Reconstruction, modeling and future implications of changes in past climate variability

Heidelberg Physics Graduate Days 2019

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Introduction

Climate variability influences our lives

Climate variability influences our lives

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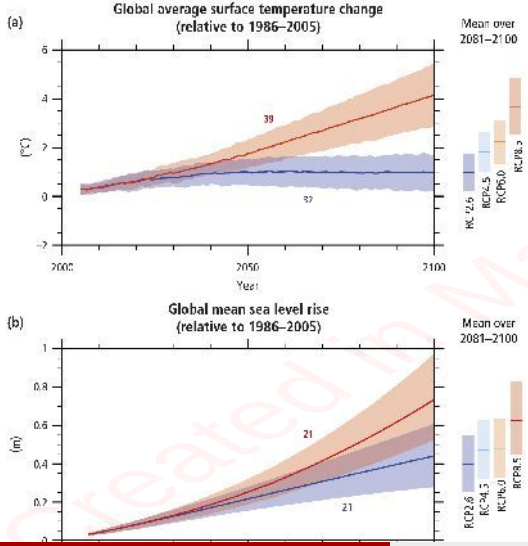
Predictability

- Coupling of temperature and precip variables with land use (management)
- Humanitarian and economic interests in resource management

Images: wtop.com, RNZ, wetter.com

Global mean temperature projections



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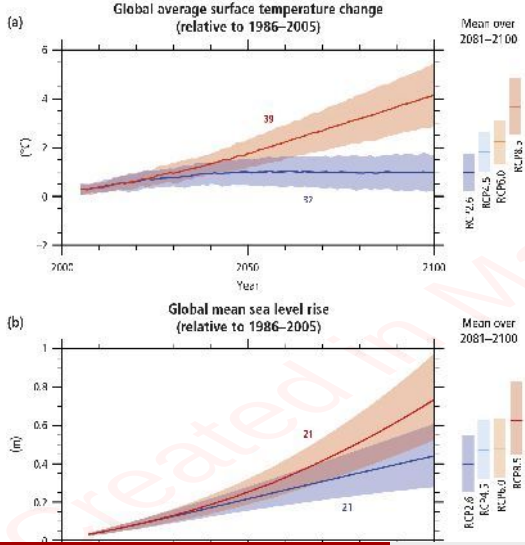
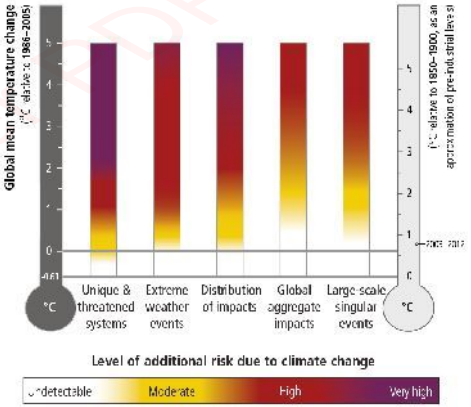
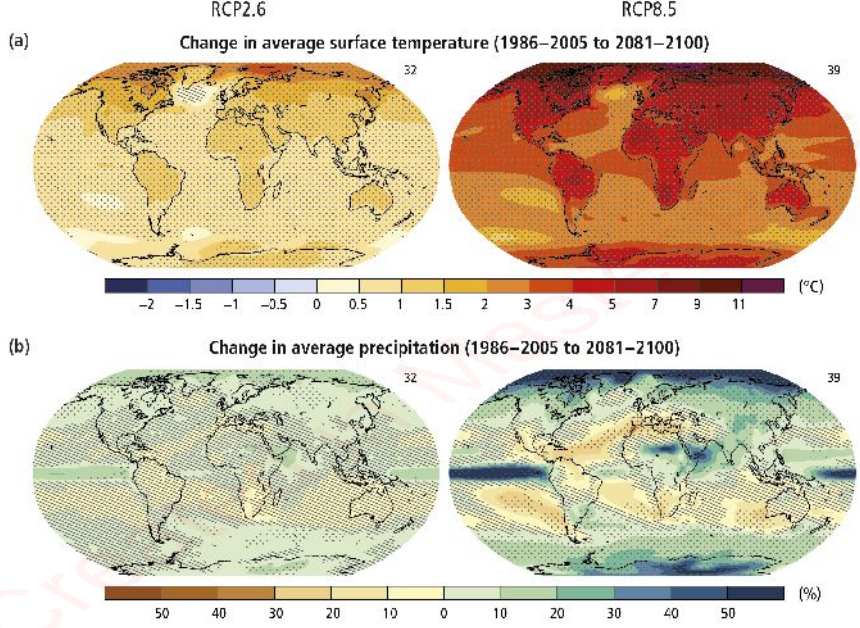


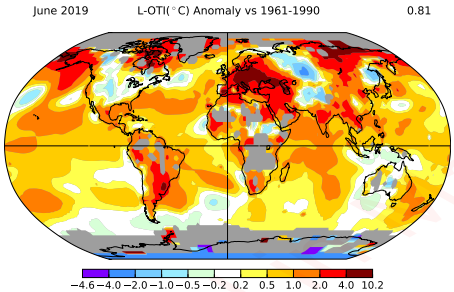


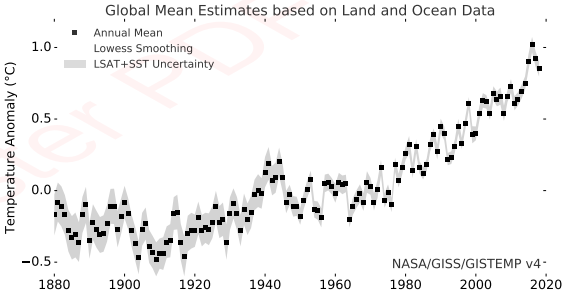


Future: Projected changes (MMM, CMIP5)

IPCC, 2014

Present: Recent evolution of temperature





Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The gray shading represents the total (LSAT and SST) annual uncertainty at a 95% confidence interval.

Methods: Hansen et al (2010), Lenssen et al. (2019); Data: GHCNv4 and ERSST5; data.giss.nasa.gov/gistemp/

Kira Rehfeld: Scientific career

- M.Sc. Medical Physics, Boston/Heidelberg

Lyatskaya et al., 2012

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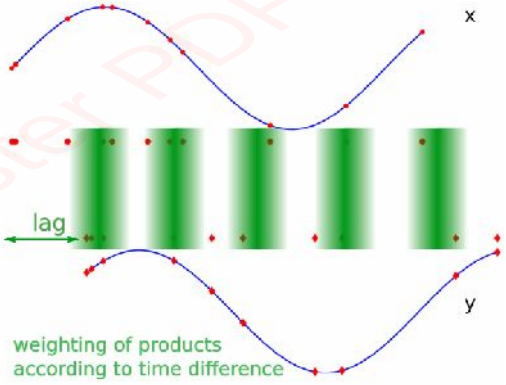

Rehfeld,

Marwan, et al., 2011

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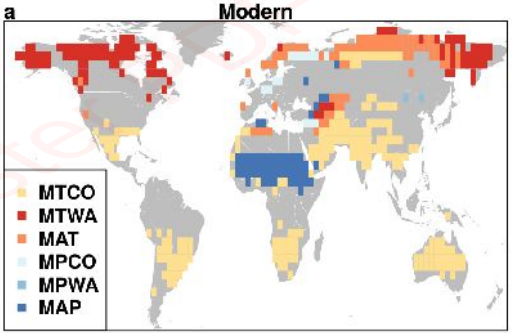

Rehfeld, Trachsel, et al., 2016

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- Emmy Noether group leader, since 9/2018

STACY: Moritz Kirschner, Janica Bühler, Nils Weitzel, Benni Schmiedel, Elisa Ziegler, Carla Roesch, Moritz Adam; not in picture Beatrice Ellerhoff, Julian Schäfer. Shirin Ermis

Research to understand climate variability changes

Different states → paleoclimate data

Rehfeld, Münch, et al., 2018

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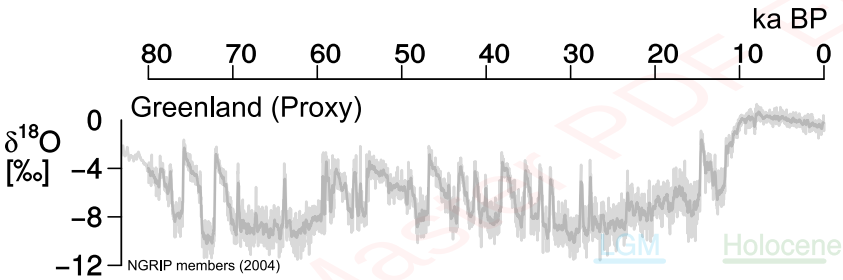


Delta-Notation

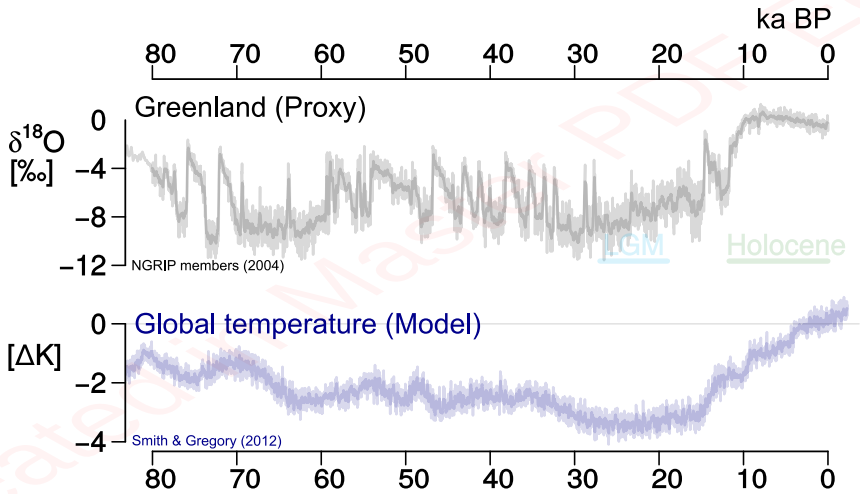
$$\delta^{18}O = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000\ ‰$$

$$R = \frac{O^{18}}{O^{16}}$$

abundance O^{18}: 0.2%, O^{16}: 99.76%

Rehfeld, Münch, et al., 2018

Research to understand climate variability changes



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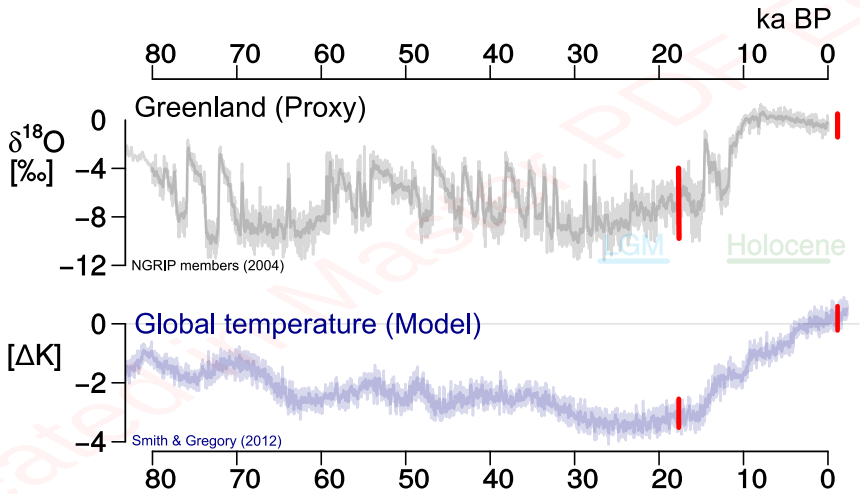

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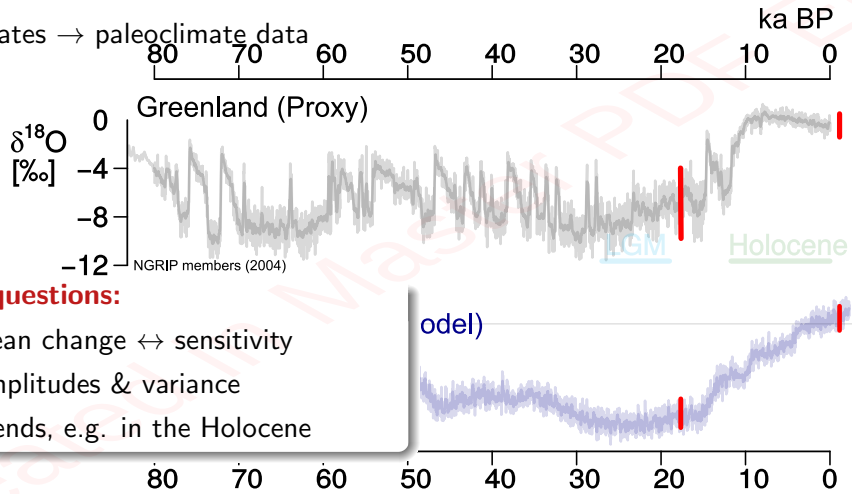

Open questions:

1. Mean change ↔ sensitivity
2. Amplitudes & variance
3. Trends, e.g. in the Holocene

Rehfeld, Münch, et al., 2018

Key questions

1. Does climate variability depend on the mean Earth system state, and how?
2. How is variability on short and long timescales related?
3. How does the sensitivity to disturbances change? 

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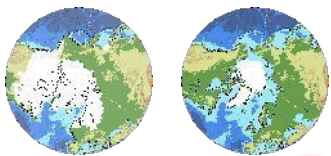

Methods

1. Data analysis
2. Model experiments
3. Proxy system models

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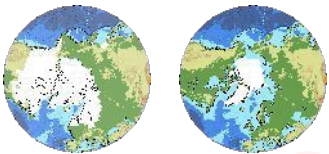

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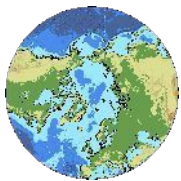
⇒ **System understanding & model validation**



STACY

Emmy Noether-Programm

DFG

Course overview

Abstract

Investigating past climate changes offers a unique key to understanding the future behavior of the Earth system under anthropogenic perturbation, because our past is the only true realization of the "Earth system experiment" we are part of. The nonstationary dynamics of the climate system evolve at the interplay between its topological, chemical, biological and thermodynamical boundary conditions and the external forcing that is exerted mainly by the sun. Yet, a closed description of the system's dynamics is impossible due to the large number of variables, continuously changing boundary conditions and nonlinear interdependencies which give rise to chaotic behavior. Climate modeling and paleoclimate reconstruction are therefore the two central means to improve the knowledge and understanding of past Earth system dynamics. They depend on each other: Paleoclimate data are the only witnesses that can yield knowledge on the state of the Earth system in the past; climate models solve fundamental equations for physical, chemical, and biological processes, against the background of solar forcing and global geography.

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Certainty and uncertainty

1. Warming of the climate system is unequivocal.
2. Key aspects of the change are unconstrained:
   Variability, extremes, sensitivity and regional change

IPCC-AR5, 2013

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Course philosophy

Climate research is not about beliefs. It is about understanding.

IPCC-AR5, 2013

Monday	Tuesday	Wednesday	Thursday	Friday
Past	**Present**	**Future**	**Experiments**	**Summary**
• Climate reconstruction • Variability • Tsc: 10^5 to 10^3a	• Common Era • Sun and volcanoes • Tsc: 10^3a to days	• Models • Climate sensitivity • Projections	• Hypotheses • Experiments • Assessment	• Your results • Knowns & Unknowns • Feedback

Course aims: Climate variability

After this seminar you will be able to

- describe timescales and main modes of climate variability
- outline methods for the detection of variability changes
- summarize the relevant forcing mechanisms and the climate system's response
- access and analyze reconstruction and model data

Graduate days course group

How much do you think you know about . . .

- . . . climate *[scale from 1 to 10]*

Graduate days course group

How much do you think you know about . . .

- . . . climate *[scale from 1 to 10]*
- . . . data analysis and programming *[scale from 1 to 10]*

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How much do you think you know about ...

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- ... and where do you come from? *[lon/lat]*

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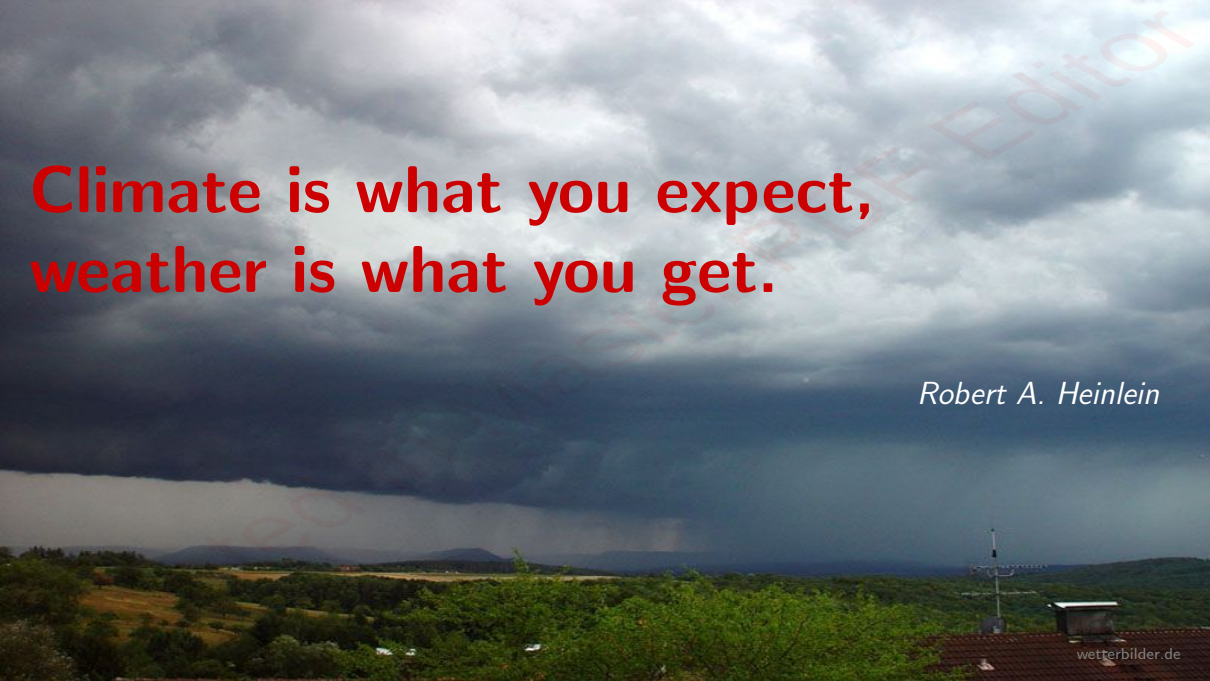
Groups A to H

- You are a team with diverse skillset
- You will work together to discuss, experiment and solve
- Help each other.

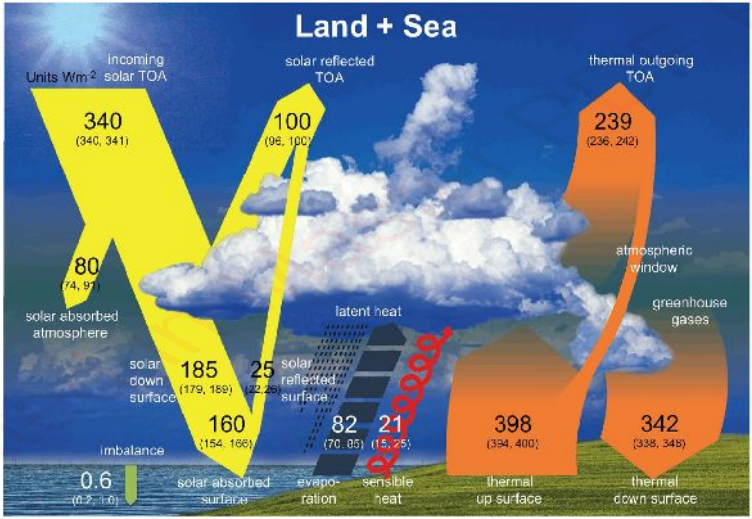
How do we want to work together during this course?

https://answergarden.ch/1020861

The climate system

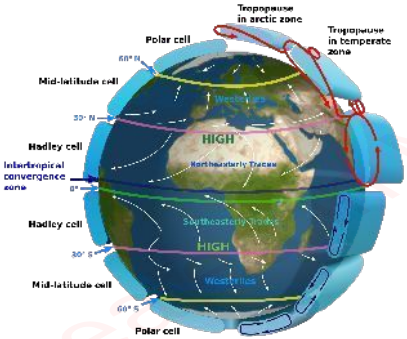

Climate is what you expect,
weather is what you get.
Robert A. Heinlein
wetterbilder.de

Earth's energy balance



Wild2013

Definition of climate



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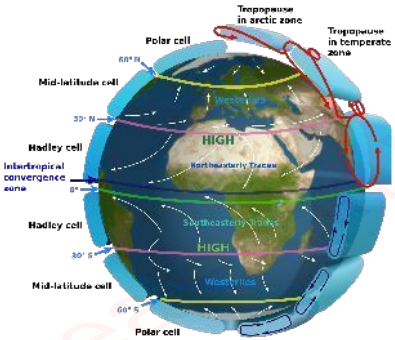


Definition

Climate is the statistical description, in terms of mean and variability, of relevant quantities over a period of time ranging from months to thousands or millions of years.

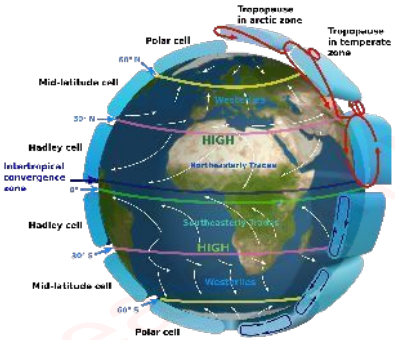
The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization.

The relevant quantities are most often surface variables, such as temperature, precipitation and wind.

In a wider sense, climate is the state of the climate system.

IPCC AR5 Annex

Definition of climate



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IPCC AR5 Annex

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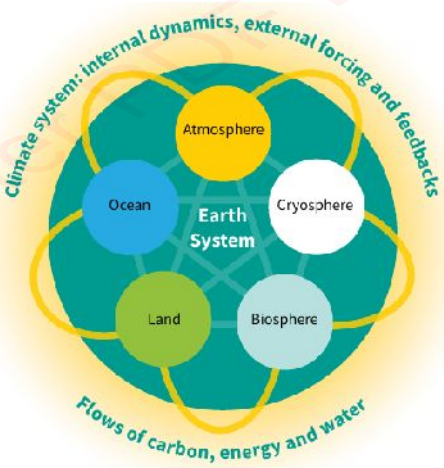

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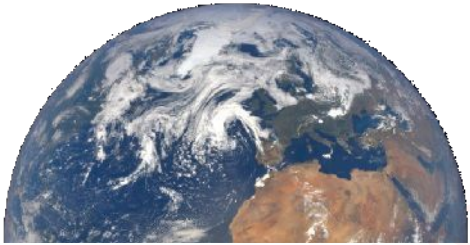
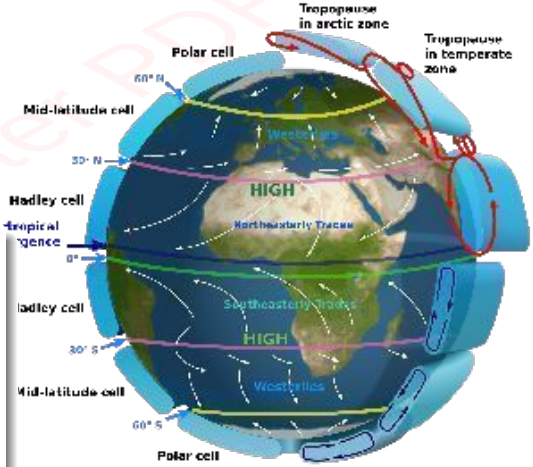




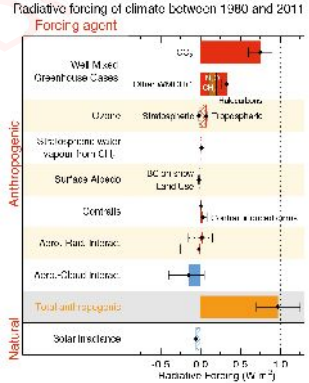
Climate System

The Earth system parts relevant to climate: **atmosphere, ocean, land surface, cryosphere as well as their coupling processes and feedback mechanisms**. The Earth system includes all of Earth's interacting physical, biogeochemical, biological and human systems.

Climate, Climate variability and Climate change

The meteorologist's view:

- **Weather**: Atmospheric state (Temperature, precipitation, cloudiness, humidity) in a location over periods of hours to days – **deterministic**
- **Climate**: Averaged conditions over years to decades
- Climate variability: –**statistic/probabilistic**
  - Fluctuations around averages on timescales of months to multiple decades
  - Internal
  - Forced (spatio-temporal modes, local variability)



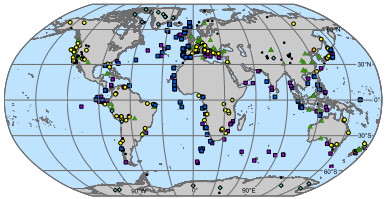
IPCC-AR5, 2013

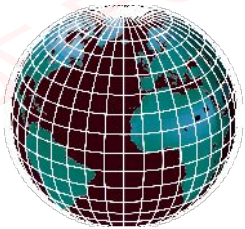
Climate change: Surface changes over periods of decades to millennia

- Natural drivers
  - Earth's orbital changes
  - Solar variability
  - Volcanism
  - Plate tectonics
- Anthropogenic
  - Greenhouse gases
  - Aerosols
  - Land use change (deforestation, irrigation, urbanization)

Climate reconstruction

Tools to understand past climate





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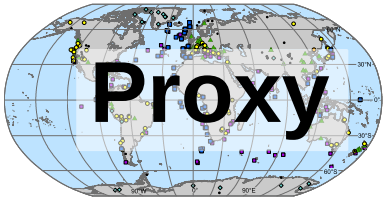
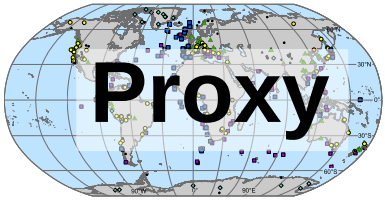


Proxies & Archive

indirect –
unit e.g.: $\delta^{18}O$,

measured in an **archive**:
Speleothem: $\delta^{18}O_{calc}$
Ice: $\delta^{18}O_{eis}$
Sediment: Pollen

Tools to understand past climate



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Climate models

Simulation,
unit e.g.: $^{\circ}C$

- global **grids**
- **unresolved processes**
- dv-AOGCM + i

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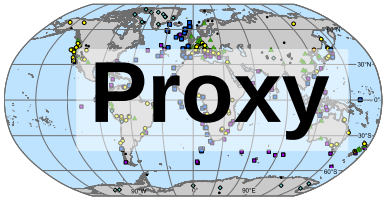

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PSMs

$P \approx f(C, E, x) + \eta$

- **local/non-climatic processes** η
- physical & empirical

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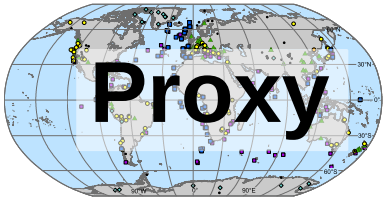

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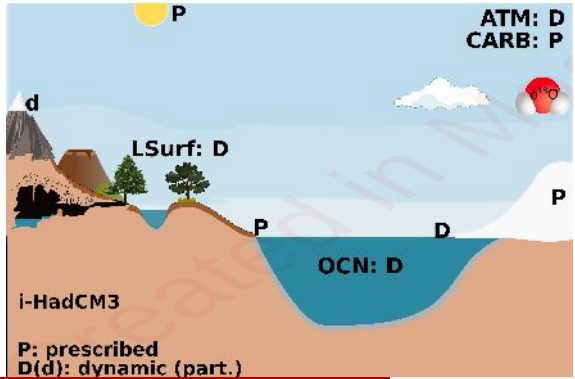
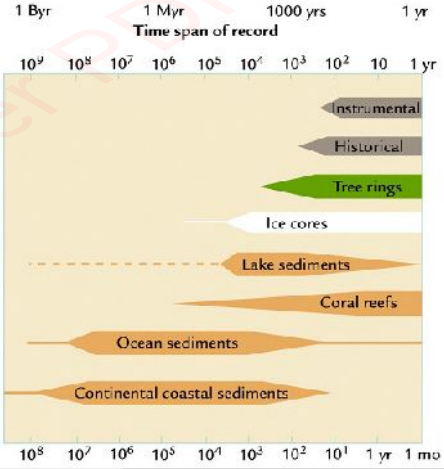
Archives, coverage and timescale

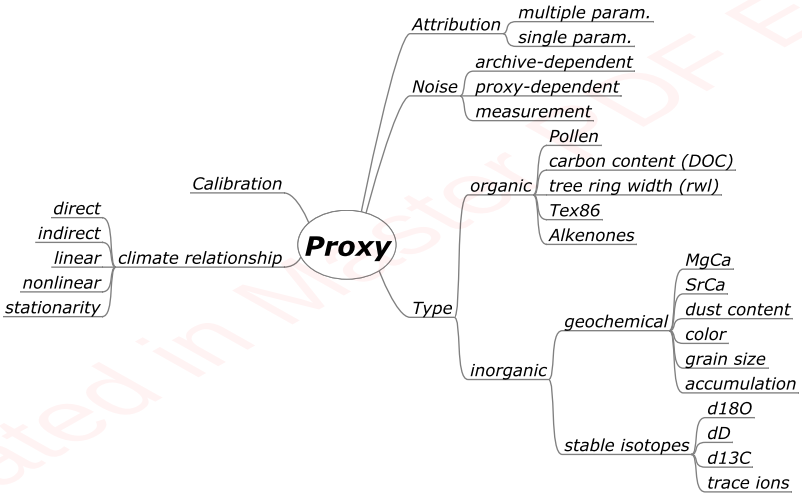
Earth system (model)



Proxy coverage



Proxies for Climate: Overview

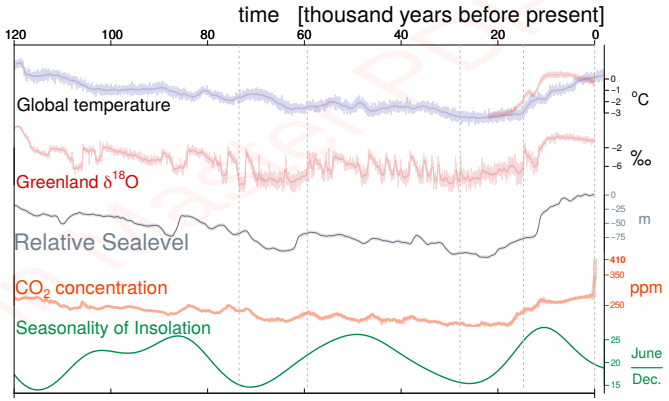


Rehfeld & Laepple 2014, http://epic.awi.de/35819/1/Chain_Poster.pdf

Past4Future: Climate since the last Interglacial

Past4Future: Climate since the last Interglacial

Sources: Smith & Gregory, 2012 Clim. Dyn.; Shakun et al., 2012 Nature; Marcott et al., 2013 Science; NGRIP consortium, 2004 Nature; Grant et al., 2012 Nature; Köhler et al., 2017 ESD 2017;
Insolation (at 65 north) computed based on Berger, 1978 J. Atmos. Sci.



Proxies in Focus

- **Ice:** polar and alpine glaciers → air and precipitation 


94
95
96
97
98
99
100

Proxies in Focus

- **Ice:** polar and alpine glaciers → air and precipitation 

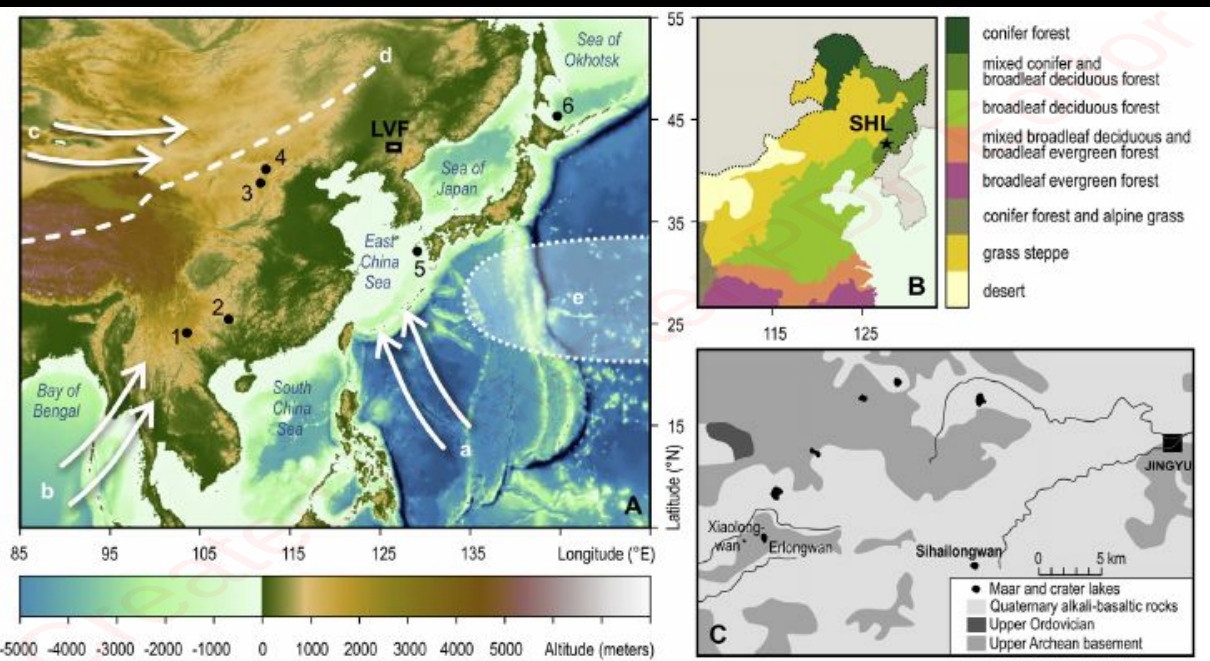
- **Speleothems** - mid/low latitudes → precipitation, land surface 

Proxies in Focus

- **Ice:** polar and alpine glaciers → air and precipitation 

- **Speleothems** - mid/low latitudes → precipitation, land surface 

- **Pollen** from sediments - lakes and marine, vegetation composition 


Sea of Okhotsk
LVF
Sea of Japan
East China Sea
South China Sea
Bay of Bengal
a
b
c
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e
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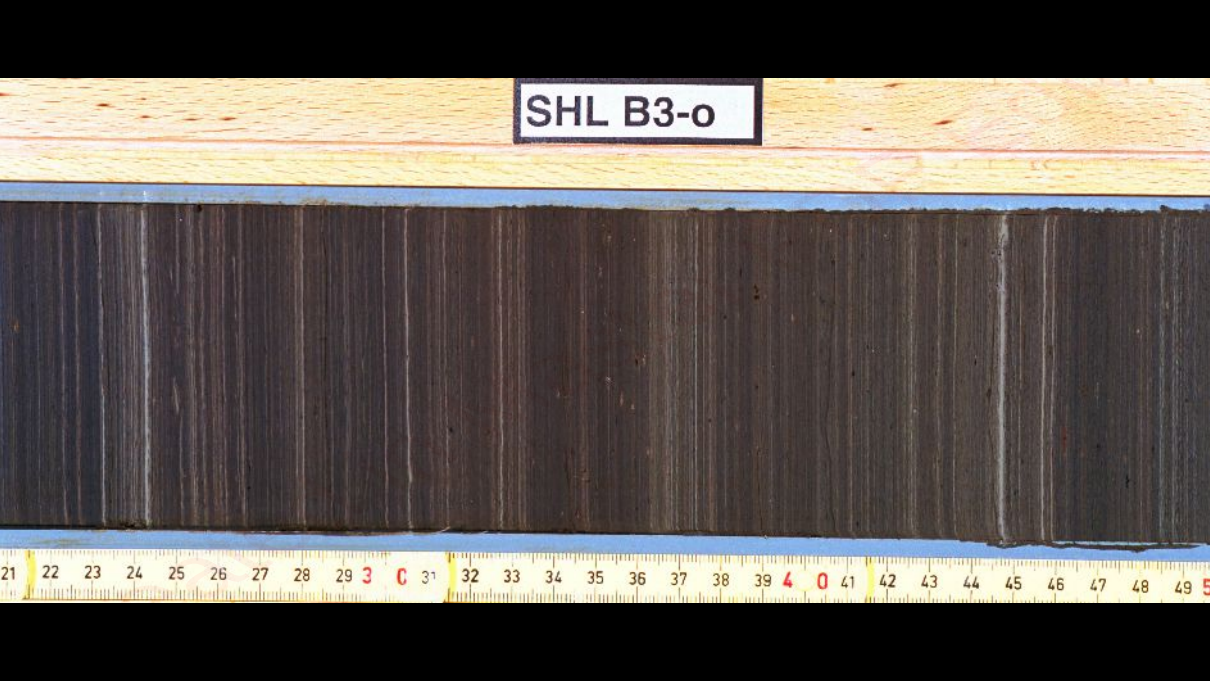
6
A
85
95
105
115
125
135
Longitude (°E)
55
45
35
25
15
Latitude (°N)
-5000 -4000 -3000 -2000 -1000 0 1000 2000 3000 4000 5000 Altitude (meters)
SHL
B
115
125
conifer forest
mixed conifer and broadleaf deciduous forest
broadleaf deciduous forest
mixed broadleaf deciduous and broadleaf evergreen forest
broadleaf evergreen forest
conifer forest and alpine grass
grass steppe
desert
JINGYU
Xiaolong-wan
Erlongwan
Sihailongwan
0 5 km
Maar and crater lakes
Quaternary alkali-basaltic rocks
Upper Ordovician
Upper Archean basement
C


SHL B3-o

Proxies in Focus

- **Ice:** polar and alpine glaciers → air and precipitation 

- **Speleothems** - mid/low latitudes → precipitation, land surface 

- **Pollen** from sediments - lakes and marine, vegetation composition 
- Marine sediments 

⊕ Combine data analysis and modeling to obtain reconstructions on millennial timescales

Marine sediments (10^3-10^6 a)

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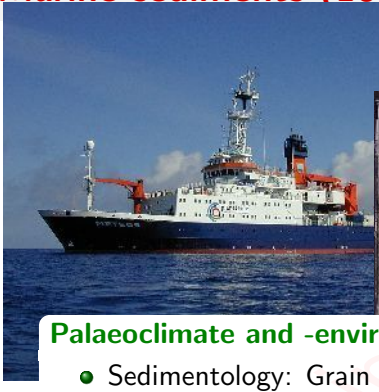
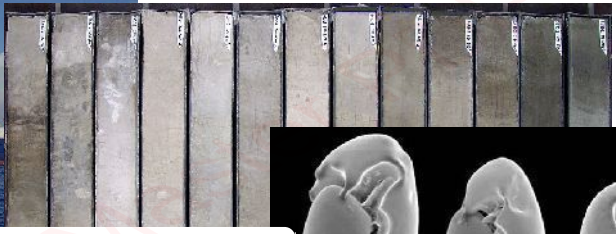
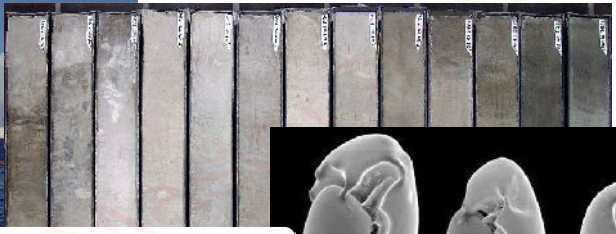




Palaeoclimate and -environmental indicators

- Sedimentology: Grain size, color ...
- Faunal assemblages: Foraminifera ...
- Geochemistry: Mg/Ca, Sr/Ca, ...
- Isotope ratios: δ^{18}O ...

Marine sediments (10^3-10^6 a)



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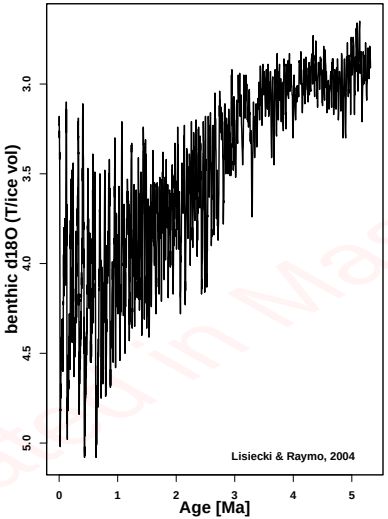
The last 5 Million years in marine sediments



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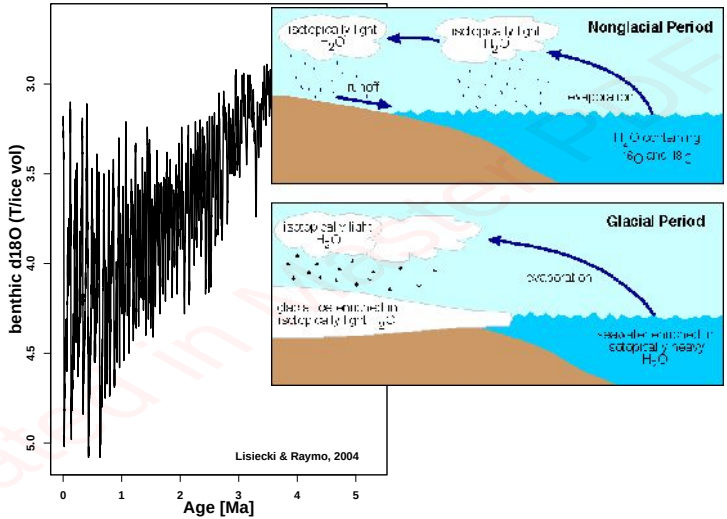
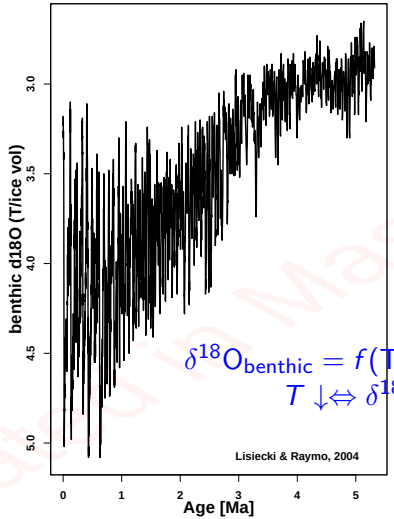


Schematic: columbia.edu

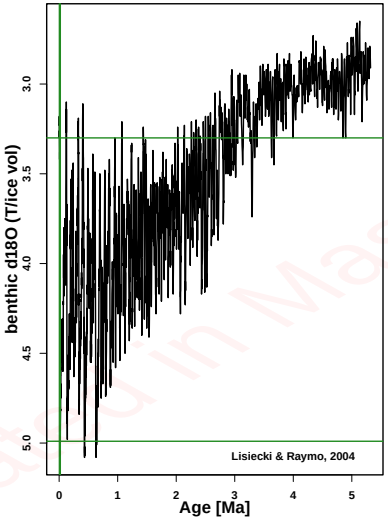
The last 5 Million years in marine sediments



$\delta^{18}O_{benthic} = f(T, \text{ice vol., salinity})$

$T \downarrow \Leftrightarrow \delta^{18}O_{benthic} \uparrow$

The last 5 Million years in marine sediments



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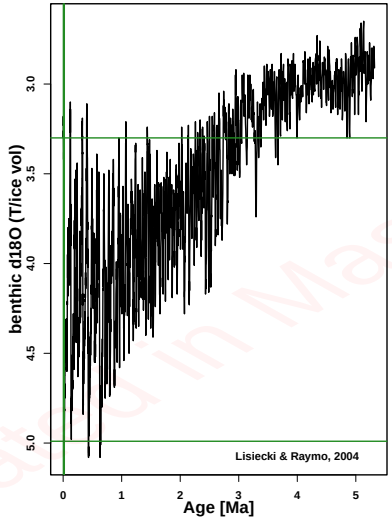

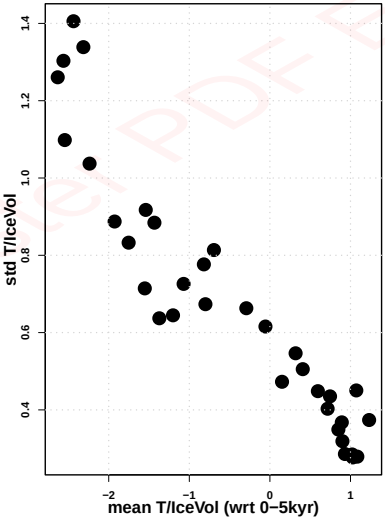

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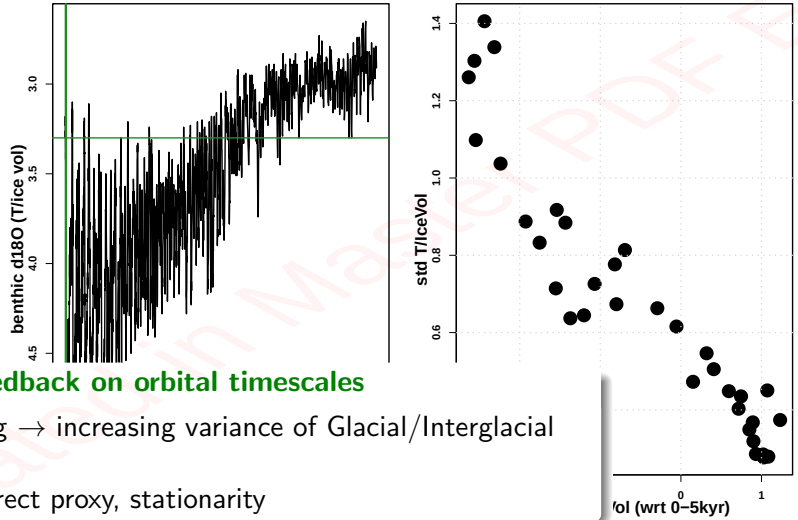


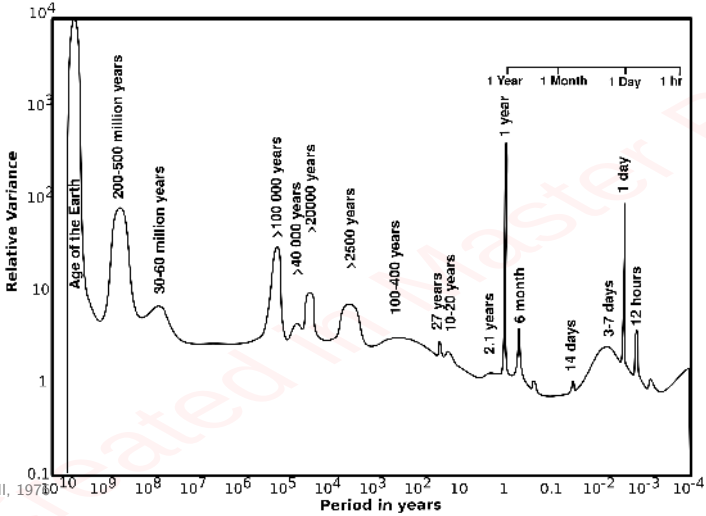
Negative feedback on orbital timescales

Global cooling → increasing variance of Glacial/Interglacial cycles

Caution: indirect proxy, stationarity

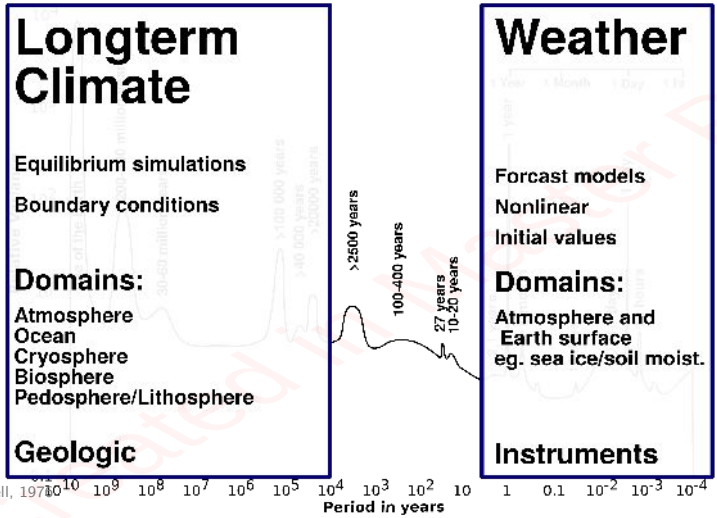
Spectrum

Spectrum of temperature variability



Mitchell, 1976

Spectrum of temperature variability



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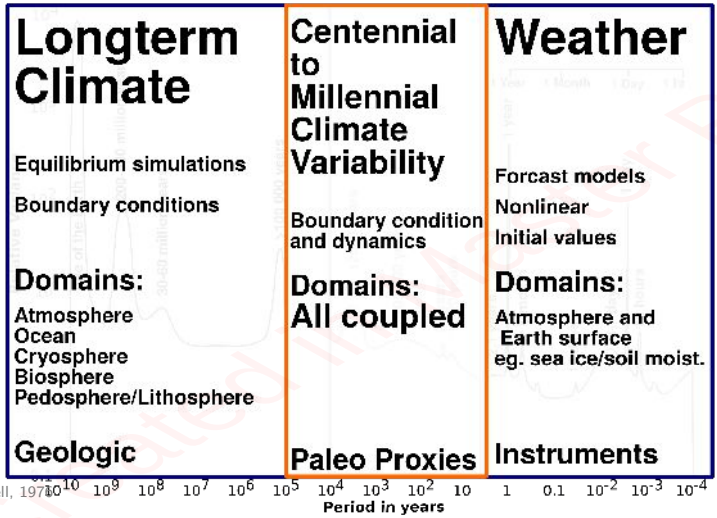
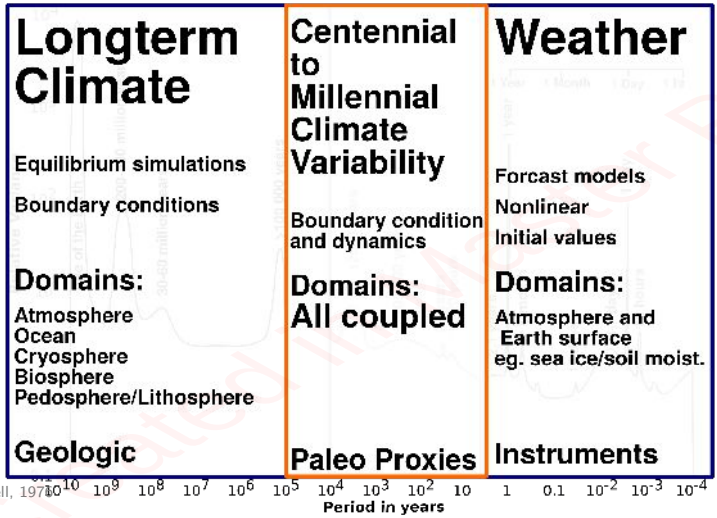
Spectrum of temperature variability



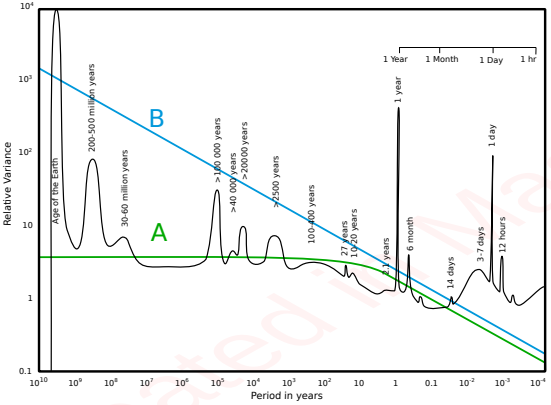
Mitchell, 1976

Spectrum of temperature variability



Mitchell, 1976

Understanding the spectrum



Hasselmann, 1976; Rypdal et al., 2014

- A:**'Hasselmann's view'**:
  $c\frac{dT}{dt} = -kT + Q$
  $k = \sum k_i$ feedbacks
  $Q = \sum Q_j$, $Q = Q(t)$ sources/sinks
  $\rightarrow$ red spectrum
- B: **Log-log-slope**: Linear or nonlinear processes $\leftrightarrow$ **Scaling**
- **Centennial timescale:** bridge between past & present, projection relevance

Salzman, 1990 Clim. Dyn., Crucifix, 2016 **PAGES mag.**

Hands-on climate research: Orbital timescales

1. Using power spectra, find the dominant periodicities in the Glacial/Interglacial cycles over the last
   - 5 million years,
   - 1 million years.
2. Compare them to orbital variations for the last 1 Million years, and discuss Milankovitch's theory of the ice ages.
3. Characterize the relationship between temperatures and CO_2 over the last 1 Million years.

Datasets in github repository

git clone https://github.com/paleovar/graddays.git

Climate response

EPICA δD and temperature reconstruction Jouzel et al., 2007
Benthic stack Lisiecki et al., 2005

Climate forcing

CO_2 data Bereiter et al., 2015; EPICA-Community-Members, 2004
Orbital Berger et al., 1991
Python: climlab https://github.com/brian-rose/climlab
R: palinsol https://cran.r-project.org/web/packages/palinsol/index.html

Workflow

1. Get data + clean it
2. Formulate hypothesis
3. Inspect data (plot)
4. Analyze data
5. Summarize results (1-2 slides!)
6. Submit

Please put check on the board when you've completed a stage. If you need help, put a sticker on your computer.

Results

git commit ...
git push ...

Intermediate summary

1. Climate variability is societally relevant.
2. At different timescales, variability is dominated by different Earth system components and feedbacks.
3. To project future changes, past changes need to be assessed quantitatively, compared to underlying forcing and mechanisms of change understood.

Intermediate summary

1. Climate variability is societally relevant.
2. At different timescales, variability is dominated by different Earth system components and feedbacks.
3. To project future changes, past changes need to be assessed quantitatively, compared to **underlying forcing** and **mechanisms of change** understood.

One-minute-paper

1. What was the most relevant thing that you learned today?
2. What was surprising to you?
3. What would you like to hear more about this week?

References I

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Rehfeld, K., T. Münch, et al. (2018). "Global patterns of declining temperature variability from the Last Glacial Maximum to the Holocene". In: *Nature* 554.7692. DOI: 10.1038/nature25454.

Rehfeld, K., M. Trachsel, et al. (2016). "Assessing performance and seasonal bias of pollen-based climate reconstructions in a perfect model world". In: *Climate of the Past* 12.12. DOI: 10.5194/cp-12-2255-2016.

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Additional resources

https://a-little-book-of-r-for-time-series.readthedocs.io/en/latest/
https://www.ncdc.noaa.gov/data-access/paleoclimatology-data
Modified orbital illustrations after railsback.org
Used graphics: see references, openclipart.org, own work and wikimedia commons