Transient high-resolution Holocene simulations

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New opportunities emerge from new model development and increased computational capacity. For the first time it is possible to perform transient simulations over several thousand years in a horizontal resolution that is similar to the one used for the IPCC climate change scenarios. Identification of the role and contribution of different external forcing factors in shaping our climate and its feedbacks with internal components of the climate system are the focus. Past climate changes provide a unique test-bed for investigating the model performance to reproduce different climates and provide an opportunity to assess model performance outside the range of recent observed climate variability.

Three main transient simulations with the MPI-ESM LR (Giorgetta et al. 2013) over the Holocene period (8k to preindustrial) were performed. The experiments feature relatively high horizontal resolution for multi-millennial simulations. The simulation TRSF is forced by atmospheric greenhouse gas concentrations as well as orbital insulation forcing and land-use changes. TRAF and TRAFc are additionally driven with stratospheric volcanic aerosol distribution and extra stratospheric ozone as well as spectral solar irradiance forcing. In TRAFc the atmosphere can interactively exchange CO2, but its concentration is forced towards ice-core target values. Various sensitivity experiments are done to determine the contribution of individual forcing factors.

Hypothesis testing using AOGCMs: The Antarctic Ice Sheet and multi-centennial climate variability

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Interactions between the Antarctic Ice Sheet and the rest of the climate system are known to have affected centennial- to orbital-scale climate variability during past glaciations and are likely to be important in future climate change. But could the Antarctic Ice Sheet also have played a role in centennial to multi-millennial climate variations during the Holocene, a period for which the Antarctic Ice Sheet is generally considered a static entity? We show that there are indeed indications in this direction, both from high-temporal-resolution records of iceberg-rafted debris derived, as from high-spatial-resolution modeling of the Antarctic Ice Sheet. With this as a starting point we set out to test the hypothesis that the Antarctic Ice Sheet played a role in multi-centennial Holocene climate variability. To this end we performed multi-millennial climate simulations with an intermediate complexity climate model, complemented with high resolution equilibrium simulations and discuss on which time-scales and in which regions the Antarctic Ice Sheet can have played a role, and where its influence would have been too limited to be detectable in proxy-based Holocene climate reconstructions.

Dating uncertainties in layer-counted paleoclimatic archives

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Accurate time series representation of paleoclimatic proxy records is challenging because such records involve dating errors in addition to proxy measurement errors. These uncertainties can severely bias any analysis of an archive under study. I will first introduce a Bayesian approach to represent layer-counted proxy records as as sequences of probability densities on absolute, error-free time axes. Thereafter, I will show how dating uncertainties can be imporporated in the parametrization of models that are supposed to reproduce the dynamics observed in the proxy record. The proposed methods will be demonstrated using the NGRIP record, and some dynamical characteristics of this record will be discussed in the context of a conceptual model.

Temperature reconstructions from polar ice cores.

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Ice core water stable isotopes are a favoured proxy to reconstruct past climate variations in polar regions. Yet, their interpretation requires calibration from other proxy records and is affected by various processes which alter the signal after it has been imprinted. We will present the detailed impact of these post-depositional effects on the spectral properties of ice core water isotope records, through illustrative case studies.
Recently, alternative proxies have been used to reconstruct temperature variations : inert gas isotopes (N2 and Ar mainly), and borehole temperature. Unlike water isotopes, these proxies only record a certain range of the frequency spectrum, but provide valuable constraints on past climate variability on longer timescales, and are precious to calibrate the water isotope signal. We will describe how these indicators can be used together to improve our undestanding of cliamte variability across scales.

Assessing scaling from paleodata – Some contemporary challenges

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The problem of quantifying climate variability across scales faces many challenges, especially when considering paleoclimate proxies with possibly heterogeneous sampling and time scale uncertainty. In the latter situation, one key challenge (among many others) is discriminating between "continuum multi-scale variability" and variability at specific time scales. This talk will present a subjective overview on recent methodological developments related with the problems of time-scale decomposition and scaling analysis in paleoclimate. It shall thus serve as some starting point for the more specialized subsequent presentations and trigger further discussions during the workshop.

Testing the Reconstruction Potential for North Pacific Circulation Anomalies inside the TraCE-21ka Paleoclimate Simulation

Oliver Elison Timm

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This talk summarizes results from a study that tested a covariance-based climate field reconstruction method, which uses present-day modes of climate variability as a reduced climate space. The underlying assumption is that temperature or precipitation proxies provide sufficient information to make inferences about extratropical atmospheric circulation changes over the North Pacific during the Holocene. The reconstruction problem was investigated under idealized conditions using model simulation results from the TraCE-21ka transient climate simulation, which covers the Last Glacial Maximum to present.

It is demonstrated that modes of variability found on interannual to multidecadal timescales during the preindustrial era provide inadequate pattern for reconstructing long-term mean changes during the past 22,000 years. Our circulation reconstruction target was the geopotential height field at 500hPa (Z500) over the North Pacific Ocean during winter. We applied a field reconstruction method using Maximum Covariance Analysis (MCA). The MCA was applied to Z500 and surface temperatures as predictor information. The MCA was given model data containing interannual to multidecadal variability from the pre-industrial climate. We worked with ten leading MCA modes in the reconstruction, which can reproduce about 90% of the covariability during the preindustrial period.

Within the model simulation, we validated the field reconstructions against the model's circulation states over the last 22,000 years. Spatial skill scores show that the reconstruction skill drops significantly prior to the late Holocene. Reasons for the loss of reconstruction skill are due to the fact that externally forced climate changes do not resemble the internal modes of variability and that covariance between circulation and temperatures on interannual-multidecadal time scales changes with the background climate state.

However, the reconstruction can be improved by including data from the early Holocene and the LGM era in the MCA. Based on these results, we advocate that paleoclimate model simulation results should be used define a set of first-guess pattern for the reconstruction of circulation anomalies from sparse and noisy proxy data.

Tropical corals - What can and cannot climate proxies tell us about Holocene climate variability?

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Shallow-water corals provide precisely-dated annually to monthly-resolved reconstructions of marine climate variability from across the global tropics to subtropics. They are a key archive to constrain past seasonal, interannual and decadal variability near the ocean surface beyond the start of systematic instrumental observations of climate. Coral reconstructions extending back for a few centuries provide a link between the observational period and lower-resolution sediment archives. This is of high relevance for comparisons of proxy data with model simulations of global climate variability. Well-preserved fossil corals can provide annually to monthly-resolved snapshots for time intervals of up to more than a century during Holocene, but commonly are just a few decades long.

Most Holocene records are based on δ18O analysed in coral skeletons, a variable that reflects a combination of both the temperature and the δ18O of the seawater near the ocean surface. The coral Sr/Ca temperature proxy has the potential to decouple the temperature and seawater δ18O signals from coral δ18O records in order to deliver reconstructions of seawater δ18O variability, a variable that is closely related to ocean salinity. However, only very few combined temperature and seawater δ18O reconstructions from corals currently exist for time intervals prior to the late Holocene. Such reconstructions would enable, when combined with coupled atmosphere-ocean general circulation models equipped with water isotope tracer modules, insights on the dynamical controls on both temperature and hydrologic variability of the tropical to subtropical ocean over the Holocene.

Methods for inferring variability from data

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At the last CVAS meeting, the scaling behaviour observed in paleoclimate reconstructions was discussed by the participants using the following methods: Detrended Fluctuation Analysis (i.e. DFA), the Haar structure function and the power spectrum. We present a comparative study of these methods in order to evaluate their strengths and shortcomings, and also to establish a common framework for discussion. Their ability is tested in recovering the known scaling exponent of synthetic time series of fractional Gaussian noise, and also (non-gaussian) multifractal simulations. The three methods are then applied to actual paleoclimate time series.

Cross-scale information transfer in climate records

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Viewing climate system as a complex system constituting of a large number of interacting components brings out interesting properties and vast possibilities for analysis. The so-called network approach — where the individual interacting components are considered as nodes in a network — opens a window to new paradigms and tools for studying the climate system in a data-driven fashion. One of interesting and trending topics in climate science is, without a doubt, scaling properties and cross-scale transfer. Although, the governing equations of fluid dynamics are scale-invariant, the atmosphere (as other parts of climate system) is actually stratified with energy injection at the largest scales, energy transfers to smaller and smaller scales, up to the dissipation scale at the molecular level. We expect to observe an information transfer along with the energy transfer between scales, and we approach the estimation problem using phase dynamics decomposition and measures from information theory, yielding synchronization and causality phenomena between different modes of variability on their respective scales. Apart from general methodology and theory, I will present an example of such analysis.

Space-time structure of climate variability - a spectral perspective

Torben Kunz

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The joint space-time structure of climate variability across a wide range of scales is investigated from a spectral perspective. Specifically, global near-surface temperature fields - taken from the TraCE-21ka paleo-climate simulation, from CMIP5 historically forced and control simulations, as well as from the NOAA 20th Century Reanalysis - are decomposed into spherical harmonic and frequency components. The obtained spectral space-time scaling behaviour is discussed and compared to that of simple stochastic-diffusive energy balance models, focusing on (a) the timescale-dependence of the effective number of spatial degrees of freedom, and (b) the impact of external climate forcing on the space-time scaling behaviour of the variability.

Holocene variability in proxies vs. models

Thomas Laepple

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Determining magnitudes of climate variability is important for attributing past and predicting future changes in climate. Multidecadal and longer temperature variability is poorly constrained, however, primarily because instrumental records are short and proxy records are noisy. Using a global compilation of Holocene marine temperature proxy records and correcting for non-climate variability, we derive an estimate for regional temperature variability between annual and millennial time-scales. Our estimate of temperature variability is consistent between different proxy types and with instrumental records. In comparison, general circulation model simulations have systematically less temperature variability than instrumental and proxy-based estimates. Discrepancies in variability are largest at low latitudes and increase with timescale, reaching two orders of magnitude for tropical variability at millennial timescales.

Antarctic High-Resolution Dust vs. Temperature: Similarities and Differences

Fabrice Lambert

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Dust fluxes in the East Antarctic EPICA Dome C ice-core have been measured at 1 cm resolution, which translates into a highest continuous temporal resolution of 25 years over the whole 800ka record. In contrast, isotope measurements were performed at a 55 cm resolution, which allows a 500-1000a temperature temporal resolution at best. We show that dust and temperature data record the same climatic variability at large timescales, but with a more and more distinct signal towards short timescales. We discuss these in the context of forcing and feedbacks at distinct scales. The Holocene shows very little variability in both Greenland and Antarctic ice cores, whereas paleoclimatic records from low latitude regions suggest a larger variability. We take advantage of the very high resolution in the EDC dust record to compare climatic variability in all interglacials and all glacial maxima to establish if the Holocene records in Polar Regions are uniquely flat both spatially and temporally.

What can be said about Holocene changes in the ocean state deduced from marine proxies?

Guillaume Leduc

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Marine sediment are routinely used to reconstruct past changes in ocean variability. For the Holocene, a large number of published records of temperature and salinity is available. I will briefly review how marine proxies work and remind uncertainties associated with the marine variable estimates, as well as how those uncertainties might impact global-scale temperature reconstructions. I will then discuss new emerging directions to extract key oceanic features out of the mean climatic background, such as seasonal and interannual variability embedded in marine proxies.

CVAS Challenges

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Climate variability is traditionally understood as a consequence of diverse dynamical processes occurring over well defined time scales with variability concentrated in narrow spectral bands: quasi-periodic processes such as El Nino or Milankovitch cycles. The in-between “continuum” processes and their variability are considered to be inconsequential, contributing only to “background noise” and have been largely ignored. Yet, the explosive development of paleo and instrumental data and archives combined with nonlinear geophysics data analysis techniques, has shown that this picture is quite misleading. They empirically show that the bulk of the variability comes instead from the background processes, and that these have been underestimated by a factor of as much as a quadrillion.

The picture revealed by modern archives is of the variability dominated by a hierarchy of wide range, scaling processes: weather, macroweather and climate. These either “wander” up and down - with typical fluctuations growing with scale (weather, climate), or they converge - with typical fluctuations decaying (diminishing) with scale (e.g. when averaged over longer and longer periods, macroweather). In each regime, the variability is determined by various exponents. These determine the rates that typical fluctuations change with scale, their intermittency (“spikiness”), the nature of the extremes and it quantifies their respective (nonclassical) long range memories.
A full characterization requires knowledge of the two transition time scales. The weather – macroweather transition is relatively well understood as the lifetime of planetary scale weather structures. It is fairly constant (about 10 days), varying only slightly with latitude, it justifies the practice of using monthly averages to filter out weather scale variability. At longer time scales, the internal macroweather variability decreases and at the macroweather - climate transition scale, fluctuations again start to increase. In the anthropocene, this is the scale at which the responses to climate forcings become dominant over the internal variability, for the global temperature, it is currently at about 16 – 18 years with local transition scales showing some geographic variability, it justifies the use of 30 year climate normals. However, in the pre-industrial epoch, this transition scale is highly variable and solar and volcanic forcings may be unable to account for them. At multicentennial and multimillenial scales, there may be new, slow internal processes that come to the fore.

In this talk, I discuss some of the challenges currently facing CVAS:
1) How does the amplitude of fluctuations vary with time scale?
2) With spatial scale?

3) In space-time?
4) How can we use this information to make better multiproxy reconstructions?
5) What are the basic dynamical regimes?
6) "Spikiness" (intermittency), extremes and tipping points and black swans.
7) Do the models have realistic variability?
8) How can we use this for prediction and what are the limits?
9) Over what range of time scales is the response to forcings roughly linear?
10) How can we use this for projections (and for reducing uncertainty)?

Is civilization due to freak macroweather?

<u>Shaun Lovejoy</u>

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"The long, stable Holocene is a unique feature of climate during the past 420,000 years, with possibly profound implications for evolution and the development of civilizations." So concluded an influential analysis by [Petit et al., 1999] of the 3300 m long Vostok (Antarctic) ice core record that spans four complete ice age cycles. The second half of the sentence implies that there is a direct link between stable temperatures since the end of the last ice age (the Holocene) and the development of civilization. Presumably, the implied link is that farming developed less than a thousand years after the retreat of the ice sheets and agriculture was crucial for transforming society.

Similar conclusions about Holocene stability were later made on the basis of other high latitude ice cores, including from Greenland. However using on paleo SST from ocean cores just off the coast of Greenland, [Berner et al., 2008] concluded on the contrary that the Holocene is "highly unstable". In this talk we discuss the debate: "Have our species been spoiled by a long and blissful macroweather hiatus, or – on the contrary - did harshly varying climate adversity force us to invent new ways of coping?" [Lovejoy, 2017].

The issue of stability/instability can be quantified using fluctuation analysis, it depends on the sign of the fluctuation exponent H. Since by definition macroweather has $H<0$, it is stable with successive fluctuations tending to cancel each other out, in contrast, the weather and climate are unstable with $H>0$, implying that successive fluctuations tend to accumulate so that the temperature signal seems to "wander". Since we know that global preindustrial temperature fluctuations are of the order of ±0.2°C at centennial scales, but ≈ ±2°C at 50-100 kyr scales, macroweather must make a transition to the lower frequency climate regime at a critical scale 100 yrs < τ_c <50 kyrs. For comparison, due to anthropogenic forcing, τ_c ≈is currently 16- 18 years.

This is issue is at the heart of CVAS. By examining various proxy and multiproxy records, we discuss our current knowledge of the epoch to epoch variability of τ_c as well as its geographic variability. If Petit et al are correct - that the $H<0$ is valid throughout the Holocene (so τ_c is of the order of 10 kyrs) and is representative of global conditions, then it would be so exceptional that we might conclude that freak macroweather was indeed responsible for civilization. Alternatively, if it turns out that large τ_c, was mostly a high latitude phenomenon, then Berner et al is correct and civilization might more plausibly have arisen as a reaction to high climate variability, instability.

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Is there a break in scaling on centennial time scales in Holocene temperature records?

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A persistent fractional Gaussian noise has proven suitable as a model for the global temperature variability at time scales from months to centuries (Rypdal and Rypdal, 2014). On longer time scales direct temperature measurements are not available, and proxy-based reconstructions are needed. These are subject to uncertainties originating from the reconstruction methods and the age models used, and the uncertainties are often not taken into critical consideration when scaling exponents, and their errors, are estimated. By elaborating on the physical mechanisms for the actual climate fluctuations seen in the paleoclimatic temperature records as well as uncertainties in both data and methods, we hypothesize in Nilsen et al. (2016) that a simple model with one single scaling regime is sufficient to describe the Holocene temperature variability. Our results show that the one-regime model cannot be rejected for the data under study. We cannot identify a break between two different scaling regimes at centennial time scales in Holocene climate from scaling analyses. However, we do observe departures from scaling, which can be attributed to variability such as a single internal quasi-periodic oscillation, an externally forced trend, or a combination of factors.

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Modeling feedbacks, sensitivity, and variability across time scales

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The observed historical warming has mostly come about due to the so-called fast response to greenhouse gas emissions. Forecasts of future warming are hampered by the fact that climatic feedbacks, and therefore the magnitude of the response to external forcing, may be different on long time-scales that cannot be constrained by the short record of anthropogenic warming. Significant interest therefore exists in understanding the magnitude of feedbacks associated with natural variability. Here we present a model for temperature variability and climate feedbacks from monthly to Milankovitch time scales. The observed scaling in temperature variability is modeled as a superposition of several linear modes, each associated with a Hasselman type model. Each source of internal and external forcing is found to elicit a potentially distinct feedback. Finally, a significant component of the increased variance on long time scales is found to arise as a consequence of scaling in the external greenhouse gas forcing.