What do we know about multicentennial, multimillenial variability?

28-30 November 2016, Hamburg, Germany
Gästehaus der Universität
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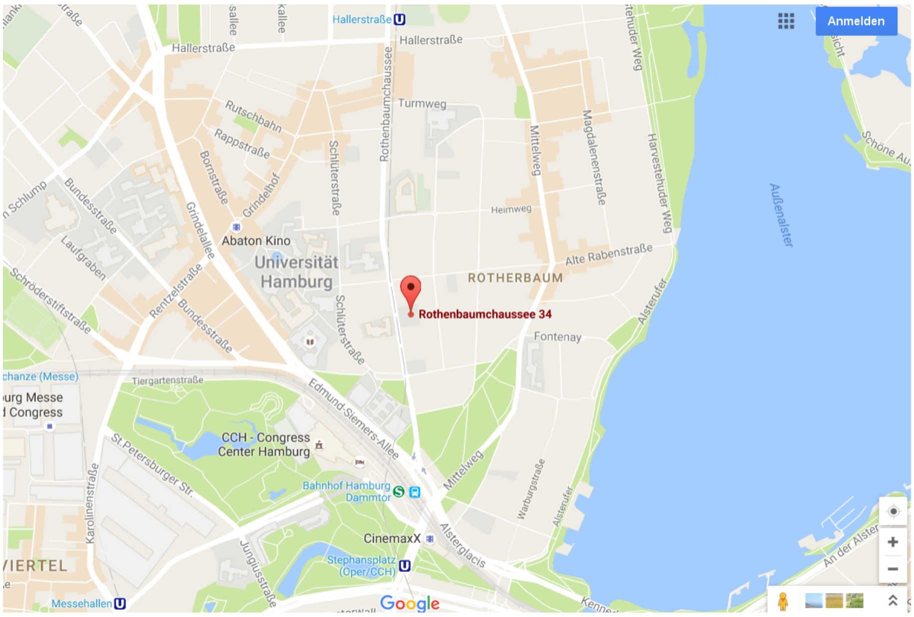

Archival of the water stable isotope signal in East Antarctic ice cores

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The oldest ice core records are obtained on the East Antarctic plateau. Analysing the stable isotopes of water in the ice samples enables faithful reconstructions of past climatic conditions both over the ice sheet and at the evaporation source. The accuracy of the climate reconstructions relies on the knowledge of the processes affecting the isotopic composition in Polar Regions. Both, simple models such as Rayleigh distillation and complex isotope enabled climate models provide a good prediction of precipitation isotopic composition in East Antarctica. However, post-depositional processes alter the isotopic composition on site, in particular the exchanges with local vapour and diffusion inside the firn. In low accumulation sites such as found on the East Antarctic Plateau, these poorly constrained processes are especially likely to play a significant role. This limits the interpretation of isotopic composition from ice core records, specifically at short time scales.

Here, we combine observations of isotopic composition in the vapour, the precipitation, the surface snow and the buried snow to identify the processes involved in the archival of the climatic signal in snow on the East Antarctic Plateau. At the seasonal scale, we highlight the significant impact of metamorphism on surface snow isotopic signal. This is completed with a particular focus on the summer exchanges of molecules between vapour and snow linked with the sublimation/condensation cycles at the diurnal scale. Then, we compare the variability in snow isotopic composition profiles from 5 sites around the East Antarctic Plateau and identify a recurrent 20 cm cycle which cannot be associated with the seasonal cycle. We present evidences of additional post-deposition processes affecting the variability of the isotopic composition in the snow pack. To
characterise these processes is crucial to understand the link between snow isotopic composition and climatic conditions and to push the limits of the interpretation of isotopic composition as a paleoclimate proxy.

Stochastic dynamical systems to apprehend climate sytem’s

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This is a pervasive theme in the CVAS working group: climate system exhibits mode of variability from the second to billions of years : a huge spectrum indeed. We know that it is not possible to provide a deterministic model that would span all these time scales with perfect accuracy. Not only would the computing cost would be immense (in fact beyond reach within any foreseeable future) but mostly the material complexity of our climate system is overwhelming. There will never thus be such a thing as a “ab inito” climate model. Instead, we organise our research on climate dynamics along different axes.

One axis is time scales: some study cloud turbulence, others model El-Niño, others ice ages. Another axis is model complexity. The simpler models allow us to connect a specific phenomenon (like ENSO) with fairly general concepts in mathematics. When we model ENSO as a “delayed oscillator”, we can borrow experience gained in other areas of science including mathematics, engineering or even in life science, to learn how to analyse the phenomenon, compare it with observations and draw general conclusions. If we model ice ages as an ‘oscillation’, we can understand how the astronomical forcing can act as pacemaker, and we can refer to generic concepts such as synchronisation or resonance. A general concern is that simple determinstic models such as those cited here focus too narrowly on a given mechanism of motion, while the actual dynamics are intricate and complex. Stommel’s ocean box model, for example, predicts that the ocean circulation may have several equilibria. Is this relevant about the real world?

The phenomenon of ice ages can serve us to illustrate this question. Numerous models describe ice ages as a process of gentle and steady ice accumulation over time possibly modulated by the astronomical forcing. Deglaciation then occurs when some non-linear process, triggered either internally or externally, produce an accelerated melt of accumulated ice. Figure 1 (red) shows the trajectory simulated with such a model and to keep the discussion simple and illustrative we even ignored here the astronomical forcing. Ice ages appear in this case as a periodic motion. The challenger to this model will be one almost entirely based on the cumulated effects of erratic fluctuations emerging from the complex motions of the atmosphere and the oceans. The mathematics to represent random effects have their roots in the XIXth century and they were popularised in climate science among other by the works of Hasselman (1976), who proposed such stochastic model to describe the effects of atmospheric fluctuations on ocean mixed-layer temperature. Hasselmans’ model lies on the concept of “random walk”. The mathematics of the random walk show how accumulating random steps can move you a long way from your original state. Some relaxation forces must intervene somewhere to constrain the dynamics and let a stationary distribution of system states emerge. Based on this stochastic paradigm Wunsch (2003) modelled the accumulation of ice with a random walk, and he decided that deglaciation abruptly occurs when a threshold is reached, as if some runaway unstable process were triggered.

As can be seen on the Figure 1, the deterministic and the stochastic models exhibit in this example quite different power spectra: the deterministic model is characterized by well-marked lines on the Fourier spectrum—this is the Fourier decomposition of the periodic motion— the stochastic shows a background spanning several orders of magnitude characteristic of red noise.

Which one is true? None of course. Any model is an abstraction. We can theoretically justify that some modes of motion emerge from the noisy background because the geometry of the Earth, the physical nature of the flow, and the dynamics of the forcings induce instabilities and resonances. ENSO is again a vivid example, and some deterministic models may even generate much more complex spectra than shown on Figure 1. On the other hand, fluctuations generated by innumerable other processes may contribute to the system dynamics on a wide range of time scales. The very notions of “mode” and “background” are in fact hard to separate out. In excitable systems, for example, the noise is necessary to generate quasi-periodic oscillations. This is the phenomenon of coherence resonance. Fortunately, mathematics make it possible to combine the mechanistic reasoning that underlies deterministic models with stochastic effects. Simple deterministic models are often written in terms of ordinary differential equations, like Newton’s law. A long time ago Langevin showed how to “noise up” deterministic differential equations to account for random fluctuations. This yields stochastic differential equations. In turn, stochastic differential equations can be viewed as one way to generate a wider class of objects called random dynamical systems (Arnold, 1998). Nowadays, mathematicians are in business to understand how definitions familiar in deterministic dynamical systems, such as the bifurcation, must be adapted to random dynamical systems. In turn, climate scientists attempt to take advantage of these new mathematical definitions to review fundamental climatic concepts such as that of climate sensitivity (Ghil, 2014).

The question that poses itself here is whether random dynamical may effectively help us to better understand the dynamics of the climate system. It seems that we can respond positively. The interest of a research programme based on random dynamical system can be justified if we can merge random dynamical systems within the full hierarchy of climate models and time scales. As we already argued, random effects are a priori an efficient approach to represent cumulative effects which populate the spectrum of fluctuations. In certain cases it is possible to justify the form and properties of random terms from first principles. Other studies have shown how the complex dynamics of an atmospheric model can be convincingly generated with a small number of stochastic differential equations (see review by Franzke 2015 and Kravtsov and Kondrashov, 2005). Random dynamical systems may therefore constitute a more powerful basis to represent complex processes than deterministic equations.

On the other hand, they are simple enough to be calibrated on actual observations. The latter is however never simple. When a dynamical system is stochastic, the evolution observed is considered as one out of an infinity of alternative random histories. In principle, Bayesian statistics may still tell us how to select a “best” model from a set of candidate stochastic models, and the statistical methodology is well known and applied on linear systems such as auto-regressive processes. If the system is non-linear, however, complex algorithms are generally required for sampling random variables. One of the harder cases occurs when the system is controlled by an external forcing. Carson et al. (2015) applied particle filtering methods to select a best random dynamical system of ice ages among alternatives, which suggest that the technical difficulties at least can be addressed, albeit at some cost. Model discrepancy may be a more important challenge because its nature is more deeply epistemological. No model is perfect, and we need to think carefully how the account for the difference (discrepancy) between the model and the truth. Depending on how this discrepancy is represented, which forecast horizon we are interested in, and how all of this is encoded into a cost function, statistics might tell us to prefer one model or the other.

These very issues are present when dealing with GCMs. GCMs are imperfect representations of the reality and they generate chaotic motion which can be interpreted as stochastic flows. We therefore have to learn how to deal with fluctuations, randomness and structural uncertainty at the GCM scale. From that point of view, experimenting with random dynamical systems can be extremely fruitful.

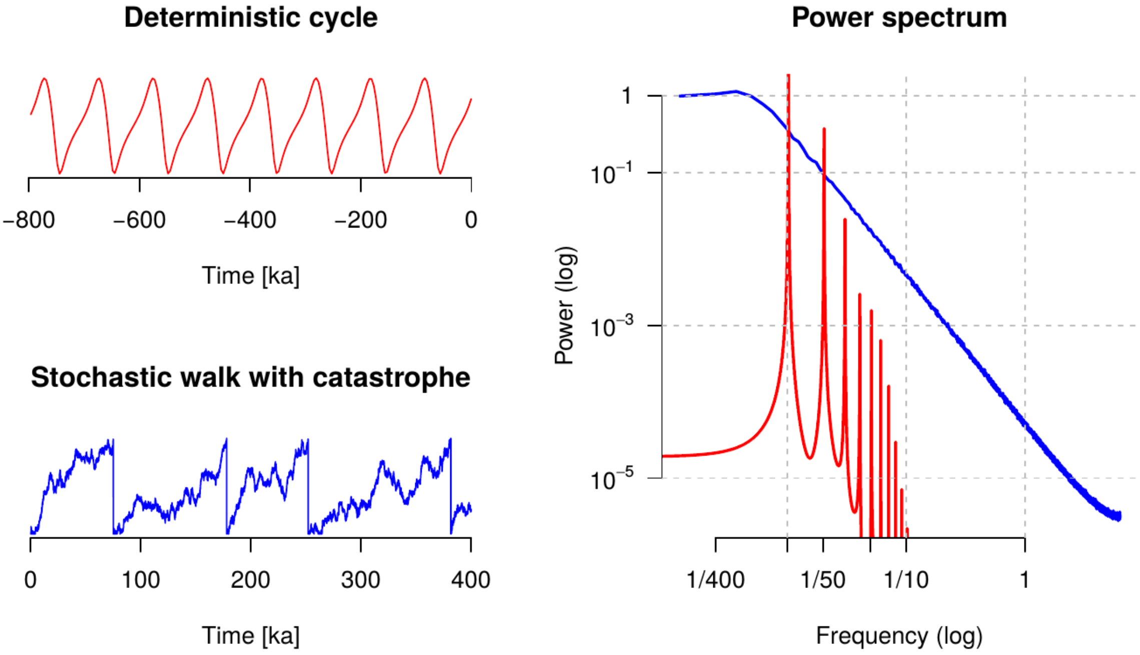

Figure 1:

Time series generated by extremely simplified models of ice ages, assuming either that ice ages are the manifestation of a deterministic limit cycle obtained from a dynamical sytem (based on Saltzman and Maasch, 1990), or a stochastic process generated with a random walk and terminated by catastrophic collapses (based on Wunsch 2003). Observe how the power spectra differ. Some deterministic model may have a richer spectrum background.

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Variability of Asian monsoon and its linkage with deep-sea water and ecological system of benthic foraminifera assemblages over 700 Ka

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The Japan Sea is an excellent recorder of the orbital to suborbital scale variability of the East Asian monsoon over last 3.5 ma. The Japan Sea has its own unique deep-water circulation, which is sensitive to glacial-interglacial cycles. The presence of narrow straits makes the Japan Sea ideal site to understand glacial-interglacial changes using deep sea sediments.

Evidences support changes in deep sea benthic ecosystem modulated by glacial cycles effecting deep water oxygenation levels oscillation between oxic and anoxic environment, millennial–scale sea level and climate changes. We have analysed benthic foraminifera from the IODP site U1426 of last 700 Ka to understand millennial scale variations in climate over Japan Sea and its global implications. Site U1426 is located in the south-central part of the Japan at 37°2.00′N, 134°48.00′E and 903 mbsl, near the top of the Oki Ridge that bounds the southern margin of the Yamato Basin. This site is affected by the second branch of the Tsushima Warm Current, which is a highly meandering current characterized by eddies. We did the multivariate analysis and found benthic assemblages sensitive to the millennial scale changes in the glacial-interglacial cycle. We have also correlated our benthic assemblage data with LR04 benthic stack and found that the beginning of interglacial stages are marked by dominance of benthic assemblages associated with shallow infaunal species Cassidulina norcrossi; whereas glacial interval by benthic assemblages associated with Cassidulina japonica. The period of strong winter monsoon is dominated by the high productivity indicating shallow infaunal species of Uvigerina genus. The increasing trend in the diversity parameters observed during glacial period and decreasing trend during interglacial period in the studied interval. The time series analysis of these data shows orbital to sub-orbital scale cyclicity.

Climate variability across scales: the case of Arctic-subarctic sea ice cover from marine sediment proxies

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Sea ice is an important component of the climate system which deserves special attention as it is responsible for Arctic amplification through ice-albedo feedbacks and because it controls the exchanges of heat and gas at the ocean-water interface. Sea ice formation and melt vary in response to incoming energy and depending upon stratification and thermal inertia of upper waters, which are function of salinity. It also varies in space in relation with surface ocean and/or atmospheric currents that form the pack-ice in convergence zones and redistribute sea ice in subpolar seas. Hence, the variations of sea ice distribution in time and space is complex.

At the satellite sea ice observation time scale (1979 et p.), the largest variation of Arctic sea ice undoubtedly occurs at the intra-annual scale, from summer (September ~ 6.3 ± 1.1 10^6 km^2) to winter (March ~ 15.5 ± 0.5 10^6 km^2), which represent about 60% of change in the areal coverage (cf. http://nsidc.org/data/seaice_index/). Beyond seasonal variation, a multi-decadal decreasing trend was recorded since 1979. The trend is larger in summer (13.3%/decade) than winter (2.7%/decade). It is globally correlated with the rise of surface air temperature (r^2 ~ 0.63). Although a relationship between sea ice extent and climate seems unquestionable, the recent trend of sea ice decrease appears non-linear and time series longer than those of satellite observations are needed for a proper assessment of trends and variations. Long time series are also indispensable to document the full range of sea ice variations under natural forcing/feedbacks and for modelling the fate of sea ice cover in a context of large amplitude climate change.

The development of long time series covering centuries to millennia is a challenge. The historical information is useful to illustrate annual extremes, but it is restricted to a few centuries and mostly cover the subarctic North Atlantic where human populations have settled. To extend back in time the record of Arctic sea ice extend, special effort has been made by compiling circum-Arctic paleoclimate data from tree ring and ice core records (cf. Kinnard et al., Nature 2011). The results encompassed the last 1400 years and led to estimate the natural variability of Arctic sea ice cover, which ranged mostly from ~9 to ~11 10^6 km^2 in late summer, thus suggesting that the recent trend is unprecedented, at least since 600 AD. However, the proxies used are very indirectly related to seaice and the set of data is heterogeneously distributed with very rare data points from the Russian Arctic, which is the most critical regions with regard to the recent decline in sea ice cover extent. Furthermore, the last 1400 years are insufficient to represent the full range of natural variations. From this point of view, the entire Holocene (last 11,000 years) that was notably characterized by higher than present-day summer insolation during an early phase deserves special attention to document changes under various climatic regimes.

Millennial time series can be obtained from proxy records of marine sediment cores collected in Arctic and subarctic seas. However, the marine records suffer from a number of caveats.

(1) The first one is the temporal resolution of the data. In marine cores, sediment accumulation rates and biological mixing of sediment determine the temporal resolution that can be achieved. In shelf environments and fjords, where sedimentation rates may reach about 1 mm/year, one may achieve analyses with decadal resolution. Offshore, in the open ocean, sedimentation rates are often of the order of 0.01 mm/year and the time window represented by the usual sampling of 1-cm thick sediment slices is thus of the

order of one century. In the central Arctic Ocean, it is even more critical since sediment accumulation rates are very low (1 cm for 10^3-10^4 years) and may include hiatuses, which makes it extremely difficult to develop time series.

(2) A second caveat is the spatial distribution of marine core records, which is not dense enough for extrapolation at the scale of the Arctic-subarctic area. The available records from direct measurements, historical observation or proxy data tend to indicate an asymmetrical behaviour of sea ice variations, which prevent spatial extrapolation from only a few data points (cf. for ex. de Vernal et al., QSR 2013).

(3) A third caveat is the actual significance of the proxies. There are many tracers that permit assessment of seasonal sea ice occurrence. They include ice-rafted debris and biogenic remains of micro-organisms related to biological production along the sea ice margins (diatoms, dinocysts, IP25 biomarkers notably). Year round ice free conditions are easy to assess as well as occurrence of seasonal sea ice. Perennial or multiyear sea ice is more difficult to reconstruct and it is often deduced from negative evidence (nil productivity resulting in sediment barren in biogenic remains). Quantification of sea ice occurrence in terms of concentration or seasonal extent is not straightforward. To date, the indicators that permit such inferences are dinocyst and diatom assemblages, which are the remains of planktonic populations. The advantages of dinocysts is the usually good preservation and the access to a comprehensive reference databases allowing reconstructions at the scale of the Northern Hemisphere. Diatoms are useful but they often suffer from dissolution and only regional datasets are available.

(4) Finally, the “modern” relationships between the proxies and sea ice are defined from a data matrix that includes for each reference data point, (a) the results of population analyses in surface sediment samples and (b) the measurements based on aerial photographs and satellite observations. The two data sets (a and b) do not necessarily encompass the same time window, which can be an important source of error in the proxy quantification in terms of sea ice concentration or seasonal duration.

Despite limitations, the marine data provide clues on sea ice cover variations with time windows ranging from decades in nearshore environments to centuries in open ocean. Hence the paleo-proxies yield smoothed records, in which the occasional extremes are probably hidden. From this point of view, the marine-proxy records of sea ice change should be compatible with mean climate states. Example of sea ice time series spanning several thousands of years are available from the subpolar North Atlantic where they show large contrasts from glacial to interglacial (e.g. de Vernal et al., QSR 2005). At the scale of the Holocene, proxy-data suggest limited variations in the Canadian Arctic, where sea ice seems to be resilient, but show large amplitude centennial-millennial scale variability in the subpolar seas (e.g. de Vernal et al., 2013). In particular, high resolution (decadal) records from the Labrador and Greenland margins (e.g. Ouellet-Bernier et al., The Holocene, 2014; Richerol et al., The Holocene, 2015) show large amplitude variations (>50%) with a centennial pacing that illustrates the high sensitivity of the subpolar coastal areas with regard to sea ice.

On the enigma of the climate spectrum at centennial and millennial time scales

Peter Ditlevsen and Michel Crucifix

The climate system is varying on all time scales from seconds to the age of the Earth. This is a combined result of many physical processes acting on a huge range of spatial and temporal scales. Without dwelling too much into semantics, we deliberately use the term "climate system" to distinguish from the notion of "climate" defined as a long term mean of weather. Without rigor, we consider the climate system as the open combined system of the components, atmosphere, oceans, cryosphere, lithosphere and biosphere, which may exchange mass and energy. By this definition, we may consider some processes internal and some as external. The latter we can consider as forcing the system. The distinction will to some extend depend on the processes under consideration: As an example, consider the present days climate model simulations of atmospheric temperatures reported by the IPCC. Here three main external forcing agents are used: (a) CO2 concentration, (b) volcanic eruptions and (c) solar variability. On centennial and longer timescales the atmospheric CO2 concentration (a) is completely determined by the interchange with the world ocean, thus internal to the climate system. On these time scales only the emissions from fossil fuel burning can be considered external. On even longer geologic time scales even this part of the CO2 concentration in balance with volcanic outgassing, weathering, biomass burial and ocean floor sedimentation. Likewise, the volcanic eruptions (b) is only external to the extend that we exclude the lithosphere, below the surface, from the dynamical climate system. On geological time scales this is again questionable as plate tectonics is an important climate factor. In this case we may argue that the influence is mainly one way, from the lithosphere to the climate system, and not so much the other way, such that we can consider continents as a (slowly changing) external boundary condition for the climate system. This leaves us with the solar forcing (c) as the only truly external forcing of the three.

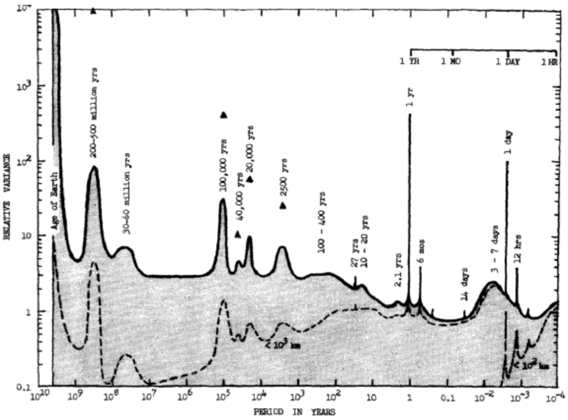

Figure 1. Schematic power spectrum reprinted from Mitchell, 1976

A comprehensive view of the climate variability over this huge range of scales is expressed in the spectral decomposition of the variance expressed in the power spectrum. This was done schematically in a paper by ?. The spectrum, reprinted in figure 1, has been influential for many years in the way we think about climate variability. Mitchell made the distinction between a continuous stochastic background spectrum and a discrete (line) spectrum imposed by the periodic, diurnal, annual cycles and the quasi-periodic astronomically induces cycles in the insolation at glacial time scales. This external forcing to which the climate responds linearly, giving rise to predictable spectral peaks above the continuous background.

Mitchell ascribed the continuous background to different stochastic processes at various time scales each contributing a white noise spectrum at longer time scales contributing to the spectrum at low frequencies. ?, a few months later, published his seminal paper on Stochastic climate theory, noting that the influence of the fast climate variables (atmosphere temperature) on the slow variables (ocean temperature) can be considered as the integrated effect of a stochastic noise. Thus the dynamics of the slow variables is described as an Ornstein-Uhlenbeck red-noise process, with a correlation time scale set by the feedback processes of the slow variable. Though it is difficult to find a clear spectral gap between the turbulent atmospheric and oceanic spectra, this is a surprisingly successful description of observed ocean temperatures, showing red noise spectra with approximately decadal correlation times. Thus we would expect a flat background spectrum above the decadal and below the time scales of orbital changes. On this much longer time scales, Milankovitch' theory states that the glacial cycles are responses to astronomical forcing. However, the paleoclimatic records give a completely different picture. The flat spectrum at decadal time scales turns into a red noise spectrum on longer time scales. Figure 2 show a composite of spectra from records covering time scales from days to millions of years.

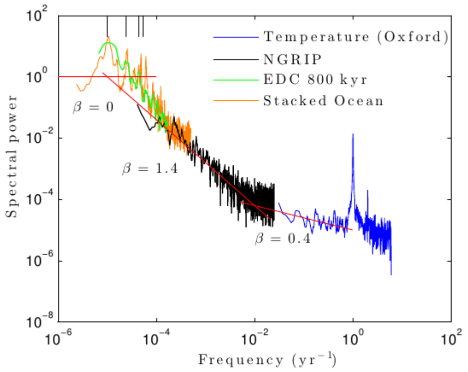

Figure 2. Climate spectra from different records, adapted from (Shao and Ditlevsen, 2016)

Is shows that the continuous part of the spectrum is completely dominant. This was noticed by ? : While the schematic spectrum in Figure 1 vary merely half a decade over the range 10-105 years, the observed spectrum in Figure 2 vary four to five orders of magnitude in the same frequency range. Thus in some respects the observed scaling of the climate variability overshadows dominance of processes at more narrow frequency bands.

This view is represented in the "multifractal paradigm", where the entire record is seen as a scaling process [??]. Since the paleoclimatic records get more sparse in deep geological time and atmospheric temperatures less constrained, the actual weight on variability above perhaps 10 million years is uncertain. The sediment records of the present ice house epoch (is this the right terminology?) suggest that the spectrum could be flat at time scales much longer than those of the glacial cycles.

Though the Middle Pleistocene Transition between a 41 ka to a ∼100 ka periodic response witnesses that the forcing-response relationship is non-linear, the essential dynamics of the climate response to the astronomical forcing seems to be captured in models with few dynamical variables representing the climate [?]. This suggest the glacial climate variability to be concentrated in a narrow spectral band around the band of orbital periods, thus not giving rise to the dominant continuous spectrum at centennial to millennial time scales.

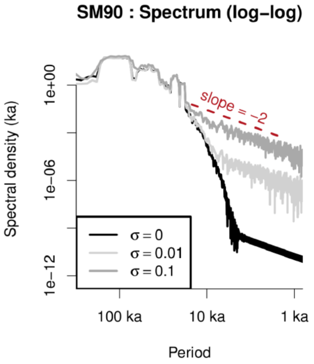

Figure 3. Short caption

As an illustration, Figure 3 shows the spectrum of a specific model of the glacial cycles ?. The model shows very little variability on time scales shorter than 10 kyr (black curve). In order for the model to show a spectrum consistent with the observed record, so much noise must be added (gray curves), that it more or less loose any resemblance to the actual glacial cycles. (is this a correct interpretation?). It is thus difficult to explain the continuous spectrum at centennial to decadal scales as a result of the glacial time scales variability.

On the other hand it was observed by [?] that the variability on time scales longer than decadal are underestimated by an order of magnitude in long state-of-the-art CMIP5 climate model simulations. This suggests that; either the climate models lack substantial part of the internal variability in the atmosphere-ocean system, or they do not include the governing physical processes. Here we shall not attempt to identify the physical processes responsible for the variability at centennial to millennial time scales, we shall rather discuss the possible implications that can be drawn from the observed continuous spectrum on identifying possible dynamical mechanisms.

LATE PLEISTOCENE INTERHEMISPHERIC ASYNCHRONICITY OF LARGE-SCALE CLIMATE FLUCTUATIONS

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Recent ice core records from both Greenland and the Antarctic have provided evidence for the presence of anti-synchronous oscillations between large-scale climate fluctuations at both hemispheres, known as the bipolar seesaw. Here, we utilize a suite of modern data analysis techniques to study the phase relationship between the corresponding dominant fluctuations. On the one hand, phase synchronization analysis in combination with time-scale decomposition techniques like wavelet analysis or empirical mode decomposition identify particular time scales, time intervals and associated phase lags of coherent variations. On the other hand, we employ event coincidence analysis to study the synchronicity and phase relationship between distinct events embedded in the signals at both hemispheres. Both approaches provide complementary views on the bipolar seesaw phenomenon during the last glacial cycle.

Scaling Models and Processes

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What is scaling?
Scaling and fractals are ubiquitous in nature. Fractals have the property that an enlarged or contracted part of the whole looks similar in a statistical sense like the original part. In mathematical language we write for this

$$X(c^*t) \sim c^H X(t)$$

where H is the Hurst exponent. This relationship describes scaling. An important property is that such scaling data series have no intrinsic or typical scale; they are scale free. For instance, a widely used time series models is an autoregressive process of first order AR(1). The autocorrelation function of an AR(1) process decays exponentially with a typical time scale; the so-called e-folding time scale. On the other hand, the autocorrelation function a scaling time series decays according to a power-law and, thus, has no typical time scale.

Why is it important?
Scaling impacts on several aspects of climate and climate change research. Scaling leads to so-called long-term persistence (LTP). LTP is the property many climate time series exhibit that positive values are followed by other positive values and vice versa. This means, that the climate system has the ability to wander off the climatological mean state for rather long periods of time. When working in practice with only finite time series lengths of say 150 years for the instrumental record it can be hard to distinguish between externally forced climate trends and apparent trends due to intrinsic climate variability.

How to measure it?
The scaling exponent is typically called the Hurst exponent which describes the Hurst effect. The Hurst effect has two contributions: 1) LTP and 2) non-Gaussian jumps. Both contribute to the Hurst exponent:

$$H = d + 1/\text{alpha}$$

where d denotes the LTP exponent and alpha the exponent of the PDF tail. alpha=2 for a Gaussian distribution. For values between 1< alpha < 2 the variance if infinite and for alpha < 1 the mean does not exist.

There are various estimators and free software: R/S (R package fArma), DFA (R package PowerSpectrum), Power spectrum GPH estimator (R package PowerSpectrum), MLE (R package fracdiff, longmemo), FEXP (R package longmemo), Bayesian estimator (R code by Graves et al. (2015)) and many more.

In my presentation I will discuss different physical models and processes which can explain the observed scaling behavior: 1) Turbulence, Cascades (e.g. Lovejoy and Schertzer 2013), 2) regime behavior (e.g. Diebold and Inuoe 2001; Franzke et al. 2015), 3) Temporal aggregation (Granger 1980), 4) Non-stationarity (Klemes 1974), 5) fractional

Gaussian noise, ARFIMA (e.g. Beran 1994, Graves et al. 2015) and 6) Fractional Poisson process.

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Scaling of temperatures produced by linear energy balance models

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We demonstrate how scaling of temperature data on time scales from months to centuries can arise from simple, linear energy balance models. In these models, the internal 1/f-like variability is approximated by a sum of AR(1) processes that result from running the model with a white noise forcing. In other words, the model acts as a linear filter of the input forcing. The same filter is also applied to known external forcing, producing a temperature response in good agreement with the global instrumental temperature record.

We also explore how we can separate land and sea surface temperatures in this model to obtain a slower response and a higher spectral exponent for sea surface temperatures, compared to what is observed for land temperatures.

A condition for using such a linear model is that the climate system not close to a tipping point, requiring a nonlinear description. As long as this condition is fulfilled, as it has been throughout the Holocene so far, we suggest there is no need for nonlinear models to explain the observed temperature spectra and responses.

TEMPORAL SCALES AND SIGNAL MODELLING IN DENDROCLIMATOLOGY

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The palaeoclimatological proxies represent records of climate that were generated through physical, chemical and/or biological processes. Reconstructions of climate rest on attempts to turn this around in order to get back to the climate information (*1*). These reconstructions are characterized by a time resolution depending on the sedimentation or growth processes depending on the archive type. These processes act as low-pass filters and determine the resolution of the climatic signal, which can be inferred from. Tree-ring series reproduce annual variability of the climate with a relative good reliability, but like all biological proxies, they record a more or less complex combination of climate variables because the tree-growth is the result of numerous complex mechanisms.

The first problem to face with the tree-ring series is that they are characterized by trends which are not related to climate but result from various factors related to the geometry of the stem and various ecophysiological factors commonly called "age-related factors" (*2*). Usually the tree-ring series are detrended using deterministic (mathematical analytical functions) or stochastic (filters) techniques (*3*). Other types of methods are based on the estimation of the representative growth of the trees related to their biological age. This can be done by statistical approaches (*4*) or ecophysicological models (*5*). Whatever the approach used, the tree-ring series are detrended and the climate reconstruction is based on the residual series, called also standardised master series.

Numerous attempts have been made to reconstruct the centennial or millennial history of regional or global temperature by way of tree-ring information. Most of them are based on the calibration of regression between temperature and the standardised tree-ring series (*6*) and have been largely used in the 2001 IPCC report. It was followed an intense debate mostly turned on the trend of the reconstructions (called the "hockey stick") (*7*). Christiansen and Ljungqvist (*8*) has analysed the fact that the classical reconstruction methods (which are most often inverse methods) seriously underestimate the amplitude of low-frequency variability and trends. They showed that a solution could be considering local reconstructions where the proxy is the dependent variable (forward method) instead of global reconstructions where the proxies are the predictors (inverse method).

Another problem, which disturbs the climate signal recorded by the tree-ring series is the so-called "divergence problem" (*9*). It consists in an anomalous reduction in forest growth indices and temperature sensitivity and has been detected in tree-ring width and density records from many circumpolar northern latitude or high elevation sites since around the middle 20th century. At that period, the relationship between the climate variable and the tree-ring series seems to have been changed. This often leads to an underestimation of the temperature. Various hypotheses can be called, such as a change in the limiting factors, the fertilization effect of CO_2, non-linear relationships, etc…

The deconvolution of the climate signal is a difficult task when it is done by simple statistical techniques. The mechanisms acting at decadal time scale can be different to those acting at the annual time scale. Statistical methods dealing with these time scales are a way to solve this problem. Another way is to use mechanistic models. The first group of approaches is to deal separately with low and high frequency variations. Esper et al (*10*) showed that the low frequency behaviour of tree-ring series can cause an underestimation of temperature in some past periods. This, in turn, would lead to an over-emphasis on recent warming. To address this challenge, they proposed to standardize the tree-ring series in a way that preserves climatic low frequencies. An alternative solution (*11*) used tree-ring series to estimate high frequency climate variations, and applies ice cores and lake/oceanic sediment proxies to reconstruct low frequency variations. However, they did not solve the proxy calibration problem because proxies were just rescaled in temperature units and assumed to record the same climatic signal, which is far to be proved (*12*). Guiot (*13*, *14*) proposed to use a decomposition of spectral characteristics of various proxies into complementary bands. A separate calibration and a separate reconstruction are done in each of these bands, using only the proxies with a sufficient variance in the band. The final reconstruction is the sum of the spectral band reconstructions.

Another source of biases in the estimation of low frequency variations of the climatic signal is that which is related to the evolution of the CO2 atmospheric concentration. Before the industrial period, this concentration was about 280 ppm and recently passed 400 ppm. As the CO2 is a major factor of the photosynthesis, a relationship calibrated on the last century with a high CO2 concentration cannot be straightforwardly extrapolated to periods when it was less abundant. This problem can only been solved by mechanistic models used in an inverse mode. Boucher et al. (*15*) showed that fixing CO_2 concentrations at preindustrial levels results in overestimating evapotranspiration and then temperature. So most of the statistical methods may lead to biases. Nevertheless this inversion, done in a Bayesian framework, remains difficult to be implemented because mechanistic models need a deep knowledge of the tree ecophysiology and because the approach is computationally heavy.

This rapid review shows well that the main strength of the dendroclimatology is its ability to reconstruct annual series of climatic changes, and its main weakness is in the difficulty to reconstruct low frequencies. This difficulty follows from (1) the standardisation procedure, (2) the selection of model relating tree-growth and climate and (3) the calibration of the model itself. Whatever is the source of low frequency biases, the comparison and the combination of several proxies with different time characteristics is often a good approach. The use of mechanistic models in a Bayesian inverse mode is likely the best (but difficult) approach.

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The Climate response function and multicentennial climate variability

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Separating internal from forced variability has become a crucial question, especially with the recent increase in anthropogenic forcing which adds complexity to comparisons of paleo and modern data. We explore new ways to characterize the forced temperature variability using a parsimonious model operating within the linear response framework with a power-law scaling climate response function (CRF, the Green's function). Industrial era observations are used to estimate the best parameters of the CRF and applied to pre-industrial millennial reconstructions. In addition, global climate model (GCM) outputs are considered for analysis and comparison to show the ability of the framework. The scaling behaviour of the internal variability found in control runs is also compared with real world data over multi-centennial scales after removal of the forced component of variability.

Holocene climate variability in an orbital-forced simulation: Cold events, abrupt mode transitions and quasi-decadal oscillations in the North Atlantic

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Centennial-to-millennial-scale climate variability during the Holocene in the North Atlantic realm is often considered to be linked to variations in the strength of the Atlantic meridional overturning circulation (AMOC). This variability as well as tempo-spatial climate patterns associated with AMOC transitions are studied in an experiment with the Community Climate System Model version 3. In a transient simulation of the Holocene starting at 9 ka before present, the model is forced with changing orbital parameters. Initially, the model is in a state characterized by a strong AMOC (13±1 Sv). During this mode two events happen where drift-ice is expanding over almost the entire northern North Atlantic down to ca. 40 °N. These events resulted in a freshening of the North Atlantic, especially in regions of deep water formation. The events last for around 200 resp. 100 years. The strength of the AMOC, however, weakens by only 0.77 Sv during the first event and by 0.15 Sv during the second one. An abrupt shift to another stable climate state does not take place. However, after 7514±5 years (≙1486±5 BP) the model switches within 117±8 years to a weak state with AMOC strength of 9±1.5 Sv. Over the North Atlantic region the state transition results in a cooling of 2.9 °C at the sea surface (based on annual mean) and an expansion of sea-ice by $3.6 \bullet 10^{12}$ km^2 in the North Atlantic during March. Similar to an existing study with the same model, the weak state is dominated by AMOC oscillations (amplitude 4.3 Sv) at a period of approximately 12 years. To understand the origin and behavior of these decadal oscillations we analyzed the temporal-spatial correlations of several variables. In accordance with earlier results salinity, temperature and density in the upper 100 m in the Labrador Sea have their maximum approximately 4 years before the AMOC change. The correlation maps show a large positive density anomaly in the northern North Atlantic at lag of about -4 years which is reflected in a lowering of sea surface height and an increasing mixed-layer depth. The density anomaly becomes negative with a peak at lag +2 years and then positive again at lag +6 years.

Variability of water isotopes in snow and ice-core records

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Stable water isotopes stored in polar ice are a key archive for the reconstruction of past climate conditions. While isotopic variations in ice are usually interpreted as proxy for local air temperature, the signal is formed by the interplay of processes between the evaporation source of the water and the snowfall as well as depositional and post-depositional effects. Understanding these processes is essential to interpret the temporal variability of water isotopes.

This seminar will present our ongoing work on the relationship between climate variability and isotope variability across different time-scales and their implications for the interpretation of scaling in isotope records.

Starting point is a field campaign at the drilling site of the EPICA Dronning Maud Land ice-core (Kohnen station) on the East Antarctic plateau where we analyzed oxygen isotopes in two 50 m long snow trenches. This allowed us to create an unprecedented, two-dimensional image characterizing the isotopic variations from the centimeter to the hundred-metre scale (Münch et al., 2016, Laepple et al., 2016). Outcomes are a descriptive model of the local stratigraphic noise that also provides an upper bound of the reliability of climate reconstructions from seasonal to inter-annual time scales at this study site.

While the local noise can be largely removed by averaging across many cores, the comparison to local temperature observations demonstrates that other spatially coherent (>1km) effects before, during or after deposition must influence the isotopic record. Repeating a similar snow trench experiment two years later allowed us to recover the same climate signal. This demonstrates that post-burial effects are minor and points to processes before and during deposition that change isotopic variability.

Analyzing snow-pits across the East Antarctic plateau and comparing isotopic and temperature variability under differing accumulation conditions allowed us to further characterize the formation of isotopic variability. Our results suggest, that at least at low accumulation sites, a large part of the seasonal climate variability is reshuffled (redistributed across frequencies in the power spectrum) before and during the deposition process leading to a strong noise component in the surface signal. After burial, isotopic diffusion changes the signal again, leading to apparent ‘cycles’ often described in Antarctic snow pits and shallow firn cores.

While these processes likely inhibit the reconstruction of fast (seasonal to multidecadal) climates signals from low-accumulation sites, at least from single cores, their effect on the presumably stronger climate signal on longer time-scales is unclear as the temporal covariance structure of the noise is poorly known. To tackle this problem we analyzed networks of shallow ice-cores in order to separate the common and local signal on larger temporal scales.

Finally, based on these findings a toy signal model is build to discuss potential implications for the interpretation of time series and power spectra from long isotopic records.

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Precipitation variability - regional to global, decadal to centennial scales and beyond: space-time analysis and modeling

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The characterization of precipitation variability (natural, anthropogenic) across wide ranges of scales requires both data with adequate resolution and length as well as an appropriate theoretical framework. We suggest several ways forward based on the systematic application of scaling fluctuation analysis to characterizing different precipitation scaling regimes (weather, macroweather, climate – from higher to lower frequencies). In macroweather, atmospheric fields including precipitation have scaling properties characterized by negative temporal fluctuation exponents, which implies – contrary to the weather and climate regimes – that fluctuations tend to cancel each other out. In the anthropocene, the macroweather regime covers the range of time scales from about a month to ≈30 years – but it is believed to extend to centuries or longer in the pre-industrial epoch. Therefore our conclusions about space-time macroweather statistics likely inform us about the fundamental nature of centennial and multicentennial natural precipitation variability that is impossible to derive from proxy data.

Our study uses three qualitatively global scale precipitation products (from gauges, reanalyses and a satellite and gauge hybrid) – that allows to investigate precipitation from monthly to centennial scales and in space from planetary down to 5ºx5º scales. We find serious divergences between different products, which reflect our limited ability to estimate areal precipitation even when averaged over decades and at global scales. However, for each product, the space-time statistics are fairly similar and can be characterized by scaling regimes in both space and time. For example, we find that in the industrial epoch the transition from the macroweather to the climate regimes occurs at roughly 20 years at global scales, 30-40 years at 5ºx5º scales. In the pre-industrial period, the upper limit scale of the precipitation macroweather regime is larger but not well established.

Perhaps the most important conclusion is that up to decades (anthropogenic effects begin to dominate the variability), the space-time statistics factorize so that for example the joint space-time spectrum $E_{st}(k,\omega) \approx E_s(k) E_t(\omega)$. It implies that the spatial variability corresponds to different climate zones that multiplicatively modulate the local, temporal statistics. This justifies the common practice of adjusting climatological series by their local statistical properties. It also implies that unlike in the weather regime, there is no size-lifetime relationship and thus has important implications for monthly to decadal prediction. In the pre-industrial epoch, the space-time scaling and factorization should extend to centennial and multicentennial scales. The improved understanding of monthly to centennial scale precipitation variability opens new perspectives to separating natural and anthropogenic precipitation variability, and quantifying anthropogenic changes in precipitation. These techniques can be applied to temperature and other climatological data.

Inference and comparison of inverse models for glacial climate from Greenland ice core data

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The most pronounced variability in the climate during the last glacial period are the so-called Dansgaard-Oeschger (DO) events. These abrupt climate changes are elusive in simulations of state-of-the-art coupled climate models. Furthermore, the underlying dynamical mechanism remains unknown.

We employ statistical model comparison to compare different classes of stochastic dynamical systems to the NGRIP ice core record from Greenland. The dynamical systems represent different dynamical paradigms, such as bi-stability, relaxation oscillations and excitability. Specifically, we investigate whether the climate system is exhibiting self-sustained oscillations of vastly varying periods or rather noise-induced jumps in between two quasi-stable regimes.

We avoid calibrating the models by time series fitting, but rather focus on the most important qualitative features of the data, such as distributions of waiting times in between successive events. These features are quantified as summary statistics and are used to perform inference and comparison of the models via Approximate Bayesian Computation. Based on our choice of summary statistics, we find evidence that simple stochastic motion in a double well potential is better supported by the data than noisy relaxation oscillations or excitable oscillators. With our model comparison approach we furthermore investigate to which extent the dynamical process underlying the observed climate record can be regarded as stationary.

How scaling fluctuation analysis transforms our view of the climate

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The atmosphere is highly variable on scales ranging over a factor of a billion in space and over a billion billion in time (planetary scales down to millimetric, the age of the planet down to milliseconds). This has been classically conceptualized in a phenomenologically based “scale bound” framework that isolates and focuses on specific phenomena operating over narrow ranges. At first this served to develop simplified mechanisms/models but today, problems are usually solved using full-blown General Circulation Models (GCM’s) that have wide scale ranges; they are scaling by construction.

The scale bound view was famously articulated by M. Mitchell[1] who hypothesized an atmospheric spectrum featuring specific quasi-oscillatory processes (spectral spikes) superposed on an uninteresting (mostly) white noise “background”. In the following brief overview, we describe the contrary - wide scale range view - made possible (and necessary!) - by modern models and paleo data and helped by new nonlinear geophysics analysis techniques. Due to space limitations, the overview is neither exhaustive in content, nor in citations.

We now know that from hours to the age of the planet - Mitchell’s range - that he was wrong by factor of a quadrillion[2-4] and that the great bulk of the variability is in the background spectral continuum[5]; Mitchell must be stood on his head. The background itself can be divided into four or five wide scale range (scaling, power law) regimes (fig. 1) in which mean absolute fluctuations ΔT vary with time scale Δt as $\Delta T \approx \Delta tH$. From fast to slow, these regimes alternate in the sign of H from weather, macroweather, climate, macroclimate and megaclimate (table 1; ignoring intermittency (below), the sign of the slope in fig. 1). When $H>0$, the temperature “wanders”, it appears unstable. When $H<0$, successive fluctuations tend to cancel, so that as the period is increased, averages converge, the temperature appears to be stable. Such scaling regimes arise whenever the dominant dynamical processes respect a temporal scale invariance symmetry (this is a general feature of the equations used for GCM’s). An important feature is that scaling processes generally exhibit long-range statistical dependencies implying potentially huge memories that can be used for prediction.

This simple picture took a long time to emerge. At first, this was because paleodata were limited and our views were scale bound. Later, it was because analysis techniques were either inadequate (e.g. when fluctuations were quantified via differences or from autocorrelations), or were simply too difficult to interpret (e.g. spectra, most wavelets and Detrended Fluctuation Analysis). The breakthrough was the systematic use of simple-to-interpret “Haar” fluctuations[6]. The Haar fluctuation over the interval from time t to $t-\Delta t$, (i.e. at scale Δt) is simply the average over the first half of the interval minus the average over the second half. When the absolute mean decreases with scale ($H<0$), H quantifies the rate at which anomalies decrease with averaging scale. Conversely, when the absolute mean increases with scale ($H>0$), H quantifies the rate at which typical differences increase with scale. Haar fluctuations are useful for processes with $-1<H<1$ and this encompasses virtually all geoprocesses. Historically, Haar fluctuations were the first wavelets yet one does not need to know any wavelet formalism to understand or use them.

Unsurprisingly, the time scales of the critical transitions from one regime to another have fundamental interpretations (table 1). For weather, the inner scale τdis is the dissipation scale and the outer scale is the typical lifetime of planetary structures: τw ≈ 5-10 days. τw is determined by the energy rate density (W/Kg) due to the solar forcing[7]: a good approximation is obtained by using dimensional analysis on the ratio: (rate at which solar energy is converted into mechanical energy)/(the total atmospheric mass) ≈ 1mW/Kg. Replacing solar by atmospheric forcing, the same theory explains the analogous “ocean weather” to “ocean macroweather” transition at ≈ 1 - 4 years as well as the analogous transition on Mars at ≈1.8 sols[8].

The regime in between weather and climate is termed “macroweather” since both (turbulence based) stochastic weather models and GCM’s readily reproduce it. The transition to a true climate regime (τc) occurs at the scale where external forcings and/or slow internal processes become dominant (significantly for Climate Variability Across Scales (CVAS), GCM simulations of the Last Millenium are apparently lacking in low frequency variability[9]). In the anthropocene we find τc ≈ 20-30 years; in the pre-industrial epoch, τc ≈ centuries to millennia[10]. A key goal of CVAS is to clarify the spatial (and epoch to epoch) variability and origin of τc: it is unlikely to be due to either solar or volcanic forcings[11]: more likely processes include land-ice and/or deep ocean currents.

Over the last million years, the outer climate scale is τmc ≈ 80 - 100 kyrs; it is apparently the quasi-periodic scale of the astronomical forcings[12,13]. Alternatively it marks the beginning of a short scaling regime. τmc is both longer than the obliquity and precessional scales (26 kyrs, 41 kyrs) and shorter than the main ellipticity scales (413kyr, 125 kyrs), corresponding only to the weakest of these (at 95 kyrs). Clarifying the origin of this scale is a key goal of climate science as is the determination of the outer macroclimate scale at τMc ≈ 500 kyrs. Longer scales - the megaclimate - takes us to at least 550 Myrs (the limit of reliable benthic proxies). Over these long scales, $H > 0$ so that the temperature “wanders”, it is unstable, a fact that directly contradicts the Gaia (homeostasis) hypothesis[2].
While the exponent H provides a basic classification of the different regimes, it only describes the behavior of mean fluctuations. A fuller description requires other exponents - there is generally a multifractal hierarchy - the simplest and most useful of which is the exponent C_1 that characterizes the intermittency near the mean[14,15]. In turbulence, intermittency can be defined as the “sudden transition from quiescence to chaos”; in a time series, it characterizes the “spikiness”. To a good approximation, C_1 is 1/2 the exponent of the ratio of the RMS to the mean fluctuation: $<\Delta T^2>/ <\Delta T> \approx \Delta t\ C_1$. C_1 also quantifies the distance from Gaussianity since for Gaussian processes, $C_1 = 0$. For reference, fully developed turbulence has the (large) value $C_1 \approx 0.1$ (the weather regime, table 1). In macroweather, C_1 is much smaller so that monthly resolution series are often (implicitly) considered Gaussian (e.g. 1[6-19,12,14,16,20]). Indeed approximating macroweather by “fractional Gaussian noise” already allows us to exploit the huge memory implicit in the scaling and to make skillful monthly, seasonal, interannual and decadal forecasts[21].

For scaling processes, the spectrum is of the form $E(\omega) \approx \omega$ (ω is the frequency) so that $\beta \approx 1+2(H-C_1)$, (technically, this approximation is good because climate processes are roughly log-normal multifractal processes). When C_1 is small, $\beta \approx 1+2H$ and the critical exponent $H = 0$ corresponds to $\beta \approx 1$. Scaling processes generally have nonclassical (power law, “fat-tailed”) probability distributions that characterize their extremes. This means that the probability of a fluctuation ΔT exceeding a threshold s is: $Pr(\Delta T>s) \approx s_D$. Depending on the value of q_D, extreme fluctuations occur much more frequently than expected classically (starting with ref. 4, q_D has regularly been estimated as ≈ 5). Indeed, they generate “outlier” events that are so extreme that they are sometimes called “black swans”.

A key objective of CVAS is to go beyond time series, to understand variability in both space and in space - time. In the weather regime, the Eulerian (fixed frame) spatial H exponents are the same as in time (in a co-moving Lagrangian frames, they are 2/3 of this). This is a consequence of the scaling of the wind field and of the existence of a well-defined size-lifetime relationship[22]. However in macroweather – to a good approximation (verified empirically as well as on GCM and turbulence models) - one has “space-time statistical factorization” so that the joint space-time spectral density satisfies $P(\omega,k) \approx E(\omega)E(k)$ and there is no longer a meaningful lifetime-size relation[22]. This is important since – without contradicting the existence of teleconnections – it decouples space and time, transforming the GCM “initial value” problem into a much easier to handle stochastic “past value” (but fractional order!) macroweather forecasting problem. A key difference between temporal and spatial statistics is that the spatial intermittency is always high. In the weather regime, this is due to the lifetime-size relation that implies $C_{1w,s} = C_{1w,t}$ (it also implies $H_{1w,s} = H_{1w,t}$). In the slower regimes, it is because of the well known existence of climate regions/zones that imply strong spatial intermittency so that - for example - in macroweather and climate we have $C_{1mw,s} \approx C_{1c,s} \approx 0.15$, (the equality is theoretically expected[22]). By distinguishing “anomalies” and long time averaged “actuals”, we can use instrumental data to get the rough estimates Hmw,s ≈ -0.2 and $H_{c,s} \approx 0.4 - 0.6$, although far more work is needed. The space-time relationship for the climate regime requires paleodata and is currently unknown. There is much scope for CVAS!

Answering these questions requires the analysis of massive amounts of paleo data. Fortunately, techniques from nonlinear geophysics - especially Haar fluctuations - are ideally suited for the task since they handle irregularly sampled data at variable resolutions (for software, see appendix A of [2]). Rather than immediately attempting to find a transformation (“calibration”) that transforms a proxy series Tproxy into a reference series Tref (either another proxy or an instrumental series), one should first check that the statistics of ΔTproxy and ΔTref are the same at all scales. The idea is to first check $\Delta T_{proxy} = \Delta T$ ref where “ = ” indicates equality in probability distributions, and only attempt to verify the usual – but much more stringent deterministic equality “=” after it is established that = holds reasonably well. Another reason for focusing on proxy fluctuations is that it avoids spurious statistical artifacts that arise in autocorrelation based techniques when these are applied to data with $H>0$.

The systematic application of nonlinear geophysics analysis and models to climate data has only just begun, CVAS will help to take it to the next level.

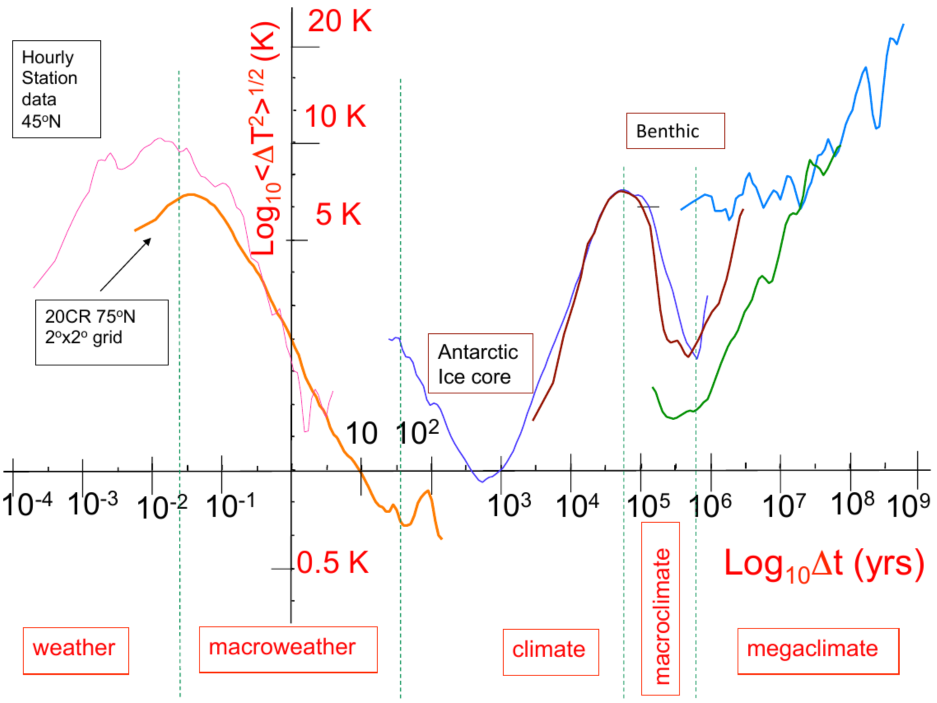

Fig. 1: The root mean square Haar fluctuation showing the various (roughly power law) atmospheric regimes, simplified and adapted from[2] where the full details of the sources is given. 20CR is the twentieth century reanalysis.

	Weather[a]	**Macro-weather**[b]	**Climate**	**Macro-climate**	**Mega-climate**
Inner scale	$\tau_{dis} \approx$ 1ms	$\tau_w \approx$ 5-10 days	$\tau_c \approx$ 20-30 yrs[c]	$\tau_{mc} \approx$80 kyrs	$\tau_{Mc} \approx$0.5 Myr
H	0.4	-0.4 to -0.1	0.4	-0.8	0.4
C_1	0.08	≈0.01-0.03	0.07	0.12	0.03
β	1.8	0.2	1.8	-0.6	1.8
q_D	5	5	5	_	_

Table 1: Atmospheric scaling regimes with their approximate inner scales and temporal scaling exponents H, C_1, β ,q_D (adapted from [2]).

[a]The globally averaged temperature has $H \approx 0.75$, $C_1 < 0.01$, $\beta \approx 2.5$.

b The local value $H \approx$ -0.3 to -0.4 is for land, $H \approx$-0.1 to -0.2 for ocean, the global value $H \approx$-0.1, ($\beta \approx 0.8$) being dominated by ocean (with $C_1 < 0.01$).

[c]This is for the anthropocene: the preindustrial transition scale is between centuries to millennia, a key goals of CVAS is to clarify this including its geographical variation in the Holocene.

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Analysis of 800 kyrs of dust data at 25 yr resolution

S. Lovejoy & F. Lambert

Dust fluxes from the East Antarctic EPICA Dome C ice-core with unprecedented near complete 25 year resolution over more than 800 kyrs are systematically analyzed over 8 glacial-interglacial cycles and within each cycle over 8 “phases”, each “phase” a successive segments of a cycle. We find that whereas there is relatively little systematic variation from one ice age to another, there is a strong dependency of the scale by scale variability (as revealed by scaling fluctuation analysis) on the phase of the ice age. The analysis revealed that the transition scale from macroweather to climate (from fluctuations decreasing with scale to fluctuation increasing with scale) starts off in the range 1 – 2kyrs in the first two phases (i.e. at the end of a cycle), but then decreases to ≈ 300 years over the last 6 phases (the long glacial inception). A long transition scale means that fluctuations at a fixed scale (e.g. 10 kyr) will be small since they have not had much of a range of time scales over which to develop. This tendency is amplified by the finding that the rate that the fluctuations increase with scale (the exponent H) is large over the last 6 phases.

We also considered the intermittency, the tendency for the series to be “spiky”, non Gaussian. We found a similar transition for medium intermittency - comparable to turbulence - to high intermittency over the middle phases (intermediate glacial conditions). Finally, we examined the probability distributions of concentration changes at the 25 year scale. This showed that the fluctuations are of the extreme power law, “fat tailed” type associated with “black swan” events. Quantitatively, the third order moment diverged; in the first phase of the cycle, so did the second moment (the variance). The extreme concentration changes were typically of the order of 10^{80} times more probable than would be expected from the best fitting Gaussian.

This is the first scaling analysis that has documented systematic changes within the ice age cycle while confirming the relative robustness of the cycle itself over 8 cycles. We discuss how these findings may help explain the fact that the basic periodicity is nearly exactly 100 kyrs which corresponds to only a relatively minor Milankovitch (ellpiticity wobbling) forcing.

Interpreting the spectrum of Dansgaard-Oeschger events by an idealized ocean circulation model

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The power spectrum of Dansgaard-Oeschger (DO) events has attracted attention over two decades with debates on the 1470yr spectral peak [1–4] and scaling properties [5–7]. We study the power spectra of Greenland ice core records (log Ca2+ and δ18O) on GICC05modelext timescale [8] by using Multitaper method (MTM). We show that an idealized ocean circulation model (recently introduced by Roberts and Saha [9]) generates MTM spectra statistically consistent with observed spectra over the whole range of frequency (1/41 kyr1–25 kyr1) when the model is forced by the approximate global ice volume and white Gaussian noises [10]. Our result suggests that we cannot reject the null hypothesis [9,10] that DO events are stochastic slow-fast oscillations modulated by a changing background climate.

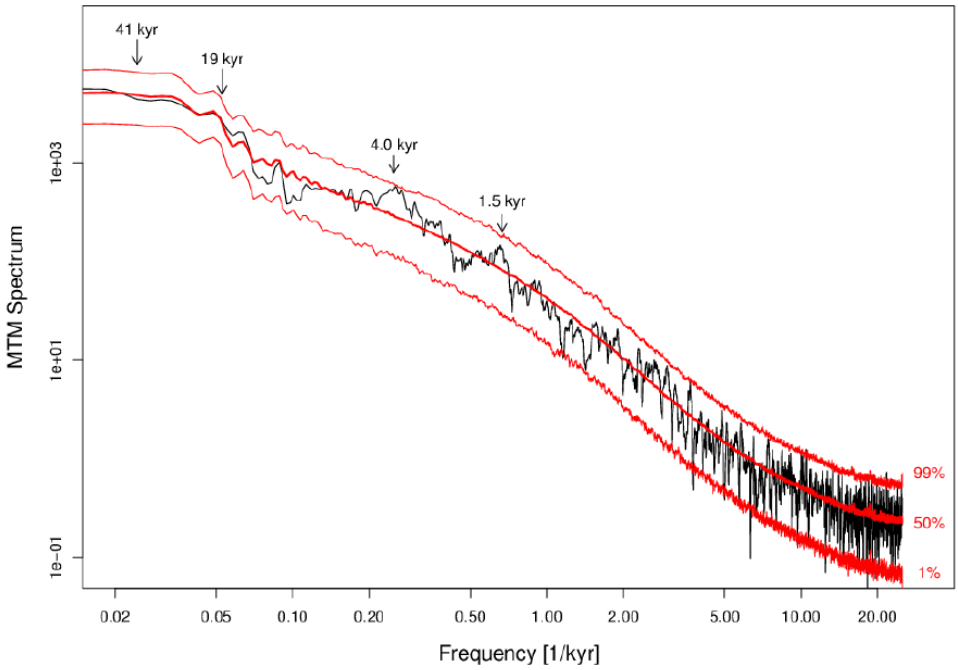

Figure. MTM spectrum for NGRIP log Ca2+ record over 11–100 ka BP (black), and 1st, 50th, and 99th percentile
lines (red) for the ensemble of sample spectral densities, calculated from 1000 trajectories simulated by an ocean circulation model [9] with different noise realizations.

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Antarctic climate variability at regional and continental scale over the last 2000 years

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Paleotemperature reconstructions from Antarctica mainly rely on water stable isotope records from ice cores. The key factor controlling this proxy has been mainly related to temperature variations; however this is not always straight forward and other processes acting on different spatial and temporal scales may influence the calibration between water stable isotopes and temperature. These processes can include precipitation-weighting of recorded air temperature, post-depositional movement and loss of snow, and ice flow and elevation effects. Early efforts to reconstruct the continental-scale temperature history of Antarctica over the past 2000 years indicated that at the continent-scale Antarctica is the only land region where the long-term cooling trend of the last 2000 years has not yet been reversed by recent significant warming. However, this Antarctic temperature reconstruction has large uncertainties and masks important regional-scale features of Antarctica's climate evolution over the last 2000 years. Here using a greatly expanded paleoclimate database and new reconstruction methodologies we present the results obtained from the Antarctica2k working group in the framework of the PAGES 2k initiative aiming to reconstruct the climate of the past 2000 years at both global and continental scales. This will include the compilation of ice core isotope records over 7 distinct climatic regions: the Antarctic Peninsula, the West Antarctic Ice Sheet, the East Antarctic Plateau, and four coastal domains of East Antarctica.

A global perspective on Glacial- to Interglacial variability change

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Greenland ice core oxygen isotope records provide evidence of past climate variability at high temporal resolution, and are used as reference datasets in many paleoclimate studies worldwide. A striking feature they display is the distinct reduction in centennial to millennial-scale variability from the Glacial to the Holocene, which has been interpreted as pivotal for human migration and evolution.

Using a compilation of high-resolution proxy records for temperature which span both the Glacial and the Holocene, we show that the reduction in variability found in Central Greenland is an order of magnitude larger than the change observed anywhere else. We derive spatial patterns of variability changes, and discuss which mechanisms they could arise from. Overall, our results contradict the view of a globally quiescent Holocene following the instable Glacial, and imply that the two states may have been more similar than previously thought.

Isotopes in ice cores

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This talk concerns isotopes in Antarctic ice cores during the Last interglacial. During this time, the Last Interglacial or LIG from 130,000–115,000 years ago, global climate was warmer than today. The global average temperature was likely 1-2 K warmer than the preindustrial at the peak of the warming. Measurements of water isotopes in Antarctic ice cores imply that Antarctica had a peak warmth which was substantially warmer than this global mean value. Whilst the classical interpretation of these Antarctic ice core data would suggest that temperatures at East Antarctic ice core sites may have been 4.5 K higher than preindustrial values, some later model-based work implied that, even at 4.5 K higher, it is difficult to model measured LIG isotopic values in Antarctic ice cores. This suggests that the classical interpretation of isotopic data, as representing a LIG Antarctic warming of +4.5K, could be underestimating the amount of LIG warming.

A suggestion of Antarctic temperature rises greater than 4.5K is curious in that atmospheric CO2 levels, during at the Antarctic isotopic peak at 128 000 years ago, were only slightly higher than those in the preindustrial interglacial. LIG values were around 300 ppm, versus a value of 285 ppm for the preindustrial.

This seminar presents our recent work exploring this issue. We look at a variety of hypothesised causes of these 128 000 year ago Antarctic ice core isotopic anomaly. After considering the classical Rayleigh-type interpretation of the isotopic data, we consider whether the loss of the West Antarctic ice sheet at 128 000 years ago could provide an alternative explanation. Given our recent work on this also suggests that this does not provide a solution, we then explore whether a reduction in Southern Ocean sea ice provides a better explanation.

The methodology underlying this work is the use of water isotope enabled climate model simulations. We use these models to explore scenarios, or alternative hypothesised causes, of the ice core observations. And apply a Bayesian framework to attempt to calculate the uncertainty associated with each scenario.

Implications from the work include that we may be able to use of water isotope data from multiple Antarctic ice cores to provide constraints on past ice sheet morphology, and also sea ice changes. There may also be implication about the calculation of polar amplification of temperature changes in the Southern Hemisphere during past warm climates.

Variability of sea ice on small and short to large and long scales from observations

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University of Bremen

Sea ice is an integral part of the global climate system and at the same time a sensitive climate indicator. Since observations of the sea ice cover from satellites started more than 40 years ago the year-around Arctic sea ice area showed a strong decrease of about –4% per decade, and a much stronger decrease of –13%/decade of the summer ice extent, which also defines the area covered with old, thick ice. The spatial scales on which sea ice interacts with the climate system cover several magnitudes. Sea ice dynamics act on a very local, meter scale. On the one hand the forcing of winds and ocean currents creates ridges and leads, which are initially only several meter wide but have strong implications for the sea ice mass balance and surface energy fluxes. For example, ridging creates thicker ice, which is less prone to melting, and the ridges change the surface topography, which influences the surface drag coefficients and the area covered by melt ponds in summer, i.e., the ice albedo. In leads, during winter time, energy fluxes between the ocean and the atmosphere are several magnitudes larger than for the pack ice. In turn leads are the places with strongest ice growth and production. On the other hand, leads can get hundreds of meters to kilometres wide, and sea ice deformations are observable as linear kinematic features, which cross the Arctic Ocean for hundreds to thousand kilometres. This fractal nature of sea ice calls for observations systems covering several spatial scales. Satellite remotes sensing allows to cover scales from 100 m up to the complete hemisphere. If extended with airborne and in-situ observations all scales important for sea ice related processes are covered. We will present here an overview of sea ice parameters derived from satellite observations in combination with more detailed observations from field campaigns. The longest close to continuous time series of sea ice area from satellites started in 1972 and several other sea ice parameters are now observed on hemispheric scales for more than 20 years, which allows to observe and assess changes of the sea ice cover on climate time scales. From these long observational time series possibilities emerge to combine and validate sea ice reconstructions from ice cores with modern time observations. Two examples are shown how the satellite data record can be used to construct new halogen-based sea ice proxies from ice cores in the Arctic and Antarctic.

Stable water isotopes as climate tracers in the Laclavere Plateau, Antarctic Peninsula

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In the last decades the western side of the Antarctic Peninsula has presented the highest temperature increase of the southern hemisphere. The lack of instrumental meteorological records in this region has hindered the study of regional climatic trends. In this context the study of ice cores has became a powerful source of information because they contain records of greater temporal extension and from areas where meteorological information hasn´t been retrieved. Ice cores from high-accumulation regions can significantly contribute to understand the undergoing climate variability and expand short meteorological time-series to the past.

Laclavere Plateau (63°27´15''S / 57°41'53''W / 1130 m.a.s.l.) is situated in the northern tip of the Antarctic Peninsula and is the northern area in the Peninsula which has a height above 1000 m.a.s.l. The climatological regime in the north of the Peninsula presents a complex interaction between the different elements that form the climatic system. Meteorological conditions in this area are strongly controlled by the variation in the sea ice extension, the position of the Antarctic Circumpolar Current and the differences in the lapse rate throughout the year.

The air parcels that precipitate over the Laclavere Plateau are strongly related with the conditions that prevail on the Southern Seas at the west of the Antarctic Peninsula and in particular with the conditions present near coastal areas of the Bellingshausen Sea. Since 2008, we have studied the northern part of the Antarctic Peninsula, where several surface firn cores (<20m depth) have been collected from sea level to the divide between west and east coast at the Plateau Laclavere. The isotope signature of the cores shows a complicated signal to interpret. No clear seasonality is observed from δ18O (δD). Here we show the statistical treatment that allow us to conclude that the deuterium excess (dexcess = δD - 8 δ18O), oxygen and deuterium ratios can be potentially used as a seasonal marker. We propose that variations observed in the stable isotope signal and in meteorological conditions are related with the development of an inversion layer in the lower troposphere (below 1000 m.a.s.l.) during the winter because of the formation of sea ice in the western coast of the Peninsula.

We estimate that the Laclavere Plateau present appropriate conditions for the conservation of the isotopic signal recorded in the snow that accumulates on its surface (mean value of 1,700 kg m-2 a-1). Therefore, we conclude that isotopic signal recovered from Laclavere's Plateau ice show that ice is a strong indicator of actual meteorological parameters, which make them capable of being proxy of local variability in atmospheric circulation, snow
accumulation and temperatures above surface. The well preserved isotope signal, along with the thick ice cover over the Laclavere Plateau (surveyed by geophysical methods), project this place as a favorable spot to recorver a medium depth ice core (>250m), from which it could be developed a paleoclimatic reconstruction covering at least half century at a high temporal resolution.

Linearity versus nonlinearity in climate modelling

S. Vannitsem

Royal Meteorological Institute of Belgium

The classical way to analyze time series is to evaluate linear-type quantities like auto-correlations (or cross-correlations for multi-variate time series), and to model the dynamics using auto-regressive or Ornstein-Uhlenbeck processes (or damped oscillators in the multi-variate case). This type of approach could be very successful in many instances, but could fail when non-linearities play an important role. In the latter case, alternative modelling approaches should be consider that are falling into two main categories, the parametric and non-parametric modelling approaches. The former is based on the derivation of an explicit expression for the dynamical equations of the system of interest, and the latter on the use of implicit assumptions on the dynamics of the system and the associated dynamical properties.

To fix ideas let us consider that the process -- from which the observed time series is/are coming from -- is governed by a system of nonlinear equations,

$$\frac{d\vec{x}}{dt}=\vec{f}(\vec{x},\vec{y},t)$$
$$\frac{d\vec{y}}{dt}=\vec{g}(\vec{x},\vec{y},t) \qquad (1)$$

where the variables $\vec{x}$ and $\vec{y}$ are the (usually) slow and fast variables of the system, and in which an explicit dependence is time is introduced in order to take into account potential external time-dependent forcings.

The parametric approach consists in building a model as (also known as stochastic modelling),

$$\frac{d\vec{x}}{dt}=\vec{s}(\vec{x},t)+\vec{\gamma}(\vec{x},t) \qquad (2)$$

where a new function $\vec{s}$ is introduced describing the deterministic part of the dynamics and $\vec{\gamma}$, a stochastic term, describing the impact of the fast scales on the slow dynamics we are interested in. This approach consists therefore to parameterize the impact of fast processes on the slow ones and has been the subject of many works in the past, and in particular in the context of environmental processes (see e.g. for a review in the context of atmospheric and climate sciences, Vannitsem, 2014).

When we do not have access to the dynamical equations of the system, one can still use this equation to model the process of interest. In this context several scenarios could arise depending on the importance of nonlinearities: (i) the non-linearities play the dominant role in the dynamics of variable $\vec{x}$, implying that the function $\vec{s}$ is nonlinear and one could assume that $\vec{\gamma}$ is a Gaussian noise term; (ii) the function $\vec{s}$ is linear and non-linearities which have fast time scales are incorporated in the noise term; (iii) non-linearities are playing a role at both levels. The major impact of having a linear deterministic term $\vec{s}$ is that there is only one single deterministic solution around which $\vec{x}$ is fluctuating. When this function is nonlinear, multiple solutions may exists between which $\vec{x}$ could jump under the effect of the fluctuations, or, depending on the parameters of the problem, gives rise to a richer variety of solutions such as periodic or chaotic ones. When the nonlinearities are present at the fast time scales, complicate noises could arise inducing skewness of the variable even is $\vec{s}$ is linear and/or inducing power laws (Sardeshmukh and Penland, 2015).

An alternative approach is to adopt a non-parametric approach to model the system given in (1). One does not use Equation (2) anymore, but rather use the concepts developed in the context of the ergodic theory of nonlinear dynamical systems. In this case the system

is supposed to be driven by important nonlinearities that are deterministically driving its dynamics, and that the noise is not fundamentally modifying its behavior.
The system is first embedded in the phase space defined by its variables (sometimes using the celebrated Takens' theorem), and its dynamics is then tracked and analyzed using nonlinear tools such as embedding dimension, Lyapunov exponents, regime transitions, etc (Nicolis and Nicolis, 2012). These can be complemented with linear techniques such as spectral and correlation analyses, Emprical orthogonal functions…
In this talk, we will discuss the advantages and drawbacks of both approaches and we will focus on the application of the non-parametric nonlinear analyses outlined above in the context of the coupling between the ocean and the atmosphere

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Spectral and (real space) fluctuation analysis: a case study on the recent episode of the Quasi-Biennial Oscillation and the strong El Niño event

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The Earth's climate system is a subsystem of a larger system of so-called world system and displays various modes of variability (e.g. Lovejoy, 2015). The spatio - temporal features of the major modes of natural variability have not yet been accurately simulated, while an unknown number of low-frequency modes have not yet been determined, mainly because of the comparatively short observational record and climate noise components (e.g. Franzke, 2009). Nowadays, advanced models are able to simulate accurately one or more mode of climate variability, but there is not a single model (or an array of them) that performs reliable simulations across all modes of variability. For example, today, less than one third of the general circulation models may reliably reproduce the first three most dominant and very regular quasi-periodical oscillations of the climate system. A classic paradigm of quasi-periodic oscillation is the Quasi-Biennial Oscillation (QBO), which refers to a regular 2 - to 3 - year cycle (e.g. Reed et al., 1961).
We hereby explore the anomalous behavior of the equatorial QBO in zonal wind which it exhibited, since February 2016 (Osprey et al., 2016). In more detail, QBO interrupted its regular pattern and the eastward stratospheric winds unexpectedly reversed to a westward direction. We focus on the temporal evolution of the equatorial zonal wind in the altitude region 70 - 10 hPa, investigating particularly whether this unprecedented event could be considered as a result of scaling effect in the equatorial zonal wind.

For this purpose we use the monthly mean values of the zonal wind over Singapore, at the pressure levels 10, 20, 30, 40, 50, 70 hPa (http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/singapore.dat) during the period 1987-2016, as well as the monthly mean values of zonal wind over the equator at 30 hPa, during 1948-2016, as computed from the NCEP / NCAR Reanalysis. We also use the monthly mean anomalies time series of the Niño 1+2 and Niño 3 SST indices as three month running means. The analysis technique used in order to study the intrinsic properties of zonal wind time series was the detrended fluctuation analysis (DFA), which eliminates the noise of the non-stationarities that characterize the zonal wind and permits the detection of intrinsic self-similarity (Peng et al., 1994). Moreover, to further investigate the temporal evolution of the sensitivity of the wind field, both time series (1948-2016 and 1987-2016) of the monthly mean values of the zonal wind at 30 hPa have been also analyzed during their overlapping period by using a new time domain termed natural time which uncovers hidden dynamic properties (e.g., Sarlis et al., 2013)

Did the cause of the recent QBO disruption come from the past?

Remarkably, an exploration of the temporal evolution of the El Niño Southern Oscillation - ENSO from Jan 1876 to Nov 2011 by means of natural time revealed that the major ENSO extremes provide precursory signals that are maximized in a time window of 2 years on average, i.e. a QBO cycle (Varotsos et al., 2016).

It should be emphasized that in the 3 to 4 years after the warm ENSO events (i.e. 1982, 1997, and 2015), the QBO and the ENSO were aligned indicating that strong warm ENSO events can lock the phase of the QBO (Christiansen et al., 2016). However, the evolution of the latest warm ENSO needs further investigation. We stress the point that it was unusual owing not only to its NH summer onset, but the way in which the tropical Pacific atmosphere was affected, displaying unusual features, which may have affected the QBO (Dunkerton, 2016; Newman et al., 2016).

It should be of interest to investigate whether the equatorial zonal wind in the region between the pressure levels 10-70hPa obeys scaling behavior. For this purpose we have used the monthly mean zonal wind components (0.1 m/s) at Singapore provided by the Free University of Berlin (Department af Earth Sciences). The results obtained from the detrended fluctuation analysis (DFA) revealed persistence with a crossover at roughly 25 months that resulted from the QBO signal. To establish however the power-law scaling in the equatorial zonal wind two criteria should be fulfilled: the constancy of local slopes in a sufficient range and the rejection of the exponential decay of the autocorrelation function must be confirmed. While the local slopes pattern shows that they reach a constant level at long scales, the data do not meet the second criterion, i.e. rejection of the exponential decay of the autocorrelation function.

The same analysis was repeated by considering the QBO time series (30 hPa zonal wind at the equator) calculated at NOAA/ESRL Physical Science Division for the period 1948-2016. The results showed that the local slopes reach a constant value at long scales, but the rejection of the exponential decay of the autocorrelation function fails. Moreover, we reach the same conclusion, when using the QBO time series of 30 hPa zonal wind index during 1979-2016, obtained from NOAA/ Climate Prediction Center.

Is there any association between the last strong ENSO and QBO disruption events?

We now turn to the results obtained from the natural time analysis. It interestingly shows for both data sets (related with 30hPa) a precursory behavior before the maximization of the zonal wind velocity and that the recent strong El Niño event might be related with the unprecedented QBO behavior.

In conclusion the data of the equatorial zonal wind field do not satisfy both the above-mentioned criteria and thus the long-range correlations cannot be established. In other words, the unprecedented event of the equatorial QBO in zonal wind this year could not be considered as a result of scaling, viz. that has not its roots in the distant past. However, it should be noted that this unexpected QBO event was not anticipated by forecast models and hopefully it will motivate a better understanding of driving mechanisms of QBO (cf. natural time analysis may provide precursory phenomena before the maximization of the zonal wind speed).

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Variability in the East Asian Summer Monsoon during Holocene in East China Sea

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Multiple interactions between land, ocean and atmosphere give rise to a unique climatic phenomenon known as Monsoon.Variability in the Asian summer monsoon has been observed using various proxies, however many external and internal forces functions along with its sensitivity is not well defined. We are looking into the millennial to centennial scale variability in the Asian summer monsoon using Foraminiferal perspective from the East China Sea (ECS).We have analysed sediment core of IODP (International Ocean Drilling Program) site U1429 and generated benthic foraminifera data for last 70ka. The location of site U1429 is in the northernmost sector of the Okinawa Trough, which gets influenced by the eastern branch of Kuroshio Current and Yangtze River discharge causing changes in the productivity of the region. The highly productive species of Uvigerina was dominating during the strong Asian monsoon season. The dominance of highly productive species causes overall decrease in species diversity parameters. The increased productivity also changed the oxic condition of the East China Sea. The overall species assemblage data suggest changes in the water mass at East China Sea linked with the variability in the East Asian Summer Monsoon resulting varying discharge from the Yangtze River. The time series analysis of the data indicate centennial to millennial scale variability in the EASM.

LINEAR OR NONLINEAR? EXPLORING PAST CLIMATE VARIABILITY USING VISIBILITY GRAPHS

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Nonlinear methods of time series analysis have recently proven their great potentials for unveiling past changes in climate variability. Among others, visibility graphs have shown their ability to identify episodes of time-reversal irreversibility in the fluctuations of paleocliamte proxies, which can be interpreted as temporary dynamical reorganization of atmosphere or ocean dynamics. Here, we employ this method for characterizing the dynamical characteristics of two different sets of proxies capturing two time intervals of particular interest in paleoclimate research: the late Holocene (last 2 ka) as an example for a relatively stable climate, and the full last glacial cycle exhibiting global temperature variations at various time scales and magnitudes of fluctuations. In the latter case, our analysis reveals a consistent transition between irreversible and reversible fluctuation properties at around 40 to 45 ka BP in both, high-latitude ice core and lower-latitude speleothem records, which clearly precedes the glacial termination by more than 20 ka.

The variability of North Atlantic climate on centennial-to millennial time scales – A Modeling study based on transient simulations of the Holocene

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The climate of the North Atlantic realm changes on different time scales. There is a vivid current debate whether these fluctuations are internally generated or controlled by changes in external forcing agents, such as orbital, solar, volcanic and GHG variations. Here we test whether changes in simulated Atlantic meridional overturning circulation (AMOC) obtained from two transient simulations with the coupled atmosphere-ocean general circulation model ECHO-G can help to disentangle the debate.

The forcings that are implemented in the global simulations are i) orbital and ii) additional solar and GHG forcing – the solar forcing is scaled to long term variations for present-day minus Maunder Minimum conditions of 0.3%. Our test case is an AR(1) process with r(1)=0.8 with Gaussian distributed random numbers . The r(1) is estimated by the simulated AMOC autocorrelation function based on annual values.

A side remark concerning the Atlantic Meridional overturning relates to the fact that the index integrates the entire North Atlantic basin from bottom to top. Here we use the maximum of the meridional overturning stream function that is typically located in the North Atlantic around 30° and 50° north.

The comparison of the simulated versus the synthetically generated AMOC indices shows that the timescale of investigation is critical for both i) mean state and ii) variance. For instance, changes in slow-varying orbital forcing are only reflected when considering the full time series. The long-term evolution cannot realistically be reproduced by fitting an AR(1) process. However, sub-millennial AMOC variations are very well represented by an AR(1) process and no clear discernible signals of changes in external forcings are evident. This opens the questions as to whether the AMOC variations over the Holocene including the last millennium on centennial time scales and their climate impacts are largely driven by internal dynamics. A second implication relates to evolution of the AMOC on long (millennial) time scales without additional information on slow-varying external forcings in the context of its potential predictability.

Water isotopes in ice cores

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Water isotopes (δ18O, δD) are the measure most commonly used in ice cores to represent air temperature. In this talk introducing a session on water isotopes in ice cores, I want to emphasise the strengths and weaknesses of them, and the pitfalls that data scientists using water isotope data must be aware of.

For a single airmass carrying water from a warm (ocean) source to a cold (polar) sink, isotope fractionation is described by Rayleigh fractionation/distillation, dependent on the higher vapour pressure of the lighter isotopologues. This predicts that the isotope ratio (expressed in delta notation) is linearly related to temperature, and this is indeed what is found in spatial distributions of isotope/temperature data at high latitudes. However there are a number of issues that can confound this relationship on a temporal scale – changes in location and conditions at the water source and changes in seasonality of precipitation are two obvious ones.

For the scaling community, I hope we will highlight a number of issues. Firstly, depositional variability means that a single isotope profile cannot be relied upon at the highest frequencies. I believe this will be discussed by Thomas Laepple, but in summary, at many sites the signal can only be taken as dominated by temperature (as opposed to the recording process) if many cores or many years are averaged. As shown for example by spatial profiles at Vostok, these kind of problems can extend into the multidecadal realm, and caution against drawing conclusions about the scaling of temperature variability at higher frequencies. A second issue is that the quantitative relationship between isotope values and temperature has been shown (in data and models) to be variable over different temporal scales and different conditions. This must be taken into account in assessing the amplitude of climate variability over different frequencies.

Ice cores are a very powerful way to determine the pattern of temperature variability in the polar regions in particular. However, taken alone, they may misrepresent the variability of temperature across scales. In this session, we will amplify some of these points, which certainly apply in different forms to other proxy temperature signals in other archives.