syntheses, sea ice modeling and proxy-data/model comparisons. In addition, recent progress in proxy development was presented, such as a new proxy using crustose coralline algae to extend the instrumental observations of Arctic sea ice at annual resolution (Halfar et al. 2013). Recent identification of the source of the biomarker IP_{25} makes it a more powerful proxy for Arctic sea ice (Brown et al. 2014). Antarctic sea ice estimates are primarily based on diatom records (e.g. Esper and Gersonde 2014) because the establishment of biomarkers as robust proxies for Antarctic sea ice still requires more study. Strong efforts to better understand aerosols (sea salt, halogens, methanesulfonic acid) and their production mechanisms, transport and deposition have enhanced their applicability as sea ice proxies in ice cores (e.g. Levine et al. 2014). While the limitations, strengths and significance of individual proxies can be tested through proxy intercomparison (Fig. 1), a deeper understanding requires more joint projects between paleoclimatologists, and biologists and physicists studying modern sea ice processes. Additionally, the development of new proxies (e.g. DNA-based identification of foraminifers living in sea ice) should be intensified.

Arctic sea ice development in the Holocene at 2000 year time slices was presented. Time-series studies from different sectors of the northern polar realm since the last glacial document the complex pattern of sea ice variability, and allow us to better evaluate sea ice/climate feedbacks during the last glacial-interglacial transition. Similar data, but at lower resolution, were also presented from the Pacific and Atlantic sectors of the Southern Ocean. This provides a picture of bipolar sea ice variability under natural conditions giving a context for modern changes. Antarctic sea ice data have also been developed for the penultimate glacial-interglacial transition and the last interglacial, which may represent conditions that could develop in a future warmer-climate state.

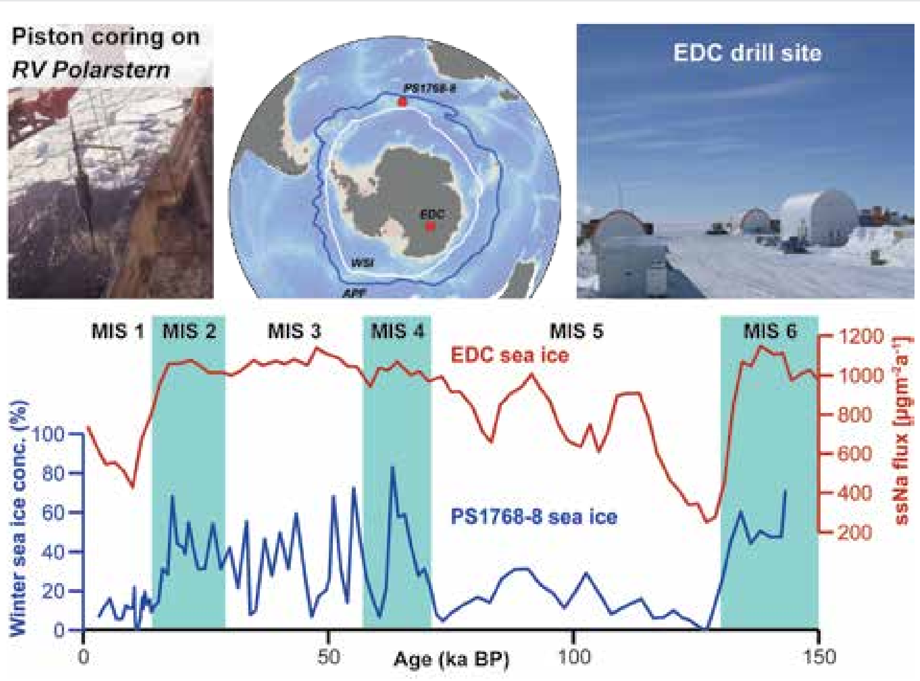

Figure 1: Comparison of marine (PS1768-8) and ice core (EDC) records documenting Antarctic sea ice variability during the last climate cycle. In the middle top panel, the location of the EDC and the marine core are presented relative to the modern average winter sea ice extent (WSI, at 40% concentration) and the Antarctic Polar Front (APF). The records show concurring sea ice minima during the Marine Isotope Stages (MIS) 5 and 1, and similar sea ice retreat during the glacial/interglacial transitions. The marine record displays strong variability during MIS 2-4, while the ice core record shows a more stable signal. Data from Esper and Gersonde 2014 and Wolff et al. 2006.

The participants concluded that robust sea ice estimates with large spatial coverage under a broad range of climate conditions should rely on a combination of different proxies according to their specific applicability. Model-data comparisons perform best when there is an abundance of data for assimilation. Data gaps in spatial and seasonal information may be bridged by sea ice modeling. However, such modeling needs further improvement as there remain uncertainties possibly related to sea ice parameterization and applied boundary conditions. The development of bipolar sea ice syntheses for the last two glacial-interglacial transitions and subsequent interglacials presents a crucial step towards improved integration of sea ice as a polar amplification and feedback factor, which is important for more robust projections of future conditions. SIP3 encourages the increased integration and comparison of data and modeling results to improve future paleoclimate research. Although this was the last PAGES-sponsored SIP meeting, SIP intends to continue with sessions at major meetings (e.g. as scheduled at AGU Fall 2014 and INQUA 2015) and through mailings between the participants. To join the SIP mailing list, visit https://listserv.unibe.ch/mailman/listinfo/seaice.pages

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PAGES2k: Advances in climate field reconstructions

Kevin J Anchukaitis[1] and Nicholas McKay[2]

Woods Hole, United States, 15-16 April 2014

A major outcome of the PAGES2k synthesis was the creation of continental-scale reconstructions of mean regional temperatures that span the last millennium or more (PAGES 2k Consortium 2013). Four of the PAGES 2k regions (Asia, Europe, North and South America) also reconstructed spatial variability in temperatures using approaches that fall within a class of methodologies called climate field reconstruction (CFR; Evans 2001). CFR consists of a set of statistical tools that can be used to estimate past climate variability on a regular grid, typically using networks of annual-resolution paleoclimate proxies. They exist on a continuum from simple reconstructions of a single leading spatiotemporal mode (analogous to a weighted mean reconstruction) to more complex methods including hierarchical models that incorporate knowledge of the proxy systems and climate covariance (Tingley and Huybers 2010; Steiger et al. 2014). These reconstructions are desirable as they allow climate variability to be estimated in both space and time, providing targets for general circulation model comparisons and knowledge about the fingerprint of regional-scale climate variability in response to radiative forcing and internal climate system variability.

The PAGES2k proxy dataset provides specific challenges for CFR. The data are highly heterogeneous in space and time, they are known to contain a range of frequency-dependent, seasonal, multivariate climate signals, and include proxy archives that are lower resolution and time-uncertain. During the Phase I synthesis of the PAGES2k project, we identified three primary methodological challenges to developing field reconstructions across all the regional networks. These included (1) the need to develop unbiased approaches to the selection of proxy data from a large database of potential predictors, (2) the incorporation of non-annual and time-uncertain records in climate reconstructions (e.g. Anchukaitis and Tierney 2012), and (3) the complications presented by the PAGES2k Phase II goal to reconstruct hydroclimate, specifically with respect to seasonality and spatial covariance.

The PAGES2k Advances in Climate Field Reconstruction workshop brought together paleoclimatologists from across the 2k Network with experts on reconstruction methods to explore these questions and to work toward developing new techniques that address extant challenges. The workshop included a thorough overview from proxy domain experts on the spatial, temporal, and spectral characteristics of different proxy systems, including sources of uncertainty and bias. Existing CFR methods were reviewed in light of their ability to be adapted specifically to the PAGES2k network. A major feature of the workshop was the initiation of a reconstruction methods intercomparison exercise. Using the Arctic 2k data (McKay and Kaufman 2014), researchers representing different CFR approaches were given the actual proxy data as well as a set of pseudoproxies (Smerdon 2012) designed to mimic the spatial, temporal, seasonal, and chronological characteristics of the real network. The goal was to observe differences in estimates of past climate variability as a function of reconstruction method and to provide a testbed for evaluating their origin. Initial efforts exposed practical challenges posed by the sparseness of the network, the signal-to-noise signature of the proxies, and time-uncertainty. These also provided information about the design of more realistic pseudoproxy experiments (e.g. Fig 1). The goal of creating a global reconstruction using the PAGES2k database was also explored.

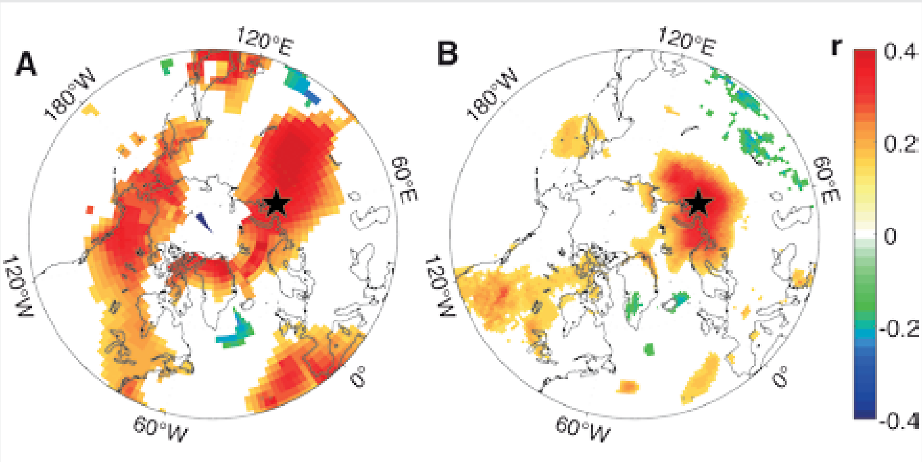

Figure 1: Correlation between March-August mean temperatures and **(A)** simulated pseudoproxy and **(B)** actual tree-ring chronologies from the Yamal Peninsula (Briffa et al. 2008; McKay and Kaufman 2014). The pseudoproxy series was created using simulated temperatures from the last millennium NCAR CCSM4 simulation with additional Gaussian noise to mimic the signal-to-noise ratio of the actual chronology. Correlations for the pseudoproxy series are with the corresponding CCSM4 mean surface temperature field, while the actual Yamal chronology is correlated against the GISTEMP (Hansen et al. 2010) combined land-sea temperature field. The star indicates the location of the chronology.

The workshop developed several concrete goals and recommendations, including: continued development of database structures that allow for expert and community assessment to facilitate open discussion of proxy strengths, weaknesses, biases, selection, and fidelity, a prerequisite for future regional and global reconstructions; continued and expanded development of proxy system models (Evans et al. 2013) for capturing the multivariate, nonlinear, and seasonal aspects of different proxies; incorporation of explicit hierarchical modeling of chronological uncertainty within CFR techniques; and exploration of CFR approaches that transparently integrate scientific knowledge of the proxies and climate systems within the statistical modeling framework (Tingley et al. 2012). Based on initial efforts toward a methods intercomparison, the group has designed a new series of experiments to isolate the influence of model specification, climate signal, network distribution, and time uncertainty. Methods development and testing with respect to incorporating time uncertainty within hierarchical models is ongoing, and a community effort to develop an improved database and a global-scale reconstruction is proceeding.

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Understanding and reconstructing the Asian climate of the last 2000 years

Quansheng Ge[1], Z. Hao[1], X. Shao[1], H. Borgaonkar[2], J. Luterbacher[3], T. Nakatsuka[4], M. Sano[4], O. Solomina[5] and L. Zhou[6]

3rd Asia2k workshop, Beijing, China, 26-27 May 2014

This workshop constituted the starting point for Phase II of Asia2k and was attended by 40 participants from 11 countries. They reviewed a variety of proxy records from Asia, coordinated the setup of a database following the selection criteria of the 2k Network, and agreed on a timeline towards the production and publication of regional spatial reconstructions of temperature and precipitation covering the past 2000 years.

Presentations addressed reconstruction methodologies, paleoclimate modeling, and paleoclimatic records from Asia based on historical documents and natural proxies. New, yet unpublished studies were presented. These included an extreme events record from historical documents, a tree-ring based temperature and drought reconstructions covering the past 2000 years from the Tien-Shan and Altay Mountains, a 2000-year long varved sediment record from northeastern China, a relative humidity variation record for the southwestern Gobi Desert reconstructed from oxygen isotopes in Qinghai spruce, and a two millennia long tree-ring cellulose oxygen isotope chronology from Japan. In addition, 500 year long tree-ring based precipitation records from the Nepal Himalayas, Northwestern Thailand and Pakistan were discussed. All these new proxy records are important contributions to the Asia2k database, especially since the Phase I database only included a limited number of records, all of which are tree ring series (Fig. 1).

To focus the discussions on the upcoming key tasks and plan the next specific steps of the Asia2k project, the participants broke out into three groups. Two groups focused on inventories of paleoclimatic records at high and low-resolution, respectively. Their aim was to develop strategies for compiling published (or soon to be published) proxy records of (sub-)annual to multi-decadal-resolution and their associated metadata from different paleoclimate archives. A third group focused on statistical reconstruction methods and ways forward to arrive at regional-scale spatially explicit reconstructions of temperature and precipitation variations.

In both data-related breakout groups participants agreed to contribute their data when published in papers, encouraged their colleagues to also contribute their datasets, and planned to extract other data from the existing literature. A coordinated publication, such as a special issue, was encouraged to support swift publication of yet unpublished data. The data submission process via the template downloadable from the 2k website was found suitable. When reviewing the submission criteria, the high-resolution group expressed concern that a required minimum record length of 500 years would exclude too many good records. Accordingly, the 2k Network has in the meantime relaxed the criteria for annually-resolved records to a minimum length of 300 years. The low-resolution group on the other hand expressed concern that one date per 500 years would be a too strict criterion. In response, a more flexible definition for required chronological accuracy has been developed. The high-resolution group identified multi-decadal scale variability and extreme climatic events as the main scientific topics. In the low-resolution group the scientific topics of interest included multi-decadal to multi-centennial climatic changes such as of the meridional temperature gradient and of the treeline position.

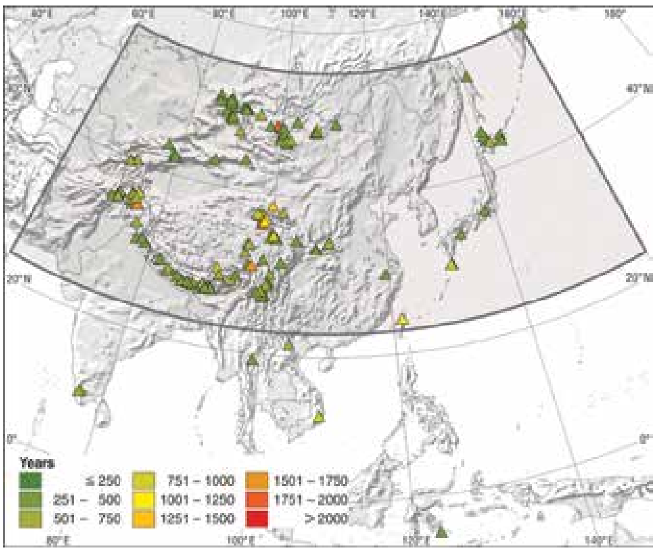

Figure 1: Phase I database of the Asia 2k group as published in the PAGES 2k Consortium paper (2013). A major task for the group is to add many of the available non-tree ring records to the database.

The reconstruction group agreed to try different reconstruction methods, including downscaling from global reconstructions, and to compare the output with each other. The aim is to start with temperatures first, but not only for annual averages but also for seasonal temperatures. Experts agreed that a full spatial reconstruction of precipitation changes is unlikely to be achieved. Following the suggestion by the 2k Consortium (PAGES 2k Consortium 2014), the generation of independent reconstructions at high and low resolution will be considered, and Asia sub-divided into climatic regions if a full scale spatial reconstruction is not possible due to the lack of sufficient proxy records. Monsoon variability was identified as the scientific question of prime interest that could be addressed with the reconstructions.

The participants also discussed the new group and leadership structure. A steering committee of nine task leaders (the authors of this article) chaired by Quansheng Ge was established. Committee members include representatives of the four biggest countries, data management, and reconstruction methods.

The next step of the Asia2k group is to update the temperature dataset by the end of the year 2014 and to apply a range of reconstruction methods to them. In parallel, the group will start compiling hydroclimatic proxy records. The fourth Asia 2k workshop will be held in Japan in March 2015 with the goal being to compare and review the first-order reconstructions and finalize the data compilation.

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A novel multiproxy approach: The PAGES North America 2k working group

Nicholas McKay

Fort Collins, USA, 23-26 June 2014

The North America 2k (NAM2k) Working Group recently met at the USGS Powell Center to begin Phase 2 of the NAM2k project in earnest. Phase 2 aims to build on the success of the first phase by expanding the scope of the project, both by including a more diverse and comprehensive array of paleoclimatic evidence for the past two millennia in North America, and by analyzing additional indicators and reconstructions of parameters beyond surface temperature, most notably, hydroclimate. Twenty working group members with expertise in tree rings, lake and marine sediments, corals, speleothems, boreholes, ice cores, glacial landforms, and climate modeling participated in the meeting.

The group reviewed the initial collection of data, and discussed best practices for extracting and combining paleoclimatic information from different natural archives, each with its own uncertainties and biases, and each with a different climate-signal filter. The group found that the initial PAGES 2k Phase 2 Data Selection Criteria were quite restrictive, and difficult or inappropriate to apply to some archives (e.g. boreholes and corals). Consequently, a more relaxed and nuanced approach was adopted. These criteria were reviewed by all PAGES 2k regional groups and have now been adopted network-wide (see: www.pages-igbp.org/workinggroups/2k-network/data).

The first and primary goal of the working group is to produce a clearly-formatted digital database of 2k-relevant proxy records for the continent that will facilitate a better understanding of climate variability in North America over the past 2,000 years. The deadline for assembling the next version of the database is the end of 2014. Subsequently, the group targeted three primary projects to be completed before the end of Phase 2 of the PAGES 2k project in 2016:

1) Subregional temperature reconstructions for North America

Based on the dominant airmasses, ecology, and the availability of proxy data throughout the continent, the group developed initial spatial targets for subcontinental temperature reconstructions (Fig. 1). Within each subregion, depending on data availability, we plan to produce (a) 2,000-yr-long multiproxy temperature index (time series) reconstructions, (b) 100-yr resolution pollen-based temperature reconstructions, and (c) borehole temperature reconstructions. These will be supplemented by a new tree-ring based temperature field reconstruction, which will utilize restandardized "signal free" tree-ring chronologies (Melvin and Briffa 2014).

2) Water isotope proxy synthesis

The group discussed how to take advantage of O and H isotopic composition observations in many archives. With interpretation based on generalized data models for each proxy system, archive and observation (Evans et al. 2013), the group will compile $\delta^{18}O$ and δD records from across North America. By comparing both data models and observations, we hope to facilitate comparison and synthesis across records and archives. Because stable isotopes in meteoric waters represent source differences, the temperature path history of air masses, and mixing and precipitation processes, we hope this compilation will support the study of past changes in hydrology and atmospheric circulation, and comparison with the output of isotope-enabled earth system models (e.g. Schmidt et al. 2014).

3) Multiproxy investigation of extreme droughts and pluvials

Gridded, tree-ring-based paleohydrologic reconstructions for North America are well developed (Cook et al. 2004 and updates), and full, multiproxy integration of disparate archives and paleohydrologic parameters into a single reconstruction is beyond the timeline of phase 2 of the NAM2k project. Consequently, the working group decided to focus on multiproxy comparison during periods of particular interest during the past 2k, for which diverse evidence for hydrologic extremes is available. When possible, the group will compare geomorphic evidence and event records (e.g. shorelines) with multiproxy hydrologic, temperature and isotope data, using simple models of hydroclimatic processes (e.g. Graham et al. 2007) to better constrain the timing, amplitude and cause of the changes during these intervals of particular relevance.

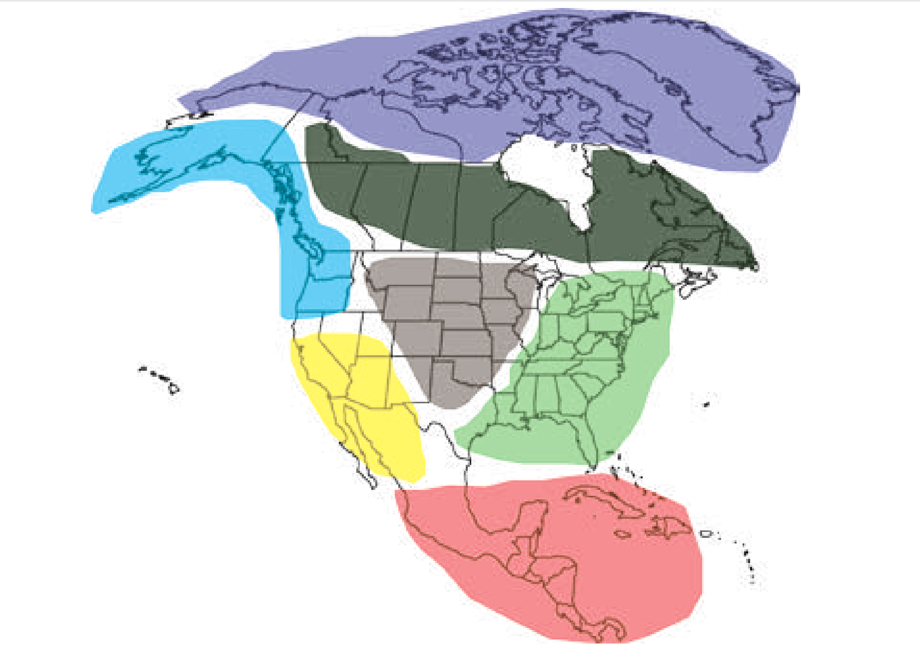

Figure 1: Preliminary delineation of sub-continental regions for multiproxy, pollen, and borehole temperature reconstructions. Regions will likely be adjusted to accommodate natural breaks in proxy data coverage.

The North America 2k working group is planning a brief gathering in San Francisco during the Fall Meeting of the American Geophysical Union this December. Anyone interested in contributing to the project is encouraged to join us. The time, date and location of the meeting will be distributed through the PAGES website. NAM2k is supported by both the USGS Powell Center and PAGES.

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Australasia's climate variability: clues drawn from paleoclimate and model data over the last 2000 years

Joëlle Gergis[1], P. Hope[2], N. Abram[3] and B. Henley[1]

3[rd] Aus2k workshop - 26-27 June 2014, Melbourne, Australia

The aim of the 3[rd] Aus2k workshop was to review progress made by the Aus2k community to date, and to specifically plan how Australasian science will contribute towards Phase 2 of the PAGES 2k Network. Around 40 paleoclimatologists, meteorologists, hydrologists, and oceanographers attended the workshop, resulting in a very constructive and stimulating cross-disciplinary meeting.

The Aus2k working group took the opportunity to hold the workshop jointly with the Australian Climate Change Science Program (ACCSP), and present the results of their joint paleoclimate data-climate model comparison project *Variability of Australian climate over the last 1000 years in coupled model simulations and proxy data*. The intention was to engage the wider meteorological community with expertise in climate data-model comparison and diagnostic analyses, and work towards the ultimate goal of understanding the mechanisms driving Australasian climate variability over the last 2000 years.

The specific goals of this workshop were to:

- Expand the Aus2k database to incorporate low-resolution material for the development of a common dataset for Australasian climate reconstructions;
  The database will be frozen on 31 December 2014. Contacts for data submissions or questions: Bronwyn Dixon, Jonathan Tyler and Ben Henley
- Develop guidelines for the future collection of climate proxy records based on spatial and temporal gaps in the Australasian paleoclimate record;
  Nerilie Abram will lead the testing of the number and location of records required to reconstruct specific features of Australian climate and to deal with potential biases caused by non-stationarities.
- Discuss existing multivariate data synthesis techniques being used by the Aus2k and global 2k communities. Discuss setting a post-meeting goal to run a comparison exercise using different reconstruction methods;
  An inter-comparison project with Australian and New Zealand data will be coordinated by Ben Henley, Mandy Freund and Andrew Lorrey.
- Assess the feasibility of developing Australasian climate field reconstructions (temperature, precipitation, and geopotential height) to contribute towards the global PAGES 2k Network;
  To be led by Joëlle Gergis, Andrew Lorrey and Steven Phipps.
- Foster linkages between the paleoclimate and climate modeling communities, with the aim of closing the loop between proxy development, data synthesis and climate modeling. Modeling contacts: Steven Phipps and Duncan Ackerley; Modern climate: Pandora Hope.

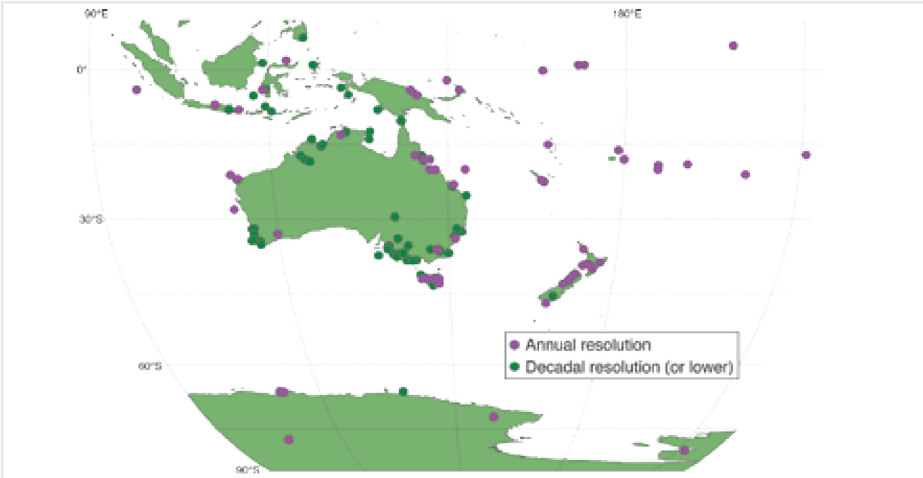

Figure 1: Locations of annually resolved and lower resolution paleoclimate archives in the Australasian region.

Day one of the workshop showcased recent research developments in regional data synthesis; opportunities for collecting new paleoclimate records from the region in the future; reconstructions of climate drivers such as El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM); and climate modeling being undertaken in Australia and internationally.

A range of projects including paleoclimate runs with CAWCR's ACCESS model; testing the assumption of teleconnection stationarity; and pseudo-proxy exercises to test the fidelity of paleoclimate reconstructions were discussed and collaborative contacts made.

Day two focused on i) developing the database of Australasian low-resolution records, including data consolidation and directions for future data collection; ii) multi-archive data synthesis techniques being used by Aus2k and the PAGES 2k Network, and iii) climate field reconstructions and climate modeling.

It was agreed that the Australasian region's "low resolution" database for Phase 2 would be frozen on 31 December 2014 to allow for consistency in subsequent climate analyses undertaken by the group. It was agreed that reconstructions based on records with higher time uncertainty should form an independent way to verify low frequency trends and variability identified from the more chronologically precise high-resolution material. Figure 1 shows the current spatial distribution of these two datasets.

The final discussion focused on developing a temperature field reconstruction for Australia within the Phase 2 timeframe of the PAGES 2k project. Climate modeling and data assimilation might assist with this. The workshop wrapped up by developing sub-groups based around the five workshop objectives (as listed above) and a clear forward direction that will help deliver Australasia's best available science in Phase 2 of PAGES' 2k Network project.

The next Aus2k workshop will be held in Auckland, New Zealand in the austral spring of 2015.

A longer version of this workshop report is available online at www.pages-igbp.org/calendar/2014/127-pages/1198-accsp-aus2k-wshop

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Paleovariability: Data Model Comparisons

Chris Brierley[1] and Kira Rehfeld[2]

London, UK, 12-14 March 2014

Past global changes provide a useful test for evaluating climate models. With modeling efforts increasingly focused on decadal predictions and climate services, there is a growing need to evaluate simulated climate variability. Past climates offer some opportunity for this, but require a slightly different approach than those currently adopted to look at mean changes. University College London's Geography department hosted a three-day workshop to explore the issues associated with paleoclimate variability.

In some respects, this workshop emerged in response to the problems discovered during a previous PAGES-supported workshop focused on the El Niño-Southern Oscillation (ENSO; Braconnot et al. 2012). Coming out of this workshop, two requirements were identified as pivotal to model evaluation using PaleoENSO: (i) a more integrated approach across regions and disciplines, and (ii) the development of statistical and analytical tools to enable that intercomparison.

A special issue of *PAGES news* dedicated to ENSO highlighted recent advances across the ENSO regions and disciplines with the aim of kick-starting this more integrated approach (Braconnot et al. 2013). It was recognized that a dedicated activity is required to effectively tackle the two requirements – which are relevant for all modes of climate variability, rather than just ENSO.

In response, a working group on variability was established under the auspices of the Paleoclimate Modelling Intercomparison Project (PMIP3); this workshop was its first meeting. The focus of this meeting was on variability on inter-annual to multi-decadal timescales, in part because on longer timescales models appear to underestimate variability (Laepple and Huybers 2014). It was established that variability comparisons suffer additional difficulties compared with conventional analyses for the mean state.

Indeed, intermediate processing is often required between the models and data, which is its own field of expertise. Some of this intermediate processing relates to forward proxy modeling, represented at the workshop by efforts to model lake isotopic systems (Jones and Imbers 2010). The rest relates to how proxy properties impact a record's statistics – for example looking at the impact of sampling individual forams (Thirumalai et al. 2013) or seasonal biases (Laepple and Huybers 2013).

One conclusion was an appreciation that additional meta-data is often required to use a proxy-climate record for variability data model comparisons. This additional information is needed to understand how the individual measurements relate to each other. This becomes much more important for studies of paleoclimate variability than when looking at mean changes, as illustrated with the example of London annual temperatures (Fig. 1). We urge people to consider the following three questions when publishing a proxy record:

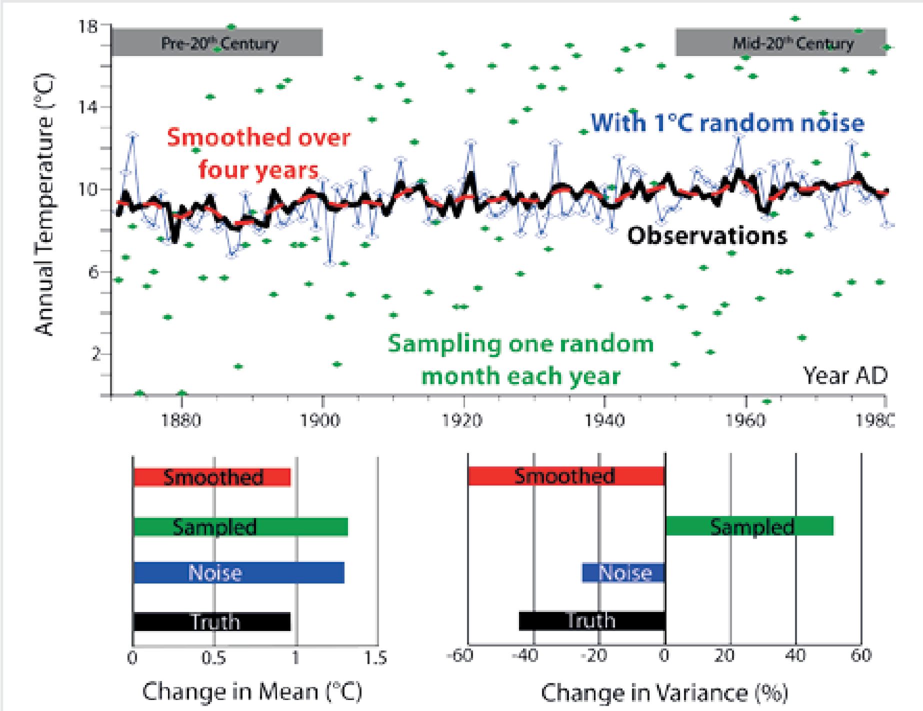

Figure 1: Annual temperatures measured at Kew Gardens, London (Peterson and Vose 1997) as an example of the three potential factors' impacting climate variability. Neither adding random noise (e.g. instrumental error), nor smoothing (e.g. bioturbation), nor snapshot-type sampling (e.g. individual organisms that only live for a single random month) substantially alters the roughly 1°C of warming; however, the normalized estimates of variability differ in both magnitude and even sign.

- To what extent are your stated errors random?
- Does each sample represent a time-average or a snapshot?
- Is the effective temporal resolution lower than the sampling resolution (e.g. through bioturbation or residence times prior to sedimentation)?

Practically speaking, for large proxy syntheses it is important that age modeling and calibration are replicable. This requires access to the proxy dataset (including depths, proxy measurements and sample size), the age modeling information (i.e. age estimates and errors with their depths), and the calibration information, as well as knowledge of the sampling strategy and proxy processes.

In summary, to obtain reliable and comparable estimates of past climatic variability, we must correct for the additional processes affecting proxy variability. This is not an easy task: it requires input from several disciplines, but has the potential to be much more relevant for the coming decades than studies of mean climate alone.

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Third general meeting of PMIP3

Michel Crucifix[1], E. Zorita[2] and J.-Y. Peterschmitt[3]

Namur, Belgium, 25-30 May 2014

This workshop, which gathered 108 delegates, was the twelfth event of the Paleoclimate Modelling Intercomparison Project (PMIP) in a series initiated in 1995 in Collonges-la-Rouge, France. Each of the successive meetings has marked a development in the PMIP project: towards more comprehensive Earth System models, a broader range of past periods, high-standard dataset documentation, state-of-the-art approaches of model-data synthesis, and, more recently, the introduction of transient experiments (last millennium and deglaciation) and methods of data assimilation. Now in its third phase, PMIP's mission is to model and reconstruct past climates and understand the implications of this research for future climate. It has become an important contributor to our understanding of Earth's climate dynamics and sensitivity.

The workshop started with a review of database technology and the current upload status of PMIP3 experiments (https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:database:status). The PMIP3 database is now fully integrated within the Climate Modelling Intercomparison Project system (http://esgf-node.ipsl.fr/) and synthesis maps are available. To complement reports from PMIP participating groups, guests from the data and modeling community were invited to deliver talks and contribute to discussions in order to provide an outsider view on PMIP's achievements and perspectives: Eelco Rohling (Australian National University), Simon Tett (University of Edinburgh), Steve Sherwood (University of New South Wales, Australia) and James Zachos (University of California Santa Cruz).

The Namur meeting made it clear that better cooperation and knowledge exchange between researchers working on proxy records and paleo modeling is essential, be it to estimate variability indices throughout the last millennium, estimate the Last Glacial Maximum temperature, or reconstruct Pliocene, Eocene, or even Devonian climates (Fig. 1). There is no magic recipe that would simultaneously provide unbiased reconstructions of past climates, reveal model deficiencies and identify anomalous observations. Effective approach will rely on an ensemble of methods, including advanced physical and biogeochemical modeling, creative visualization diagnostics, careful analysis of observations, innovative experiment design, and technical statistical inference approaches.

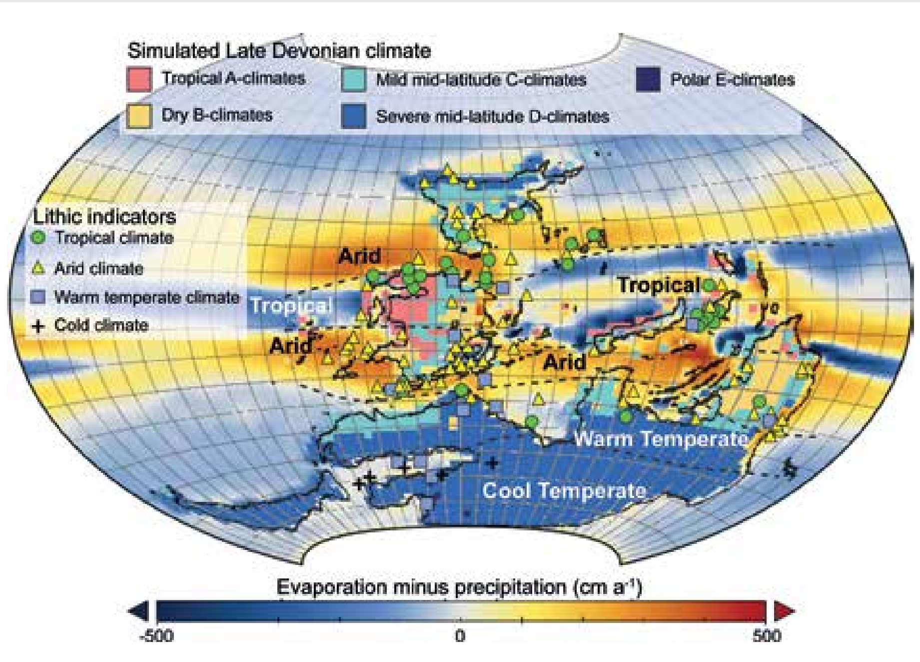

Figure 1: Data-Model comparison for a "median orbit" Late Devonian simulation. The HadSM3 slab model simulated climate types and evaporation minus precipitation data are compared to lithic indicators of paleoclimate (PALEOMAP project; Scotese and Barrett 1990). Modified from De Vleeschouwer et al. 2014.

The breadth of presentations delivered during the meeting reflected many aspects of this strategy: some focused on well-identified climate phenomena such as the Walker Pacific circulation during the Last Glacial Maximum occurring in the different models; others featured technical advances within a single model (e.g. modeling of oxygen and carbon isotopes), or introduced sophisticated statistical techniques of meta-modeling to simplify and summarize process-based model outputs. An entire session was also devoted to transient experiments.

The range of scientific challenges to be addressed within PMIP keeps expanding; there are now 13 PMIP working groups. Some are defined along time periods, others along crosscutting themes, such as "variability" or "Past2Future". This structure will be maintained, keeping in mind that working groups are efficient and flexible structures that may merge or evolve as the community recognizes significant progress or feels the need to re-focus its research priorities.

ACKNOWLEDGEMENTS

The meeting was supported by PAGES, the WCRP, the Universities of Louvain, of Gent and of Namur, the Province de Namur, the Belgian National Fund for Scientific Research, the European Research Council, the Leverhulme Trust, HP and Intel. The program and abstracts are available at http://www.climate.be/pmip3, and info on PMIP at http://pmip3.lsce.ipsl.fr.

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Age models, chronologies, and databases workshop

Eric C. Grimm[1], M. Blaauw[2], C.E. Buck[3] and J.W. Williams[4]

Belfast, UK, 13-16 January 2014

Paleo databases are critical cyberinfrastructure for paleoenvironmental research, especially for broad scale synoptic studies that place current environmental and climatic changes in context. Chronological control is critical for paleo studies, and chronologies and age models are essential metadata for paleo databases. Paleo databases typically comprise a large number of individual datasets acquired over a long time period. A major challenge for database managers and users is that criteria for estimating chronologies change through time rendering existing chronologies obsolete. In particular, chronologies based on calibrated radiocarbon ages become obsolete with each revision of the calibration curve, regardless of the sophistication of the age modeling technique. In addition, age modeling software has also evolved over the years. New programs, often using Bayesian techniques (Fig. 1), can now provide estimates of the uncertainties for interpolated sample ages. Most age models currently archived do not provide these uncertainties, which are nevertheless critical for assessing the statistical robustness of synchronous change across multiple sites and datasets.

To address these issues, 35 scientists from 12 countries met at the Queen's University Belfast ^{14}CHRONO Centre for a three-day workshop, which was followed by a one-day software training session attended by an additional eight participants focusing on the *clam* (Blaauw 2010) and *Bacon* (Blaauw and Christen 2011) age modeling programs. Initially, the Neotoma Paleoecology Database (www.neotomadb.org) had funding to support a small workshop of its Age Modeling Working Group. Additional funding from PAGES and the US National Science Foundation made it possible to also invite students and scientists involved with other database projects.

During the first day of the workshop, speakers discussed how various databases handle age modeling and chronology issues, calibration of radiocarbon dates, age modeling software, and database interoperability. During the following two days, breakout groups addressed the following topics: (1) Age models based on radiocarbon dating: problems caused by updates to the calibration curve; (2) Age models based on radiocarbon dating: strategies for regenerating chronologies from stored chronological data and age-model metadata; (3) Age models beyond the radiocarbon time scale; (4) Strategies for reducing the need for ad hoc age models; (5) Rankings of the quality and accuracy of dates and chronologies; and (6) Linking databases, calibration programs, and age modeling programs.

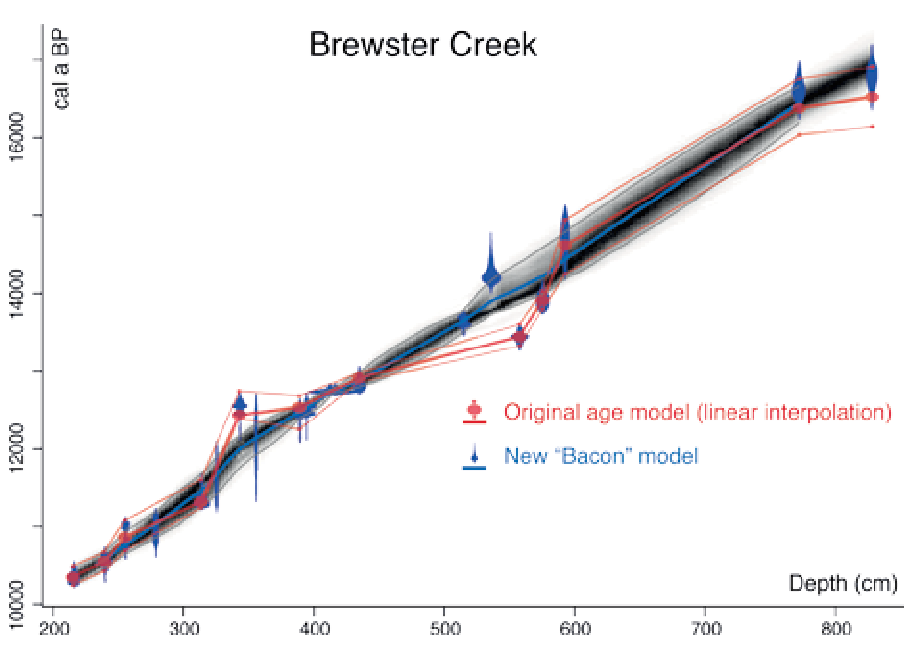

Figure 1: New Bayesian age model for the Brewster Creek (USA) site produced by the *Bacon* program (Blaauw and Christen 2011) overlaid with the published classical model (Curry et al 2007). The original model is based on the IntCal04 calibration curve, linear interpolation, and ad hoc rejection of reversed dates; while the Bacon model is based on the IntCal13 curve and can accommodate reversed dates. The gray-scale shading represents the relative probability within the 95% higher posterior density region (or Bayesian confidence interval). The thick red line is the linear interpolation between the median probabilities of the calibrated ages in the original model; the thin red lines connect the 95% confidence limits of the calibrated ages but are not a valid statistical representation of the confidence limits of the interpolated ages.

The summarized workshop recommendations* are: (1) Chronologies reported in the literature and stored in databases must be reproducible, and publications and databases should store sufficient data and metadata to ensure reproducibility. (2) The output from age modeling software should provide all the information necessary to reproduce age models in easily storable scripts or "age model definition" files, and a common metadata standard should be developed for these files. (3) Databases should archive originally published chronologies; however, database managers cannot be expected to reconstruct chronologies unless sufficient data and metadata are published or otherwise provided to them. (4) Because updates to the radiocarbon calibration curve and new modeling approaches may render published age models obsolete, database managers are encouraged to generate updated age models or to store those developed by other scientists. (5) Because ad hoc models that use different age modeling algorithms for different sections of a stratigraphic sequence are often difficult to reproduce, developers of age modeling software are encouraged to formally incorporate instantaneous sedimentation events, hiatuses, and sharp changes in sedimentation rate into their modeling frameworks. (6) An international open-access database for radiocarbon dates should be developed, and purchasers of radiocarbon dates should be given the option by the radiocarbon laboratories, and encouraged by funding agencies, to contribute their dates to the database.

*Complete recommendations of the workshop are available at: www.pages-igbp.org/calendar/127-pages/826-age-models-chronologies-and-databases

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"Paleoecological data analysis with R" course for Latin American researchers

Julieta Massaferro[1], L. Pérez[2], M.E. de Porras[3], L. Pérez Becoña[4], M. Tonello[5] and S. Juggins[6]

San Carlos de Bariloche, Argentina, 31 March- 6 April 2014

For the first time in Latin America, an intensive one-week course took place on paleoecological data analysis using the free software, R. This course was led by Steve Juggins (Newcastle University, UK), author of the R package "Rioja" for the analysis of Quaternary science data and co-editor of the book *Data Handling and Numerical Techniques* (Birks et al. 2012).

Twenty early-career paleoecologists from Mexico, Guatemala, Colombia, Chile, Uruguay and Argentina, were selected from over 50 applicants to attend this unique workshop. The course combined theoretical lectures with practicals using datasets from case studies on topics such as exploratory data analysis, data transformation, multiple regression, distance measures and cluster analysis, environmental reconstruction, and age-depth modeling. After the practicals the participants had the opportunity to process their own data. The participants also had the chance to meet other Latin American researchers working with different indicators, and some are now planning to establish an international network to address paleoenvironmental and climatic issues using a multi-proxy approach.

Below we show three examples of analyses made by course participants, illustrating how R was used to analyze preliminary data.

Ordination of pollen samples

María Eugenia de Porras counted pollen in modern rodent middens along a climatic and vegetation gradient from the Atacama Desert to the Altiplano, to identify the modern climate-vegetation signal and develop a modern calibration set. Furthermore, she collected several modern midden samples at every ca. 100 m in altitude to account for pollen signal bias due to the rodent behavior. The results from an ordination analysis (nMDS, Fig. 1A) show that pollen from modern rodent middens reflects a vegetation gradient from the Pre-Puna, to low and high Puna, to High Andean steppe, and therefore the increasing precipitation gradient related to summer rainfalls associated with the South American Summer Monsoon. Furthermore, those samples collected at the same site are grouped together, suggesting that the pollen signal is not biased by the rodent behavior, and thus confirming the potential of middens as paleoclimatic and paleoecological archives.

Ostracods bubble plot

Liseth Pérez established an ostracod training set in Central America across a precipitation and altitudinal gradient to determine the species ecological preferences. The altitudinal distribution of lakes in the study region is strongly skewed towards lowland lakes (Fig. 1B). The highest species abundances and richness are found in the lowlands. There are clearly species restricted to the lowlands and others to the highlands, while few are distributed along the entire altitudinal gradient. Mid-altitude and additional highland lakes will be sampled in future field trips. This type of figure provides a fast overview of species distributional patterns along climatic and environmental gradients.

CCA with diatoms

Laura Pérez Becoña used a Canonical Correspondence Analysis (CCA, Fig. 1C) on diatom data obtained from a sediment core from the Río de la Plata (RdlP), in the inner Uruguayan continental shelf. The analysis combines diatom data (species abundances) for 1960-2009 AD, with instrumental records of climatic (Pacific Decadal Oscillation, PDO and Southern Oscillation Index, SOI) and anomalies in the Paraná and Uruguay River discharges. Positive anomalies in the Paraná and Uruguay River discharges are associated with warm ENSO and PDO phases, which increase the precipitation over the RdlP drainage basin. As a consequence, periods of high river discharge, related to PDO>0 or SOI<0 (El Niño events), are reflected through a higher abundance of freshwater and marine-brackish diatom species in the sedimentary record. In this sense, axis x of the CCA represents a salinity gradient, with fresher conditions (i.e. high RdlP discharge) at the left of the figure moving towards more maritime conditions on the right.

ACKNOWLEDGEMENTS

We thank PAGES, the Municipality of Bariloche, the University of Comahue and the Nahuel Huapi National Park for supporting this course, and the organizing committee, for all the effort. Without their help it would have been impossible for many young scientist to attend the course.

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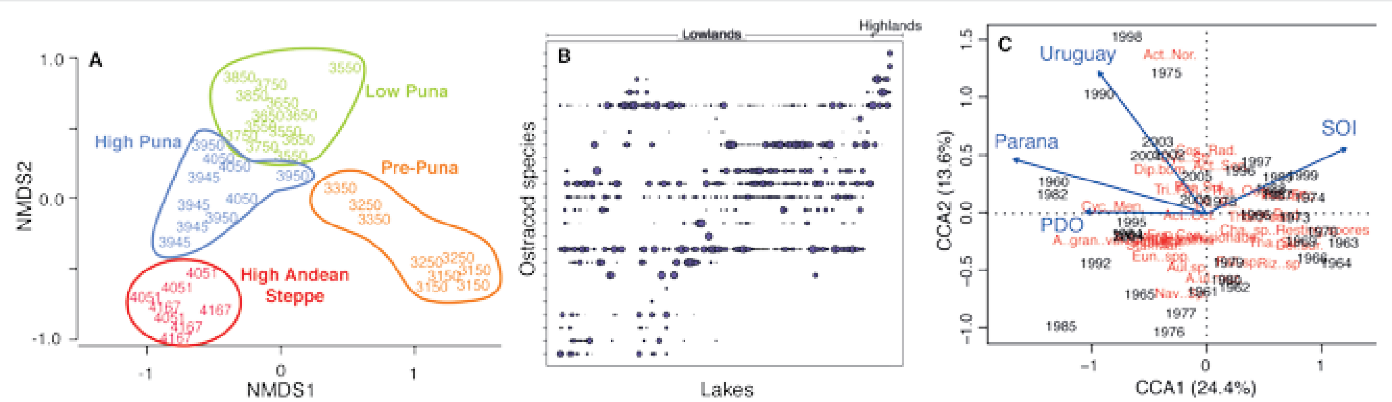

Figure 1: (A) Non-metric multidimensional scaling (NMDS) of a set of pollen samples from modern rodent middens collected along a climatic and vegetation gradient in the Atacama Desert (21°S). The numbers represent the altitudes the samples were taken at. **(B)** A two-way ordered bubble plot of freshwater ostracods along an altitudinal gradient in Central America. Altitude increases from left to right in the plot, with lowlands <500 and highlands from 500-2000 m a.s.l. Size of dots represents species richness. **(C)** Canonical Correspondence Analysis of diatom data (1960-2009) in a sediment core from Río de la Plata (red), climate indexes (PDO and SOI), and anomalies in the discharges of the Paraná and Uruguay river discharges (blue arrows).

Towards a more accurate quantification of human-environment interactions in the past

Gert Verstraeten

Leuven, Belgium, 3-7 February 2014

Since the introduction of agriculture, humans have profoundly changed the natural environment through land cover change and subsequent changes in soil and sediment properties as well as aquatic ecosystems. It is also clear now that these long-term changes are also responsible for significant changes in the global carbon cycle with feedbacks to climate. The PAGES Themes on Soil and Sediment (formerly LUCIFS) and Land Use and Cover have made great progress in the last decade in reconstructing sediment fluxes under human impact and anthropogenic land cover changes, respectively. However, despite the progress these groups have made, we still have a very incomplete picture of human-environment interactions over the Holocene, both spatially and temporally. There is a need for further integration of the various disciplines active under Focus 4 and inclusion of scientists from the humanities.

This workshop provided an interdisciplinary forum to share data, results and ideas in order to explore how our research community should proceed to work towards an integrated quantitative history of Holocene human-environment interactions. In total 105 researchers from 19 countries and from a wide variety of disciplines such as geography, archeology, palynology, history, geology and soil sciences contributed to the workshop.

The first two days of the workshop were dedicated to 31 oral and 57 poster presentations, which highlighted new research results on specific topics of past human-environment interactions to a wider disciplinary audience. These sessions included 10 invited speeches. Topics included the quantification and numerical modeling of past changes in vegetation cover, population and settlement dynamics, changes in agricultural techniques and the use of innovative geochemical and isotopic techniques for tracing historic soil erosion and sedimentation.

On the third day of the workshop, Jean Poesen, Gert Verstraeten, Bastiaan Notebaert and Nils Broothaerts (Leuven, Belgium) led a field trip through the Dijle River catchment in the Belgian Loess Belt to display and discuss how humans have changed the landscape through deforestation and subsequent erosion and sedimentation processes (Fig. 1).

The last two days of the workshop were entirely devoted to discussions. A first series of discussion sessions were organized in breakout groups and restricted to the disciplinary topics "archeology", "land cover", "geomorphology" and "paleolimnology". These groups not only discussed the state-of-the-art of each of these broad disciplines with respect to their understanding of human-environment interactions but also how each discipline could contribute to the overall questions on human-environment interactions. They also identified the major knowledge gaps and formulated some key questions for further research. Each group presented the outcome of the discussion to the entire workshop audience.

In a second step, three topical, cross-disciplinary discussion sessions, again in breakout groups were organized. One group focused on scale issues and the uncertainties involved when reconstructing past human-environment interactions, whilst another group discussed the role of thresholds or tipping points in complex human-environment systems and the feedback mechanisms that come into play. A third group discussed the difficulties that arise to define human impact through time and space considering important changes and variability in agricultural techniques, productivity, economy and culture.

During the final plenary session that concluded the workshop, the participants discussed future research strategies and synergies that fit within the Future Earth research initiative (www.futureearth.org). The participants stressed the importance of knowing more about past human-environmental interactions for future land planning and sustainable management of natural resources, and the need for environmental and humanities-based disciplines to join forces and move beyond overly-simplistic and uni-directional views on how humans have impacted the environment and vice versa. The interdisciplinary audience also endorsed moving towards a more quantitative perspective on past human-environment interactions in order to improve forecasts of future human-environment interactions.

PROGRAM AND ABSTRACTS

www.pages-igbp.org/calendar/2014/127-pages/827-focus-4-wshop

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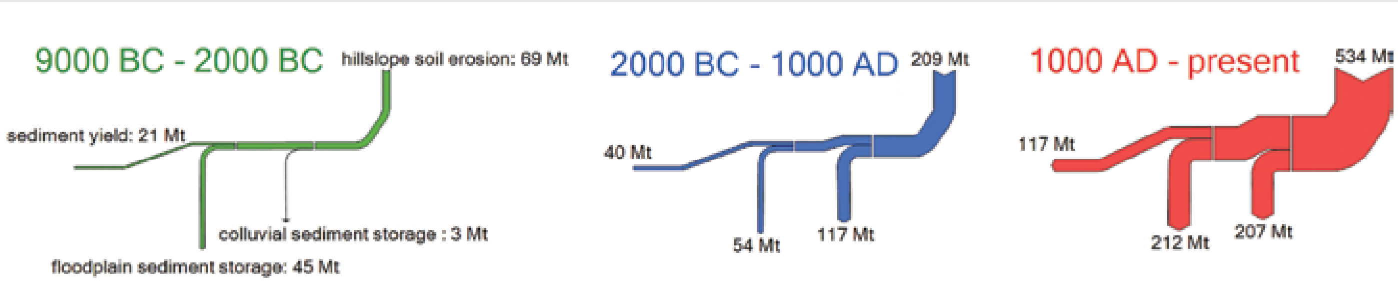

Figure 1: One of the themes discussed during the workshop is the quantification of historic soil erosion and sedimentation following human disturbance. The time-differentiated sediment budget for the Dijle catchment shows the changing importance of colluvial and alluvial storage as well as sediment yield through time. Not only the absolute increase in human-induced land cover change, but also its spatial patterns explain the observed changes in the sediment record. The entire system behaves non-linearly and is characterized by tipping points, which change the coupling relationship between hillslopes, river channels and floodplains. Adapted from Verstraeten (2012).

Ramsar Wetlands: Understanding Change in Ecological Character

Peter Gell[1], O. Burge[2] and R. Flower[3]

Queenscliff, Australia, 6-8 November 2013

To ensure protection and "wise use", many wetlands are included in the Ramsar Convention's List of Wetlands of International Importance (www.ramsar.org). Many of these wetlands are under increasing pressure from (i) (hydro-)climate change; and (ii) the direct impacts of people, notably through hydrological modification (decreasing water quantity/quality), land use change, and the proliferation of invasive species.

Listing a wetland requires a site description and account of the "natural ecological character". The site description, undertaken at the time of listing, constitutes a modern baseline against which a wetland's present condition can be measured. However, evidence from the past often reveals a wider range of "natural" conditions, and can inform the potential trajectory (or trajectories) of change through which the wetland is currently passing. This PAGES workshop provided a valuable opportunity for contemporary and paleo-ecologists to review the knowledge of wetland change needed to better manage wetlands of international significance.

Emerging from the 2010 PAGES Floodplain Lakes meeting in Arkansas, USA (Gell et al. 2011) this workshop focused on the nature of wetland change and variability at key Ramsar sites across the globe. It was a true coming together of disciplines demonstrated by the range of conveners, including paleolimnologists – Peter Gell (Focus 4 Water theme leader), Jessica Reeves (OZIntimate leader) and John Dearing (former Focus 4 leader) and neolimnologists – Max Finlayson (Ramsar Scientific and Technical Review Panel), Jenny Davis (Society of Wetland Scientists) and Nick Davidson (Deputy Secretary General, Ramsar). Staged in historic Queenscliff, on the edge of the Bellarine Ramsar site near Melbourne, the workshop attracted over 70 delegates from 10 countries.

The presentations highlighted the substantial pressures on modern wetlands driving the loss of some sites and compromising the ecological character of others. While many recent changes have been anthropogenic in cause, paleorecords demonstrate that adverse changes may have their origins deeper in time than generally realized; that natural and induced change can be of a non-linear nature, and that the past "natural" character of a wetland can be surprisingly different from the currently perceived state. With respect to wetland management, it was contended that unanticipated natural features of the past – such as forested wetlands lost at a time in history that exceeds living memory – should be considered suitable options as "restoration" goals for degraded sites. Importantly in places where there has been little investment in wetland monitoring, the paleorecord provides the sole means of understanding the nature of past changes (an example is given in Fig 1).

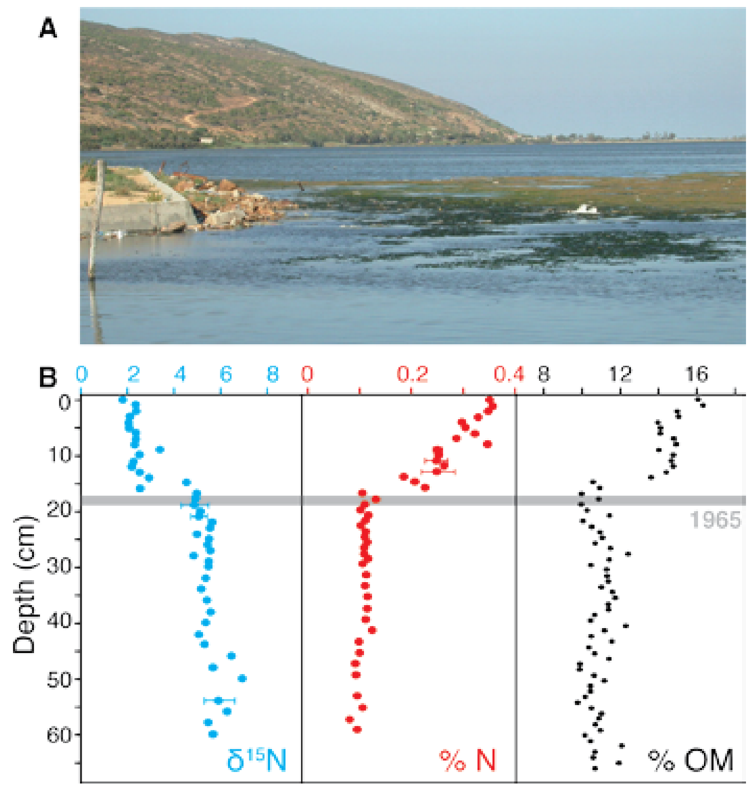

Figure 1: (A) Recent eutrophication of the coastal lagoon of Ghar El Melh (Tunisia) is currently manifested by development of green filamentous algal mats and excessive growth of *Ulva rigida*. **(B)** Sedimentary profiles for $\delta^{15}N$, percentage nitrogen and percentage organic matter in a dated sediment core from this lagoon indicate marked environmental changes occurred during the 1960s following the introduction of agro-chemical methods and artificial fertilizers (from Oczkowski et al. 2011).

The meeting had deliberate aims with respect to global wetland management. A high priority Ramsar task for 2013-2015 is to report on "Detecting, reporting and responding to change in ecological character" (mandated by the 2013 Conference of the Contracting Parties [COP 11; Resolution XI.17]), and discussion sessions in the workshop focused on framing a Briefing Note to inform the 2015 COP. Clearer understanding of the nature and drivers of environmental change is expected to provide more efficient pathways by which signatory nations may deal with changing conditions which affect their listed wetlands. As recognized at the workshop, understanding these conditions requires parties take account of past, current and future aspects of both global and local-scale forcing of change. The workshop assisted the Ramsar leadership to take steps to enable countries to take such an integrated and comprehensive approach to wetland management.

The workshop was supported by PAGES, the Australian Rural Industries RDC and several Australian NRM agencies, as well as Federation University Australia.

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Dendrochronology heats up Down Under

Patrick J. Baker

9th International Conference on Dendrochronology - Melbourne, Australia,13-17 January 2014

Tree rings are the most widespread and widely used paleoclimatic proxies in the world. They record, directly or indirectly, variability in ambient growing conditions and the occurrence of past ecological and climatological events. While dendrochronology, the science of tree rings, has been an active area of research for nearly a century, in recent decades the focus of dendrochronology has widened and the complexity of the standard analytical tools and their applications has grown dramatically. As such, every four years the international dendrochronology community convenes to discuss advances in the field, be they methodological, theoretical, ecological, or climatological. The 9th International Conference on Dendrochronology brought together 270 scientists from 37 countries, with strong representation from low- and middle-income countries. Generous support from PAGES, the Tree-Ring Society, and the Melbourne Convention and Visitors Bureau provided financial assistance to more than 50 students and early career scientists from developing countries.

The conference included 12 oral sessions and two symposia on subjects ranging from large-scale climate reconstructions and models to stable isotopes, dendrogeomorphology and insect outbreaks, as well as new climate-sensitive tree-ring records from the Australian mainland (Fig. 1). The opening plenary session talks by Janice Lough (Australian Institute of Marine Science) and Neville Nichols (Monash University, Australia) provided useful context and insights into the marine paleoproxy record for Australia and the major influences on the Australian climate system, respectively. The two symposia, one on divergence and tree-ring based temperature reconstructions and one on civilizations, climate and tree rings, which were organized for the entire conference community without competing parallel sessions, give a breadth of research presented. The "divergence" symposium focused on concerns that tree-ring chronologies and temperature records have begun to diverge over the past 20-30 years at high-latitude Northern Hemisphere sites; specifically, that tree-ring growth is not increasing at a rate commensurate with the observed temperature increases. David Frank (WSL, Switzerland) highlighted the wide range of methodological issues that could generate spurious patterns of divergence. Ed Cook (Lamont-Doherty Earth Observatory, USA) and Patrick Baker (University of Melbourne, Australia) presented results from the Southern Hemisphere suggesting that the opposite pattern (i.e. trees are growing faster than expected given the observed temperature increases) may have occurred in some preliminary tree-ring chronologies from Tasmania and Argentina. The general consensus was that the divergence issue has forced a careful re-examination of approaches to standardization and calibration of tree-ring chronologies and climate data, but the observed instances do not fundamentally challenge the case for tree-ring climate relationships. The "climate and civilizations" symposium moved away from methodological issues and focused on how tree-ring records can help to shed light on the impact of climate variability and climate extremes, in particular on human societies. Amy Hessl (West Virginia University, USA) presented recently published results describing the role of prolonged benign climatic conditions on the rise and expansion of the Mongol empire (Pederson et al. 2014). Dave Stahle (University of Arkansas, USA) presented a fascinating overview of research on the nexus between climate, disease, and societal collapse in Mesoamerica over the past 1000 years (e.g. Burns et al. 2014). Valerie Trouet (University of Arizona, USA) gave a provocative talk suggesting a possible link between the Maunder Minimum and pirate activity in the Caribbean based on tree-ring data and Spanish maritime historical records. These talks provide a glimpse of the diversity and quality of the nearly 250 other talks and posters that were presented over the five days of the conference.

Figure 1: Fire-killed *Podocarpus lawrencei* from the Snowy Mountains of New South Wales, Australia. A new multi-century tree-ring chronology from *Podocarpus lawrencei* presented by Matt Brookhouse (ANU) and colleagues is the first of its kind from the southeastern Australian mainland.

In addition to the scientific content of the meeting, there were several other highlights. These included Lifetime Achievement awards to Ed Cook and Malcolm Hughes (University of Arizona, USA), a service to dendrochronology award to Bruce Bauer (NOAA, USA), and an award for advances in dendrochronology to Rosanne D'Arrigo (LDEO, USA). Kathy Allen (University of Melbourne, Australia) coordinated a hugely successful pre-conference Field Week in Tasmania (with 35 graduate students and early career researchers participating, as well as six local high school students from Hobart). Throughout, Australia showed off its natural beauty and charm and some rather extreme summer weather (with four out of five of the conference days >42°C. Oooof!).

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Cast, cut, sample and analyze: A practical approach to processing speleothems for paleoclimate reconstruction

Ali Pourmand

Miami, USA, 12-14 May 2014

Speleothems (cave deposits) have emerged as one of the richest archives mined for paleoenvironmental reconstructions (Fairchild and Baker 2012). However, due to their fragile structure and often complex history, cave deposits must be handled with great care for accurate reconstruction of climate variability during Pleistocene and Holocene epochs. In May 2014, the Neptune, Paleoclimate and Stable Isotope Labs at the Rosenstiel School of Marine and Atmospheric Science at the University of Miami, extended the opportunity to 22 enthusiastic participants from seven countries to attend a three-day workshop on processing speleothems.

Each day began with short lectures on the analytical methodologies relevant to the activities of the day. Stalagmites were embedded in epoxy, then sectioned with circular and band saws and hand-polished. Following this, X-ray fluorescence scanning was discussed for high-resolution and non-destructive elemental analysis. We also discussed different sampling techniques using manual drills and an automated micro-mill that can be used to sample for trace element, stable isotope and U-Th analyses. We also focused on how to measure Sr/Ca and Mg/Ca ratios and trace elements by employing inductively-coupled plasma optical emission spectroscopy (ICP-OES). And lastly, direct-dilution and standard calibration techniques were introduced. The methodologies explored are described below in more detail.

Improving cave hydroclimate reconstruction

The oxygen isotope composition of stalagmites is often interpreted as a proxy for changes in rainfall amount. Cave hydroclimate reconstruction, however, can be significantly improved if the oxygen isotopic composition of the water from which speleothems precipitate is known. One such novel analytical technique for hydrogen and oxygen isotopic analyses (δ^2H and $\delta^{18}O$ values) of fluid inclusions in speleothems is cavity ring-down spectroscopy (Arienzo et al. 2013). This technique is comparable to traditional methods of dual-inlet isotope ratio mass spectrometry (IRMS) or continuous-flow (CF)-IRMS, and has been used successfully to measure the isotopic composition of fluid inclusions in stalagmites from submerged caves in the Bahamas.

Clumped isotopes in speleothem analysis

A new field of rapid growth is the clumping of isotopes in paleothermometry (Ghosh et al. 2006). Isotopologues (molecules with similar chemical but different isotopic composition) have been successfully measured in various carbonate deposits for paleo-temperature reconstructions. Speleothems, however, have thus far proven elusive. Limited available data have shown that cave temperatures reconstructed using clumped isotopes are in excess of expected or monitored temperatures (Daëron et al. 2011). During the workshop, we saw the extraction and purification line for CO_2 and how measurements of clumped isotopes are made on the mass spectrometer. New temperature reconstructions based on modern cave deposit experiments confirm previous findings on the complexity of interpreting clumped isotope reconstructions in speleothems.

Multi-collection ICP-MS: a novel technique

We also discussed a novel analytical technique for U-Th geochronometry: multi-collection ICP-MS. We saw the procedure for sample dissolution, ^{229}Th-^{233}U-^{236}U spike addition, U and Th purification, and isotope dilution mass spectrometry. Data reduction is performed through an open source algorithm that uses Monte Carlo simulation for propagation of random and systematic uncertainties (Pourmand et al. 2014). A significant advantage of this approach is consideration of U and Th isotope covariances and propagation of decay constants on corrected ages. The agreement between ages measured in two laboratories demonstrates the fidelity of this technique (Fig. 1). The workshop was concluded with presentations by several participants on modern cave monitoring and paleoreconstructions.

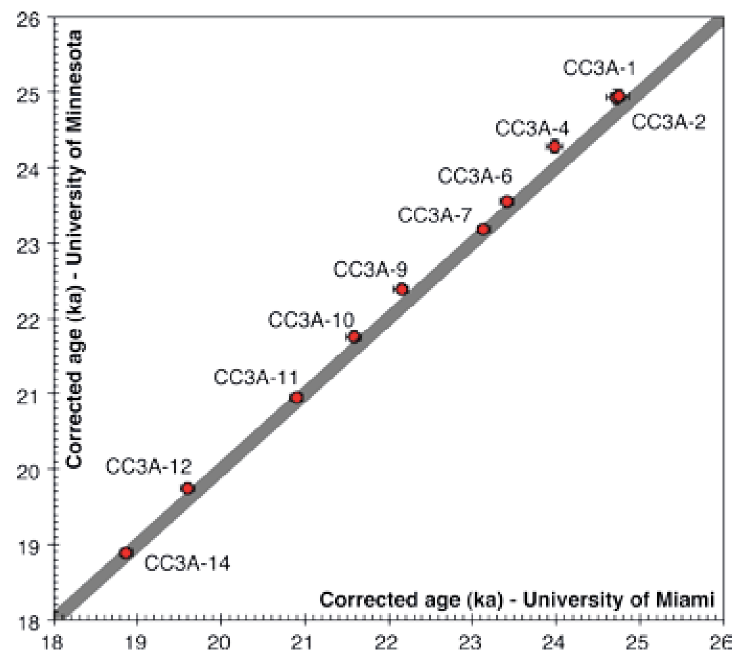

Figure 1: Comparison between U-Th ages determined at the University of Minnesota and the University of Miami on a speleothem from Cathedral Cave, Utah (Modified from Pourmand et al. 2014).

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Mediterranean Holocene climate and human societies

Karin Holmgren[1], M.-A. Sicre[2], A. Gogou[3], E. Xoplaki[4] and J. Luterbacher[4]

Messinia, Greece, 23-25 April 2014

Holocene climate reveals notable changes in the Mediterranean region (e.g. Finné et al. 2011; Roberts et al. 2011). The region also bears a long history of human society dynamics, making it a suitable site for exploring interactions between climate, environment and humans over a variety of time scales (e.g. Weiss 2012; Walsh 2013; Kaniewski et al. 2013). A workshop addressing these issues took place at the Navarino Environmental Observatory (NEO), Costa Navarino, Greece. Sixty-one participants from a total of 16 countries attended. They represented a range of disciplines, including history, archeology, paleoclimatology, hydrology and modeling.

Figure 1: Having the workshop in Greece – a country rich in archeology, history and social dynamics – inspired the participants in their creative discussions on climate, environment, people and their societies. Photo: Poseidon Temple in Cape Sounion, Attica Peninsula (by Nikolas Lambrou).

On the first half-day keynotes were presented on proxy records and important archeological and historical topics addressing the dynamics of past societies. The rest of the workshop was devoted exclusively to discussions. The participants broke out into chaired groups, with representatives from all disciplines, to critically discuss common themes on the interrelation between climate, environment and human societies. One of the key issues emphasized by the workshop participants was that although current global warming has inspired scientists to look back into the past, when trying to explore the connection between climate change and societal changes from a historical perspective, many limitations still remain. For example, links are often inferred using poorly dated "parallels" between cultural and climate changes; these chronological issues need to be better addressed. Moreover, the fact that two events happen at the same time does not permit conclusions to be drawn regarding causation; it is critical to understand the driving processes behind potential correlations. Equal attention should be paid to other, non-climatic, factors also affecting societies, e.g. political, economic and social structures.

The workshop participants recommended that future research in this area should include the full and equal participation of archeologists, historians and climate researchers throughout the entire process, from the project design stage to execution of research. This approach would enable the development of truly integrated research programs, conceptual models and local case studies, and overcome the barriers that might be perceived due to different scientific traditions, theories, methods and languages. Instead of being hindered by these perceived barriers, we should take advantage of, and use the diverse expertise we have to explore how we can generate new knowledge and pose new hypotheses and questions that may not yet have been asked. One way forward could be to focus on certain periods and areas with high data density (e.g. a specific climate event or a specific time containing substantial social transitions), and explore the evidence from different disciplines, critically evaluating the consistencies and connections, and addressing the role of different forcing factors. Another approach could be to look not only for climate change and societal "collapses", but to seek "success" stories and explore key factors behind resilient societies.

Allocating enough time for discussions in inter-disciplinary groups was key to breaking down some of the barriers between the scientists of different backgrounds, and inspired many to begin planning joint research initiatives. One first step in this direction will be to publish papers on the workshop theme in a special issue of *Quaternary Science Reviews*. The proposed 15-20 contributions to this forthcoming issue will include synthetic papers, conceptual papers and local case studies, and will be written jointly by researchers from different disciplines. Another step is to develop the proposed idea of organizing Navarino Summer Schools and Navarino Workshops, each on a biannual basis, for improving communication between communities and to develop methodologies that work towards fully integrated conceptual models that incorporate all signals, including human behavior in a common chronological framework.

ACKNOWLEDGEMENTS
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Modeling and data perspectives on reconstructing Late Pleistocene ice sheets

Pippa L. Whitehouse[1] and Lev Tarasov[2]

Grenoble, France, 22-24 May 2014

The aim of the "Joint model-data workshop for the Late Pleistocene evolution of the Greenland and Antarctic ice sheets" was to bring together scientists from the disciplines of field- and model-based ice-sheet reconstruction to identify outstanding issues in each field, and determine how the different communities could work together towards resolving them. An overarching theme of the workshop was the quantification of uncertainty, associated with both field data and model output.

In terrestrial studies of past ice extent (e.g. Fig. 1) it was highlighted that dating continues to be an issue due to a lack of dateable material, the presence of recycled carbon, and the difficulty of interpreting cosmogenic isotope data due to inheritance from multiple glacial cycles. The attribution of landform ages based on weathering characteristics is also difficult because processes can be very different from those observed in temperate regions. Relative sea-level data record the isostatic response to ice-load changes; however, such data are sparse, particularly around Antarctica.

Reviews of offshore information highlighted that many landforms relating to past ice extents are undated and sediment cores are often only acquired from trough regions, where the ice-sheet history may be very different to inter-trough regions. In addition, dating difficulties are compounded by the need to account for marine reservoir effects and interpret the stratigraphy "remotely" using underwater imagery.

In both terrestrial and marine regimes the issue of how to scale up point-based observations, e.g. from individual outcrops to ice-sheet scale, remains a challenge, although paleo-flow indicators are proving useful for reconstructing regional ice dynamics. The interpretation of radar-detected layers within the ice itself is offering novel constraints on past ice-sheet configurations over large spatial and temporal scales. However, there is little information relating to pre-Last Glacial Maximum ice margins and it remains difficult to quantify rates of ice-sheet growth.

From a modeling point of view discussion focused on how to better represent the forcing factors and boundary conditions governing past ice dynamics. Constraints on past precipitation and air temperature can be obtained from ice cores, but the interpretation of such records relies on having a reliable chronology. It was also noted that ice cores are generally drilled in ice sheet interiors, and hence may not provide reliable forcing conditions for the whole ice sheet. As an example, air and marine temperatures at the margins of ice sheets exert a strong control on ice dynamics but lack significant paleo constraints.

Figure 1: Erratics scattered on the bedrock surface of a nunatak in the Ellsworth Mountains, Antarctica. Cosmogenic exposure ages on such erratics can determine the timing of ice-sheet thinning. Photo: M. Bentley.

Models also require information relating to conditions at the ice-bed and ice-ocean interface. It was highlighted that basal topography is poorly resolved in extensive regions and there are a dearth of direct observations relating to till rheology and subglacial hydrology (both of which likely evolve over time). At the ice-ocean interface, models continue to lack realistic representations of ice calving and sub-ice-shelf melt, with the latter being restricted by our lack of knowledge on past ocean conditions.

The group identified a number of immediate research needs: better constraints on past grounded and floating ice extent (ice shelf configuration being an important component in the stress balance of an ice sheet); improved paleoclimate constraints; improved dating methods; and measurements of till strength. On the modeling side, challenges remain with regard to modeling grounding line dynamics, ice-ocean interactions and basal processes. Spatial resolution remains an issue, although adaptive grids can reduce the computational expense of modeling at high resolution. There is also a need to develop robust methods for comparing model output with data.

Finally, the development of open access databases - containing both field data and model output - was identified as an important collaborative need. A key outcome of the meeting was an agreement to promote protocols for database standardization among major Quaternary journals.

ACKNOWLEDGEMENTS

This workshop was supported by the International Association of Cryospheric Sciences, the International Union of Geodesy and Geophysics, the Laboratoire de Glaciologie et Géophysique de l'Environnement, Past Antarctic Ice Sheet Dynamics, and the Scientific Committee on Antarctic Research, and organized by the Meltwater routing and Ocean-Cryosphere-Atmosphere response (MOCA) network.

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Constraining Holocene solar forcing by "detection and attribution"

Jürg Beer

2nd Solar Forcing Workshop, Davos, Switzerland, 20-23 May 2014

Understanding climate change requires quantification of the major forcing factors (e.g. solar, volcanic, greenhouse gases). At the PAGES' Solar Forcing working group's first workshop in 2012 we addressed the role of solar forcing by trying to quantify it and then feed the results into climate models. The resulting model runs were then compared with paleoclimatic data. This approach turned out to be unsatisfactory for two reasons.

First, direct satellite based measurements of the total solar power arriving at the top of the atmosphere (total solar irradiance, TSI) and its spectral distribution (spectral solar irradiance SSI) have only been available since 1978. Because the Sun has been in a state of very high activity during this period all our detailed instrumental information about the Sun is not representative for periods of normal or low activity such as the Maunder minimum (1645-1715 AD). Also, as a result of degradation effects and discrepancies between different types of instruments there is still no generally accepted composite of TSI even for the instrumental period.

As physical solar models are not yet capable of reproducing observed solar variability, and in particular long-term TSI and SSI changes, the only information on decadal to millennial scale changes in solar activity available today is based on cosmogenic radionuclides such as ^{10}Be and ^{14}C. Although these reveal the relative level of solar activity, converting this into a quantitative solar forcing in Wm^{-2} remains unsolved. This is the reason why published TSI reconstructions usually resemble each other in shape but have a large spread of amplitudes (Fig. 1).

The second complication in assessing the role of solar forcing is that quantifying the climate's response to solar forcing is difficult. For example, it seems that SSI plays an important role in atmospheric chemistry and dynamics. But in order to study its effect, quantitative data for all forcings and reliable long-term paleoclimate records for model validation are needed – both of which are currently unavailable at the required quality. Also, different models respond differently to the same forcing change, raising the fundamental question of whether all relevant feedback processes of the climate system have been implemented correctly.

These difficulties motivated us to "put the cart before the horse" and to investigate ways to assess the role of solar forcing directly from paleodata. One challenge of this detection and attribution approach is to detect those climatic events in the past which can unambiguously be attributed to solar forcing changes. This requires a large number of millennial scale records of well-dated paleodata with high temporal and spatial resolution. Fortunately such work is in progress (e.g. the PAGES 2k initiative) and promising new paleodata were presented during the workshop.

Another challenge of this approach is that the state of the climate system at a specific point in time reflects the integral response of the system to all forcings. For example, periods of low solar activity (e.g. Dalton minimum, 1790-1830) can coincide with volcanic eruptions (e.g. Tambora, 1815). Furthermore, due to feedback mechanisms, forcings can also affect the climate system long after their initial occurrence.

To tackle these issues, the workshop participants recommend:

- Choosing periods of extreme solar activity that show minimal interference with volcanic eruptions for solar signal detection and attribution exercises.
- Using the fact that solar forcing has cyclic components with well-defined periodicities to discriminate between solar and volcanic forcing
- Identifying regions of high sensitivity for solar forcing based on existing paleodata and model runs. New local paleodata should be produced for these regions.
- Intensifying efforts to forward-model paleodata.
- Not using hemispheric or global mean temperature, because these average out regional changes and shifts in climatic features.

This was the last workshop of the PAGES Solar Forcing Working Group. The outcome of this and of the previous meetings will serve as the basis for the Solar Working Group synthesis product consisting of several publications.

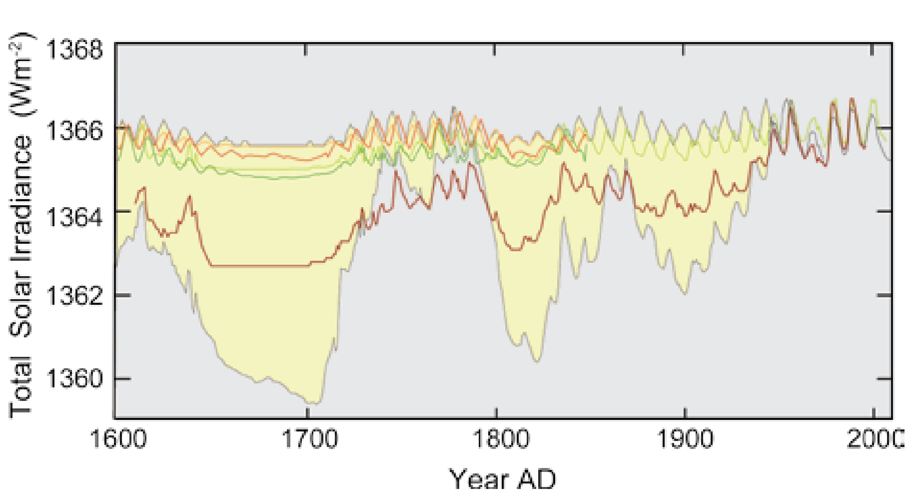

Figure 1: Seven reconstructions of total solar irradiance for the past 400 years (for details see Schmidt et al. 2012).

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Young Scientists Meeting special issue

pages goa 2013
2ND YOUNG SCIENTISTS MEETING

The Past: A Compass for Future Earth - PAGES Young Scientists Meeting 2013
Editors: Chen G, Daniau A-L, de Porras ME, Elmore A, Mills K, Saraswat R, Phipps S, Reyes A and Kiefer T
Climate of the Past
www.clim-past.net/special_issue65.html

This special issue provides a cross-section of the research presented at the PAGES Young Scientists Meeting and addresses the processes of past climatic and environmental change, as well as the methodologies required to study them. All 14 first authors and the first six of the guest editors are early-career researchers who attended the meeting held on 11–12 February 2013 in Goa, India.

Hydrographic changes in the Agulhas Recirculation Region during the late Quaternary
D.K. Naik, R. Saraswat, N. Khare, A.C. Pandey and R. Nigam

Late Glacial-Holocene climatic transition record at the Argentinian Andean piedmont between 33 and 34° S
A.E. Mehl and M.A. Zárate

Blue intensity and density from northern Fennoscandian tree rings, exploring the potential to improve summer temperature reconstructions with earlywood information
J.A. Björklund, B.E. Gunnarson, K. Seftigen, J. Esper and H.W. Linderholm

Orbital- and millennial-scale environmental changes between 64 and 20 ka BP recorded in Black Sea sediments
L.S. Shumilovskikh, D. Fleitmann, N.R. Nowaczyk, H. Behling, F. Marret, A. Wegwerth and H.W. Arz

Environmental and climatic changes in central Chilean Patagonia since the Late Glacial (Mallín El Embudo, 44° S)
M.E. de Porras, A. Maldonado, F.A. Quintana, A. Martel-Cea, O. Reyes and C. Méndez

Seasonal changes in glacial polynya activity inferred from Weddell Sea varves
D. Sprenk, M.E. Weber, G. Kuhn, V. Wennrich, T. Hartmann and K. Seelos

Reexamining the barrier effect of the Tibetan Plateau on the South Asian summer monsoon
G.-S. Chen, Z. Liu and J.E. Kutzbach

Treeline dynamics with climate change at the central Nepal Himalaya
N.P. Gaire, M. Koirala, D.R. Bhuju and H.P. Borgaonkar

Testing long-term summer temperature reconstruction based on maximum density chronologies obtained by reanalysis of tree-ring data sets from northernmost Sweden and Finland
V.V. Matskovsky and S. Helama

Expressions of climate perturbations in western Ugandan crater lake sediment records during the last 1000 years
K. Mills, D.B. Ryves, N.J. Anderson, C.L. Bryant and J.J. Tyler

Sediment transport processes across the Tibetan Plateau inferred from robust grain-size end members in lake sediments
E. Dietze, F. Maussion, M. Ahlborn, B. Diekmann, K. Hartmann, K. Henkel, T. Kasper, G. Lockot, S. Opitz and T. Haberzettl

Similarity estimators for irregular and age-uncertain time series
K. Rehfeld and J. Kurths

Investigating vegetation-climate feedbacks during the early Eocene
C.A. Loptson, D.J. Lunt and J.E. Francis

Uncertainties in the modelled CO_2 threshold for Antarctic glaciation
E. Gasson, D.J. Lunt, R. DeConto, A. Goldner, M. Heinemann, M. Huber, A. N. LeGrande, D. Pollard, N. Sagoo, M. Siddall, A. Winguth and P.J. Valdes

The future of PAGES. Participants at the 2nd PAGES Young Scientists Meeting 2013 in Goa, India.

Scientific Interview: Tom Crowley (1948-2014)

Thomas Crowley from the University of Edinburgh, a pioneer in the field of paleoclimatology, passed away on May 8, 2014. A few days before, he shared some retrospective thoughts on questions asked by his colleagues and friends, Hans von Storch and Heinz Wanner. His wife Gabi Hegerl helped to edit the interview.

Question: Tom, you are looking back on a long career in geosciences. Could you sketch your path and what attracted you to this field?

I started out as a marine geologist and had the good fortune to be involved in a project in the 1970s involving expanded exploration of the world oceans. The project leader was John Imbrie, a truly inspiring scientist. He developed a statistical methodology for converting assemblages of marine organisms into temperature, based on the observation that different types of plants and animals live in different temperature zones. This was formalized using regression methods and applied by the group CLIMAP (Climate: Long range Investigation, Mapping, and Prediction), whose purpose was to record the entire surface of the ocean during the last ice age so that climate modelers, who were just becoming known to the geologists, could test their models under radically different boundary conditions.

In my particular corner of the ocean, from the North Atlantic, East of the Grand Banks to the West coast of Africa, there was a distinct relationship between types of fauna and flora and the ocean currents. You could trace the Canary current, and the North Atlantic current just by looking at the distribution of the organisms. This got me interested in the question: What mechanisms might be invoked to infer changes in the past ocean circulation? It had already been known for almost 50 years that the Gulf Stream during the Last Glacial Maximum (~20,000 yrs BP) flowed from West to East around 40°N rather than northward into the Northeast Atlantic. The question as to what would cause the ocean to do that was a big interest in my life and always fascinated me as a trigger point.

I was extremely fortunate to meet Jerry North, a modeler interested in applying energy balance models to past climates. When moving to Texas to work with Jerry we went out for Mexican lunches every day and expanded our energy balance work to supercontinents. This was a logical and satisfying application for energy balance models, because the land sea distribution primarily dominates the temperature response. I also brought in my background in Paleozoic geology. It seemed like the best of both worlds going into the past to explore things I knew about, and yet applying new techniques of climate modeling to better understand the great Paleozoic glaciations.

Figure 1: Tom Crowley (1948-2014)

Q: What was the most important twist to your career?

I was very fortunate to receive an invitation from Klaus Hasselmann in Hamburg to visit their group and help to apply their ocean models to past climates. We looked at the Central American Isthmus, which had been open for several tens of millions of years before it closed, around the time when ice started to form in the northern hemisphere. We did some experiments opening and closing the Isthmus in order to explore the effect of its closure about three million years ago on global climate. The closure of the Isthmus turned out to be an important event, and the model showed features that bore a lot of resemblance to the geological data. This launched a series of further studies with Ernst Maier-Reimer, Uwe Mikolajewicz and Christoph Heinze, in which we examined the effects of other "ocean gateway" changes such as the Drake Passage. It was very satisfying to be moving along two scientific fronts, learning about ancient climates and using a model that was also being applied for the first detection and attribution studies of modern climate change.

Q: Your *Science* paper in 2000 was a key publication for paleoscience. Was this your greatest scientific achievement?

I started working on climate change over the last few centuries, because people were getting very interested in that topic. Over time a head of steam built up in terms of reconstructing climates and the climate forcing for those periods. I realized that many of the inferred climate changes could actually be reproduced very simply with an energy balance model, just by changing volcanism or solar variability. This result virtually fell into my lap and I was able to make an important, or at least a valuable contribution, being able to estimate how big the greenhouse gas signal was compared to solar or volcanically forced climate change and the Little Ice Age (LIA). By constraining the LIA climate change we could show that already in the 20th century global warming was taking place at about the size it was expected to be from the forcing. This paper (Crowley 2000) is one I might be known more for than anything else. Yet it is not what I necessarily consider my most important contribution.

Q: What then do you consider your most important scientific contribution?

That was a little bit more arcane, involving the subject of Snowball Earth, which is an unusual period of time, about 600 million years ago when the earth was in a deep freeze, with ice on all land and maybe on all of the oceans too. The world was in a supercontinent configuration. The earth was at one of its most critical points with respect to the evolution of life. In my view the origin of life itself is not as important

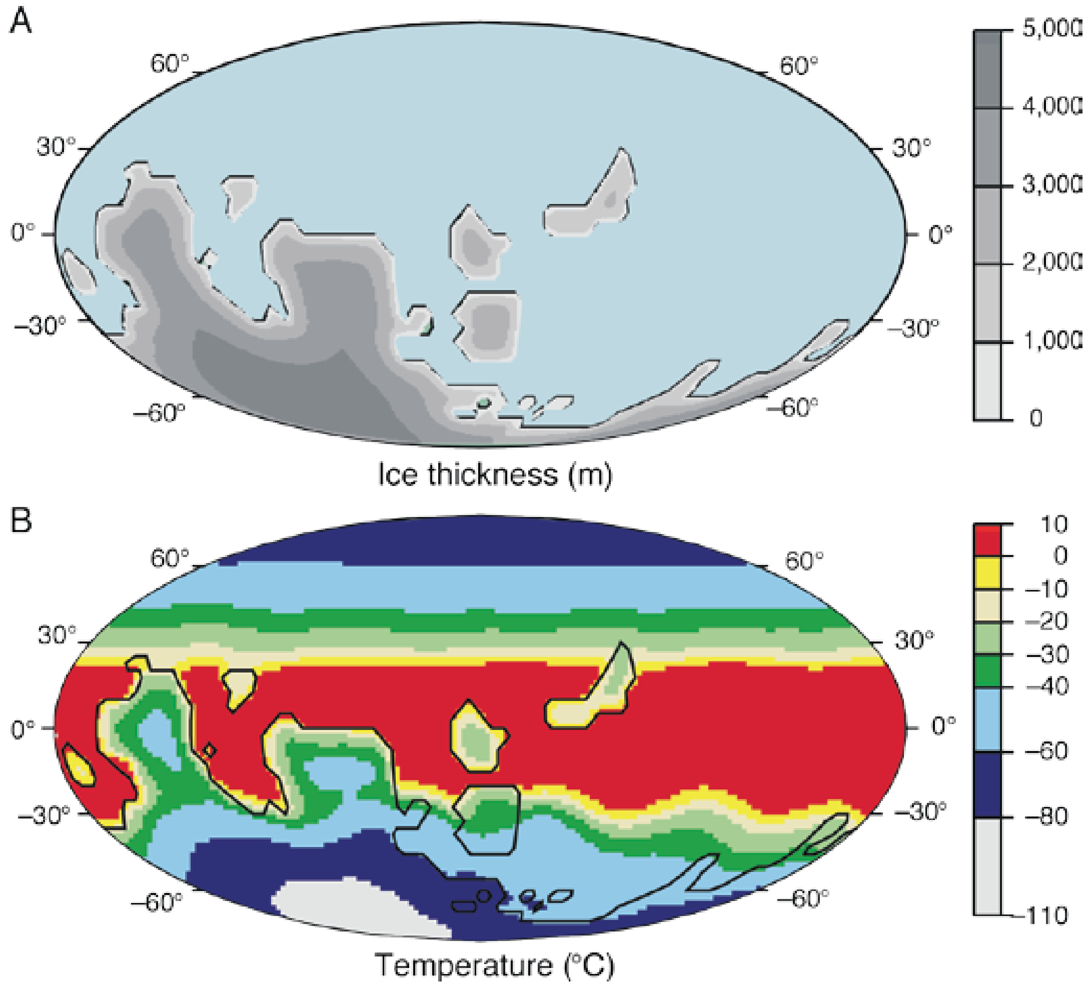

Figure 2: Tom Crowley's "most important scientific contribution". Late Precambrian (ca. 600 M yr BP) **(A)** ice cover and **(B)** temperature simulations. The annually average temperatures show that large areas of open water still might have existed while the continents were ice covered. The black lines represent the Precambrian landmasses. From Hyde et al. (2000).

as the evolution of multi-celled animals, which have a much narrower range of environmental restrictions. We knew that in order to study Snowball Earth properly we needed to couple an energy balance model to an ice sheet model. We got a grant from a very open minded NSF program director to allow us to explore Snowball Earth. We discovered that we could simulate a frozen-over earth fairly easily by just continuing to drop CO_2. However, we realized that for one of our solutions we did get ice on land, but open water over parts of the ocean (Fig. 2). This indicated that maybe life was still frozen out on land, but had taken up an oasis in the open water area of the ocean that allowed it to breed successive generations of multi-celled intermediate organisms that provided the basis for the great explosion of life at the end of that period. We didn't claim this was the correct explanation, but it is a legitimate viewpoint that cannot be dismissed despite 14 years of criticism. I feel this paper (Hyde et al. 2000) is probably the most important thing that we ever did.

Q: What is your judgment concerning the hiatus in the global temperature development of the last 15 years?

This oscillation has all the markings of a natural fluctuation, maybe an El Niño imprint. Extended-duration El Niños happen sometimes. However, I think the hiatus in global temperature has not quite been interpreted correctly. Based on my recent work that is just being published (Crowley et al. 2014), the system is now in a basic state that is more or less neutral, or maybe even in a little bit above average global temperatures for the last 15 years. So there may even be some statistical legitimacy for stating, not expecting, that temperatures could drop some 0.1-0.2°C for a few years. Of course temperature is going to bounce back very strongly but we just can't say unless we can predict natural variability.

Q: How do you feel about the development of climate models?

Climate models have been on such a consistent track for the last 20, 30 years that it is hard to imagine them changing significantly. Basic theory and energy balance still plays a legitimate role, because it keeps reminding people that despite the complexity of the system there are some responses that are almost linear with respect to forcing, and we have to understand why this is so, because it is not obvious. Take the example of the ideal gas law. Sometimes it seems like climate scientists want to solve the ideal gas law by integrating the interactions between every single atom in a box of gas. But of course the alternative way of doing it is to use the pV=nRT relationship to calculate the pressure difference. I think we need to keep going back to these basic concepts like energy balance and realize that they have a great deal to offer.

Q: You traveled around the world in the Royal Navy, did this experience have any bearing on your later scientific career?

I learned many things there, among them one worth sharing with students in particular. I was teaching lower level college classes on navy ships for the Western Pacific fleet to students that would come on their own time to take courses. I really came to respect these students and learned that it is not how smart you are, but how much you care if you are going to get an education. That stuck with me forever.

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