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GLACIAL TERMINATIONS AND INTERGLACIALS

EDITORS
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PAGES

GLOBAL IGBP CHANGE

News

PAGES SSC meeting 2015 and new SSC members
The PAGES Scientific Steering Committee will meet 24 - 25 January 2015 in Las Cruces, Chile. Topics on the agenda include the implementation of PAGES' scientific structure and collaborations with Future Earth and the World Climate Research Program (WCRP). A regional paleoscience symposium on the 22 and 23 January will precede the SSC meeting.

This year we are pleased to welcome two new members to the SSC:

• Blas Valero-Garcés is a paleolimnologist/sedimentologist in the Limnogeology & Global Change Group at the Pyrenean Institute of Ecology, Spanish Scientific Research Council in Zaragoza, Spain.

• Darrell Kaufman - a specialist in Arctic paleoclimate, paleolimnology, and geochronology at the School of Earth Sciences & Environmental Sustainability at Northern Arizona University. He is also one of the coordinators of the 2k Network and the PAGES endorsed group, Arctic Holocene Transitions.

We'd also like to take this opportunity to thank Steven Colman, who rotated off the SSC at the end of 2014. We are grateful for his commitment and stewardship throughout his two terms.

New Human/Environment working groups
Three new working groups with a focus on environmental change and the impact of humans have recently launched:

• GloSS (Global Soil and Sediment transfers in the Anthropocene)
• LandCover6k
• Aquatic Transitions

You can read more about each of them in their Program News articles in this issue. As all PAGES working groups, these are open to participation by scientists from everywhere in the world who are interested in contributing.

Databases and tools
A number of database and tools have been developed by our groups recently:

• The Global Paleofire Working Group (GPWG) produced an open source R package, paleofire, for analyzing sedimentary charcoal series in the Global Charcoal Database. It is discussed and applied in a recent study by Blarquez et al. (2014, *Comput Geosci* 72).

• Arctic Holocene Transitions, a PAGES-endorsed group, has published an extensive compilation of Holocene proxy climate records from the Arctic (Sundqvist et al. 2014, *Clim Past* 10).

• A sub-group of the former MARGO (Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface) project, which was supported by IMAGES and PAGES, has published a study addressing the constraints on surface seawater oxygen isotope change between the Last Glacial Maximum and the Late Holocene (Waelbroeck et al. 2014, *Quat Sci Rev* 105).

Future Earth update
Future Earth's Strategic Research Agenda 2014 has been published after a year-long global consultation on the priorities for global change research. It identifies priority areas for research and collaboration between funders, policymakers, and researchers over the next 3-5 years.
www.futureearth.org/news/future-earth-strategic-research-agenda-2014-published

The Future Earth Engagement Committee was recently announced. This is a strategic advisory group, comprising thought-leaders from business, policy, and civil society. Its primary purpose is to foster interactions between science and society working alongside the Future Earth Science Committee.
www.futureearth.org/news/future-earth-engagement-committee-announced

Upcoming issues of PAGES Magazine
The next issue of PAGES Magazine will be on volcanic forcing and climatic response. Contact the guest editors Allegra LeGrande (allegra.n.legrande@nasa.gov) and Kevin Anchukaitis (kja@whoi.edu), or the PAGES office to enquire about contributing to this issue.

We are also planning an issue on abrupt changes and tipping points in the Earth system. Contact the PAGES office if you are interested in contributing or exploring ideas.

In general, if you wish to lead a special section of the magazine on a particular topic, let us know at the PAGES office or have a discussion with any PAGES SSC member.

Calendar

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

Aquatic Transitions working group meeting
22-24 April 2015 - Keyworth, UK

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

PALSEA 2015 Sea Level workshop
22-25 July 2015 - tokyo, Japan

Antarctica2k working group meeting
03-04 September 2015 - Venice, Italy

http://pages-igbp.org/calendar

Featured products

Synthesis papers
• The Global Monsoon Working Group has just published the first of two major syntheses taking a global view of monsoon variability across timescales (Wang et al. 2014, *Clim Past* 10).
• Members of the former Land Use & Cover theme present pollen-based quantitative reconstructions of vegetation cover in Europe for the Holocene. (Trondman et al. 2014, *Glob Change Bio*).

Past Interglacials Working Group papers
• Martrat et al. compare similarities and dissimilarities between the last two deglaciations and interglaciations in the N Atlantic region (2014, *Quat Sci Rev* 99). Read more in this issue on page 10.
• Mokeddem et al. discuss how ocean dynamics may have contributed to the end of the last interglacial in the subpolar N Atlantic (2014, *PNAS* 111).

2k Network papers
• The 2k Consortium outlines the 2k Network's goals for its Phase 2 (Kaufman et al. 2014, *Eos* 95).
• Linderholm et al. create a tree-ring reconstruction of summer temperatures for the last 900 years in Fennoscandia (in press, *Clim Dyn*).

Recent PALSEA2 papers
• An updated database of Holocene relative sea level change in NE Aegean Sea (Vacchi et al. 2014, *Quat Int* 328-329).
• The Mid-Pliocene sea-level conundrum: Glacial isostasy, eustasy and dynamic topography. (Rovere et al. 2014, *Earth Planet Sci Lett* 387).
• Constrasting records of sea-level change in the E and W North Atlantic during the last 300 years (Long et al. 2014, *Earth Planet Sci Lett* 388).

Cover

Geomorphological and archeological evidence of climate variability during the present interglacial at Radstock Bay, Devon Island, Canada.
The melting of the Laurentide Ice Sheet during the last deglaciation has left its imprint in the High Arctic landscape. The area has experienced an isostatic rebound of about 100 vertical meters, exposing the raised beach lines visible in the background. In the foreground are the ruins of winter sod houses built by Inuit of the Thule culture 500 years ago. The Bowhead Whale bones scattered on the ground once supported skin roofs. The houses were much closer to the sea at the time the Thule built them. Photo by Henning Thing.

Past4Future: European interdisciplinary research on past warm climate periods

Dorthe Dahl-Jensen[1], E. Capron[2], P. Vallelonga[3] and D.M. Roche[4,5]

Past4Future was a Collaborative Project in the European Union's Framework Programme 7; it aimed to generate knowledge about climate changes during the last two interglacials. The approach was to combine proxy data with climate model simulations to investigate the existence and the cause of past abrupt climate changes during warm climate periods in order to evaluate the risk of abrupt changes in the future. Featuring contributions from a number of Past4Future participants, this Science Highlights section of PAGES Magazine showcases the cross-disciplinary nature of this very successful project that ended in December 2014.

One focus was to define the climatic and environmental conditions during the last two interglacials. A compilation of temperature changes in the high latitudes evidenced that the onset of the Last Interglacial warming occurred first in the Southern Hemisphere but was stronger in the Northern Hemisphere (Capron et al. p. 4). In addition, new paleoclimatic records covering the last two interglacials and their preceding deglaciations have unveiled abrupt environmental and climatic changes in sea ice extent (Sha et al. p. 24), oceanic circulation (Galaasen et al. p. 20; Marino and Zahn p. 22), sea surface salinity (Rodriguez-Sanz and Mortyn p. 6), and sea surface temperature (Martrat et al. p. 10). Abrupt changes in benthic foraminiferal $\delta^{13}C$ at the onsets of the last two interglacials (Galaasen et al. p. 20) combined with direct simulations of $\delta^{13}C$ (Bakker et al. p. 18) suggest that abrupt climate changes are likely to be related to reductions in North Atlantic Deep Water formation. Modeling experiments including freshwater and volcanic forcing (Roche et al. p. 8) further constrain that the risk of future changes at the centennial scale is related to the stability of the Atlantic Meridional Ocean Circulation, and that volcanic eruptions are unlikely to cause strong climate changes of longer duration than a decade.

Another objective of Past4Future was to better understand global biogeochemical feedbacks between climate and the carbon and nitrogen cycles during interglacials. Antarctic ice core measurements of past CO_2 concentration and its isotopic composition, provide new evidence that the rise of CO_2 concentrations over the mid-Holocene cannot be man-made, but could be related to long-term re-equilibration of carbonate chemistry in the ocean (Fisher et al. p. 12). Biomass burning is also an important process affecting both regional and global climate, through the emission of greenhouse gases and particulates that reflect and absorb incoming solar radiation. New past fire activity tracers measured in ice cores were developed (Kerwhald et al. p. 14) and techniques to better compare biomass burning model simulations with the available datasets were established (Brücher et al. p. 16).

Overall, the Past4Future findings unambiguously demonstrate that abrupt climate changes are not limited to glacial conditions, but can also occur in a warm world. Changing ocean circulation, increasing greenhouse gas concentrations and instabilities of the remaining polar ice sheets are candidates for causing future abrupt changes.

The strength of the project relied on the interdisciplinary team of experts, which brought together the paleoclimatic data and modeling communities. While the research was centered on paleoclimate conditions and can therefore be classified as fundamental research, the knowledge gained is relevant for predictions – especially those relating to the risk and time scales connected to abrupt climatic and environmental changes in the near and more distant future.

A strong emphasis was also put on communicating the project results to an audience including scientists within and external to the climate science community, as well as policymakers, and the public (Dahl-Jensen p. 26).

While this five-year project has just ended, it will be crucial to pursue the integrative approach it fostered in order to gain additional insights on the causes of past abrupt changes and the potential risk of future ones. Essential future research directions include for example improving (i) paleoclimatic record timescales, (ii) direct modeling of paleoclimatic tracers, and (iii) data assimilation techniques.

In the future, it is not so clear how programs such as Past4Future may continue under the present European research framework, Horizon2020, where more focus is put on applied research and transferable knowledge to the private sector. Under the European Research Council's funding scheme for excellence, PI-driven research projects will thrive, and it is obvious we should encourage scientists to look this way. However, instruments to drive collaborative and integrative science, the backbone of the Past4Future project, may be lacking.

Science does, however, crucially depend on such instruments to coordinate research, synthesize results, and foster the proliferation of scientific knowledge; therefore, providing a base to build our applicable scientific knowledge on issues such as the likelihood of abrupt changes in the future and predicting the associated risks.

ACKNOWLEDGEMENTS

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Photo: The camp of the North Greenland Eemian Ice Drilling (NEEM) project where the first complete record of Eemian ice was recovered for Greenland. Photo: T. Burton.

A new Last Interglacial temperature data synthesis as an improved benchmark for climate modeling

Emilie Capron[1], A. Govin[2] and E.J. Stone[3]

We compiled ice and marine records of high-latitude temperature changes and placed them on a common timescale. We also produced climatic time slices for 115, 120, 125, and 130 ka. They represent improved benchmarks to perform Last Interglacial model-data comparisons.

The Last Interglacial (LIG, ~129-116 thousand of years BP, ka) represents a test bed for climate model feedbacks under warmer-than-present conditions. A spatio-temporal picture of LIG temperature evolution is indispensable to perform robust model-data comparisons and examine the General Circulation Models (GCMs) used for future climate projections (e.g. Lunt et al. 2013; Bakker and Renssen 2014).

However, existing LIG data syntheses (e.g. Turney and Jones 2010; McKay et al. 2011) consist of a single time slice and introduced dating uncertainties of up to several thousands of years by using the paleoclimatic records on their original timescales. Nevertheless, there is evidence that LIG surface temperatures peaked asynchronously around the globe (e.g. Bauch and Erlenkeuser 2008; Govin et al. 2012).

Here, we overcome the difficulty of aligning temperature records from different paleoclimatic archives retrieved across the world by limiting a new data synthesis to the high-latitudes. Our compilation provides a dynamic representation of the LIG temperature evolution, allowing more robust model-data comparisons.

A new LIG data synthesis associated with a coherent temporal framework

We combined 47 surface air and sea surface temperature records across the LIG polewards of 40°N and 40°S, respectively (Capron et al. 2014). Surface air temperature records are deduced from water stable isotopic profiles of ice cores. Sea surface temperatures (SST) are reconstructed from foraminiferal Mg/Ca ratios, alkenone unsaturation ratios, and faunal assemblages in marine sediment cores.

We use as a reference chronology for both marine and ice records, the recent Antarctic ice core chronology AICC2012. It is the first integrated timescale over the LIG, based on a multi-site approach including both Greenland (NGRIP) and Antarctic ice cores (EDC, EDML, TALDICE, Vostok). The numerous new stratigraphic links significantly reduce the absolute dating uncertainty down to ±1.6 ka (1σ) during the studied time interval (Bazin et al. 2013) making it a particularly well-constrained age scale.

In a first step we have transferred the Dome F and NEEM ice cores onto AICC2012 since they were not initially included in the construction of AICC2012. In a second step, to align marine records onto AICC2012, we follow the strategy of Govin et al. (2012). It is based on the assumption that surface-water temperature changes in the sub-Antarctic zone of the Southern Ocean (respectively in the North Atlantic) occurred simultaneously with air temperature variations above Antarctica (respectively Greenland).

The aligned time series have already been used for comparison with transient model simulations (as in Loutre et al. 2014). In addition, we constructed four time slices to assist snapshot simulation assessment. We calculated temperature anomalies relative to present-day

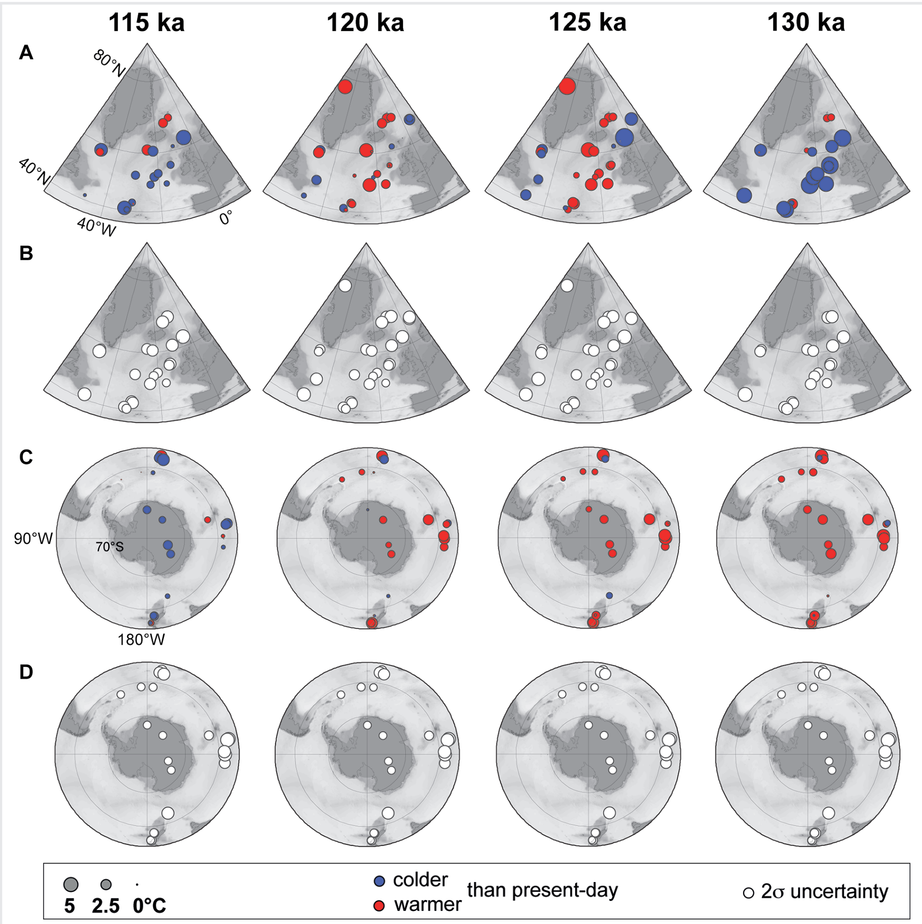

Figure 1: Temperature time slices across the Last Interglacial. NH air and sea surface temperature anomalies **(A)** associated with 2σ uncertainties **(B)**. **(C)** and **(D)** are the same as (A) and (B) for the SH. The size of the dots (both for temperature anomaly and associated 2σ uncertainty) follows the temperature scale given in the box. For all panels, warming (cooling) compared with modern temperature is represented in red (purple). The temperature anomalies are relative to the World Ocean Atlas (WOA) 1998, 10 m-depth data for marine records and relative to present-day instrumental surface air temperature measurements for ice records.

conditions over 2 ka time windows centred on 115, 120, 125, and 130 ka.

The aligned surface temperature time series and the time slice reconstructions benefit from quantitative uncertainty estimates. We used a Monte-Carlo analysis, taking into account temperature reconstruction errors as well as the propagation of dating uncertainties (see Capron et al. 2014 for details). This results in a final uncertainty estimate of ± 2.6°C on average for SST records and ± 1.5°C for surface air temperature Antarctic records (Fig. 1).

LIG climatic features

Producing robust age models and SST reconstructions remains difficult in the Nordic Seas. Thus, we focus on the robust climatic patterns found in the North Atlantic and Southern Ocean. The time slices (Fig. 2) capture the major features characterizing the spatial sequence of events described in the time series (Capron et al. 2014). In particular, the comparison of the 130 ka time slices from the two polar regions illustrates that warming in the Southern Hemisphere (SH) preceded warming of the North Atlantic. This interhemispheric asynchrony, which has already previously been reported (e.g. Govin et al. 2012), is attributed to the "bipolar seesaw" mechanism, induced by changes in the intensity of the Atlantic Meridional Overturning Circulation (AMOC; Stocker and Johnsen 2003). The melting of northern ice sheets extended beyond the penultimate deglaciation into the early LIG and the associated release of meltwater into the North Atlantic was suggested to have delayed the full establishment of a vigorous AMOC, resulting in peak Antarctic temperatures while the North Atlantic was still cold (Govin et al. 2012).

The 130 ka time slice also reveals SSTs significantly cooler-than-present-day conditions, e.g. up to 7.5 ± 3°C cooler in the northern high latitudes, while temperatures were slightly warmer than present-day (1.7 ± 2.5°C on average) in most of the SH sites. Warmer-than-present-day climatic conditions are clearly visible in the 130, 125, and 120 ka time slices in the SH, while they are only observed locally and with a relatively high uncertainty in the 125 and 120 ka time slices of the Northern Hemisphere (NH). Warmer-than-present-day conditions hence lasted longer at southern high latitudes than at northern ones. Finally, the magnitude of temperature changes is larger at northern than at southern high latitudes during the LIG onset and demise.

Toward more robust model-data comparisons

To illustrate the potential of our new LIG data synthesis for model-data comparisons, we compared 125 and 130 ka snapshot simulations performed with two GCMs, CCSM3 (Otto-Bliesner et al. 2013; Collins et al. 2006), and HadCM3 (Gordon et al. 2000), to the corresponding data-based time slices (Fig. 2; Capron et al. 2014).

We observe that both models predict warmer-than-present-day North Atlantic conditions at 130 ka, i.e. earlier than in our data compilation. Furthermore, neither of the models reproduce the reconstructed early SH warming (Fig. 2A,B). This means that the 130 ka simulations do not reproduce the bipolar seesaw pattern identified from the data synthesis. This is possibly because they only simulate the climate response to the static orbital and greenhouse gas forcing at 130 ka without taking into account potential dynamic AMOC responses to persistent NH ice sheet melting. Indeed, simulations where freshwater forcing to the North Atlantic from the Laurentide and Eurasian ice sheets is introduced perform better in reproducing the late NH warming (Govin et al. 2012). Also both models run under modern polar ice sheet and vegetation configurations, not under 130 ka ones. Other simulations considering an additional feedback linked to the disintegration of the West Antarctic ice sheet resulted in an additional warming over Antarctica (Holden et al. 2010; Otto-Bliesner et al. 2013).

At 125 ka, both models produce warmer-than-present-day conditions in the North Atlantic region (Fig. 2C,D). In Antarctica, CCSM3 suggests a cooler climate at 125 ka compared to present-day while ice core data suggest warmer conditions (Fig. 2C). The observed dissimilarities between CCSM3 and HadCM3 simulations are likely related to their different sea ice sensitivities (Otto-Bliesner et al. 2013).

Summary and outlook

We produced the first data synthesis that documents the spatio-temporal evolution of high-latitude temperatures from the LIG onset to its demise, using one single reference chronology. We paid careful attention to estimate quantitatively the temperature errors, including the propagation of dating uncertainties. Our study reveals asynchronous temperature changes between the polar regions and highlights the importance of considering the LIG sequence of events rather than averaging climate conditions over the entire LIG period.

This work should encourage more in-depth model-data comparison exercises with both snapshots and transient model simulations. Future work should not only consider surface temperature, but include additional climatic parameters (e.g. deep ocean circulation changes, sea ice extent) to move towards a more complete picture of LIG climatic and environmental changes.

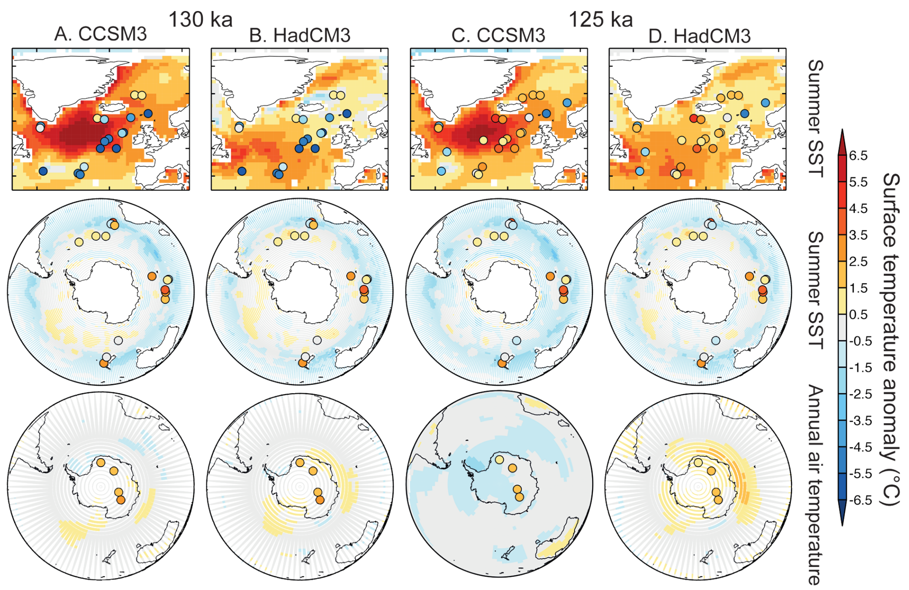

Figure 2: Model-data comparison of time slice reconstructions for 130 ka (**A** and **B**) and 125 ka (**C** and **D**) with respective snapshot simulations using the CCSM3 and HadCM3 models. Summer SST temperature anomalies from the marine sediment data (dots) superimposed onto model July-August-September SSTs in the NH and model January-February-March SSTs in the Southern Ocean; Annual mean surface air temperature anomalies from ice core data (dots) superimposed onto the model annual surface air temperature.

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Widespread salinification of the North Pacific Ocean during the last glacial termination

Laura Rodríguez-Sanz[1] and P. Graham Mortyn[2,3]

During the last glacial termination, atmospheric and oceanic teleconnections promoted millennial-scale episodes of widespread salinification in the tropical and extratropical Pacific Ocean that coincided with the Younger Dryas and Heinrich Stadial 1 cold phases in the North Atlantic.

It has long been debated how ocean circulation may have responded to the decline in the formation of North Atlantic Deep Water and weakened Atlantic Meridional Overturning Circulation (AMOC) during Heinrich Stadial 1 (HS1) and the Younger Dryas (YD). Proxy-data and model simulations suggest that convective overturning in the North Pacific reached down to intermediate (ca. 1-2 km; Jaccard and Galbraith 2013) or even deep (3 km) levels (Okazaki et al. 2010; Rae et al. 2014) during HS1, while the water column appears to have been more stable during the YD. It has been proposed that intermediate/deep water formation in the Pacific Ocean hinges on a basin-wide increase in ocean salinity driven by changes in, e.g. the strength of the Asian Monsoon, the transport of moisture from the Atlantic to Pacific, and in the North Pacific storm tracks (Emile-Geay et al. 2003). To provide an overview of the North Pacific hydrography, of its circulation, and of the potential for overturning during the last glacial termination (T1), we gathered data from several tropical and sub-tropical sites that reveal the timing and spatial distribution of surface ocean salinity changes in this region (Fig. 1).

Salinification of the North Pacific

Seawater stable oxygen isotope data ($\delta^{18}O_{SW}$) derived from paired Mg/Ca-$\delta^{18}O$ measurements in planktic foraminifera is widely applied to reconstruct salinity fluctuations in the past. This approach relies on the linear relationship between $\delta^{18}O_{SW}$ and seawater salinity observed at regional scales in the modern ocean (LeGrande and Schmidt 2006). During HS1 and the YD (Fig. 2A), millennial-scale $\delta^{18}O_{SW}$ increases at several locations in the mid- to low-latitude North Pacific (Fig. 1) indicate an overall salinification of the surface ocean (Fig. 2B-F). This picture is, however, complicated by the superimposed regional variability, likely in connection with more local circulation changes and freshwater inputs. This might explain, for instance, why salinification during HS1 was more subtle in the western tropical Pacific (Fig. 2B) than elsewhere in the basin (Fig. 2C,D).

The salinity increases in the tropical-subtropical Pacific associated with the YD and HS1 (Fig. 2B-D) coincided with cold conditions in Greenland (Fig. 2A), a more southward mean position of the Intertropical Convergence Zone (ITCZ; Fig. 2G), and a weakened boreal summer monsoon (Fig. 2H). Gibbons et al. (2014) proposed that the deglacial salinity increases in the tropical Pacific, and more widely in the Indo-Pacific region as a whole, reflect large-scale reorganizations of the hydrological cycle in response to reduced inter-hemispheric temperature gradients modulated by the AMOC slowdowns during T1. The salinity maxima coinciding with the YD and HS1 in the Western Equatorial Pacific (Rosenthal et al. 2003) have been ascribed to the millennial-scale weakening of the Asian Monsoon (Wang et al. 2001). Leduc et al. (2007) suggested that Atlantic-to-Pacific transport of moisture must have been reduced in response to the southward displacement of the ITCZ (Fig. 2G) to explain similarly timed millennial-scale salinification phases in the Eastern Equatorial Pacific (Fig. 2C). The northward expansion of these eastern tropical salinity anomalies at the expense of the fresher California Current likely controlled the salinification at 25°N off the Baja California Margin (Fig. 2D). This was possibly in response to reorganizations of the atmospheric circulation over the North American continent and/or El Niño conditions (Rodríguez-Sanz et al. 2013). Similar processes may have also controlled the surface ocean salinification at 34°N along the California Margin (Fig. 2E) during HS1, whereas the local hydrographic response during the YD apparently occurred in the opposite sense, i.e. with a freshening (Pak et al. 2012). Interestingly, at 42°N in the western Pacific Ocean (Fig. 2F) salinification is also recorded for HS1, but not for the YD (Sagawa and Ikehara 2008). Likewise, a paleosalinity reconstruction obtained from organic-walled dinoflagellate cyst assemblages from the Northeast Pacific (de Vernal and Pedersen 1997) documents saline conditions in this sector of the basin during HS1 but not during the YD (not shown).

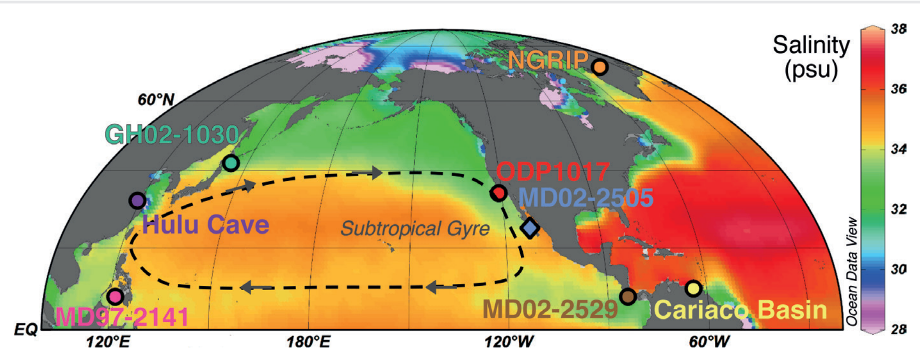

Figure 1: Modern Northern Hemisphere Sea surface salinity and location of the studied paleoclimatic records. Salinity data are from Ocean Data View (http://odv.awi.de/en/data/ocean/world_ocean_atlas_2005/).

Implications for North Pacific overturning

The salinification of the tropical and sub-tropical North Pacific, and the northward advection of saline waters across the basin during the deglacial intervals of weakened AMOC has been proposed as a key process for activating and sustaining the North Pacific overturning (Okazaki et al. 2010). However, several shortcomings challenge the picture of the interactions between ocean and climate change in the North Atlantic, response of the atmospheric circulation across the North American continent and the Indo-Pacific Ocean, and the influence of Pacific salinity on the basin's overturning. For example, the salinity anomalies in the tropical Pacific up to 25°N are of similar amplitude during both HS1 and the YD (Fig. 2B-D). This is in contrast to the evidence that changes in the mean position of the ITCZ and the Asian Monsoon (Fig. 2G-H) were more prominent during HS1 than during the YD (Wang et al. 2001; Deplazes et al. 2013). There is therefore an apparent mismatch between the magnitude of change in the drivers and the response of the salinity budget of the Pacific Ocean. This may allude to complementary factors affecting the hydrography of the tropical and subtropical North Pacific and/or to a "saturation" of the salinity signal during extreme shifts in the position of the ITCZ and monsoon strength.

Another intriguing feature of the spatial and temporal evolution of surface ocean salinity in the North Pacific across T1 is the apparent divide that developed during the YD between the low-latitude Pacific experiencing

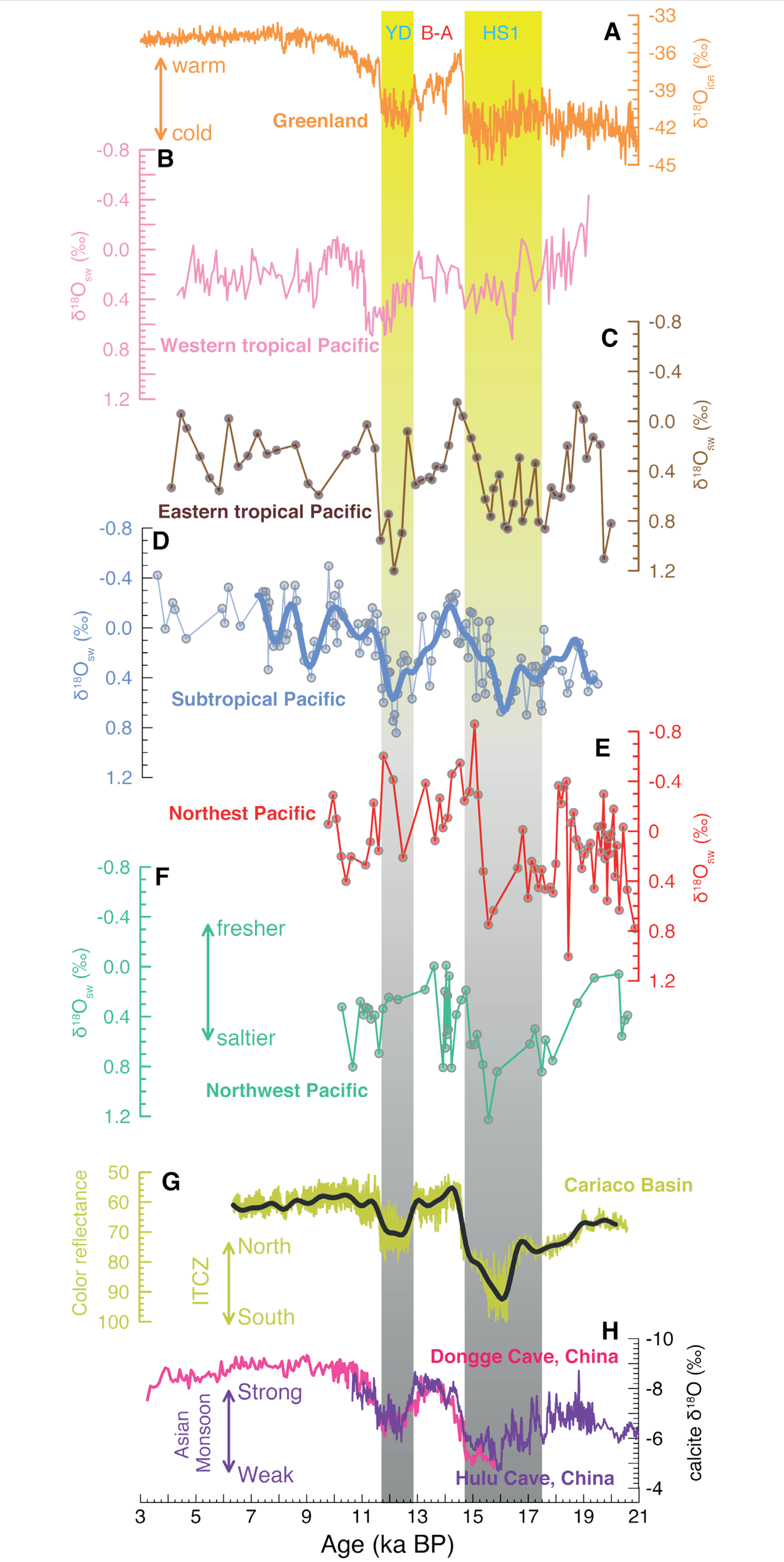

Figure 2: Paleohydrologic records from across the North Pacific compared to key paleoclimatic records. **(A)** Climate variability recorded in the Greenland NGRIP ice core $\delta^{18}O$. Ice-volume corrected seawater $\delta^{18}O$ from the **(B)** western (Rosenthal et al. 2003) and **(C)** eastern (Leduc et al. 2007) tropical Pacific, the **(D)** subtropical eastern Pacific (Rodríguez-Sanz et al. 2013), and the mid-latitude **(E)** northeastern (Pak et al. 2012) and **(F)** northwestern Pacific (Sagawa and Ikehara 2008). **(G)** Intertropical Convergence Zone (ITCZ) position, (Deplazes et al. 2013); **(H)** Asian Monsoon strength (Wang et al. 2001; Yuan et al. 2004). See Fig. 1 for the names and locations of sites. HS1, Heinrich Stadial 1; B-A, Bølling-Allerød; YD, Younger Dryas.

salinification (Fig. 2C-D) and the mid- to high-latitudes that instead either freshened (Fig. 2E) or remained stable (Fig. 2F). This raises the possibility that the North Pacific storm tracks strengthened (Emile-Geay et al. 2003) or that the positive feedback between intermediate to deep overturning and advection of subtropical saline waters to the subpolar North Pacific was not operating during the YD (Okazaki et al. 2010).

Outlook

Model simulations of freshwater inputs into the North Atlantic (e.g. Okazaki et al. 2010) have shed light on global atmospheric and oceanic processes that could have caused widespread salinification of the Pacific Ocean with possible consequences for deep water convection in the basin. Results point toward overall reduced freshwater inputs in the Pacific due to a weakening of the Asian Monsoon and southward displacement of the ITCZ, and enhanced exchange of saline water masses across the North Pacific gyres aided by a closed Bering Strait. Available paleoceanographic data could be explained by the coexistence of all of these processes during the YD and HS1. Additional model simulations and high quality salinity reconstructions across the tropical and extratropical Pacific Ocean will permit researchers to quantitatively constrain the spatial distribution of the salinity anomaly and further understand the actual mechanisms controlling the response of the Pacific Ocean to changes in AMOC.

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Freshwater release and volcanic eruptions as drivers of abrupt changes during interglacial climate

D.M. Roche[1,2], H. Renssen[1], C. Morrill[3,4], H. Goosse[5] and A. Mairesse[5]

A suite of model simulations performed within the Past4Future project have investigated the effect of freshwater fluxes and volcanic eruptions on global climate during interglacial climate conditions. Results for the Holocene evidence impacts that persist for centuries to millennia.

Reconstructions of the past climate unambiguously show that climate can shift abruptly on decadal timescales. Evidence of abrupt transitions comes from both the present Interglacial (the Holocene) and the Last Interglacial (e.g. Alley et al. 1997; Pol et al. 2014). However, there is still considerable uncertainty concerning the role of the different climate forcings in causing abrupt shifts. Constraining the sensitivity of interglacial climates to each forcing is a pre-requisite for assessing the future risk of abrupt changes and the potential impacts on societies.

To better understand our capacity to reproduce the reconstructed past climate changes, the Past4Future project evaluated the results of large coordinated modeling experiments, including those that exposed interglacial climate to freshwater and volcanic forcing perturbations. We report here on the results regarding (i) the well-known 8.2 kyr cold event and (ii) the effect of volcanic forcing in Holocene transient simulations.

Freshwater forcing of the 8.2 kyr cold spell

The 8.2 kyr event is an abrupt cooling that lasted ~150 years and is clearly identified in water isotopic records from Greenland ice-core records (e.g. Johnsen et al. 1992). It is generally associated in models with a temporary weakening of the Atlantic Meridional Overturning Circulation (AMOC) as a consequence of freshwater forcing pulse; there are data evidences that this is also the case in reality (Kleiven et al. 2008). Though some uncertainties exist on the precise amount, duration, and sequence of the freshwater pulse(s) delivered to the North Atlantic at this time, the cause is generally regarded to be the final drainage of giant North American proglacial lakes that stored deglacial meltwater from the retreating Laurentide ice-sheet (Barber et al. 1999). The largest freshwater contribution into the North Atlantic Ocean likely came from proglacial Lake Agassiz-Ojibway.

The 8.2 kyr event is an easy target for model intercomparison studies because (i) of its short duration, (ii) it occurred at the very end of the deglaciation in a climate relatively similar to our current one, and (iii) of the relatively well-known characteristics of the freshwater pulse. As such, it is accessible for the most recent complex coupled climate models. Additionally, this event is of particular interest since previous modeling studies reported that the resulting oceanic circulation decrease is of comparable magnitude to that obtained in future climate projections by the end of the century (Cheng et al. 2013; LeGrande et al. 2006).

Morrill et al. (2013) analyzed the results of four simulations from three climate models

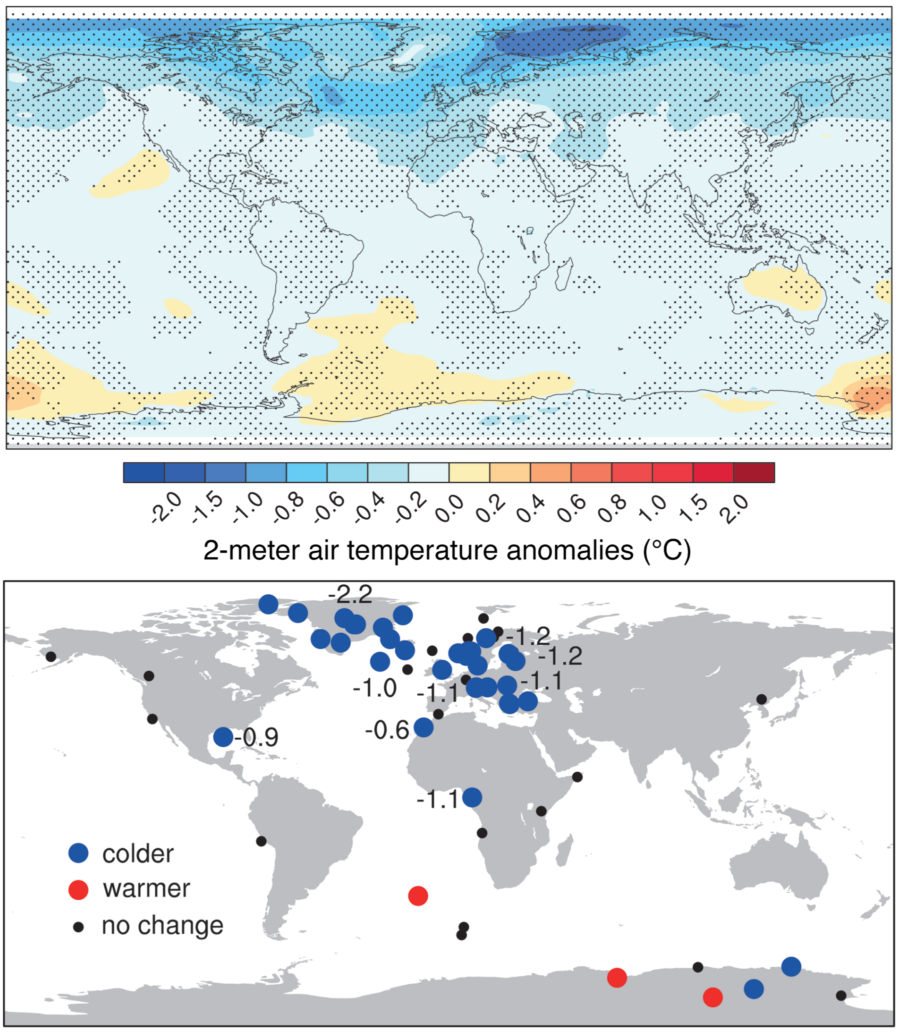

Figure 1: Comparison of mean annual temperature anomalies for the 8.2 kyr event from a multi-model ensemble **(top)** and proxy evidence **(bottom)**. Stippling shows grid cells where at least three of four simulations agree on the sign of the temperature anomaly. Quantitative estimates of temperature anomalies from proxies are shown in degrees Celsius.

Model	Atmospheric Resolution	Oceanic Resolution	Ice-sheet forcing	pCO_2 level	Background meltflux
CCSM3	T42 (~2.8×2.8°), 26 levels	1x1°, 40 levels	Yes/No	260 ppm	No/0.05Sv
GISS ModelE-R	M20 (4×5°), 20 levels	4x5°, 13 levels	No	285 ppm	No
LOVECLIM1.2	T21 (5.625×5.625°), 3 levels	3x3°, 20 levels	Yes	260 ppm	0.05Sv

Table 1: Model simulation characteristics. CCSM3 includes two simulations, one with and one without ice-sheet forcing (topography and albedo changes).

obtained using the 8.2 kyr event simulation scenario proposed within Phase 3 of the Paleoclimate Modelling Intercomparison Project (PMIP3). The three models analyzed are of various complexities and resolution (see Table 1). They show reasonable skill in reproducing the present-day climate, and of particular interest here, the strength of the oceanic circulation. There are, however, notable differences between the models in the regions where deep oceanic waters are formed.

All studied models simulate an AMOC weakening following the imposed forcing anomaly where freshwater was added for one year at a rate of 2.5 Sv (1 Sv = 10^6 m^3 s^{-1}). Generally, the AMOC reduction is a consequence of surface ocean freshening and sea-ice expansion in the North Atlantic. However, the three models show differences in the duration and amount of the AMOC decrease. Two of them show a reduction of 10% of the AMOC and a return to pre-freshwater forcing values within a few decades. However, the third model shows a more substantial 25% AMOC reduction, with a longer lasting response of a century.

As a consequence, surface temperature changes are observed in all models (Fig. 1a). Overall, a significant cooling is observed in the Northern Hemisphere, with a reduction in mean annual temperature of less than 0.5°C over most continents and around 1°C over some regions of the North Atlantic. Models also show a consistent pattern of warming of about 0.3°C or less in parts of the Southern Ocean. These features are consistent with the spatial distribution of temperature anomalies from proxy data (Fig. 1b). However, the models generally underestimate the amount of cooling by a factor of two and obtain only a shorter temperature response of just a few decades instead of the observed 150 years.

Analysis of model simulation differences shows that other factors may also influence the model result and account for some of the data-model discrepancies (Morrill et al. 2013). For example, the models may be sensitive to the presence or absence of deep oceanic convection in the Labrador Sea and to the length, amplitude, and other details in the freshwater forcing scenario.

Volcanic forcing of Holocene climate variability

Large volcanic eruptions are, in addition to freshwater releases, another well-known driver of abrupt climate variations. During explosive eruptions, sulphate can be injected into the stratosphere. This yields an enhanced absorption of solar and surface radiation and provokes a net stratospheric heating that in turn results in a net surface cooling. This effect was clearly observed following the Pinatubo eruption in 1991, which cooled lower troposphere temperatures globally by approximately 0.5°C (Dutton and Christy 2012). This cool anomaly lasted up to several years, linked to the lifetime of sulphate aerosols in the stratosphere.

Analysis of historical archives and sulphate deposited on ice-sheets enables us to reconstruct the history of large explosive volcanic eruptions. Volcanic forcing scenarios covering the last 10 kyr were developed to be utilized in climate models, expressed here as radiative impact (Total Solar Irradiance, TSI). The Mt. Tambora eruption in 1815, the largest of the last millennium, had an estimated TSI equivalent impact of 12 W m^{-2} and large eruptions in the Holocene may have had a magnitude many times greater than that, although the precise number is still uncertain (Mairesse 2014).

Using a newly developed volcanic forcing scenario, Mairesse (2014) performed transient fully coupled climate simulations with the LOVECLIM model over the last 10 kyr, with and without including the radiative effect of volcanoes. This enables the impact of large eruptions on Earth's global mean temperature to be analyzed (Fig. 2). The results show a significant (> 0.1 °C) imprint of volcanic eruptions on the simulated global climate. Medium-sized eruptions (injections of ~50 Tg of sulfate) result in recurrent coolings of 0.1 to 0.2°C at the centennial scale. The maximum effect for individual years is much larger but the exact magnitude of the response is still uncertain as the radiative impact of very large eruptions does probably not scale linearly with the sulphate emissions. Without further information, it remains difficult for now to reach a consensus on how to improve the forcing.

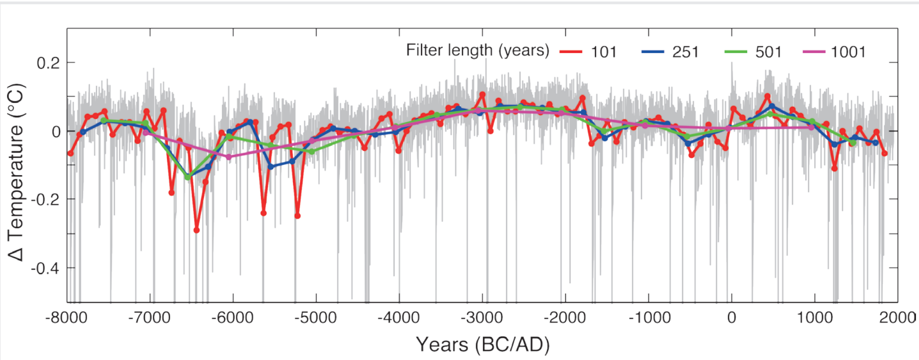

Figure 2: Global annual mean temperature difference between the simulations with and without volcanism. Gray curve is the unfiltered result. Also shown are temperature filtered by a running mean of 101 (red), 251 (blue), 501 (green) and 1001 (pink) years. Note that the vertical scale does not show the whole range of extreme values. The strongest annual global cooling was 6°C (at 6500 BC).

Outlook

The reported model experiments suggest that both volcanism and freshwater forcing have a significant impact at the century scale on the Earth's climate during the Holocene. There is a need, however, to refine the relationship between the TSI forcing and the sulfate injections for very large eruptions, since there is no analogue in the instrumental era.

The feedback from human activities on the melting of the Greenland ice-sheet may yield increased freshwater fluxes to the ocean over the course of this century. The strength of the fluxes can in principle be influenced by mitigation measures. While the rate and occurrence of disruptive volcanic eruptions is beyond human control, a risk assessment of their magnitudes and impacts may be useful for planning disaster prevention.

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Multi-decadal temperature changes off Iberia over the last two deglaciations and interglacials and their connection with the polar climate

Belen Martrat[1,2], P.C. Tzedakis[3], V. Margari[3], L.C. Skinner[2], D.A. Hodell[2] and J.O. Grimalt[1]

The Iberian margin provides climatic and environmental sediment records with multi-decadal resolution over the last two deglaciations and interglacials. These records allow us to identify climatic structures and discuss inter-hemispherical connections.

More than a decade has passed since it was verified that major temperature changes in Atlantic surface and deep waters at the Mediterranean latitudes were closely connected with Greenlandic and Antarctic climatic variability (Shackleton et al. 2000). Since then, deep sea sediments retrieved at the Iberian continental margin (e.g. Martrat et al. 2007; Hodell et al. 2013; Margari et al. 2010, 2014) have been adding further clues, showing that episodic abrupt change is a fundamental aspect of the Earth's climate. Anomalies were observed to take place rapidly enough to be noticed in the time frame of a regular human life and persist long enough to cause substantial disruptions in natural, and potentially socioeconomic, systems. Hence, far from only being of academic interest, the long-term management of our livelihoods now require pushing the data to the limits and focusing on fine-scale details (Shackleton, 2006).

A recent study of site ODP-976 (Martrat et al. 2014) has provided such detailed records over the present interglacial (Holocene, initiated at 11.7 ka before present), the Last Interglacial (LIG, onset approximately at 129 ka), and the respective deglaciations. The marine records obtained for the penultimate deglaciation and the LIG onset are particularly relevant, given the difficulties in obtaining an undisturbed ice core record from Greenland for this interval (NEEM community members, 2013). In this regard, the fact that the bipolar effect is well illustrated at the Iberian margin (Martrat et al. 2007; Margari et al. 2010) provides us with a robust basis for a Holocene-to-LIG comparison. Alkenone measurements enabled reconstruction of a sea surface temperature (SST) profile with a temporal resolution of 60 to 90 years and an associated uncertainty lower than 0.5°C. Events and transitions described and published before on the basis multi-proxy evidence (isotopes, vegetation, ice-rafted debris, etc.) from other Iberian sites (ODP-977, MD95-2043, MD95-2042, and MD01-2444) were essential for establishing hypotheses regarding long-distance climatic connections. Chronological uncertainties are commonly less than four centuries for the Holocene, but significantly higher – from two to even six millennia – for the LIG, when astronomical calibration of time scales is used as the main reference. In the paleotemperature record, three types of structures relevant to inter-hemispherical connections stand out: ''Ws'', ''saddles'', and a "cooling trend". We discuss each of these in turn below.

The ''Ws'': Heinrich stadials less static than previously apparent

Heinrich (H) events are identified in marine sediments of the mid-latitude North Atlantic as layers with a concentration of ice-rafted debris and scarcity of foraminifera. As a first-order description, H events are flat cold anomalies between some of the Dansgaard-Oeschger warm interstadials, which modelers simulate by putting freshwater perturbations or icebergs into Arctic latitudes (e.g. Jongma et al. 2013). However, increasingly detailed SST reconstructions at Mediterranean latitudes, specifically from sites ODP-976 and MD01-2444, suggest that cold stadial periods associated with H11 and H1 were anything but static. A sharp warming occurred halfway their progression, causing a characteristic ''W'' shape in

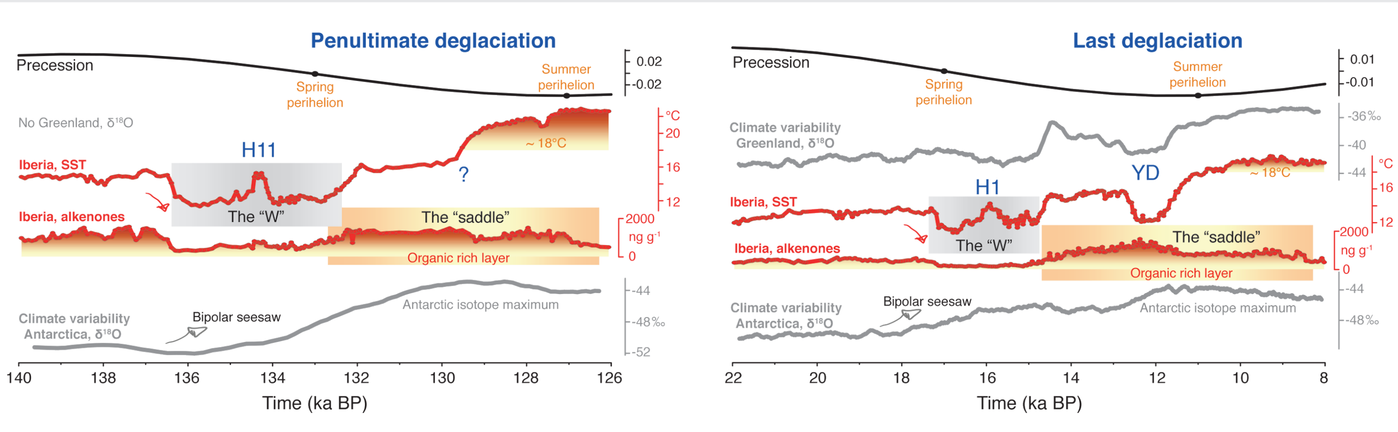

Figure 1: The penultimate **(left)** and last **(right)** deglaciations in Greenland, off Iberia, and Antarctica. From top to bottom: the precessional oscillation; climate variability traced by the Greenland NGRIP ice core (75°N); alkenone-derived sea surface temperatures (SST) and total alkenone amount from marine sediment core ODP-976 (36°N); and climate variability registered in the EPICA Dronning Maud Land ice core (75°S). Two main structures relevant to inter-hemispherical connections stand out: the ''Ws'' and the "saddles".

the SST records during these episodes (Fig. 1). Long-term vegetation patterns in the Mediterranean show that extreme dry and cold episodes took place during periods around perihelion passage in Northern Hemisphere (NH) spring equinox (Magri and Tzedakis, 2000). The cold spells observed within the stadials associated with H11 and H1 are placed around this orbital signature, i.e., ca 133 ka and 17 ka, respectively, including the abrupt warming events within them (up to 4°C in less than eight centuries; Fig. 1).

Skinner and Elderfield (2007) suggest that the occurrence of sharp warming events at the centre of the stadials associated with H events indicates the potential energy storage of the deep North Atlantic. The warmings appear linked to the culmination of a large reduction in the Atlantic meridional overturning circulation, ice surge phases with moderate rise in sea level, and possible sub-surface warming feedbacks (Flückiger et al. 2006). These multi-decadal scale oscillations within H events may have played an active role in the progressive glacial-to-interglacial re-activation of convective deep-water formation in the North Atlantic, adding a new element to the bipolar-seesaw between the Northern and the Southern Hemispheres.

The "saddles'' as a reference for deglacial processes

Deposition of organic rich layers, showing up as alkenone accumulation maxima, characterize the later part of the last two deglaciations when perihelion moves from alignment with the NH spring equinox to the summer solstice (from 132 to 126 ka and from 15 to 9 ka, respectively; Fig. 1). These layers are not comparable with the sapropels known from the eastern Mediterranean, neither in magnitude, nor timing, or mode of formation. They are features unique to the western Mediterranean. Their deposition histories show different maxima, the youngest ones separated by a significant ''saddle'' (Rogerson et al. 2008). Alkenone accumulation compares well between the last and penultimate deglaciations, but the derived SSTs differ (Fig. 1). Essentially, a cooling is recorded during the last deglaciation, around 12 ka (during the Younger Dryas; YD), while there is no analogous cooling over the penultimate deglaciation around 130 ka. This difference proves dissimilarities in the developments of the last two deglaciations. Surface and bottom water temperature records from off Iberia reflect the temperature changes over Greenland and Antarctica, respectively. They can thus be used to study temporal relationships between the Iberian and the polar regions. Maxima in the Antarctic water isotopic record (Masson-Delmotte et al. 2011) suggest mild climate in Antarctica during the deposition of both deglacial organic rich layers in the western Mediterranean. This is interesting in that both deglaciations are otherwise remarkably dissimilar in Antarctica, pointing to different configurations of ice sheets and varying strengths in thermohaline circulation during the last two deglaciations, with a dissimilar impact on SSTs across both hemispheres.

A long-term "cooling trend" and bipolar-seesaw variability

Some specific events during the interglacial progression capture our attention, though a trend towards colder climatic conditions dominates the observed SST variability quite prominently (Fig. 2). Interglacial multi-decadal scale events are superimposed upon this long-term trend towards colder SSTs. The ending of organic rich layer deposition in the western Mediterranean marks the onset of temperate Mediterranean conditions with relatively mild winters and winter rainfall, compared with the extreme seasonality of precipitation that characterized the interglacial onset. In Iberia, temperate intervals commence after the 8.2 ka-event and are over at 5.3 ka for the Holocene; for the LIG, they commence after 125 ka and are over at 121 ka (Fig. 2). During the LIG, the cooling trend is steeper (-0.4°C/ka from 122 ka to 116 ka) than during the Holocene (-0.1°C/ka from 6 ka to 0.7 ka). Trends simulated by an ensemble of climate models are qualitatively consistent with these Iberian cooling trends (Bakker et al., 2014). A cold spell of around eight centuries at 2.8 ka during the Holocene is possibly mimicked during the LIG at 118 ka by a fall of around 1°C within a millennium. These events lead interglacial SST to stabilize at around 18°C, i.e. at a value comparable to the present average annual in the western Mediterranean. The glacial inception at 115 ka commenced after perihelion passage in the NH winter solstice and culminated with a drop of at least 2°C in a few millennia, placed in the Iberian cores at 111 ka, around perihelion passage in the NH spring equinox. The end of the LIG occurred late in the ice-sheet growth cycle and involved major re-activation of the bipolar-seesaw. The Little Ice Age (0.7 ka), which had strong impacts on European societies, also occurred after the latest perihelion passage in the NH winter solstice and may be an example of a glacial pre-inception event following an interglacial.

DATA

Data from ODP site 976 are available at http://doi.pangaea.de

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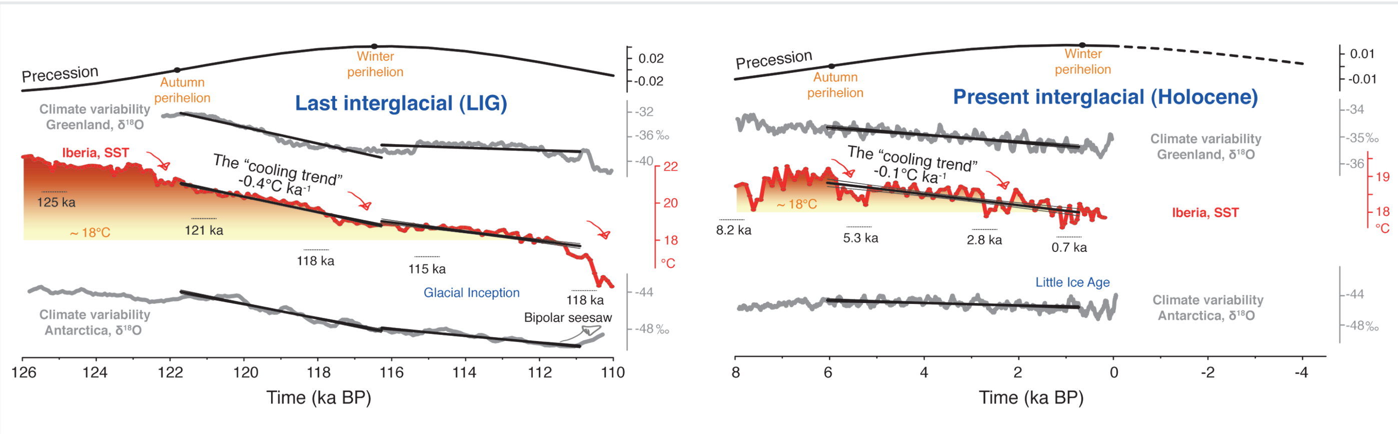

Figure 2: The last **(left)** and present **(right)** interglacials in Greenland, off Iberia and Antarctica. The descriptions of the individual curves are the same as for Figure 1. The distinctive feature is the "cooling trend", calculated between perihelion passage in the NH autumn equinox and winter solstice – and the bipolar-seesaw variability that ensues.

Ice core-based isotopic constraints on past carbon cycle changes

Hubertus Fischer[1], J. Schmitt[1], S. Eggleston[1], R. Schneider[1], J. Elsig[1], F. Joos[1], M. Leuenberger[1], T.F. Stocker[1], P. Köhler[2], V. Brovkin[3] and J. Chappellaz[4]

High-precision ice core data on both atmospheric CO_2 concentrations and their carbon isotopic composition ($\delta^{13}C_{atm}$) provide improved constraints on the marine and terrestrial processes responsible for carbon cycle changes during the last two interglacials and the preceding glacial/interglacial transitions.

CO_2 represents the most important greenhouse gas released into the atmosphere as a result of human activity. The majority of our knowledge on the increase in CO_2 since the start of the industrialization comes from ice cores, which complement the direct atmospheric CO_2 measurements obtained at Mauna Loa since the 1950s. The combined CO_2 record shows an unambiguous anthropogenic CO_2 increase over the last 150 years from 280 to about 400 ppm in 2014. Values above 300 ppm are unprecedented in the long-term ice core record covering the last 800,000 years with natural CO_2 concentrations varying between interglacial and glacial bounds of about 280 and 180 ppm, respectively (Fig. 1; Lüthi et al. 2008; Petit et al. 1999). The record also showed that even during rather stable interglacial conditions, CO_2 concentrations changed in response to long-term carbon cycle changes (Elsig et al. 2009). Although past atmospheric CO_2 concentrations are known with high precision, the causes of the preindustrial CO_2 changes cannot be easily attributed to individual processes. Substantial progress could come from better estimates of past changes in the carbon stored by the biosphere or from using stable carbon isotopes to constrain sources and sinks of carbon and exchange processes with the atmosphere.

The vast majority of the carbon cycling in the Earth system on multi-millennial timescales resides in the ocean. Accordingly, the global $\delta^{13}C$ of inorganic carbon dissolved in seawater ($\delta^{13}C_{DIC}$) may provide the best constraint on past carbon cycle changes. However, a global compilation of $\delta^{13}C_{DIC}$ from marine sediment records is hampered by insufficient spatial representation of vast ocean regions, the limited temporal resolution of many sediment records, and substantial chronologic uncertainties. The alternative, to reconstruct the mean $\delta^{13}C$ record of the well-mixed atmosphere (δ^{13}Catm) from the fossil air contained in Antarctic ice cores, has been a long-standing quest. Latest analytical progress that improved the measurement error while at the same time cutting down sample size by an order of magnitude has allowed us to gain this information from ice cores with the required precision and temporal resolution.

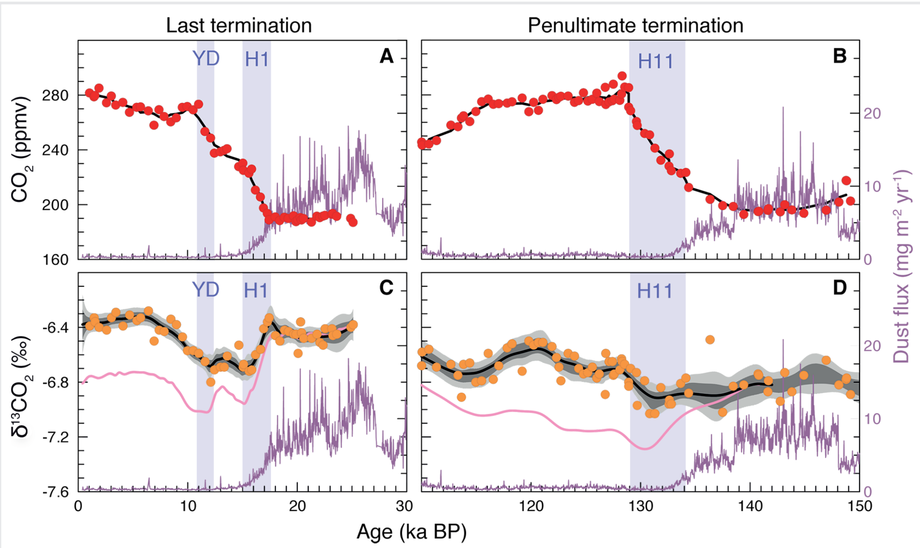

Figure 1: Evolution of atmospheric CO_2 (red dots), $\delta^{13}CO_2$ (orange dots), and dust flux (purple line) over the last two glacial/interglacial transitions and the subsequent interglacial periods. All measurements were performed on the EPICA Dome C ice core. The dark and light grey shaded fields represent the 1σ and 2σ errors of a Monte Carlo spline average of the $\delta^{13}CO_2$ (black line; Schmitt et al. 2012; Schneider et al. 2013). The pink line indicates the $\delta^{13}C_{atm}$ spline after a first order correction for global sea surface temperature changes. High-resolution eolian dust fluxes (purple line; Lambert et al. 2012) provide a measure for Southern Ocean Fe fertilization. YD =Younger Dryas, H = Heinrich events.

The enigma of glacial/interglacial CO_2 changes

The cause of the glacial/interglacial 80-100 ppm increase of atmospheric CO_2 represents a long-standing question in paleoclimate research. Several processes have been implied. These include Southern Ocean ventilation by wind or buoyancy feedbacks, iron fertilization of the marine biosphere in the Southern Ocean, changes in the re-mineralization depth of organic carbon, release of permafrost carbon during the deglaciation, decreased solubility due to ocean warming, changes in air/sea gas exchange due to changing sea ice cover, climate-induced changes in weathering changes rates, and marine carbonate feedbacks (Ciais et al. 2012; Fischer et al. 2010; Köhler and Fischer 2006; Menviel et al. 2012). However, none of these processes alone is able to explain the glacial/interglacial CO_2 change.

Our new $\delta^{13}C_{atm}$ data from the air trapped in the Antarctic EPICA Dome C ice core, provide improved constraints to revisit the enigma of deglacial CO_2 increase (Fig. 2). Mean $\delta^{13}C_{atm}$ levels during peak glacials and interglacials were not much different, despite different CO_2 concentrations and the substantially altered climate system. This implies that the $\delta^{13}C_{atm}$ record is the sum of several factors that balance each other to a large extent. For example, just considering the sea surface temperature-dependent fractionation of CO_2 between the atmosphere and the ocean surface, approximately 0.4‰ lower $\delta^{13}C_{atm}$ values are expected for interglacials (Fig. 2).

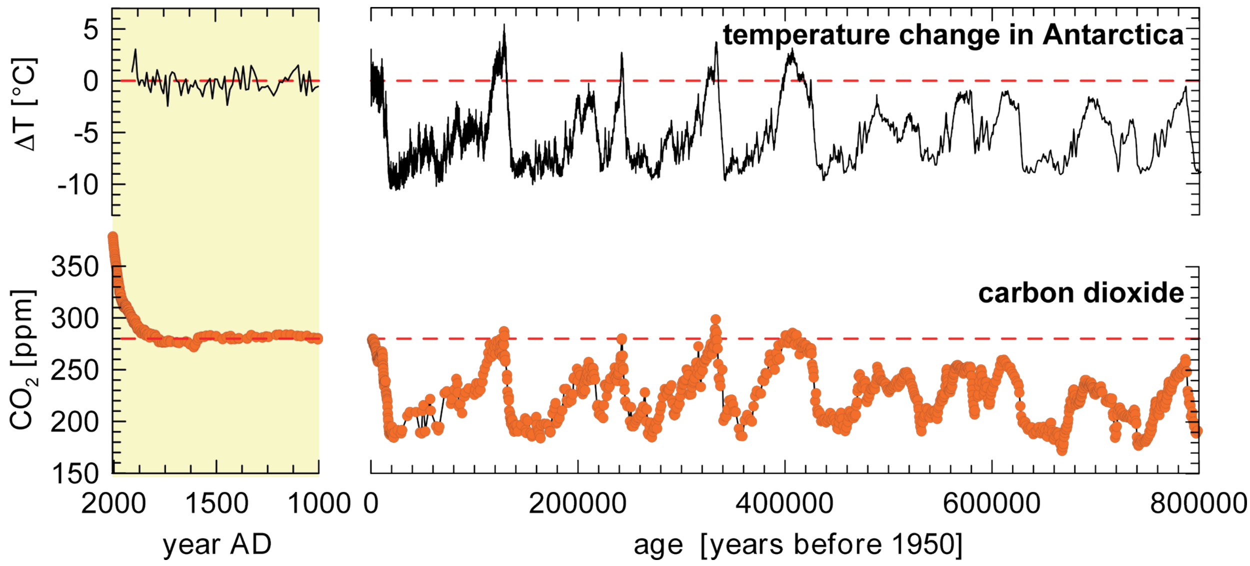

Figure 2: Right: Antarctic temperature and CO_2 variations over the last 800,000 years. Ice sheet surface temperature change was calculated from δD measured on the EPICA ice core from Dome C (EPICA community members 2004), CO_2 concentrations were measured on the Antarctic Dome C and Vostok ice cores (Lüthi et al. 2008; Petit et al. 1999). **Left:** Blow up of Antarctic temperature (EPICA community members 2004) and CO_2 concentration changes (MacFarling Meure et al. 2006) over the last 1000 years.

Our $\delta^{13}C_{atm}$ data (Lourantou et al. 2010; Schmitt et al. 2012) from the last two major deglaciations suggest a sequence of processes that drove atmospheric CO_2 changes during different stages of the transition from glacial conditions into a milder interglacial world.

- At the start of the transitions, upwelling of old ^{13}C-depleted waters in the Southern Ocean increased the release of CO_2 to the atmosphere. This process was likely synchronous with a demise in iron-stimulated bioproductivity in the Southern Ocean, when atmospheric dust concentrations declined rapidly.
- This was followed by the gradual growth of terrestrial carbon storage in vegetation, soil, and peatlands as evidenced by the slow $\delta^{13}C_{atm}$ increase. This process reached well into the subsequent interglacials. Termination I was special in that it was interrupted by another upwelling event synchronous to the Younger Dryas in the Northern Hemisphere.

The Holocene - natural changes or early anthropogenic influence?

The Holocene is often described as a rather stable period in climate history. Nevertheless, from 7 ka BP to the preindustrial era the CO_2 concentration increased by ~20 ppm, i.e. by a quarter of the glacial/interglacial change. Such a CO_2 increase is not found during the preceding three interglacials (Marine Isotope Stage (MIS) 5.5, 7.5 or 9.3), although increases at similar rates can be found in MIS 11.3 or 15.5. This gave rise to the hypothesis that the Holocene CO_2 increase may be unique and was caused by early anthropogenic land use (Ruddiman 2003). However, an anthropogenic release of isotopically light terrestrial carbon would lead to a decrease in $\delta^{13}C_{atm}$ over the last 7000 years, which is not observed in our record (Fig. 2; Elsig et al. 2009). The expected anthropogenic $\delta^{13}C_{atm}$ decline could in principle have been compensated by a concurrent natural build-up of peat at higher latitudes, but in that case atmospheric CO_2 should not have increased. In any case, a substantial early human influence on atmospheric CO_2 is difficult to reconcile with the ice core evidence. Based on terrestrial carbon cycle model results (Stocker et al. 2011), anthropogenic land-use is also unlikely to have released sufficient carbon during the last 7000 years to explain the 20 ppm CO_2 increase.

However, the carbon cycle may not only be altered by terrestrial processes during the Holocene, but also has a long-term ocean memory. The long-term carbonate compensation feedback (the re-equilibration of carbonate chemistry in the ocean) to carbon cycle changes occurring in the preceding deglaciation and enhanced shallow-water carbonate sedimentation during the Holocene due to sea level rise are acting on multi-millennial time scales and lead to a delayed increase in atmospheric CO_2 as observed in the ice core record without changing $\delta^{13}C_{atm}$ (Elsig et al. 2009; Kleinen et al. 2010; Menviel and Joos 2012).

If so, why is there no similar CO_2 increase observed during MIS 5.5? Explanations probably lie in the individual configuration of orbital forcing of each interglacial but also in the preceding deglacial history. For example the unique Younger Dryas event during Termination I may have disturbed the deglacial carbon cycle re-adjustment.

Outlook

The examples shown from the last two glacial-interglacial transitions demonstrate the value of high-quality $\delta^{13}C_{atm}$ data from Antarctic ice cores. However, maximum insight into the past carbon cycle can only be gained from joint atmospheric, terrestrial, and marine carbon cycle information in combination with coupled carbon cycle models. A stringent test for our carbon cycle understanding will be a future "Oldest Ice" ice core covering the last 1.5 Ma, which would provide the history of CO_2 and $\delta^{13}C_{atm}$ over the mid-Pleistocene Revolution, when the glacial/interglacial cyclicity changed from a 40,000 year period driven by obliquity changes of the Earth's axis to the well-known 100,000 year cycles in the later Quaternary.

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Two thousand years of boreal biomass burning recorded in the NEEM ice cores

Natalie Kehrwald[1], P. Zennaro[1,2], S. Schüpbach[3], T. Kirchgeorg[1], J. R. McConnell[4], R. Zangrando[2], A. Gambaro[1], and C. Barbante[1,2,5]

New data from Greenland ice cores reveal a major peak in boreal biomass burning during the 1600s AD, presumably related to major regional droughts in Central Asia. This climate-related peak in fire activity is greater even than post-industrial biomass burning.

Fires ignited by humans to manage the landscape may have started altering atmospheric greenhouse gas concentrations and warming the planet thousands of years ago (Ruddiman 2003). Today, biomass burning produces up to 50% as much carbon dioxide as fossil fuel burning (Bowman et al., 2009) while at the same time shrinking an important carbon sink.

Polar ice cores present a unique medium to quantitatively investigate past biomass burning at the global scale because they trap and archive fire-related aerosols before and after humans began influencing the global carbon cycle.

Here, we synthesize information from three geochemical fire activity proxies, i.e. levoglucosan, black carbon, and ammonium measured in the NEEM and NEEM-2011-S1 ice cores from Greenland (Fig. 1) to investigate interactions between Northern Hemisphere fire activity, climate, and possible human influences in boreal regions over the last 2000 years.

Fire proxies in ice cores

Several tracers of past biomass burning can be measured in polar ice cores. Aerosols are transported in smoke plumes from Eurasia and North America over thousands of kilometers. Some of the aerosols are transported all the way to Greenland, deposited there and trapped within the ice sheet (Kehrwald et al. 2012; Zennaro et al. 2014). Ammonium is a tracer of biomass burning, especially in boreal regions (e.g. Legrand et al. 1992), but also enters the atmosphere through interactions with fertilizers, manure, and marine sources. Black carbon is a more specific proxy as it is produced by the incomplete combustion of both biomass and fossil fuels (McConnell et al. 2007). Both black carbon and ammonium can be determined using high-resolution continuous flow analysis techniques (CFA; Zennaro et al. 2014). Fire information is also inferred from the isotopic composition of methane (CH_4). The $\delta^{13}C$ of CH_4 is enriched if it was produced by a pyrogenic process compared to biogenic sources including rice cultivation, ruminants or wetlands (Sapart et al., 2012) Note, however, that due to methane's atmospheric lifetime of several decades, the $\delta^{13}C$ of CH_4 is a global mixture from sources with different isotopic signatures (Sapart et al. 2012). Finally, levoglucosan, a monosaccharide anhydride, has strong potential for tracing broad-scale fire activity. It is only produced by burning cellulose at temperatures of 300°C or higher (Simoneit 2002) and represents one of the principal constituents of smoke plumes. Levoglucosan is currently only determined in discrete samples, resulting in lower-resolution records than parameters analyzed by CFA techniques.

Our study acknowledges both the strength and the weaknesses inherent in most ice core fire proxies and remedies the latter

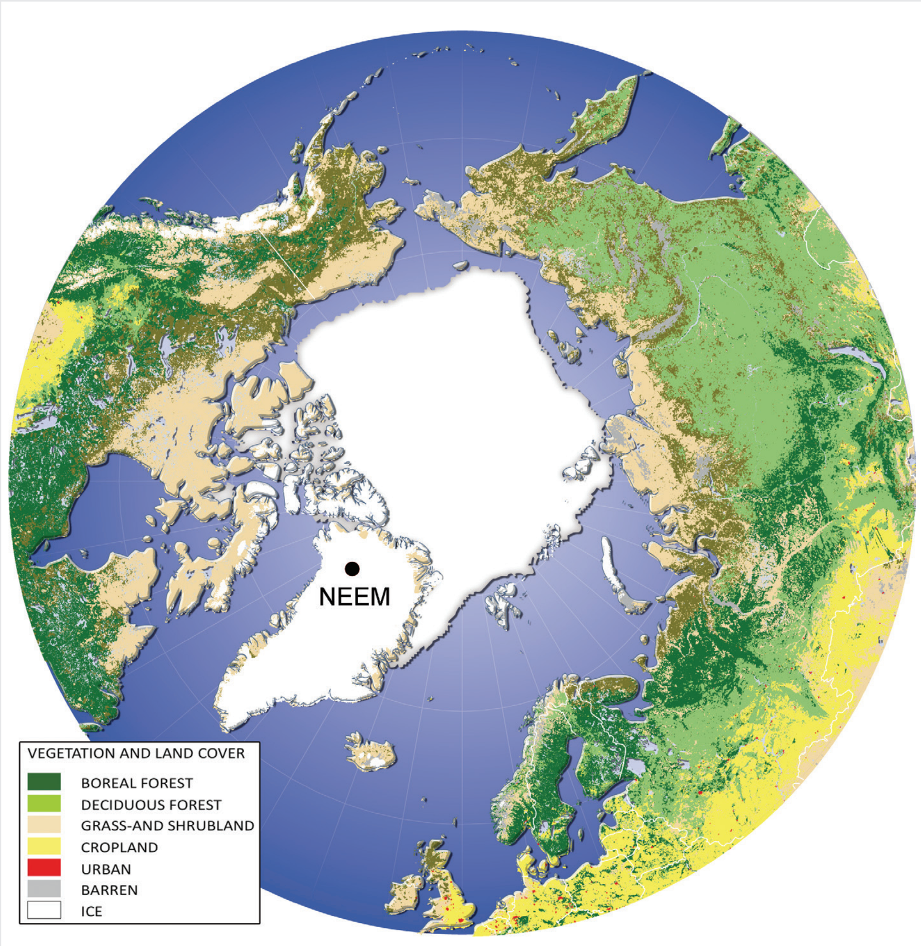

Figure 1: Distribution of the high northern latitude land cover and location of the NEEM ice core drilling site at 77.49°N, 51.2°W, 2480 m above sea level. Modified from the European Commission Global Land Cover 2000 database and based on the work of cartographer Hugo Alhenius UNEP/GRIP-Arendal.

by integrating the results from ammonium, black carbon, and levoglucosan records from the NEEM ice cores over the past 2000 years (Zennaro et al. 2014).

Boreal biomass burning and climate

Fires are individual events lasting hours to weeks, yet droughts, increased temperatures, or land use changes can increase net fire activity over years to centuries. We compare our records with other biomass burning and climate reconstitutions from elsewhere to locate the geographical extent of the fire activity reconstructed from the NEEM ice cores and to investigate their driving factors. To all of the records we applied a locally-weighted scatterplot smoothing (LOWESS, details on the statistical method in Zennaro et al. 2014) and normalized all data as z-scores to ease the comparison between the different records (Fig. 2).

The NEEM levoglucosan record peaks over a century-long period, centered on 1640 AD (Fig. 2). Although less prominent, high values around that time also exist in the NEEM black carbon records (Fig. 2). A regional average record of northern high latitude (>55°N) charcoal data from the Global Charcoal Database of the Global Palaeofire Working Group (www.gpwg.org) shows similar trends to the levoglucosan record throughout most of the last two thousand years, with the interesting exception of low charcoal values during the 1640 AD levoglucosan peak (Fig. 2). However, the majority of the boreal charcoal data are located in North America, thus geographically weighting the resulting synopsis. This could explain the observed difference between the levoglucosan and hemispheric charcoal record syntheses during this time period.

Tree-ring, speleothem, and alpine ice core data (e.g. from the Belukha ice core in Mongolia) demonstrate widespread, decadal-scale droughts over most of Central Asia coincident with major fire peaks in the NEEM ice core (Zennaro et al. 2014). These Central Asian droughts, and associated fire activity peaks, do not correspond with either increased regional or Northern Hemisphere land temperatures (Fig. 2). Therefore, over decadal timescales, we propose that precipitation changes may be an important fire-controlling factor. Except during the 1640 AD fire peak, the resemblance observed between the NEEM levoglucosan, black carbon, and Northern Hemisphere temperature reconstructions suggests that temperature might be the major control of boreal biomass burning over centennial timescales.

Conclusions

Our multi-proxy (levoglucosan, black carbon, and ammonium) reconstruction of fire activity based on the NEEM ice cores suggests that temperature was the main control on boreal fire activity over the past two thousand years, while major droughts influenced biomass burning over decadal timescales. Our dataset suggests a peak in fire activity in the mid-1600s, which coincides with the most severe Central Asian droughts of the past two millennia. This fire activity peak is higher than any biomass burning recorded at NEEM after the Industrial Revolution, when land-clearing rates were the highest in recorded history. Therefore, this dominance of the 1640 AD fire peak suggests that climate affected boreal biomass burning more than human activity over the past two thousand years.

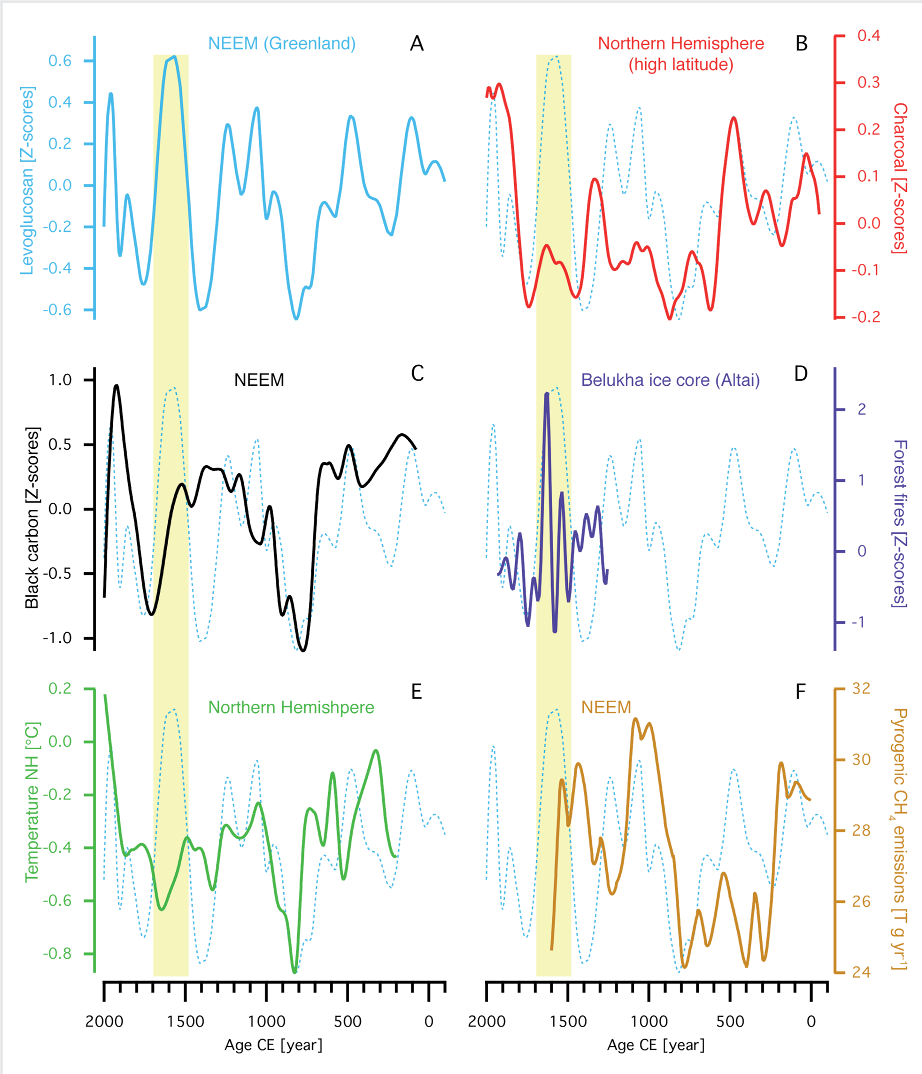

Figure 2: Climatic and environmental records over the past 2000 years, presented as z-scores smoothed by incorporating the nearest 10% of data. **(A)** NEEM levoglucosan concentrations; **(B)** Boreal charcoal concentrations (Marlon et al. 2008); **(C)** NEEM black carbon versus levoglucosan concentrations; **(D)** Siberian forest fire reconstruction (Eichler et al. 2011); **(E)** Northern Hemisphere land temperature (Mann et al. 2008); **(F)** NEEM pyrogenic CH_4 emissions (Sapart et al. 2012). Dashed blue lines in panels B-F are the levoglucosan record from A for reference. The yellow vertical bar marks the levoglucosan-based 17th century fire activity maximum highlighted in the text.

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How to compare modeled fire dynamics with charcoal records?

Tim Brücher[1], V. Brovkin[1], S. Kloster[1], J.R. Marlon[2] and M.J. Power[3]

An Earth system model of intermediate complexity and a land surface model are used to simulate natural fire activity over the last 8000 years. We demonstrate the benefits of using Z-scores as a metric for validating model output with transformed charcoal records.

Fire is an important process that affects climate through changes in CO_2 emissions, albedo, and aerosols (Ward et al. 2012). Fire-history reconstructions from charcoal accumulations in sediment indicate that biomass burning has increased since the Last Glacial Maximum (Power et al. 2008; Marlon et al. 2013). Recent comparisons with transient climate model output suggest that this increase in global fire activity is linked primarily to variations in temperature and secondarily to variations in precipitation (Daniau et al. 2012).

Methodology

In this study, we discuss the best way to compare global fire model output with charcoal records. Fire models generate quantitative output for burned area and fire-related emissions of CO_2, whereas charcoal data indicate relative changes in biomass burning for specific regions and time periods only. However, models can be used to relate trends in charcoal data to trends in quantitative changes in burned area or fire carbon emissions. Charcoal records are often reported as Z-scores (Power et al. 2008). Since Z-scores are non-linear power transformations of charcoal influxes, we must evaluate if, for example, a two-fold increase in the standardized charcoal reconstruction corresponds to a 2- or 200-fold increase in the area burned. In our study we apply the Z-score metric to the model output. This allows us to test how well the model can quantitatively reproduce the charcoal-based reconstructions and how Z-score metrics affect the statistics of model output.

The Global Charcoal Database (GCD version 2.5; www.gpwg.org/gpwgdb.html) is used to determine regional and global paleofire trends from 218 sedimentary charcoal records covering part or all of the last 8 ka BP. To retrieve regional and global composites of changes in fire activity over the Holocene the time series of Z-scores are linearly averaged to achieve regional composites.

A coupled climate–carbon cycle model, CLIMBA (Brücher et al. 2014), is used for this study. It consists of the CLIMBER-2 Earth system model of intermediate complexity and the JSBACH land component of the Max Planck Institute Earth System Model. The fire algorithm in JSBACH assumes a constant annual lightning cycle as the sole fire ignition mechanism (Arora and Boer 2005). To eliminate data processing differences as a source for potential discrepancies, the processing of both reconstructed and modeled data, including e.g. normalization with respect to a given base period and aggregation of time series was done in exactly the same way. Here, we compare the aggregated time series on a hemispheric scale.

Modeled fire activity vs. reconstructions

We simulate a global increase of approximately 3% (from 512 to 526 Mha) in burned area over the past 8 ka (Fig. 1A). The burned area is high against present day observations. The model only accounts for fire activity involving natural vegetation because it ignores land use effects. The gradual increase of burned area and the variability on millennial timescales differ between and among regions; however, the modeled time series transformed to Z-scores and the reconstructed charcoal Z-scores agree well within most of the hemispheric regions, except the Southern extra tropics which are dominated by the ocean and therefore only few model grid boxes are available to compare with. Thus, we can state that our model simulates most of the trends in the fire activity reconstructions on millennial scales.

Z-score transformed data do not provide quantitative information about changes in burned area, because the transformation is rank-conserving but not linear. A given difference in Z-score values does not imply the same magnitude in Mha of burned area among Z-scores from a different time interval or region. This suggests that regional averages of transformed and untransformed data may not necessarily result in the same trends. For example two sites with opposite trends e.g. +50% (from 20Mha to 30 Mha) and -50% (from 100 Mha to 50 Mha) would be merged to a constant Z-score of fire activity, in spite of a decrease in the absolute area burned. Thus, with respect to our research question we conclude that it is more meaningful to convert the time series of modeled burned area or carbon emissions to Z-scores for comparing modeled and observed paleofire variability than comparing quantitative data by the model with qualitative trends out of reconstructions. While we do see some general agreement between model results and reconstructions, it is still unclear whether the absolute values of simulated burned area are capturing the right magnitude of past fire activity.

In all regions, the trends in simulated fire-related carbon emissions are higher than trends in simulated burned area (Fig. 1). We propose several reasons for this observation: (i) increasing atmospheric CO_2 over the Holocene leads to a higher level of CO_2 fertilization. The resulting higher level of carbon stock in the vegetation results in higher emissions per square meter of area burned. (ii) The carbon stock of the fuel can increase with shifts in vegetation type, e.g. from grassland to forest, due to changing climate, or (iii) fire occurrence may be altered by changes in dryness due to climate changes. A rank correlation analysis points to an overall agreement between simulated and observed trends in fire activity over the whole study period, while the rank correlation on 4000-year time segments shows that the model does not match the centennial- or millennial-scale variability (bar charts in Fig. 1). Model-data agreement on fire variability on these centennial timescales is not necessarily expected. Regional climate affects local fire activity, and due to internal variability there is no reason why the timing of modeled fire events should coincide with the reconstructed timing .

Summary

This study provides a method for validating a model's capability to simulate past fire activity. Given that our fire model is not tuned by any charcoal data, the overall data-model agreement within climatic zones validates the paleofire activity reconstructions from syntheses of paleofire records in the Global Charcoal Database. Even regions that are sparsely covered by reconstructions correlate positively with the model results. This points to the benefit of using both data and models together to provide more complete spatial coverage of past fire activity.

Further investigations are necessary to test whether the model performs well for the right reasons. If the driving factor for a reconstructed fire trend is known, the factor separation approach can be applied to test the underlying fire algorithm (Kloster et al. 2014). Despite the great work to synthesize all available charcoal records for regional trends, the information is currently limited to

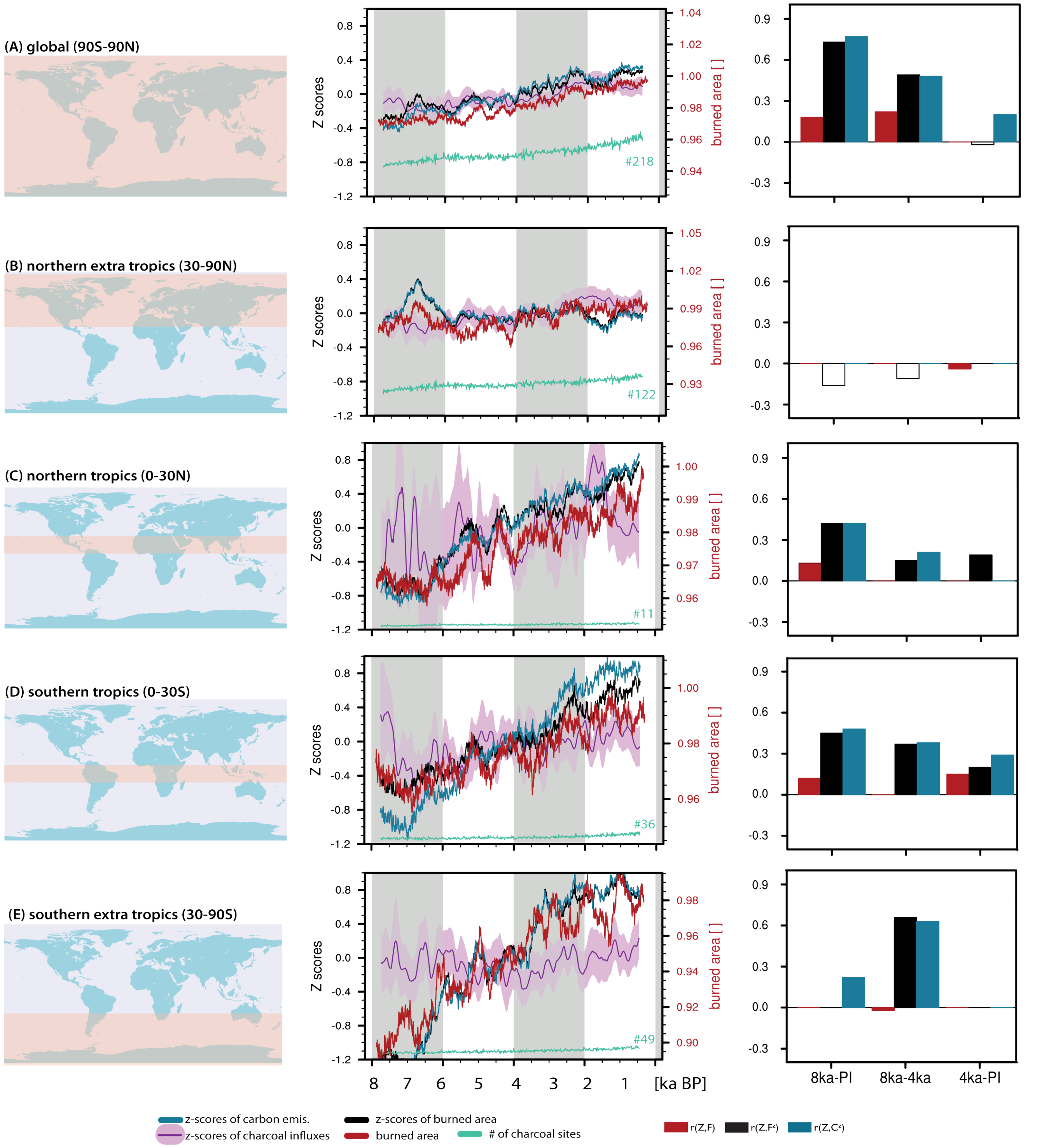

Figure 1: Reconstructed and modeled biomass burning over the last 8 ka. Curves represent zonal averages smoothed with a 250-year running mean on global **(A)**, extra tropical **(B, E)** and tropical **(C, D)** scales. reconstructions are shown by Z-scores of charcoal influxes (pink). Model output is given by untransformed burned area (red) and by the Z-score transformed values of modeled burned area (black) and fire-related carbon emissions (blue). The corresponding bar charts on the right hand side show the regional correlation between charcol records and model results (burned area, Z-score transformed values of burned area and fire-related carbon emissions seperately. Values are given for the full time series (8 ka-PI) and the first and last 4000 years, signicant and positive values are shown by filled bars.

quantitative trends, Future studies on model-data comparison should therefore consider transforming model output variables and paleo-proxy data consistently to improve the comparability of simulated and observed data. In this study, we found that the Z-score transformation helped to validate modeled fire occurrence and compare it to charcoal records. From a modelling perspective it would be preferable to get also quantitative information such as type of biomass burning and area burned.

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Modeling deep ocean flow speeds and δ13C during the Last Interglacial: Towards a more direct model-data comparison

Pepijn Bakker[1,2], A. Govin[3], D. Thornalley[4], D. Roche[1,5] and H. Renssen[1]

Using a climate model we investigate how changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) are reflected in water flow speeds and foraminiferal δ13C, two tracers of AMOC variability commonly measured in marine sediment cores.

Investigating past changes in the Atlantic Meridional Overturning Circulation (AMOC) provides us with clues about the possible multi-decadal to centennial response of the AMOC to projected global warming. Realistic and physically consistent evidence about past changes can be obtained from combining ocean model simulations of past scenarios with real-world proxy data. The common approach for this is to qualitatively compare the model output, i.e. the simulated stream function of maximum AMOC with paleocanographic reconstructions, e.g. foraminiferal δ13C as a proxy for deep sea ventilation changes (Duplessy 1981; Shackleton 1977), or sortable silt as a proxy for bottom water flow speed (McCave et al. 1995). However, this approach is limited to being semi-quantitative at best because (i) different paleoceanographic proxies record different aspects of the AMOC and (ii) comparing these proxies to climate model outputs is not trivial since non of the proxies record the physical overturning as expressed by the stream function. We therefore simulated the water flow speed and δ13C directly within the ocean circulation model. This allows us to discuss what aspects of AMOC changes the two AMOC proxies record, and how this depends on the geographical context.

Towards more direct model-data comparisons

Full carbon cycle dynamics, including isotopes, have been developed and built into the 3-dimensional global climate model of intermediate complexity, iLOVECLIM (Bouttes et al. 2014). In our study, we focus on the last interglacial (LIG; ~130-116 ka BP), which is particularly relevant to future concerns because it was characterized by significant changes in the AMOC strength (Galaasen et al. 2014, and this issue; Govin et al. 2012; Hodell et al. 2009; Oppo et al. 1997, 2006; Sânchez-Goñi et al. 2012) at global temperatures higher than today (e.g. CAPE Members 2006).

We performed a fully coupled transient simulation that covers the 132-120 ka BP time interval. We mimicked the range of reconstructed AMOC changes by gradually tuning up its strength in the model from a nearly collapsed state, to a weak state, and finally, a strong state similar to the present-day. Accordingly, the model produced changes in flow speed and δ13C.

To constrain the underlying mechanisms of flow speed and δ13C we calculated temporal correlations with several potentially important drivers. For local flow speed changes we consider two potential drivers: the transport of deep water formed in the North Atlantic (northern-sourced deep water; NSDW) and deep water formed in the Southern Ocean (southern-sourced deep water; SSDW). In addition to the transport of NSDW and SSDW, we assume that changes in local δ13C may also be driven by δ13C changes in the Northern Hemisphere or Southern Hemisphere source regions or by changes in the local export productivity of biomass from the sea surface to the interior ocean. The relative importance of the drivers is determined by maximizing the correlation for every individual grid-cell between (1) a linear combination of the drivers and (2) flow speed and δ13C respectively (Fig. 1). Only the drivers that proved

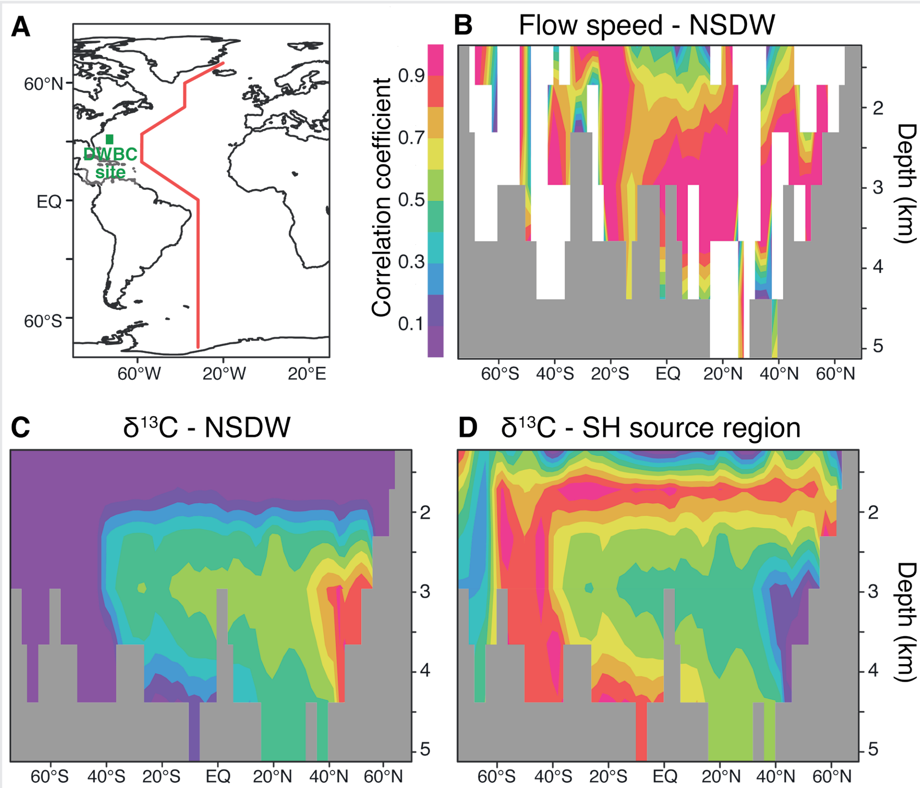

Figure 1: Correlations between AMOC driving factors and simulated flow speeds or δ13C along a vertical transect through the Atlantic. **(A)** Map showing the transect path (red line) and the site used in Fig. 2 (green rectangle). **(B)** Correlations of the flow speed with NSDW. Correlation of δ13C with **(C)** NSDW, and **(D)** SH-source region δ13C changes. The cross-section roughly follows the western boundary of the Atlantic basin. Gray shading means bottom topography; white shading means that no linear combination of the drivers yielded a correlation with the flow speed changes above 0.5.

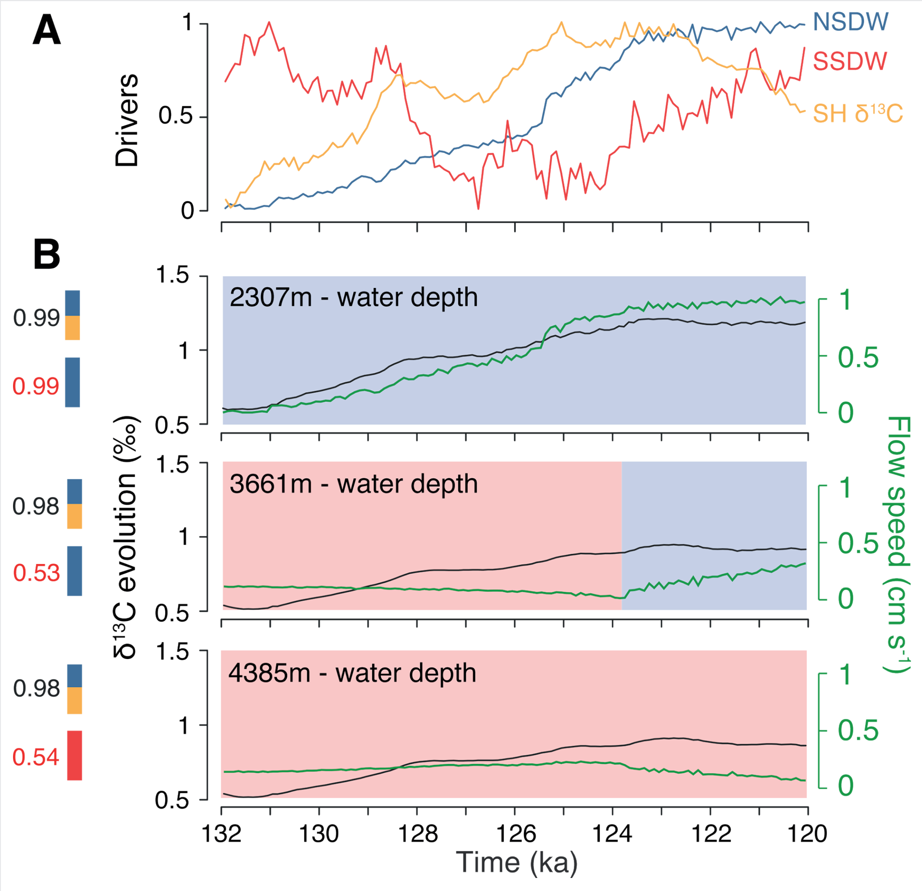

Figure 2: Comparison of the simulated evolution of AMOC indicators during the LIG and their main large-scale drivers for three water depth levels at a site (grid-cell) located in the path of the DWBC in the subtropical northwestern Atlantic (green rectangle in Fig. 1A). **(A)** Simulated main drivers. **(B)** Evolution of δ^{13}C (black) and flow speed (green). The vertical colored bars and associated R^2 correlation values indicate the relative importance of the main (normalized) drivers shown in panel A in reaching a best linear fit with the simulated records of δ^{13}C (top bar) and flow speed (lower bar), respectively. For flow speed only NSDW and SSDW were taken into account. Red and blue shading of the panels indicate the water mass prevalent at each depth level, where southward flow was taken to be indicative of SSDW, northward flow of NSDW.

important are discussed in the following and shown in Figs. 1 and 2.

Distinguishing Atlantic deep water masses

In the depth profiles in Fig. 1, the correlation coefficients between simulated δ^{13}C and the predetermined drivers show distinguished patterns that can be associated with the main Atlantic deep-water masses. For example, δ^{13}C values in the North Atlantic Deep Water region centered around 3 km depth appear driven by changes in NSDW (Fig. 1C), while changes in the surface water δ^{13}C in the Southern Hemisphere region of deep water formation (SH source region, Fig. 1D) drive the δ^{13}C evolution in the Antarctic Intermediate Waters and Antarctic Bottom Waters, centered around 1.7 km and 4.5 km respectively.

Conversely, the correlation pattern for simulated flow speed and its drivers does not reveal such clear large-scale water masses. This could indicate that flow speed changes are not reflecting large scale changes in the transport of NSDW and SSDW, however, in the following we will show that they do, and moreover, that they allow an investigation of the thickness and depth habitat of the different water masses (Thornalley et al. 2013).

Local-scale and vertical water mass changes revealed by simulated flow speed

Local flow speed changes relate to changes in the vertical structure of the water column, i.e. the migration of the boundary between the two main water masses at the site (NSDW overlying SSDW) and their thicknesses. This can be demonstrated when analyzing the LIG simulation at three depth-levels of a single model grid-cell in the core of the Deep Western Boundary Current (DWBC; Figs. 1A and 2).

At the 2307 m depth-level, NSDW predominates throughout the LIG. Accordingly, the correlation between flow speed and NSDW strength is high. Both increase almost linearly, and level off during the last few millennia of the LIG.

At the 3661 m depth-level, SSDW predominates until 124 ka BP, but as the SSDW water mass gradually migrates downwards as a result of expanding NSDW, the SSDW core region, where northward flow velocity is at its maximum, sinks away from the 3661 m depth level, resulting in a local decrease in flow speeds. At 124 ka BP, NSDW has reached the site, and as its corresponding velocity maximum gradually migrates towards the 3661 m depth-level, it causes flow speed to increase again.

At the 4385 m depth-level, SSDW predominates throughout the LIG; however, the expansion of NSDW pushes the SSDW core downwards over time. At first flow speed increases as the SSDW velocity maximum moves towards the 4385 m depth level and during the later part of the LIG flow speeds start to decrease when the SSDW velocity maximum core has passed the 4385 m depth level and moves even deeper.

Outlook

Simulating flow speeds and δ^{13}C changes in response to a strengthening AMOC shows that the two parameters yield different but complementary information about deep ocean circulation changes: the δ^{13}C record provides information about the large scale water mass changes, while flow speed changes relate to the vertical migration and thickness of the different deep ocean water masses.

The limitations of this study lie in the fact that (i) we use a low-resolution climate model and (ii) our methodology simplifies the complexity of the climate system by implying that the different drivers are independent from each other and that their relative contributions are constant through time.

This study provides the ground for quantitative δ^{13}C and flow speed model-data comparison (Bakker et al. in review). Another worthwhile target for future studies of a similar design may be the deglaciation across the Younger Dryas, a period characterized by strong AMOC changes and a good density of high-resolution paleoceanographic proxy data.

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Deep Atlantic variability during the last interglacial period

Eirik V. Galaasen[1], U.S. Ninnemann[1,2], N. Irvalı[1], H.F. Kleiven[1,2] and C. Kissel[3]

A new multi-decadally resolved benthic stable isotope record suggests that the distribution of deep Atlantic water masses experienced large, short-lived changes during the Last Interglacial. The findings question the relative stability of deep circulation during times of warmth and ice retreat.

One key uncertainty in future climate projections involves changes to the circulation of North Atlantic Deep Water (NADW) and how it responds to buoyancy gain from warmth and freshwater additions in the regions of deep-water formation. Model simulations of Atlantic overturning strength range from nearly no change to ~50% reduction by 2100 AD (Stocker et al. 2013). Reconstructions of NADW variability during past warm periods provide an opportunity to assess its potential response to conditions similar to those we may face in the future. For example, did NADW respond to the forcing of the last interglacial period (LIG; ~115-130 ka) when its source region experienced elevated warmth in the order of ~2-4°C and ice mass retreat relative to today (Otto-Bliesner et al. 2006; NEEM community members 2013)? Yes, suggests our ultra-highly resolved stable isotope record generated as part of the Past4Future project.

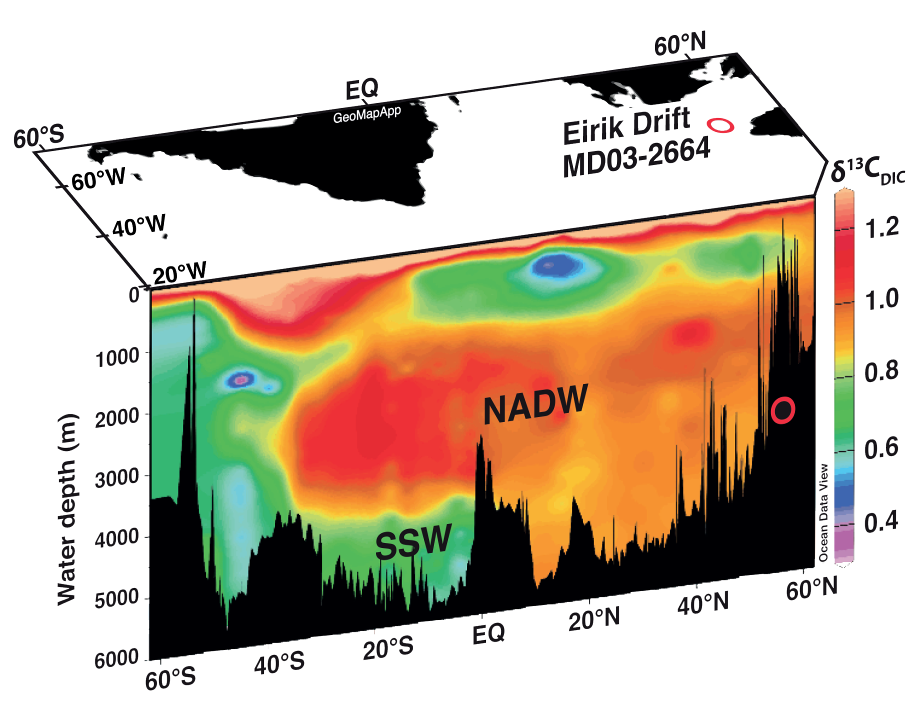

Figure 1: The location of Eirik Drift core site MD03-2664 (red circle: 57°26′N, 48°36′W; 3442 m water depth) plotted geographically and projected onto the mid-Atlantic topographic profile. Colors show the modern carbon isotopic composition of dissolved inorganic carbon ($\delta^{13}C_{DIC}$; Key et al. 2004). Note the strong influence of high-$\delta^{13}C$ North Atlantic Deep Water (NADW) in the modern Atlantic, overlying low-$\delta^{13}C$ Southern Source Waters (SSW). Figure modified from Galaasen et al. (2014).

NADW variability during the LIG

Galaasen et al. (2014) reconstructed variability in NADW over the LIG using epibenthic foraminifera *C. wuellerstorfi* $\delta^{13}C$ from the Eirik Drift (Fig. 1). This foraminifera records the ambient bottom water $\delta^{13}C$ in its shell (e.g. Duplessy et al. 1984), hence it can be used to map out the distribution and circulation of water masses in the Atlantic interior (Fig. 1). The rapid sediment accumulation of ~35 cm ka^{-1} at the Eirik Drift site allowed us to reconstruct variability in newly formed Lower NADW with a high temporal resolution of ~30 years.

The Eirik Drift bottom water $\delta^{13}C$ record indicates that NADW circulation was stable on multi-millennial timescales during the LIG, consistent with previous studies (e.g. Adkins et al. 1997). However, zooming in on shorter timescales reveals that this stable circulation state was interrupted repeatedly as the influence of NADW waned (bottom water $\delta^{13}C$ decreased; Fig. 2) and Southern Source Water (SSW) advanced to fill the deep Atlantic. These transient NADW reductions reflect marked shifts in the circulation pattern and spatial geometry of the deep Atlantic, with shoaling of NADW and northward expansion of SSW (Fig. 1). Although difficult to determine precisely, each of these anomalies appears to have lasted several centuries before recovering, operating as if the circulation was near a threshold, but occasionally flickering back and forth across it. A critical question is then, what pushed the circulation towards this threshold and triggered these NADW reductions? Buoyancy gain in the NADW source regions likely played a key role.

The transient NADW perturbations were more pronounced and more frequent around the early part of the LIG interval. This period was characterized by peak Northern Hemisphere warmth (Otto-Bliesner et al. 2006; NEEM community members 2013) and high input of icebergs (ice-rafted debris (IRD) increases) and freshwater (*N. pachyderma* (s) Ba/Ca increases) at the sea surface in the Eirik Drift region (Fig. 2). The last and most prominent of the NADW anomalies during the early LIG (at ~124 ka) was also associated with an outburst flood analogous to the one believed to have triggered the 8.2 ka event, when large amounts of freshwater entered the North Atlantic through the Labrador Sea (Nicholl et al. 2012; Galaasen et al. 2014). Taken together, this highlights buoyancy gain from a generally warm

background climate and episodic freshwater inputs as the trigger for the transient NADW anomalies of the LIG. Increases in the abundances of *N. pachyderma* (s) in the Eirik Drift core also indicate that each of the NADW anomalies was associated with an increased influence of polar, i.e. cold and fresh surface water (see Galaasen et al. 2014). A similar pattern of repeating and transient polar water expansions during the LIG was also found in the northeastern North Atlantic (Mokeddem et al. 2014). This suggests that the hydrographic surface water anomalies detected at the Eirik drift site might in fact have extended across the subpolar North Atlantic, indicating a strong coupling between surface and deep ocean conditions.

Interglacial NADW instability

Previous studies have suggested that NADW ventilation was generally suppressed during the early part of the LIG (e.g. Sánchez Goñi et al. 2012). The new high-resolution Eirik Drift record revises this notion, suggesting rather that several centennial-scale NADW changes occurred superimposed on a longer-term stable circulation state that was established at the start of the LIG benthic $\delta^{18}O$ plateau (e.g. Adkins et al. 1997). However, the dimension of these NADW reductions remains unclear. While apparent in the deepest parts of the northeast (Hodell et al. 2009) and northwest Atlantic (Galaasen et al. 2014), suggesting NADW shoaled, determining how far will require additional constraints from shallower water depths.

High-resolution records of NADW variability are now available for both the Holocene and LIG, providing new insights into the stability of NADW under warm climate conditions. In both interglacials, NADW reductions cluster around the early phase. This suggests that retreating ice masses remnant from the prior glaciation were important triggers for NADW perturbations (Kleiven et al. 2008; Galaasen et al. 2014). Yet, while the Holocene experienced only one substantial perturbation to the ventilation of NADW, associated with the 8.2 ka event (Ellison et al. 2006; Kleiven et al. 2008), the LIG had several more (Fig. 2). Indeed, NADW reductions may not even have been limited to the phase of peak warmth and ice retreat during the early part of LIG. The Eirik Drift data indicate that NADW changes also occurred during the later phases of the LIG (Fig. 2).

Although these variations still need to be replicated using other high-resolution sites, the increased frequency of NADW reductions during the LIG compared to the Holocene may suggest that deep Atlantic ventilation is increasingly vulnerable as its source region warms and freshens beyond today's levels. Further studies, including data-model comparisons and extending high-resolution records to previous interglacials, may help constrain where that potential buoyancy threshold lies and elucidate its full consequences for the circulation of the deep Atlantic.

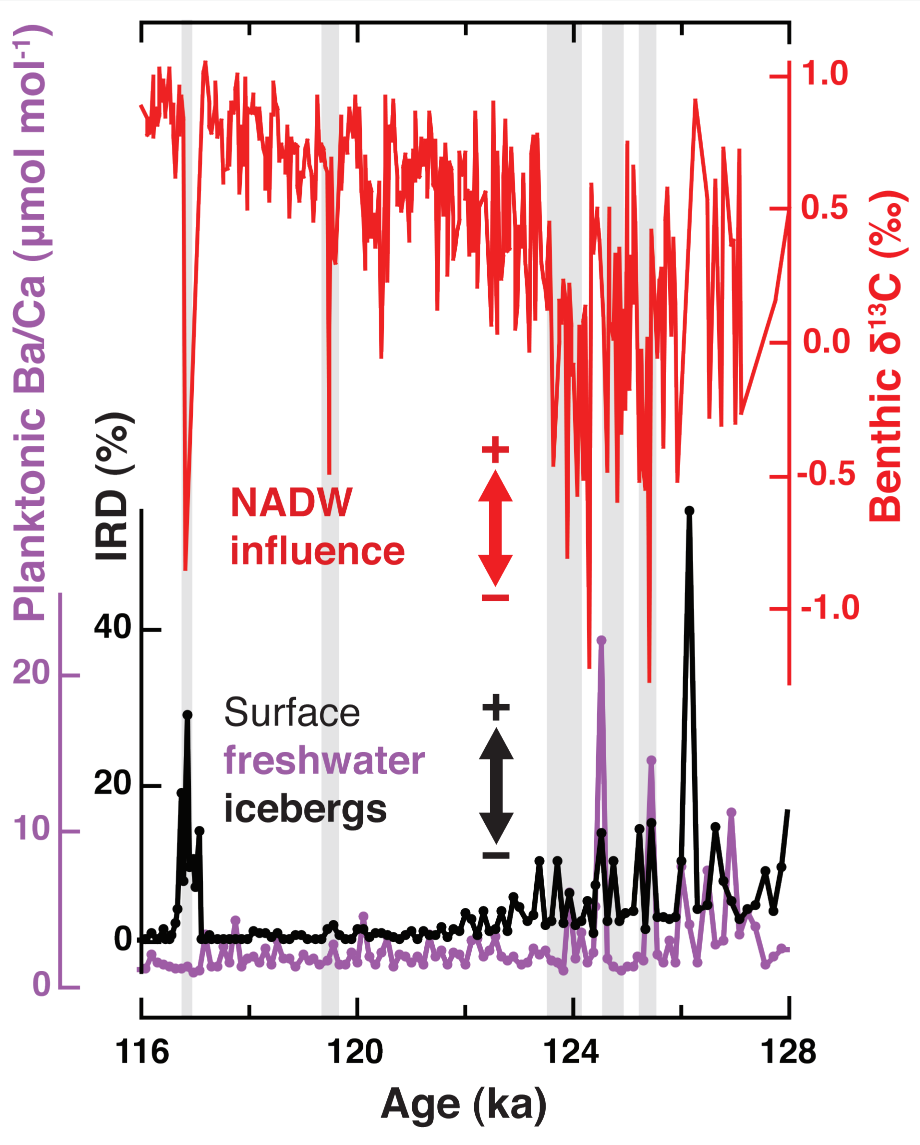

Figure 2: Eirik Drift sediment core MD03-2664 records across the LIG, focused on the Marine Isotope Stage 5e benthic $\delta^{18}O$ plateau, (116.1-128.0 ka; Shackleton et al. 2002; Shackleton et al. 2003): Red curve: $\delta^{13}C$ measured on shells of the epibenthic foraminifera *C. wuellerstorfi*; Purple curve: Ba/Ca ratio in shells of the planktonic foraminifera *N. pachyderma* (s); Black curve: Ice-rafted debris (IRD) percentage in the coarse fraction. Gray shading highlights intervals of reduced bottom water $\delta^{13}C$ and NADW influence. Figure modified from Galaasen et al. (2014).

DATA

The Eirik Drift core MD03-2664 epibenthic foraminifera stable isotope data are available as supplementary material to Galaasen et al. (2014).

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The Agulhas Leakage: the missing link in the interhemispheric climate seesaw?

Gianluca Marino[1] and Rainer Zahn[2,3]

The Agulhas Leakage is a key component of the Atlantic Meridional Overturning Circulation. Unraveling the past patterns of leakage variability and associated heat and salt anomalies into the Atlantic Ocean holds clues for their role in ocean and climate changes.

The Atlantic Meridional Overturning Circulation (AMOC) modulates climate on a range of temporal and spatial scales. The northward heat transport associated with its upper limb ameliorates the North Atlantic climate, while its southward flowing lower limb transfers carbon from the atmosphere into the ocean interior (Visbeck 2007; Lozier 2012). Processes taking place in the Northern Hemisphere are historically regarded as the main drivers of the AMOC through their direct influence on the North Atlantic Deep Water (NADW) formation (Lozier 2012). Mounting evidence, however, emphasizes that the inter-ocean exchange of water south of Africa (Beal et al. 2011) and the upwelling of deep water offshore Antarctica (Visbeck 2007) are also potentially important control factors for the AMOC. We are focusing here on the transport of warm and saline waters from the subtropical Indian Ocean by the Agulhas Current, which flows southward along the shelf edge of southern Africa. While most of the Agulhas Current water recirculates into the Indian Ocean, a variable fraction, Agulhas Leakage (AL), escapes into the South Atlantic Ocean (Beal et al. 2011). Recent studies contend that the AL sets the southern control for the Atlantic upper ocean buoyancy budget and thus ultimately for the AMOC variability. Potential mechanisms for buoyancy control include planetary-wave adjustments in the Atlantic thermocline and/or advection of salt to the NADW formation sites (Beal et al. 2011 and references therein).

Paleo-reconstructions of the Agulhas Leakage

Several approaches have been used to investigate past AL dynamics. In their seminal study, Peeters et al. (2004) tracked the inter-ocean transport of Indian Ocean subtropical waters into the South Atlantic, using variations in tropical-subtropical planktic foraminifera, the Agulhas Leakage Fauna. From reconstructions of sea surface temperature (SST) and productivity changes Bard and Rickaby (2009) inferred the position of the Subtropical Front. Its meridional migrations reflect the oceanographic response to changes in the westerlies, impacting the width of the Indian-to-Atlantic oceanic gateway and, in turn, the inter-ocean water exchange (Beal et al. 2011). SST and seawater stable oxygen isotope ($\delta^{18}O_{sw}$, a qualitative proxy for salinity) fluctuations, based on paired Mg/Ca-$\delta^{18}O$ data in planktic foraminifera, allowed changes in inter-ocean heat and salt transports to be deciphered (Marino et al. 2013). All these reconstructions consistently show that the AL intensified during glacial terminations. However,

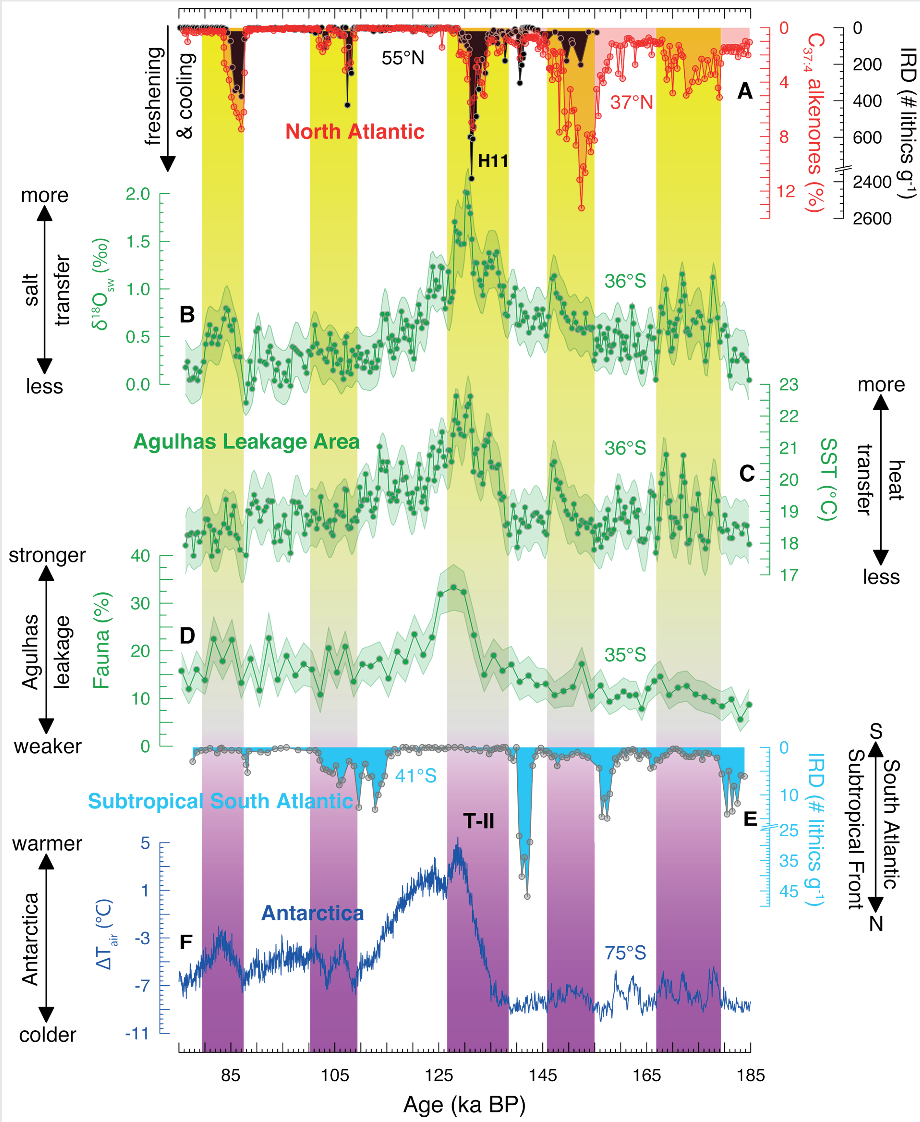

Figure 1: Agulhas leakage variability and interhemispheric climate change across the penultimate glacial-interglacial cycle. **(A)** North Atlantic Ice Rafted Debris (IRD, black) from ODP site 980 (Oppo et al. 2006) and tetraunsaturated alkenones ($C_{37:4}$, red) from MD01-2444 (Martrat et al. 2007). **(B, C)** Seawater stable oxygen isotopes ($\delta^{18}O_{sw}$) and sea surface temperatures (SST) from MD96-2080 (Marino et al. 2013). **(D)** Agulhas Leakage Fauna from GeoB3603-2 (Peeters et al. 2004). Uncertainty envelopes (2σ) are shown in B-D. **(E)** IRD from MD02-2588 (Marino et al. 2013). **(F)** Antarctic temperature anomaly from EPICA Dome C ice core (Jouzel et al. 2007). Vertical bands highlight intervals of North Atlantic cooling and Agulhas leakage strengthening. T-II=glacial Termination II; H11=Heinrich event 11. Figure modified from Marino et al. (2013).

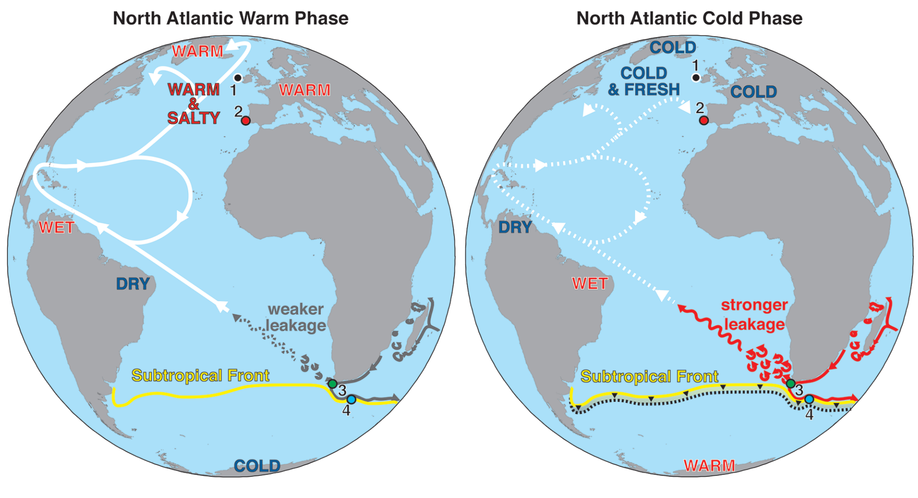

Figure 2: Sketch illustrating the relationship between Agulhas Leakage (AL) and North Atlantic climate. **North Atlantic warm phase**; the Atlantic Meridional Overturning Circulation (AMOC) is strong, while the AL is weak. **North Atlantic cold phase**; the AMOC weakens, likely due to enhanced freshwater discharge into the North Atlantic. The attendant changes in the interhemispheric ocean and atmospheric circulation cause the southward shift and potential intensification of the mid-latitude westerlies in the Southern Hemisphere, accompanied by the southward migration of the Subtropical Front that strengthens the AL. Core locations are shown: ODP 980 (1), MD01-2444 (2), MD96-2080, GeoB3603-2 (3) and MD02-2588 (4).

comparison of high- (Marino et al. 2013) and low-resolution (Peeters et al, 2004) records spanning the penultimate glacial-interglacial cycle reveal that maxima in salinity, SST, and (where sufficiently resolved) faunal assemblages associated with the AL, as well as southward shifts of the regional oceanic fronts, were not limited to the prominent change across glacial Termination II (T-II). Rather smaller-scale maxima also coincided with several millennial-scale episodes of North Atlantic cooling and freshening and concurrent Antarctic warming during glacial and interglacial times (Fig. 1A-F).

Millennial-scale Agulhas Leakage variability

The paleo-evidence discussed above testifies to the link between variations in AL strength and interhemispheric or even global climate changes. In particular the Pleistocene glacial terminations feature prominent AL events. The detailed paleoceanographic reconstructions spanning T-II (Fig. 1) document that: (1) the AL maximum of T-II coincided with Heinrich event 11 (Marino et al. 2013), when the North Atlantic was cold and the AMOC weak (Fig. 1A-D); (2) as was the case during earlier glacial terminations (Peeters et al. 2004), the AL maximum was limited to the termination and did not extend into the subsequent interglacial, which featured only transient and low-amplitude AL intensifications (Marino et al. 2013) (Fig 1B-D); (3) more anticyclonic eddies carrying warm and saline waters entered the South Atlantic (Scussolini et al. 2013).

Based on these observations and previous paleoceanographic analysis, we propose that the AL and its influence on the South Atlantic hydrography in the past were dominated by variability on a millennial timescale. The "terminal leakage events" during glacial-interglacial transitions were millennial-scale maxima of inter-ocean transport that, like their smaller scale counterparts, developed in response to AMOC weakening and ensuing North Atlantic cooling (Fig. 2). This initiated a sequence of feedback responses that impacted the Southern Hemisphere westerlies (Lee et al. 2011), with knock-on consequences for the position of the regional oceanic fronts and AL strength. During glacial terminations, large CO_2 rise (Toggweiler et al. 2006) and sustained Southern Ocean warming (Knorr and Lohmann 2007) may explain the particularly strong AL indicated by the data, e.g. by amplifying the responses of the Southern Hemisphere westerlies and the Subtropical Front. Nevertheless, questions remain on the postulated interplay between changing wind field and the AL strength. In fact, the scenarios inferred from the paleorecords seem to disagree with state-of-the-art numerical simulations, which, however, are only run with modern boundary conditions (Durgadoo et al. 2013).

Outlook

Despite the strong paleoceanographic evidence for an AL involvement in glacial-interglacial transitions and possibly in more abrupt climate episodes (Peeters et al. 2004; Marino et al. 2013), it remains to be determined whether the AL responded passively to these changes or played an active role in them. Analysis of the temporal phasing suggests that AL maxima lead AMOC strengthening. Based on that, one can argue that the AL was both a passive and an active player. The leakage intensified passively in response to AMOC weakening/North Atlantic cooling (passive role), but the attendant negative buoyancy forcing may then have actively contributed or even caused the subsequent AMOC resumption (Knorr and Lohmann 2007; Beal et al. 2011).

Several limitations prevent us from unambiguously solving this riddle. The detailed phasing between AL fluctuations and changing AMOC is limited by difficulties inherent in aligning the paleo-records from the southern tip of Africa with those from the North Atlantic and Antarctica (Marino et al. 2013). Paleo-modeling supports the hypothesis that intensified leakage and AMOC resumption are coupled (Knorr and Lohmann 2007). Explaining the apparent temporal offset between AL strengthening and AMOC resumption would require a buoyancy threshold for reinvigorating NADW formation. However, quantitatively constraining the buoyancy threshold is limited by our ability to quantitatively translate paleo-$\delta^{18}O_{sw}$ variations into salinity changes, because the $\delta^{18}O_{sw}$-salinity relationship varied in the past particularly in regions dominated by advective processes (Rohling and Bigg 1998).

To identify the exact role of the AL in climate change, the focus of paleoceanographic research must shift to a quantitative analysis of the heat and salt transports around the southern tip of Africa and across the Atlantic Ocean. The high-amplitude leakage events at glacial terminations may be used to reconstruct with a higher degree of confidence the signal propagation into and across the Atlantic Ocean, thereby serving as templates for the millennial-scale leakage maxima that punctuated glacial and interglacial climates.

ACKNOWLEDGEMENTS

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DATA

Data presented here are available from the corresponding author and are in the process of being submitted to NOAA NCDC.

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Sea-ice variability off West Greenland over the last five millennia derived from diatom assemblages

Longbin Sha[1], H. Jiang[1], M-S. Seidenkrantz[2], K.L. Knudsen[2], J. Olsen[3] and A. Kuijpers[4]

A diatom-based sea-ice transfer function was developed for the north-western Atlantic. A first reconstruction of sea-ice concentration off West Greenland shows multi-centennial oscillations superimposed an overall trend of expanding sea ice over the last 5000 years.

Sea ice is a sensitive component of the Earth's climate system. It acts as an effective insulator between the oceans and the atmosphere, restricting the exchange of heat, mass, momentum and chemical constituents (Divine and Dick 2006). However, reliable and continuous observations of sea ice only exist since 1978. Extending the sea-ice record further back in time is necessary, e.g. to provide well-constrained boundary conditions and benchmarks for model simulations.

Diatoms are marine siliceous algae which have been used successfully for quantitative reconstructions of sea-ice conditions, mostly in the Southern Ocean (Crosta et al. 1998; Gersonde et al. 2005) but also in the north-western Atlantic (Justwan and Koç Karpuz 2008). We have now established a new diatom-based transfer function for past sea-ice concentrations (SIC) for the region off West Greenland (Fig. 1) and applied it to produce a ca. 5000 year-long reconstruction (Sha et al. 2014).

Modern diatom-SIC dataset

We determine the modern calibration between diatom assemblages and SIC data based on (1) diatom assemblage analysis from 72 surface sediment samples from the north-western Atlantic (Fig. 1) and (2) monthly means of the satellite SIC data collected from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data.

Diatom assemblages are distinguished, with respect to monthly average SIC, using canonical coordination techniques (ter Braak and Šmilauer 2002; Lepš and Šmilauer 2003). Of the 12 monthly mean SICs, only April, August, October, and November SICs influence variations in the diatom data noticeably. And of those months, forward selection and an associated Monte Carlo permutation test reveal that only April and August SICs explained a statistically significant ($p \leq 0.001$) amount of variation in the diatom assemblage data, representing 52% of the total canonical variance. The April SIC alone accounts for 38% (August 14%), suggesting that it is the most important environmental control on diatom ecology in this area. This is coherent with the observation that April is one of the most critical months for diatom blooms as the combined light and temperature conditions are often optimal in this month.

Transfer function for April SIC

Multiple numerical reconstruction methods such as Modern Analogue Technique (MAT, based on one to five analogues), Weight Averaging regression (WA), and Weighted Averaging with Partial Least Squares regression (WA-PLS, based on one to five components) were tested and evaluated for developing the most reliable diatom-based transfer function for April SIC. These tests reveal that the numerical reconstruction based on WA-PLS with three components results in the most reliable diatom-based SIC for the area (see Sha et al. 2014 for details).

Testing the SIC reconstruction

In order to test the reliability of the diatom-based SIC reconstruction as a measure for paleoceanographic changes in the north-western Atlantic region, we compared the reconstructed SIC of the last ~75 years from box core GA306-BC4 (445 m water depth) with the satellite SIC record for 1979-2006 (Fig. 2A). Additionally, we compared our reconstructed SIC with the model SIC from the HasISST 1.1 dataset (Rayner et al. 2003) during 1953–2006, and with the mean water temperature in the upper 200 m west of Fylla Bank during 1963-2006.

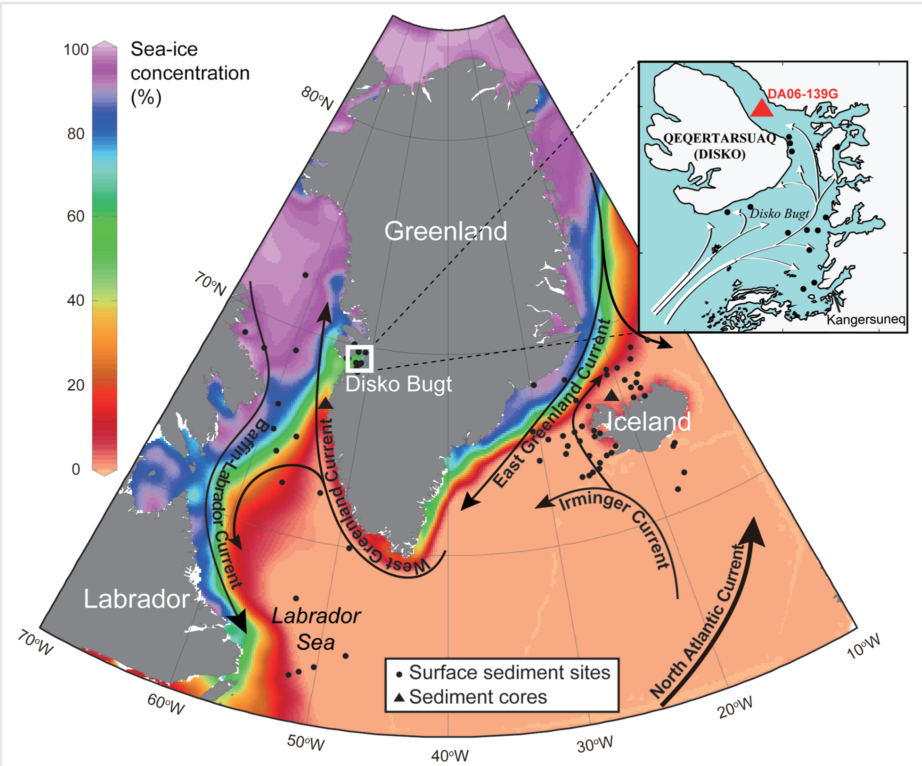

Figure 1: Maps of the NW Atlantic, indicating the prevailing surface currents, the distribution of surface sediment samples for the regional diatom-based sea-ice transfer function, and the locations of the sediment cores mentioned in the text. The satellite April sea-ice concentration for 1979-2010 is indicated as a background.

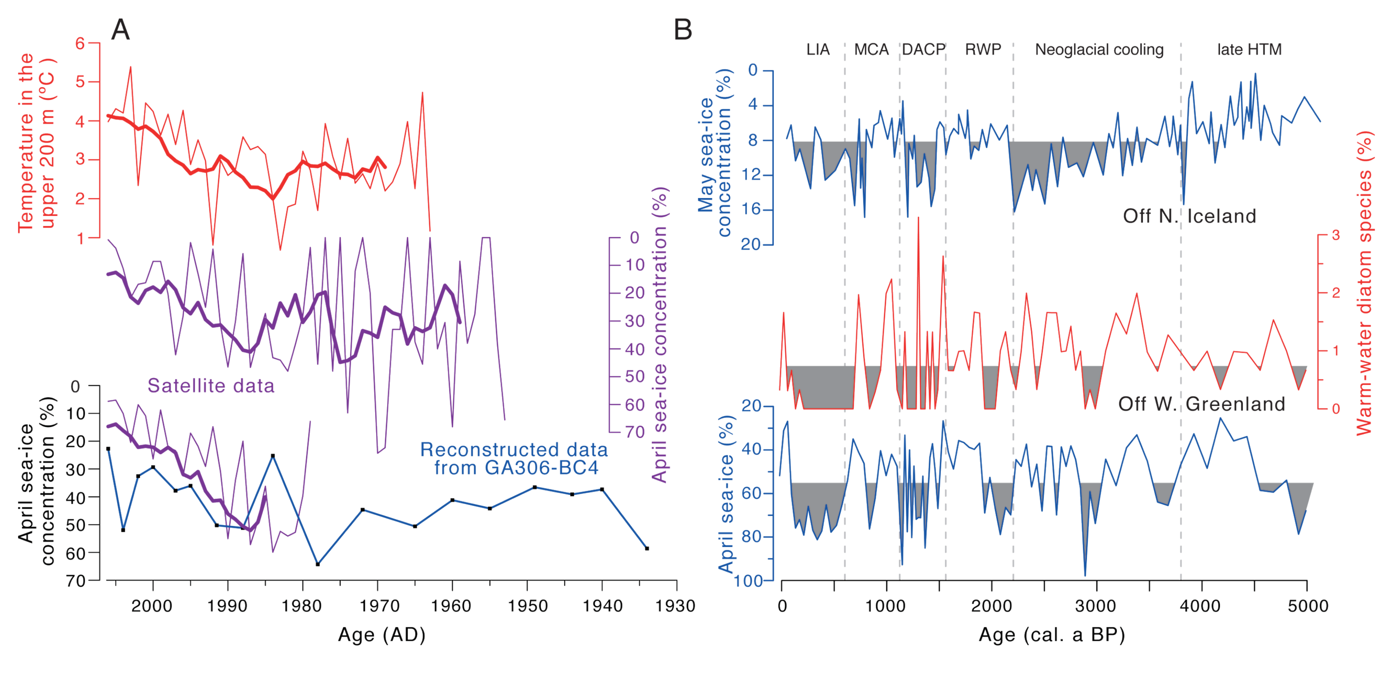

Figure 2: Sea-ice records over the last century and the last 5000 years, respectively. **(A)** From bottom to top: Reconstructed SIC (blue) from core GA306-BC4 compared with the SIC from satellite observation (red) and model output (purple), and annual mean instrumental temperatures (orange). Original data are shown as thin lines; thick lines are 7-point weighted moving averages. **(B)** From bottom to top: Reconstructed SIC (blue) and warm-water diatom taxa (green) from core DA06-139G, reconstructed May SIC from core MD99-2269 (purple; Justwan and Koç Karpuz 2008). The gray shading indicates value below each record's mean. Approximate time intervals for historical NE Atlantic climate events are given (LIA: Little Ice Age; MCA: Medieval Climate Anomaly; DACP: Dark Ages Cold Period; RWP: Roman Warm Period; HTM: Holocene Thermal Maximum). Figure modified from Sha et al. (2014).

The diatom-based reconstructed SIC exhibits a generally similar distribution pattern to the satellite and model sea-ice data, as well as the instrumental temperature records, although with a few temporal differences (Fig. 2A). These temporal differences may be caused by uncertainties in the chronology and the low temporal resolution of the sediment core. However, the comparison suggests that overall our diatom-based SIC transfer function is a reliable method for studying paleoceanographic changes in the north-western Atlantic.

A 5000-year record of April SIC

The transfer function was applied to the diatom assemblages from core DA06-139G (384 m water depth, Fig. 1) to establish an April SIC record for the last 5000 years in the Disko Bugt (Fig. 2B; Sha et al. 2014). The reconstructed SIC values varied between 25-95% around a mean of 55%, with an overall trend towards increasing sea ice. Between 5000 and 3860 cal yr BP, our results suggest that the SIC was generally below the mean value except for a short period around 4900 cal yr BP. This coincides with relatively warm conditions suggested by an abundance of warm-water diatom species (Fig. 2B). This period corresponds to the latest part of the Holocene Thermal Maximum. Between 3860 and 1510 cal yr BP SIC oscillated around the mean value. From 1510-1120 cal yr BP and after 650 cal yr BP was above the mean, indicating that sea-ice cover in Disko Bugt was particularly extensive.

Warm-water diatom species reflect warm Atlantic water, as evidenced by the abundant distributions in surface sediments (Sha et al. 2014). The distribution pattern of sea-ice diatom species correlates well with the strength of cold polar water from the East Greenland Current (Sha et al. 2014). Agreement between reconstructed SIC and changes in the diatom species suggests that sea-ice conditions in Disko Bugt were influenced by variations in the relative strength of the two main components of the West Greenland Current, i.e. the cold East Greenland Current carrying polar water from the Arctic Ocean and the relatively warm Irminger Current of Atlantic origin (Fig. 2B). The North Icelandic shelf was influenced by both the Irminger Current and the East Greenland Current. A diatom-inferred May SIC record from there, shows a similar SIC pattern to that found in the Disko Bugt, particularly during the time periods before 3500 cal yr BP and after 2000 cal yr BP (Justwan and Koç Karpuz 2008; Fig. 2B). Differences observed between the two reconstructions during the 3500-2000 cal yr BP time interval may reflect that the different approaches used to reconstruct past sea-ice variations could describe different aspects of sea-ice cover. Finally, a preliminary comparison between the reconstructed SIC record and total solar irradiance suggests a relationship between solar forcing and sea-ice changes (Sha et al. 2014).

Outlook

We established a new diatom-based SIC transfer function for the north-western Atlantic region and provided a quantitative reconstruction of April sea-ice conditions in this region over the last 5000 years. Discussions remain about what causes sea-ice variations in the area and more detailed analysis are currently being performed to decipher the controlling factors.

In spite of its advantage for quantitatively extending sea-ice record to geological past, our diatom-based SIC transfer function still has some limitation due to re-suspension and preservation of some diatom species through time. In order to reconstruct sea-ice variability with confidence, a multi-method strategy will be focused on, which may capture complementary information from the complex relationships between surface sediment diatoms and the modern environmental variables.

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The Past4Future project: outreach and dissemination of results

Dorthe Dahl-Jensen

Climate change is not only of concern to scientists but also to the public, media, and policymakers. Therefore, it is critical that EU projects dedicate effort to reaching out to these groups. This article describes the approaches taken by Past4Future.

The Past4Future project was a five-year project combining the expertise of 22 European and associated international project partners (Fig. 1). The project's core objective was to inform our knowledge about future climate and possible abrupt changes by researching similar conditions in the past and share the findings widely. Therefore, a substantial part of efforts and resources went into communicating the project results to a broad audience, including scientists both within and external to the climate science community, as well as policymakers and the public (Fig. 2A). This article provides an overview of the efforts undertaken and describes some of the achievements and barriers encountered along the way.

Communicating with stakeholders

Early in the project, a stakeholder survey was carried out to identify the method of dissemination that would be of most value to the main user groups, including scientists, policymakers, and the public. While the survey confirmed a general demand for scientific information, demands also extended to the clarity of communication. Scientific issues need to be presented in a clear way, which includes that robust results are identified and distinguished from more speculative scenarios and unlikely developments. Due to the complexity of the scientific issues involved in climate change, many misconceptions and contradictory statements appear to exist, particularly among the public.

Getting feedback from the stakeholders turned out to be a major difficulty. Accordingly, we only received complete information from 13 of the 141 contacted (Thing 2013). This might illustrate that stakeholders are busy people and that a science survey has a low priority for them. Communication must therefore be particularly targeted and brief.

From the feedback we had received, it become very clear that stakeholders do not want information to be presented in the form of glossy brochures, and that information using the Intergovernmental Panel on Climate Change (IPCC) way of communicating uncertainty in text and graphs is preferred. Stakeholders preferred that shorter timescales of climate change impacts (10-100 years, within human lifetimes) were reported, although longer timescales were also acknowledged to be relevant. Information on most aspects of the climate system was considered important, with temperature and sea level considered top priorities.

Based on the feedback from the survey, we focused Past4Future communication efforts on participation in and contribution to the Fifth Assessment Report of IPCC's Working Group 1 (IPCC 2013), on press material related to publications by Past4Future researchers, and on press sessions at the EGU meetings in 2013 and 2014. Furthermore, final Past4Future findings were presented in three summary papers during a lunch meeting for decision makers in Brussels.

Communicating results to the scientific community

The scientific communication in Past4Future focused on peer-reviewed publications. A total of 207 papers in peer-reviewed journals, 97 of them open access, have acknowledged the Past4Future grant from the EU's Seventh Framework Programme (Fig. 2B, and full list at www.past4future.eu). These papers have been cited at least 777 times (as of Nov 2014), resulting in an overall h-index of 13.

The publications present major results on the behavior of the climate system in the last and the present interglacial periods. The systematic study of changes in these periods in the framework of Past4Future

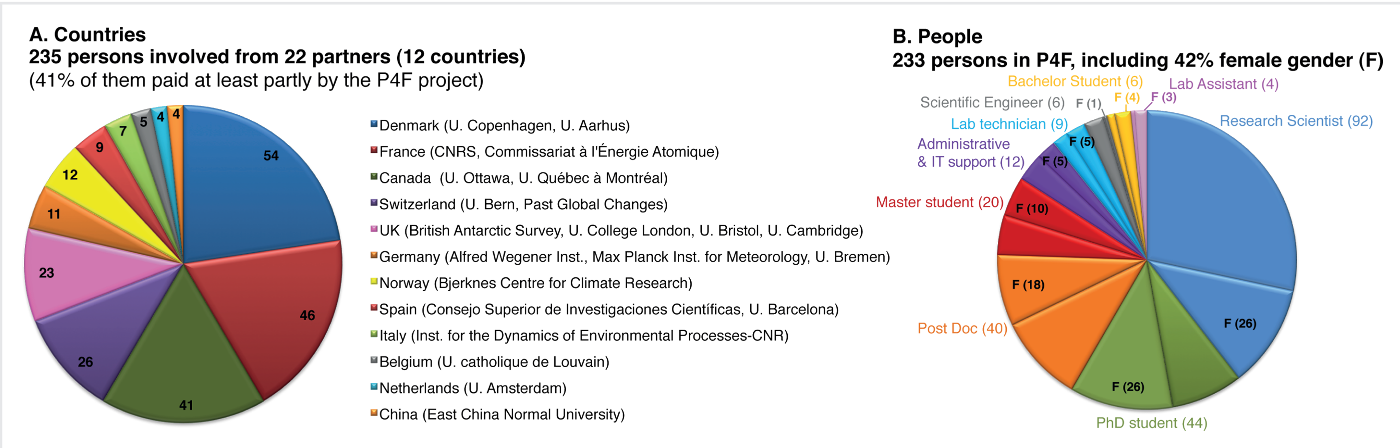

Figure 1: Statistics related to the structure of the Past4Future project, including **(A)** the project partners and their national affiliations and **(B)** the functions and gender of people involved.

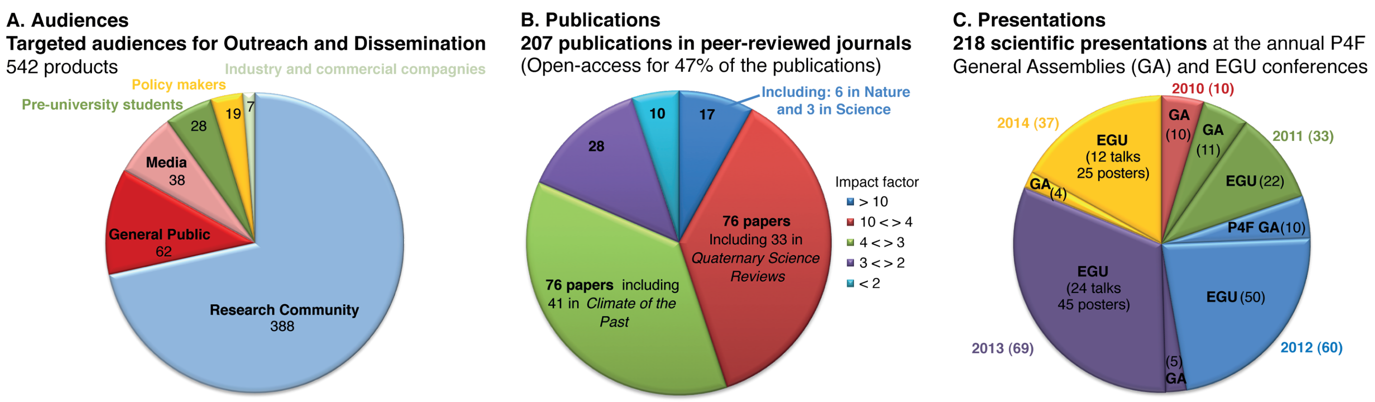

Figure 2: Statistics related to the products of the Past4Future project, including **(A)** its target audiences, **(B)** scientific publications and **(C)** presentations (as of mid-November 2014).

allows us to improve our understanding of the causes and risks of abrupt changes by aligning the timescales of paleoclimate records and using transient model simulations. And in line with one of the key project ambitions, a significant number of the papers were cited in the Fifth Assessment Report of the Working Group 1 of the IPCC.

In each of the five years of the project, Past4Future scientists planned and organized a session at the general assembly of the European Geosciences Union (EGU) where ongoing research and major results were communicated through oral presentations, traditional posters, and in the new format of interactive two-minute presentations. The sessions were among the biggest and most attended in the climate section of EGU, featuring between 22 and 69 presentations and attracting hundreds of attendees each year (Fig. 2C).

Global visibility of Past4Future was increased through the involvement of the global organization PAGES. Two special sections of the PAGES magazine (including the one at hand) were dedicated to Past4Future. They highlight key project results in an accessible format. The global distribution of the magazine and the project website, also hosted by PAGES, generated international synergies and brought the goals and outcomes of Past4Future to the attention of the paleoscience and wider scientific community well beyond Europe.

Data compilation and provision

As one of the dissemination and integration goals, Past4Future has produced a database of paleodata from a range of proxy archives available for the last two interglacial periods. In 2012, it was decided to use the PANGAEA database for the proxy records so they would be available for the entire scientific community. At present, 457 datasets directly related to Past4Future are in the database at www.pangaea.de. In addition to the proxy metadatabase, a modeling database has been created on the www.past4future.eu website as a portal for the project's model output.

Providing open access to Past4Future products was a key goal that was very successfully met, providing a valuable platform for ongoing research. Leveraging and building communication and archival resources using the structures of PAGES and PANGAEA also ensures that the information produced by Past4Future will exist and remain accessible after the project has come to an end.

The data compilation was complemented by a review of the dating methods of paleoclimatic archives and the alignment strategies of paleoclimatic records, with the goal of producing a protocol that enabled us to correctly and consistently compare paleoclimatic records from different archive types and between remote regions. As a result, a dating and synchronization guideline report was delivered in 2012, presented in the form of a PAGES magazine article (Capron et al. 2013) and prepared for submission to a peer-reviewed journal (Govin et al. in prep). These guidelines have been used throughout the project.

Internal project communication

Past4Future brought together an interdisciplinary team of skilled experts to advance the under-standing of interglacial climate from global paleorecords. Among the 22 partner institutions of Past4Future, 197 scientists were directly involved in the project. Amongst them, 110 (i.e. 56%) were early-career scientists, including 40 PhD students (Fig. 1D). Of these, 19 were directly funded through the Past4Future grant, the others were funded mainly through national grants that linked to the Past4Future project.

Note also that the project has a gender ratio of 42% women (Fig. 1D). This is very high for paleoclimate science which has traditionally been dominated by male researchers.

Encouraging young researchers to be mobile and to expand their network was an important goal for Past4Future. To facilitate educational benefit for students in the project we maintained a roster of relevant laboratory and field courses available for PhD and MSc students. This meant that Past4Future's researchers-in-training could choose to attend courses offered in other institutes from other nations.

A General Assembly for project participants was organized in each year of the project (Fig. 2B), during which the team could meet and exchange information about their latest results and plan and coordinate activities. Besides reports and presentations by the working groups, we organized special sessions for young scientists and a discussion session with decision makers, in which the EU Commissioner for Climate Action, Connie Hedegaard, participated.

Outlook

A final goal of the project is the dissemination of products targeting decision makers. To this end, a lunch meeting was held in Brussels where the major results generated by Past4Future are presented to policy and decision makers. Through an integrative approach combining information from climate model simulations and paleoclimate records, Past4Future reached far and accomplished a lot in understanding the processes that controlled the climate during the last two interglacial periods. The results have been published and presented at big meetings as the EGU. In addition the results have influenced the IPCC Fifth Assessment Report. I am pleased to conclude that Past4Future has lived up to its vision and fulfilled its mission to play an important role in applying knowledge of the past for the benefit of our common future.

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Holocene climate change and its context for the future

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Mount Hood, USA, 13-16 October 2014

The Holocene, which covers the last 11,700 years including the entire time span of human civilization, stands out as an interval of relative climate stability. A major goal of the paleoclimate community has been to develop a longer-term perspective on climate change to understand natural variability and provide context for future warming, which model projections indicate will substantially exceed even the warmest Holocene conditions (Fig. 1b). Major efforts by PAGES working groups to synthesize and analyze global paleoclimate records and model simulations of the late Quaternary have mostly focused on the Common Era of the past two millennia (PAGES 2k), the last deglaciation (SynTraCE-21), and past interglacials (PIGS), with relatively less attention paid to the transient evolution of the Holocene. Given that the Holocene is the closest analog for today's climate state and covered by abundant proxy data, coordinated scrutiny of the Earth System over this timeframe should add important information regarding future climate change.

To better define both the short and long-term goals of the scientific community working on reconstructing and modeling Holocene climate, a meeting was held at Timberline Lodge at Mount Hood, Oregon. The meeting focused primarily on three themes: regional and global climate trends, variability in space and time, and data-model comparison.

Trends

As highlighted in Marcott et al. (2013) and Liu et al. (2014), a data-model disparity exists for global surface temperature during the Holocene that is not apparent for the last deglaciation, with proxies recording a long-term cooling and models simulating a warming (Fig. 1a). This "conundrum" was distilled to either relating to seasonal biases in the data, incomplete forcings, or insufficiently sensitive feedbacks in the models, or a combination of these. Seasonal biases in paleoclimate proxies pose a major challenge for reconstructing annual temperatures and comparing unlike datasets (e.g. Mix 2006), particularly during the Holocene when seasonal insolation changes were strong compared to other forcings that act across the year. Model simulations are likewise challenged by initiating glacial inceptions from insolation forcing and are limited by some weakly constrained forcing inputs, such as volcanic and solar activity. Resolving the Holocene temperature conundrum is important for understanding the forcing-response mechanisms during the current interglacial and for putting present and future climate into context, as the global temperature trend dictates to what extent today's earth system has already exited the Holocene range (Fig. 1b).

Variability

Temperature, precipitation, and glacier variability at sub-millennial frequencies and in multiple regions was also discussed. Given the relatively small changes in climate during the Holocene, differentiating a meaningful climate signal from proxy or local noise was highlighted as a critical goal for accurately reconstructing Holocene variability. This issue is central to comparisons between data and model results, which currently disagree over the spectrum of regional variability. Models tend to suppress the regional-scale variability seen by proxies at multi-decadal and longer periods (Fig. 1c). This discrepancy suggests that models may not generate enough low frequency internal variability, thus limiting their ability to produce accurate simulations of climate at longer time scales (Laepple and Huybers 2014).

Proposing a PAGES 12k Working Group

To move forward, a PAGES 12k Holocene working group was agreed to be a useful bridge between the existing PAGES 2k project and previous efforts focusing on the deglaciation. The focus should be on both temperature and hydroclimate changes across the Holocene, and include independent modeling and data analysis efforts. Forward modeling will be an important link between the modeling and proxy communities that will enable true data-model comparisons. The initial phase of the working group should focus on developing a Holocene database, first synthesizing existing compilations, and then incorporating remaining data. Community involvement and potential crowd sourcing should be encouraged to finalize the database and maximize its analysis, leading to a series of synthesis products. To run and maintain such an effort requires that dedicated personnel be supported. This could include a well-versed postdoc(s) who would lead the initial phase of the project and help steer the early scientific objectives.

ACKNOWLEDGEMENTS

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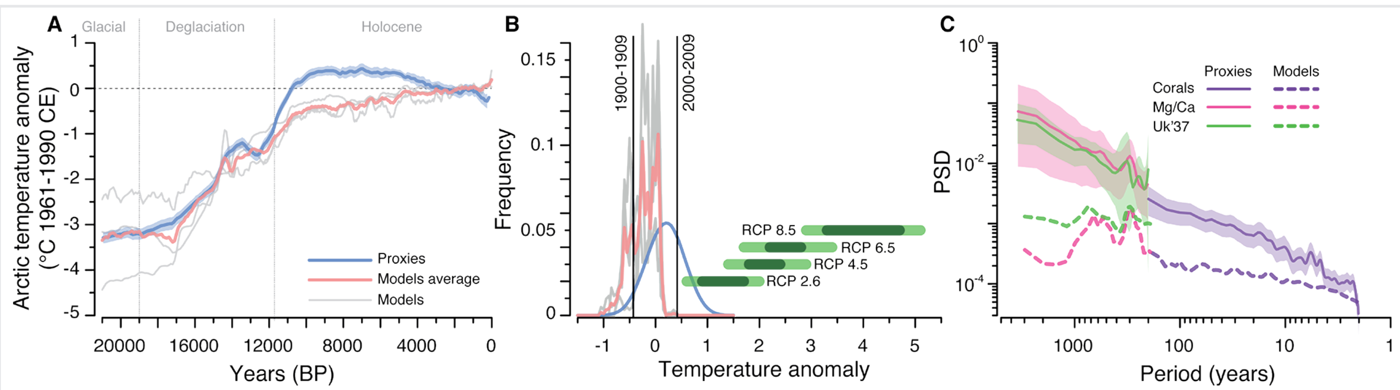

Figure 1: (A) Global mean temperature from proxies (Marcott et al. 2013; Shakun et al. 2012) and models (Liu et al. 2014). **(B)** Histograms of the Holocene time series in (A) showing how the distribution of Holocene temperatures compare to the 20th century instrumental range and IPCC projections for 2100 (Collins et al. 2014). **(C)** Power Spectral Density (PSD) of sea surface temperature for Holocene time series (Laepple and Huybers 2014). RCP = Representative Concentration Pathway.

Multiproxy approach to reconstruct the Pliocene climate

Antoni Rosell-Melé[1], E.L. McClymont[2], P.S. Dekens[3], H. Dowsett[4], A.M. Haywood[5] and C. Pelejero[6]

Barcelona, Catalonia, Spain, 17-19 September 2014

The Pliocene epoch has often been proposed as a climate analogue for future conditions on Earth. However, despite relatively small differences in climate control factors, including atmospheric CO_2 concentration, the Pliocene climate was markedly different from the modern climate. This has made the Pliocene a relevant target for validating climate models. This in turn requires confidence in the paleoclimate estimates to be able to fully ascertain model strengths and weaknesses. In this context, and in order to further develop efforts by earlier projects such as PRISM (Pliocene Research, Interpretation and Synoptic Mapping group) and PlioMIP (Pliocene Model Intercomparison Project), about 65 specialists of the international community of Pliocene researchers met at a workshop in Barcelona. The key mission was to establish guidelines to facilitate further a community wide international effort to reconstruct key climatic parameters (temperature, CO_2, continental and sea ice, sea level, vegetation) in selected time intervals within the Pliocene epoch. The ultimate goal of this community effort is to provide a comprehensive global representation of Pliocene climate, which would facilitate data modeling comparisons. To this end, the workshop consisted of invited plenary talks that synthesized the current state of the art, followed by working group discussions of research priorities, and reporting and synthesis presentations towards the end of the workshop. Participants presented their current research in poster sessions.

Plenary talks highlighted the challenges of trying to reconstruct Pliocene climate and the need to reassess some concepts. These included the recognition that the Pliocene does not fit the paradigm of a "stable climate", nor should it be considered an isolated time period, but instead part of a climate continuum, preceded by the much warmer Miocene. Thus, no specific time slice within the Pliocene will be representative of the epoch's entire range of climate variability, while the character of Pliocene interglacials could be as variable as those of the Quaternary. Integrating or comparing models and data requires dealing with reconstructions with very different constraints on the time (e.g. series or slices with no time lapse) and spatial domains (e.g. global vs regional), all with their own uncertainties. Among the many implicit challenges, urgency was placed on the need to revise the existing Pliocene marine isotope reference templates on which time series age models are based, and the quantification of uncertainty in proxy reconstructions.

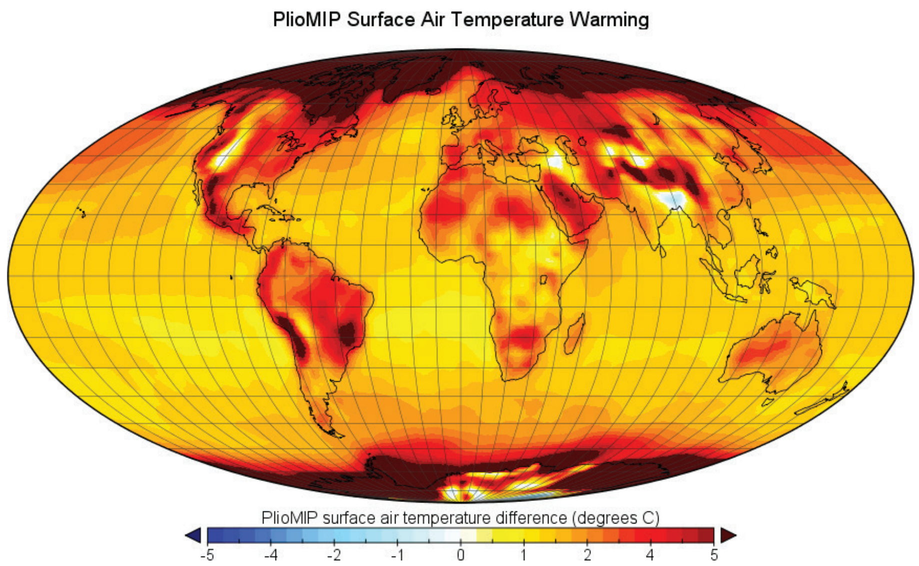

Figure 1: Mean annual surface air temperature anomaly (mid-Pliocene minus pre-industrial simulations) based on a multi-model means ensemble obtained by the Pliocene Model Intercomparison Project. Adapted from Haywood et al. (2013).

From the discussions, a consensus emerged on setting research priorities for different time lines. For instance, in the short-term, there is a need to focus efforts on the reconstruction of isotopic stages M2 through to KM3 (i.e. ca. 3.2-3.3 Ma) and on the improvement of the spatial and temporal reconstructions of proxy data sets to constrain meridional temperature gradients and conditions in high latitude environments.

In the mid-term, one of the priorities is to further the development and application of proxies and models, for instance related to precipitation, or the disentanglement of multiple environmental effects affecting our proxies of temperature and sea-level. It is also paramount to target key regions and issues on which information is lacking, such as the reconstruction of sea-ice or continental precipitation.

In the long term, efforts should focus on creating syntheses that include both relative changes (e.g. information on forcings) and absolute changes required for quantitative data-model integration, for time periods that include the early Pliocene and eventually provide space and time transect information. The priorities will be available in a more elaborate form on the workshop web site: http://jornades.uab.cat/plioclim/.

The next step of the initiative is to seek its consolidation through the creation of a formal working group, and summarize some of the discussion in research papers. We also aim to create a database to summarize the proxy data and make them accessible for further research such as data-model comparisons. The group agreed to review and reassess its objectives in a meeting in two years, to be held in Norway.

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Deglacial Ocean Circulation and Carbon Cycling

Andreas Schmittner[1], S.L. Jaccard[2], A.C. Mix[1] and E.L. Sikes[3]

Inaugural OC3 Workshop, Bern, Switzerland, 1-3 October 2014

The stable isotopes of carbon ($\delta^{13}C$) provide a uniquely valuable tracer of the carbon cycle, and are an essential component for understanding changes in the Earth's various carbon reservoirs and their relation to climate change. Its spatial distribution in the ocean is affected by circulation and fractionation during gas exchange, and carbon cycling. Foraminifera, which are microscopically small animals living near the surface (planktic) or in/on the sea floor (benthic species), incorporate the dissolved inorganic carbon (DIC) isotopic signature of the water $\delta^{13}C_{DIC}$ into their calcium carbonate shells, which are eventually preserved in the sediments providing a glimpse into past $\delta^{13}C_{DIC}$ levels. Ever since the first comparison of foraminifera $\delta^{13}C$ data ($\delta^{13}C_{foram}$) from core-top sediments with water column $\delta^{13}C_{DIC}$ measurements (Duplessy et al. 1984), paleoceanographers have used $\delta^{13}C_{foram}$ as a proxy to reconstruct past changes in ocean circulation and other environmental variables. The record is more complex than originally assumed, however, and to advance understanding requires careful consideration of these complicating factors.

The goal of the new PAGES "Ocean Circulation and Carbon Cycling" working group OC3 (www.pages-igbp.org/working-groups/oc3) is to synthesize sedimentary $\delta^{13}C$ data in order to reconstruct changes in ocean circulation and carbon cycling over the last deglaciation. This time period is of particular interest since it was characterized by overall global warming and large changes in the climate system and the carbon cycle. In addition there exist well-constrained paleo-records at high temporal resolution, with a reasonable spatial distribution.

The kick-off OC3 meeting was held back-to-back with the related International Quaternary Association's International Focus Group IPODS (Investigating Past Ocean Dynamics) in order to exploit existing connections and foster collaboration between both working groups. IPODS has similar goals of understanding deglacial circulation changes but focuses on different proxies, such as radiocarbon, and other dynamic proxies of ocean circulation (εNd, Pa/Th). Here we only report on the OC3 part of the workshop. The IPODS report is available elsewhere (Skinner and Schmittner 2014).

OC3 presentations included new efforts to simulate $\delta^{13}C$ in comprehensive Earth System Models, simulations of deglacial changes using intermediate complexity models, and inverse modeling of the modern- and Last Glacial Maximum (LGM, 23-19 ka BP) ocean. Compilations of available data as well as new downcore records of $\delta^{13}C$ from the Atlantic and the Pacific oceans showed coherent changes consistent with the interpretation that the deep ocean circulation changed particularly strongly in the Atlantic and at mid depths during the Heinrich Stadial 1 (HS1, 19-15 ka BP), whereas deeper layers in the South Atlantic and South Pacific changed later during the Bølling-Allerød (15-13 ka BP) coeval with the Antarctic Cold Reversal and the Younger-Dryas (13-12 ka BP).

One session explored uncertainties of $\delta^{13}C_{DIC}$ reconstructions. Carbonate ion concentrations have been shown to lead to species-specific offsets between planktonic foraminifera $\delta^{13}C_{foram}$ and the water column $\delta^{13}C_{DIC}$ (Spero et al. 1997).

One of the immediate goals of OC3 is to update the original global calibration against seawater $\delta^{13}C_{DIC}$ of benthic $\delta^{13}C_{foram}$ of Duplessy et al. (1984) by using a much larger database of both water column and core-top sediment data. Figure 1 shows the current distribution of both datasets. Preliminary analysis of these data indicates that the carbonate ion effect is also present in the benthic $\delta^{13}C_{foram}$ data.

Discussions during breakout groups and within the plenary focused on details of data synthesis such as metadata needed, formats, and conventions for archiving individual data sets, and retrieval methods. Finally, a strategy and plan for the next steps was developed that cuts out the work until the next meeting, which will presumably be held in 2015.

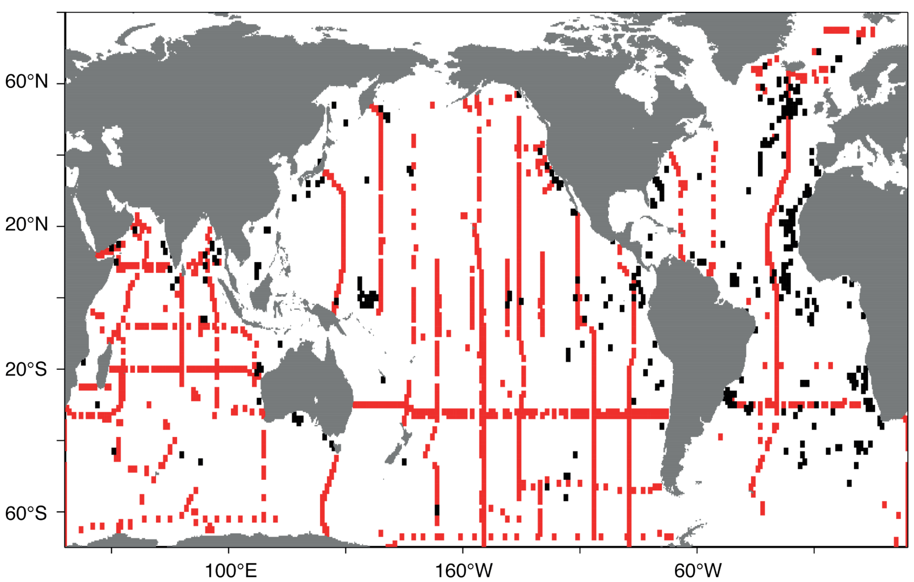

Figure 1: Map of available $\delta^{13}C_{foram}$ data (on a 1° grid) from core-top sediment foraminifera (black; Pederson et al. 2014 plus unpublished data from A. Mix) and water column $\delta^{13}C_{DIC}$ (red) measurements. These two datasets will be used for calibrations.

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Developing databases of past sea-level and ice-sheet indicators

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PALSEA2 Workshop, Lochinver, Scotland, UK, 16-22 September 2014

PALSEA2 is the second phase of work to reduce the uncertainty around past ice-sheet and sea-level variability that began with the PALSEA (PALeo constraints on SEA level rise) working group co-sponsored by PAGES and INQUA. The second meeting of PALSEA2 took place against the backdrop of north-western Scotland's postglacial landscape. Twenty-nine people from seven countries attended to explore, discuss, and debate the methods by which large databases of past sea level and ice-sheet extent can be developed over a range of spatial and temporal scales, from the Pliocene climatic optimum to the current interglacial period. Delegates presented on the production and analysis of composite datasets, and enjoyed extensive field discussions at sites that had contributed to present day knowledge of the British and Irish ice sheets at the Last Glacial Maximum.

Cutting edge advances at the ice-sheet scale are only possible through the compilation of large datasets, highlighting the value databases offer to the scientific community. The contribution of region-specific databases to our current understanding of the Antarctic, British and Irish, and Greenland ice sheets were explored by Peter Clark, Sarah Bradley and Anders Carlson (Carlson et al. 2014; Kuchar et al. 2012; Lecavalier et al. 2014).

Discussions throughout this workshop highlighted the need for data management plans with a global scope, and the consistent and comprehensive treatment of data. Key points of agreement included the necessity of mandating the inclusion of meta-data in order to facilitate the use of sample data across multiple scientific disciplines and that the template should attempt to future-proof data to meet the demands of future analyses. The finalised protocol should also ensure the continuation of valuable conversations between the primary producers and users of the data and subsequent researchers.

Complementary approaches to structuring databases were presented. André Düsterhus outlined a thematic structure comprising the value, measures of uncertainty, associated expert knowledge, and commentary, whilst Marc Hijma presented an existing and highly detailed protocol for a post glacial database of sea level indicators (Hijma et al. 2015).

Bridging the gap between geological and instrumental records, the Late Holocene is a prime target for reconstructing regional patterns of sea level change, which provide constraints on volume and extent of the different ice sheets at the Last Glacial Maximum through knowledge of glacial isostatic adjustment. Ben Horton outlined the applicability of low-energy environments such as US Atlantic Coast salt marshes in meeting the exacting demands placed on temporal and vertical resolution of sea level through this time. Glenn Milne highlighted why regional perspectives remain vital to improve projections of relative sea level in areas with a large glacial isostatic adjustment signal. Roland Gehrels presented a paleo-perspective on the sea-level hotspot work of Sallenger et al. (2012), indicating that specific wind conditions can drive significant variability between nearby sites (Andres et al. 2013). Presentations from Andrea Dutton and Fiona Hibbert reminded the community not to underestimate the complexity of fossil sea-level indicators. Coral species-specific effects and the changing chemical composition of seawater on glacial timescales provide traps for the unwary.

The use of databases, and the application of statistical techniques to large data sets, is already providing us with exciting steps forward (Briggs and Tarasov 2013). The workshop clarified the desire to improve standardisation and transparency in the treatment of uncertainty, so that our uncertainty models are more representative of the level of variation found in reality. All of us involved in the generation of data, from field observations through to models, share a responsibility to ensure that our work is as transparent as possible, and communicated via publication vehicles that recognise and support the diverse needs to which database content may be directed. Production of a best practice document and working protocol for collating sea-level and ice-sheet indicators is anticipated for early 2015.

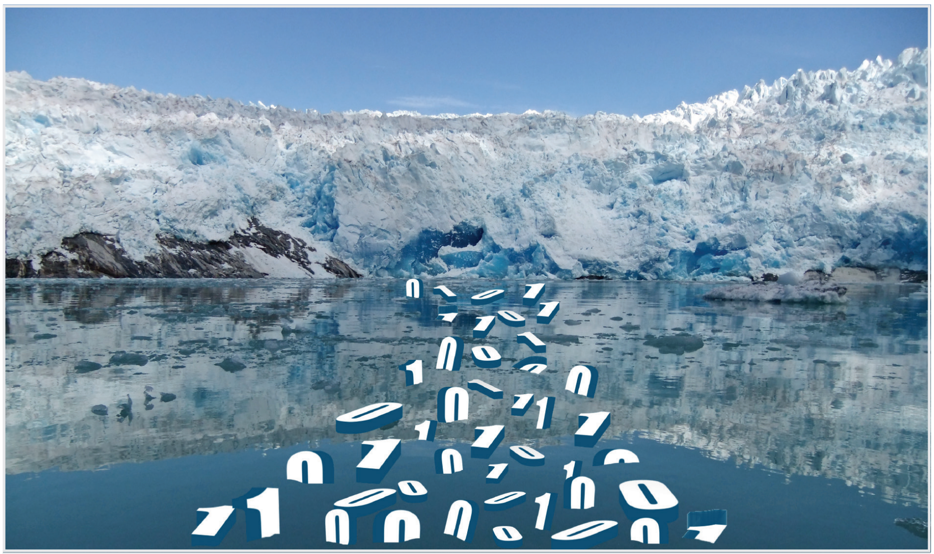

Figure 1: The systematic conversion of observation into data is a cornerstone of scientific method as suggested by the marine-terminating ice margin of Nigerdlikasik Bræ in southern Greenland. Image credit: A Carlson and F Williams.

PALSEA2 WEBSITES

www.pages-igbp.org/workinggroups/palsea2

http://people.oregonstate.edu/~carlsand/PALSEA2/Home.html

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Climate Change and human impact in Central and South America over the last 2000 years

J. Ignacio Martínez[1], C. González[2], M. Grosjean[3] and R. Villalba[4]

LOTRED-SA 3rd Symposium and Training Course, Medellín, Colombia, 7-12 July 2014

Within the framework of the PAGES 2k Consortium, which aims to reconstruct large-scale global temperature patterns for the past two millennia, the LOng-Term multi-proxy climate REconstructions and Dynamics in South America (LOTRED-SA) initiative has produced new high-quality datasets for millennial-long quantitative climate reconstructions for South America. Former LOTRED-SA symposia, held in Malargüe (2006) and Valdivia (2010), focused mostly on southern South America. Two special issues edited by Villalba et al. (2009) and Masiokas et al. (2012) featured key datasets from these meetings.

Neukom et al. (2011) demonstrated that significant data gaps exist in (sub)tropical South America preventing a continent-wide paleoclimate reconstruction. Later assessments (PAGES 2k Consortium 2013; Neukom et al. 2014) have shown that pronounced climatic differences existed between South America and the Northern Hemisphere, e.g. the unique warm event in South America during the late 18th to early 19th centuries. Beyond discussing such interhemispheric differences, a big challenge ahead for LOTRED-SA is filling the data gap in the tropics. Available datasets from tree-rings and lake sediments, speleothems, historical documents, vegetation, pollen, and ice cores are mostly from southern South America. Therefore, more data from the tropics, including other proxy archives from marine and lowland areas need to be collected.

South America, extending from the northern tropics to the sub-Antarctic region and incorporating coastal and high Andean settings, offers a wealth of opportunities for studying the paleoclimate of the late Holocene. The LOTRED-SA 3rd Symposium achieved another of its key goals, which was to provide an up-to-date synoptic picture of South American climate dynamics. Over 115 researchers from 13 countries currently working on tropical and southern South America presented over a hundred contributions, including new findings from the Neotropics and the adjacent oceanic regions. Although the emphasis of the symposium was on the last 2 ka, contributions ranged from the late Holocene to modern climate and included lake and marine sediments, speleothems, tree-rings, and ice core paleoclimate records, in addition to documentary data and model results.

Beyond the climatic aspects of the 2k initiative, contributions at the symposium also explored how ecosystems responded to and created feedbacks to climate change, and how humans have dealt with the variability. The wide diversity of processes operating in the region include the annual/decadal migration of the Intertropical Convergence Zone (ITCZ), the dynamics of El Niño-Southern (ENSO), and the multidecadal Pacific (PDO) and Atlantic (AMO) Oscillations. These regional dynamic features seem to explain the Medieval Climate Anomaly, the Little Ice Age, and the current warm period scenarios, all apparently connected through the South American Monsoon System.

An intensive two-day training course for young scientists took place prior to the symposium. It provided training on the building of radiocarbon age models, on the integration of archives, proxies, and sites from the Neotoma Paleoecology Database, and on using R software and Quantum GIS for statistical and spatial analyses. The course, attended by 30 young scientists from 12 countries, was taught by Maarten Blaauw (Queen's University, UK), Alexander Correa-Metrio (UNAM, Mexico), Suzette Flantua (University of Amsterdam, The Netherlands), and Ricardo Villalba (IANIGLA, Argentina).

After the meeting, a field trip took attendants to examine the geomorphology and paleolimnology of the Santa Fé–Sopetrán Basin, where the late Holocene San Nicolás terrace was visited (Fig. 1). This terrace contains a high-resolution succession of laminated sediments whose hydrological multi-decadal frequencies were controlled by the dynamics of the ITCZ.

Figure 1: Panoramic view of the San Nicolás terrace in the Santa Fé-Sopetran Basin, northern Colombia.

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Indicators to address climate change impacts on marine ecosystems

Lisa Maddison[1], I. van Putten[2] and F. Zuo[3]

IMBER ClimEco4 summer school, Shanghai, China, 4-9 August 2014

Summer schools are an important capacity building activity for Integrated Marine Biogeochemistry and Ecosystem Research (IMBER; www.imber.info), a sister project of PAGES in the International Geosphere-Biosphere Programme. Summer schools provide training for students and early-career researchers in some of the techniques and methods used in IMBER's cutting-edge research. The training also aims to equip young researchers to work in interdisciplinary teams and address global issues in coastal and marine socio-ecological systems. The fourth in the ClimEco (Climate and Ecosystems) summer school series, ClimEco4, focused on defining and constructing biophysical, social, and economic indicators for evaluating marine ecosystems and using them to inform policy and decision-making.

Twenty-four lectures were given by international experts and live-streamed from the East China Normal University's live channel. These were followed by group exercises in which modeling and statistical techniques were applied to real-world socio-ecological data. Group projects were presented at the end of the summer school. Participants also had the opportunity to showcase their own research during a poster session.

To bring everyone up to speed, the first set of lectures introduced relevant terminology and concepts. Then climate change issues and impacts on marine ecosystems from biophysical, socio-economic and governance perspectives were discussed. This was followed by a general overview of indicators; what they are and how and where they are used (Box 1). Next, the use of indicators to examine climate change and marine biogeochemistry at different time scales was outlined. Eric Galbraith from McGill University, Canada provided the paleo perspective and gave an entertaining depiction of the history of the Earth occurring within a single calendar year (view the YouTube video).

The next set of lectures focused on acquiring, accessing, and analysing data including quality control and nonlinearity exploration, such as detecting "tipping points" and developing decision criteria. Statistical techniques, data sharing, and approaches on publishing and reusing scientific data were also discussed.

Case studies were used to illustrate how coastal communities and socio-economic indicators can be linked to marine ecosystems and socio-ecological models. The importance of assessing the performance of indicators, their precision, and statistical power was also discussed.

The final lectures outlined the use of economic and social indicators for policy and decision-making, and, in particular, fisheries management. Participants discussed the advantages of knowing how to communicate the salient information the indicators provide to a range of different audiences.

The week ended with group project presentations, enabling participants to apply the theory and practical learning they had acquired. Using techniques and methods covered in the lectures, participants were tasked with analysing a real-world dataset comprising a socio-ecological system. Several participants brought their own data, which they augmented with other data sourced from the Internet. Each group undertook a socio-ecological analysis and reported on the state of the system and the management tradeoffs. The project results, including potential entry points for system management, were presented to a panel of "managers", who provided feedback.

By all accounts, ClimEco4 was a great success, and participants came away equipped with the knowledge of how to source, analyze, and transform data into usable products, tools, or advice. In addition to the training, and perhaps even more beneficial, were the opportunities the course offered for networking and interacting with both established researchers and with their peers from a variety of different scientific disciplines. Linkages like these are essential for fostering interdisciplinary and collaborative science in the future.

The ClimEco4 summer school lectures can be viewed on the IMBER International Project Office's YouTube channel at: www.youtube.com/channel/UCinzjRz7_TKHESn6uggCKlw or the Dailymotion channel at: www.dailymotion.com/user/IMBER_IPO/1

Simple indicators
- Biomass of functional groups e.g. piscivores, omnivores, zoopiscivores, benthivores, detritivores
- Sea surface temperature, pCO_2, salinity, nitrate
- Number of fishery jobs, average wage, average price of fish

Complex indicators
- Stoichiometric ratios e.g. Redfield ratio (C:N:P = 106:16:1)
- Large Fish Indicator (LFI), Large Species Indicator (LSI)
- Proportion of predatory fish in the community
- Pelagic : demersal ratio
- Landed value/GDP
- Average fisheries wage/average national wage

Even more complex indicators
- Shannon index of diversity
- Pielou's species evenness
- 4D Ecosystem exploitation index
- Slope of the biomass spectrum
- Ocean Health Index

Box 1: Examples of simple, complex, and even more complex indicators used to summarize complex and often disparate datasets.

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Towards a spatiotemporal expansion of temperature and hydroclimatic proxy archives

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Soria, Spain, 14-17 September 2014

By hosting our workshop, the CESEFOR Foundation (www.cesefor.com) made a considerable contribution to a successful start of Phase 2 of PAGES' EuroMed2k working group. Soria was selected as the location not the least because it is a region on the Iberian Peninsula where a marked drying trend has affected ecosystem functioning and productivity since the 1970s (Büntgen et al. 2012, 2013). As a consequence, some local agriculture foci already shifted from traditional timber harvesting to non-woody forest products, e.g. mushrooms, and irrigation during summer had to be intensified. The underlying processes forcing this climatic trend are, however, not well understood. Gaining further knowledge on such regional climatic patterns is one of the goals of the EuroMed2k working group. Therefore, and considering a broader spatiotemporal perspective, this working group aims to compile a wide range of proxy data for providing a long-term perspective on the modern climate, performing model-data comparison assessments, and supplementing detection and attribution studies.

A total of 39 scientists from 11 countries with expertise in paleoclimatic data, reconstructions and climate models for the North Atlantic/European/Mediterranean sector and the western part of Russia attended the workshop. In contrast to the first project phase, the interest has changed towards the compilation and evaluation of high- to low-resolution terrestrial and marine proxy archives covering at least some centuries, but ideally several millennia. The workshop participants also acknowledged the value of integrating lower resolution marine records from the Atlantic Ocean and Mediterranean Sea that are longer than 2ka. At the same time, they were aware of the statistical challenges of combining annually resolved and lower resolution timeseries, such as the incorporation of different levels of temporal uncertainty inherent to different proxy archives.

EuroMed2k will extend the initial temperature-oriented proxy compilation towards high-, mid-, and low-resolution terrestrial and marine hydroclimatic archives, and expand the network beyond Eastern Europe including the Caucasus, Polar Ural, and Altai Mountains (Fig. 1). The working group aims to generate a comprehensive paleoclimatic database for the development of at least four independent reconstructions of annual and lower resolution temperature and hydroclimate. Moreover, the most recent generation of Earth System Climate Models, now spanning the last two millennia, incorporate hydrological changes in Europe. Those will allow proxy-model cross-comparison of overlapping periods, in-depth assessments of spectral properties (PAGES 2k Consortium 2014), and testing methods for empirical climate reconstructions in the context of regional-scale pseudo-proxy experiments (Gomez-Navarro et al. in press).

The working group plans to substantially expand the EuroMed2k database: around 70 records will be added, representing different resolutions and covering different age ranges from several centuries to most of the Holocene. The records will cover the area from 25-70°N and 10°W-45°E, with geographical foci on the Iberian Peninsula, Alpine arc, and Fennoscandia. Particular emphasis will be given to so far under-represented marine and terrestrial records of lower resolution to help fill seasonal, temporal, and spatial gaps in the existing network. An extensive compilation of sediment cores from both the North Atlantic and Mediterranean may indeed offer seasonally disjunct information on decadal to multi-millennial time-scales; and speleothems from the Near East (Göktürk et al. 2011) can contain winter signals and cover several millennia.

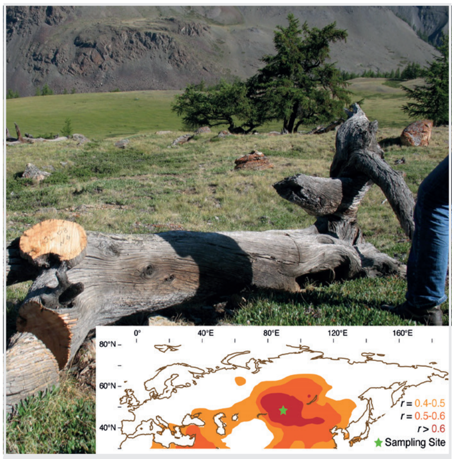

Figure 1: A dry-dead Siberian larch (*Larix sibirica* Ledeb.) in the Russian Altai Mountains (~88°E, 50°N). The trunk, located well above the current tree line (~2,450m asl), contains several hundred rings and dates back into medieval times (Myglan et al. 2012). Such samples allow to develop an annually resolved and absolutely dated summer temperature reconstruction. The inset shows spatial field correlations of a new Altai tree-ring width record against gridded JJA temperatures from AD 1821-2011. Partners include V.S. Myglan, D.V. Ovtchinnikov and A.V. Kirdyanov (all Krasnoyarsk, Russia). Photo: Myglan VS, Inset: Büngten U, unpublished.

As a community-driven project, a key success factor of PAGES2k will be its public visibility. We therefore complemented our workshop with a public roundtable at the headquarters of the regional government, where members of the EuroMed2k consortium enthusiastically discussed climate issues with the regional media, representatives of the sylvicultural and agricultural sectors, delegates of the agro-food and myco-touristic industries, and an interested lay audience. PAGES paleoclimatologists were able to place the ongoing Iberian drought in a historical context and compare the regional Spanish conditions with trends in other parts of the world.

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The online Varve Image Portal: A new tool for studying annually laminated sediments

Bernd Zolitschka[1], P. Francus[2,3], A.E.K. Ojala[4], A. Schimmelmann[5] and C. Telepski[6]

Annually laminated (i.e. varved) sediment sequences are important natural archives of paleoenvironmental conditions that offer an accurate indication of time span in absolute years, exceptional high (up to seasonal) temporal resolution, and the possibility of calculating sediment flux rates. During the 19th International Sedimentological Congress 2014 in Geneva, Switzerland, a new tool for the dissemination of visualized information from annually laminated sediments – the online Varve Image Portal – was officially launched. This new website displays images of various varve types based on contributions from the scientific community. This online resource is now fully operational and growing and we are asking for input from scientists around the world (Fig. 1). Please contribute your additional varve images from new and published sites together with metadata to Bernd Zolitschka: zoli@uni-bremen.de

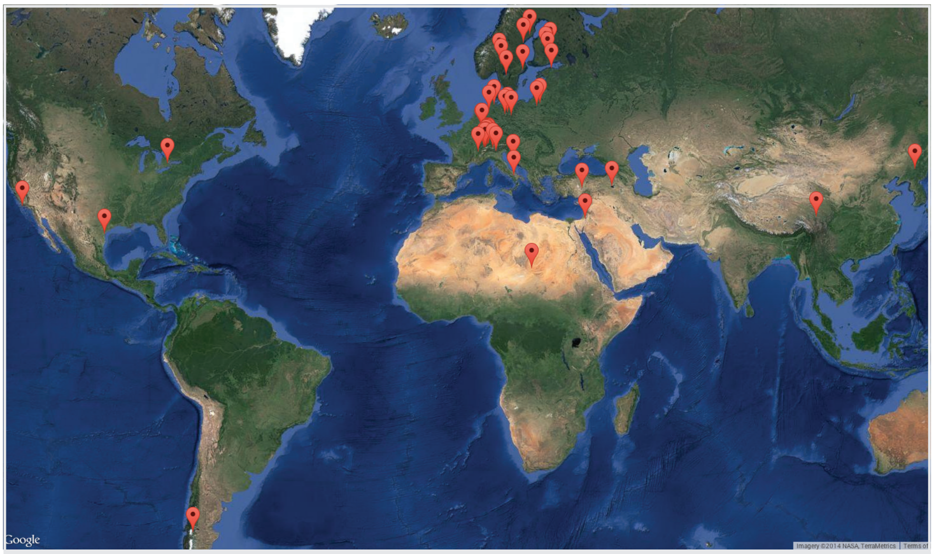

Figure 1: Screenshot from the Varve Image Portal documenting the current global coverage of varve images.

Improving varve analysis

Although the scientific community has come to appreciate the value provided by both marine and lacustrine annually laminated sediments, there remains a widespread lack of awareness about the need to provide careful evidence that finely laminated sediments are truly varved before exploiting lamina counts for geochronological purposes and environmental interpretations through time.

Such a misconception between varved and finely laminated sediments might partially originate from the history of the expression "varve", a term introduced by the Swedish geologist De Geer during the early 20th century to describe minerogenic proglacial lake sediments of Sweden as annually laminated. Later on, the term varve was extended to other lacustrine as well as marine sediment types with preserved annual successions and seasonal sub-laminae. The large diversity of sediments featuring a varved character sometimes led to the misconception that most, if not all finely laminated sediments must be varved, which clearly is not the case.

The Varve Image Portal aims to provide exemplary visual information regarding the compositional and structural diversity of varved sediments, and to assist, train and guide researchers in the critical judgment of the relative timing of (sub)-laminae and how to constrain their geochronological potential. The Varve Image Portal also intends to disseminate existing image information about varves and to facilitate the efforts of students and young scientists to get acquainted with the challenging topic of finely laminated sedimentary structures. It is accessible via

http://pages-igbp.org/workinggroups/varves-wg/varves-image-library

Using the portal

Each varve image of this online database is accompanied by metadata including information about the study site, satellite and terrestrial images as well as references with DOI links to publications reporting the specific varve record.

The Varve Image Portal has three different search functionalities: (1) A map-based search, (2) a search based on a genetic concept where varves are compositionally categorized as clastic, biogenic, endogenic (incl. evaporitic) and mixed, and (3) an alphabetic search of site names.

This online tool offers exemplary views on many different aspects of varved sediment structures including macroscopic images of gravity and freeze cores. Microscopic images with different magnifications provide examples in normal and polarized light. Scanning electronic microscope images, radiographs and images combined with analytical data or interpretations complete this internet-based resource. Additionally, general information about varves as well as links to varve-related and methodologically relevant websites are provided. Finally, the Varve Image Portal provides easy access to varve reviews, to other iconic publications closely linked to varve studies as well as to publications related to methods and techniques that apply to the investigation of varved sediment records.

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Aquatic Transitions Working Group

Peter Gell[1], J.A. Dearing[2], S. Juggins[3], M.-E. Perga[4], J. Saros[5] and C. Sayer[6]

Wetlands and water remain a key realm of applied paleoecological research with many proxies reflecting the changing status of the water body as well as reflecting the climatic and human drivers of these changes. This working group will review direct human impact on aquatic ecosystems at times in the past critical to each region and the internal ecological shifts of the wetlands, to explore the responsiveness, resistance, and resilience of aquatic systems worldwide to natural and anthropogenic forces.

Human activities have impacted greatly on global aquatic systems through the release of pollutants and the regulation and abstraction of surface and groundwater. This has, and will continue to impact critically on ecosystem productivity with further consequences for human wellbeing. Simultaneously, aquatic systems have responded to long and shorter-term variations in temperature and effective precipitation.

Many of these responses have been non-linear, with aquatic ecosystems both responding abruptly, and showing a certain level of resilience to forces until a threshold is breached. Wetlands are a classic ecosystem used to demonstrate alternative stable states whereby feedbacks can act to resist pressures, but also act to entrench the system in a new state once pressures force a regime shift.

Many of the changes witnessed, or modeled, by ecologists have existed in the past. Accordingly, research on major transitions in aquatic systems represents a significant field of enquiry that demands contribution from both contemporary ecology and paleoecology. Further, long term records of change provide evidence of the ecosystem dynamics that may have occurred leading up to a threshold change and, thereby, can reveal early warning signals that may be lessons to prioritise intervention measures for future management.

Scientific goals and activities

The Aquatic Transitions Working Group has two principal charters or projects. The first is to document the global history of the impact of humans on aquatic systems. By identifying the first point of human impact and the inception and peak of the impact of the industrialised phase, Project 1 will reveal the responsiveness of aquatic systems to the presence of humanity, within a framework of climate variability. Project 2 will drill down into the nature of these transitions to examine the ecosystem dynamics that have resisted human pressures, as well as the changes leading up to the point where the system succumbed, and the degree to which new, stabilising forces have entrenched the system in a new regime.

Aquatic Transitions will achieve these goals by collating published global paleohydrological and paleoecological records, sifting through these records and attributing changes in records to critical phases in human settlement and activity. It will select critical points of impact that may be time transgressive. By focussing its research on these points of transition, the working group will apply established ecological reason to attribute the identified changes to press or pulse responses or regime shifts. Thus it will respond directly to several key questions in paleoecology as identified at the PAGES-supported Palaeo50 workshop in 2012 (Seddon et al. 2014).

Aquatic Transitions seeks representation from across the globe and will use meetings to assemble a global database, use change point analysis to identify timing and cause of change, synthesize records at continental and global scales, and write outputs.

Visit the Aquatic Transitions website at: www.pages-igbp.org/workinggroups/aquatic-transitions
and sign up to our mailing list to keep up to date with our activities.

Figure 1: Taihu Lake, on the southern part of the Yangtze River delta, is the third largest freshwater lake in China. Taihu became eutrophic following intensive development from the 1980s and has been covered by an extensive *Microcystis* bloom since the late 1990s. Understanding the nature of aquatic transitions provides insights for the challenge of wetland restoration.

Upcoming activities

The first meeting of the Aquatic Transitions Working Group will be in Keyworth, UK, 22-24 April 2015, and there will be a follow up workshop on 3 August 2015 in association with the International Paleolimnology Congress in Lanzhou, China.

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Global Soil and Sediment transfers in the Anthropocene

Thomas Hoffmann[1], D. Penny[2], G. Stinchcomb[3], V. Vanacker[4] and X.X. Lu[5]

Anthropogenic soil erosion reduces soil productivity, compromises freshwater ecosystem services, and drives geomorphic and ecological change in rivers and floodplains. It is now well accepted that the rate of anthropogenic soil erosion exceeds the rate of soil production by several orders of magnitude in many parts of Earth (Montgomery 2007), threatening the sustainability of food production that is so essential to human well-being. Deposition of the eroded soil downstream has profoundly altered the structure and function of fluvial and deltaic ecosystems, often with negative impacts on the societies and economies that depend on them (Hoffmann et al. 2010). The legacy of these impacts exerts strong influence over modern and future ecosystem functions. In many agricultural ecosystems, natural processes no longer primarily control soil erosion and deposition, and greatly altered sediment fluxes are a key marker of the Anthropocene (Syvitski and Kettner 2011).

The vulnerability of soils to human-induced erosion is highly variable in space and time; dependent on climate, geology, the nature and duration of land use, and topography. Our knowledge of the mechanistic relationships between soil erodibility, land use, and climate is well developed. However, the global heterogeneity of land use history and the co-occurrence of other erosion-relevant factors such as climate variability have prevented us from sufficiently understanding the global patterns of long-term soil erosion and fluvial sediment flux and storage, and quantifying their budgets.

Objectives

GloSS (Global Soil and Sediment transfers in the Anthropocene) will analyze the global pattern of past and present anthropogenic soil erosion, and the transfer and deposition of sediment. It aims to determine the sensitivity of soil resources and sediment routing systems to varying land use types during the period of agriculture, under a range of climate regimes and socio-ecological settings.

To achieve this objective, GloSS will integrate the scientific domains of geomorphology, paleoecology, archaeology, and history. GloSS focuses on the local and regional impact of anthropogenic activities on soil erosion and sediment transfer through fluvial systems in different socio-ecological contexts since the onset of agriculture, which began in Eurasia as early as approximately 8,000 years ago.

Figure 1: Smallholder rain-fed agriculture in the Ethiopian Highlands, Amhara Region, Ethiopia. Photo by Veerle Vanacker.

GloSS therefore aims to:

- *Update* the global network of scientists developing long-term soil erosion and sediment flux histories within socio-ecological systems, building on the work of the former Land Use and Climate Impacts on Fluvial Systems (LUCIFS) working group;
- *Develop* proxies and indices for human impact on rates of soil erosion and fluvial sediment transfer that are applicable on a global scale and throughout the Holocene;
- *Create* a global database of long-term (10^2-10^4 years) human-accelerated soil erosion and sediment flux records;
- *Identify* hot spots of soil erosion and sediment deposition during the Anthropocene;
- *Locate* data-poor regions where particular socio-ecological systems are not well understood, as strategic foci for future work.

The objectives and goals of the GloSS working group sit at the nexus of climate, environment, and humanity and thus contribute to the interdisciplinary activities at the heart of the revised PAGES science structure and the Future Earth initiative.

Visit the GloSS webpage at: www.pages-igbp.org/workinggroups/gloss and sign up to our mailing list to keep up to date with the group's activities.

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LandCover6k: Global anthropogenic land-cover change and its role in past climate

Marie-José Gaillard[1] and LandCover6k Interim Steering Group members[2]

There is today a general understanding of the need for powerful climate models to inform societies on the climate's possible development in the future. Climate models help us to understand the climate system as a whole and envisage our future. They have existed for many decades and have developed progressively into very complex Earth system models (ESMs) in which the atmosphere, the ocean and land-surface processes are coupled. Although already powerful, many of these ESMs are still under development. By using a model-data comparison approach, i.e. comparing model outputs with actual climate data over decades, centuries, and millennia back in time (paleoclimate data), both model outputs and paleodata can be better understood and evaluated, which also contributes to model improvements.

Land cover (here referring essentially to vegetation cover, but also bare soils and rocks) is an inherent part of the climate system. Natural, primarily climate-driven vegetation and ecosystem processes interact with human land use to determine vegetation cover on earth and its development through time. The resulting land-surface properties feed back to climate by modulating exchanges of energy, water, and greenhouse gases with the atmosphere through biogeochemical feedbacks (affecting sources and sinks of greenhouse gases, aerosols, pollutants, and other gases) and biogeophysical feedbacks (affecting heat and water fluxes, and wind direction and magnitude). The sum of these feedbacks may be either positive, i.e. amplifying changes in climate (e.g. amplifying a warming or a cooling trend), or negative, i.e. slowing trends in climate (e.g. slowing a warming or a cooling trend). Biogeochemical feedbacks, especially involving the carbon cycle, have received particular attention. However, biogeophysical feedbacks can have an effect of comparable magnitude; but because biogeophysical feedbacks generally operate at the regional scale they may be missed or underestimated at the relatively coarse resolution of Global ESMs. These feedbacks still represent a major source of uncertainty in climate projections under rising greenhouse gas concentrations. Therefore, the incorporation of dynamic vegetation into ESMs currently is one of the high priorities among climate modelers.

The effects of anthropogenic burning and deforestation on past global climate are not fully understood yet, and the question of whether humans had more impact than previously assumed on climate in prehistory (the Ruddiman hypothesis; Ruddiman 2003) is still a matter of debate. As long as the effects of land-use changes are not properly understood, mitigation strategies such as afforestation to sequester CO_2 and cool the climate might be erroneous. Moreover, the scenarios of past ALCCs often used in climate modeling, such as HYDE (Klein Goldewijk et al. 2011), the KK scenarios (Kaplan et al. 2009), and others (e.g. Pongratz et al. 2008), show large differences between each other (Gaillard et al. 2010). Therefore, climate modeling in paleo-mode taking into account anthropogenic land-cover change (ALCC) is seriously hampered. Thus, there is an imminent need for independent descriptions of past vegetation cover based on empirical data and an improved ALCC history at regional scales and globally. Such independent descriptions can be provided by pollen-based quantitative reconstructions of past vegetation cover such as those recently achieved for a large part of Europe (Trondman et al., in press; Fig. 1).

The methodological starting point for LandCover6k

Objective, quantitative long-term records of past vegetation cover changes are, however, still limited globally. Although biomization of pollen data (Prentice et al. 1996) has become a robust tool to reconstruct the distribution of biomes and their boundaries over the

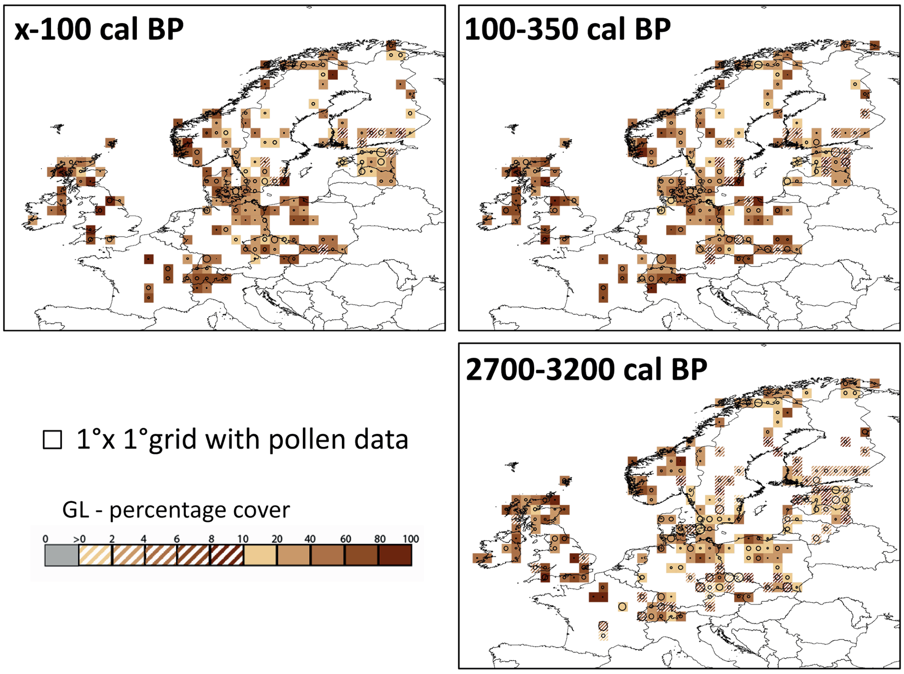

Figure 1: Grid-based REVEALS estimates for the plant functional type (PFT) grassland (GL) for three Holocene time-windows. The scale is percentage cover, with the different colors indicating different percentage intervals: >0–10% in 2% intervals, 10–20% in a 10% interval, and 20–100% in 20% intervals. The category 0 (grey) corresponds to the grid cells with pollen records but no pollen data for the actual PFT and, therefore, no REVEALS estimates. The category >0–2 corresponds to REVEALS estimates different from zero (can be less than 1%) up to 2%. The uncertainties of PFT REVEALS estimates are shown by circles of various sizes in each grid cell with an estimate. The circles represent the coefficient of variation (CV; the standard error divided by the REVEALS estimate). When SE ≥ REVEALS estimate, the circle fills the entire grid cell and the REVEALS estimate is considered unreliable. This occurs mainly where REVEALS estimates are low. GL (all most common herbs): *Artemisia* species, Cyperaceae, *Filipendula* species, Poaceae (Gramineae), *Plantago lanceolata*, *Plantago media*, *Plantago montana*, *Rumex acetosa*-type (several species). Modified from Trondman et al. (in press).

globe, the methodology does not provide quantitative reconstructions of plant cover, e.g. fractions of deforested land or fractions of conifer trees versus deciduous trees. Until a few years ago, it was not possible to translate fossil pollen found in lake sediments or peat into a quantitative description of the past vegetation. However, Sugita (2007) developed an algorithm for inverse modeling of the relationship between pollen and vegetation (Regional Estimates of VEgetation Abundance from Large Sites; REVEALS) that makes it possible to translate fossil pollen data into vegetation cover at regional spatial scales. The LandCover6k working group aims to capitalize on the established REVEALS methodology in a large globally coordinated effort.

Scientifically, LandCover6k also builds on the European research project LANDCLIM (LAND cover – CLIMate interactions in NW Europe during the Holocene; Gaillard et al. 2010). This project applied a model-data comparison scheme that integrated a dynamic vegetation model (LPJGUESS), a regional climate model (RCA3), and the REVEALS model. The results indicate that past human-induced deforestation from Neolithic time (6 ka BP) did indeed have positive and negative biogeophysical feedbacks of +/- 1°C on the regional climate; the sign of the feedback varies between regions and seasons (Strandberg et al. 2014).

Other LANDCLIM results on which LandCover6k will build include the existing reconstructions of land cover over large parts of Europe during five time windows of the Holocene (Trondman et al., in press; Fig. 1) and new spatial statistical models to turn REVEALS reconstructions into spatially continuous maps of past land cover (Pirzamanbein et al. 2014; Fig. 2).

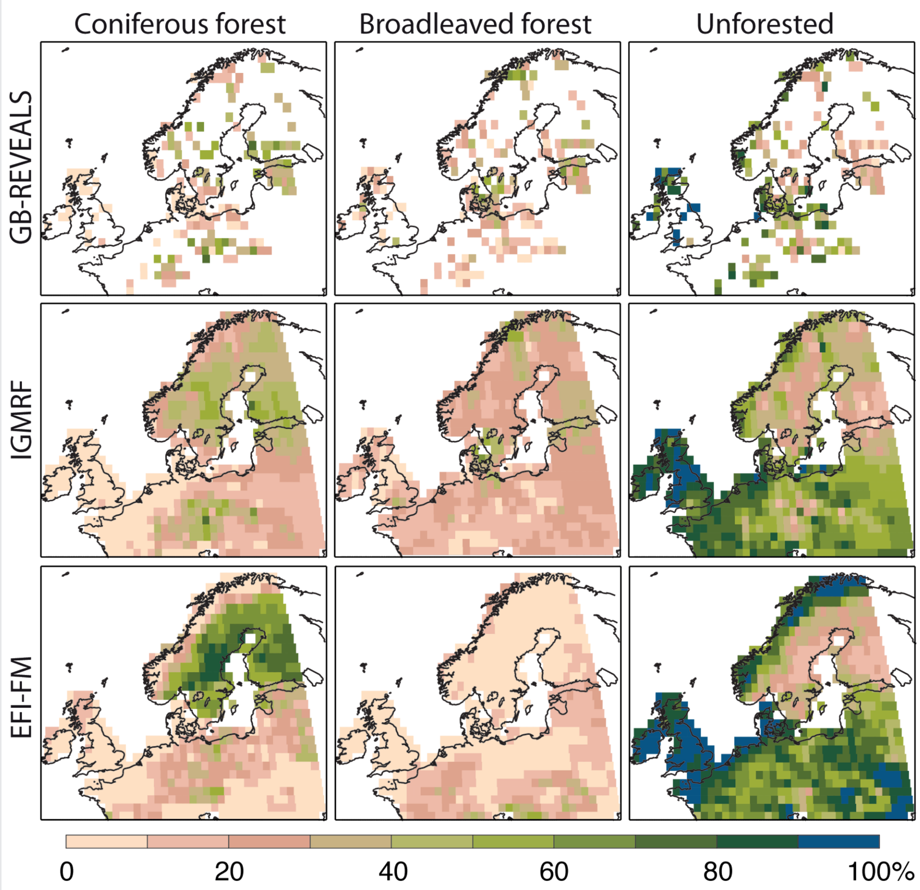

Figure 2: Reconstructions of proportion (% cover) of the three land-cover types coniferous forest, broadleaved forest and unforested for the 0.05 ka time window (modified from Pirzamanbein et al. 2014). From top to bottom, the pollen-based REVEALS estimates, the reconstruction from the intrinsic Gaussian Markov Random Field model (IGMRF), and the present day land-cover data extracted from the forest map of Europe compiled by the European Forest Institute (EFI-FM). For details, see text and Pirzamanbein et al. (2014).

LandCover6k's ambitions and strategy
The ultimate goal of LandCover6k is to produce useful outputs for ecologists, Earth system scientists, conservation bodies, land-use managers, and policy-makers. Broken down into specific goals, the working group aims to:

- produce pollen-based land-cover reconstructions for regions of the world where human impact has been particularly intense over the Holocene prior to AD 1500, i.e. North America, South America, Europe, Africa, Asia (China and India in particular), and Oceania (Australia, New Zealand, and other Pacific islands).
- evaluate the existing ALCC scenarios with the combined information from the pollen-based reconstructions, archeological and historical data, and other evidence of human-induced land-cover change such as paleofire reconstructions.
- improve the ALCC models and produce spatially continuous land-cover descriptions íntegrating the REVEALS-based reconstructions, biomization, dynamic vegetation modeling, ALCC modeling and spatial statistical modeling. We strive to achieve this final product within six years from now.

The ambitious and challenging plan of LandCover6k requires a large, well-organized group of devoted scientists. The group is coordinated by experts in the various disciplines and by one or two co-leaders for each of the six regional subgroups.

The tasks of the regional subgroups will be to:

- compile the fundamental information needed to produce pollen-based REVEALS reconstructions of past land cover, i.e. obtain new pollen records of past anthropogenic vegetation change, develop pollen databases, and estimate pollen productivities and fall speeds of the regionally prevailing plant taxa.
- develop datasets of archeological and historical information on past land cover.
- achieve as many REVEALS reconstructions as possible for each region.
- evaluate the REVEALS reconstructions by comparison with archeological and historical datasets (AHDs).
- evaluate the ALCCs for each region on the basis of the REVEALS reconstructions and AHDs.

LandCover6k welcomes new members, particularly archeologists and historians, who are interested in this kind of work and feel they can provide useful information and make a contribution to the group's goals. A launch meeting is planned in Paris, France from 18–20 February 2015, which aims to determine the organization, structure, and milestones of the group for 2015-2017. For more information visit the LandCover6k website at: www.pages-igbp.org/workinggroups/landcover6k

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