Astronomical theory

Krakow 2014

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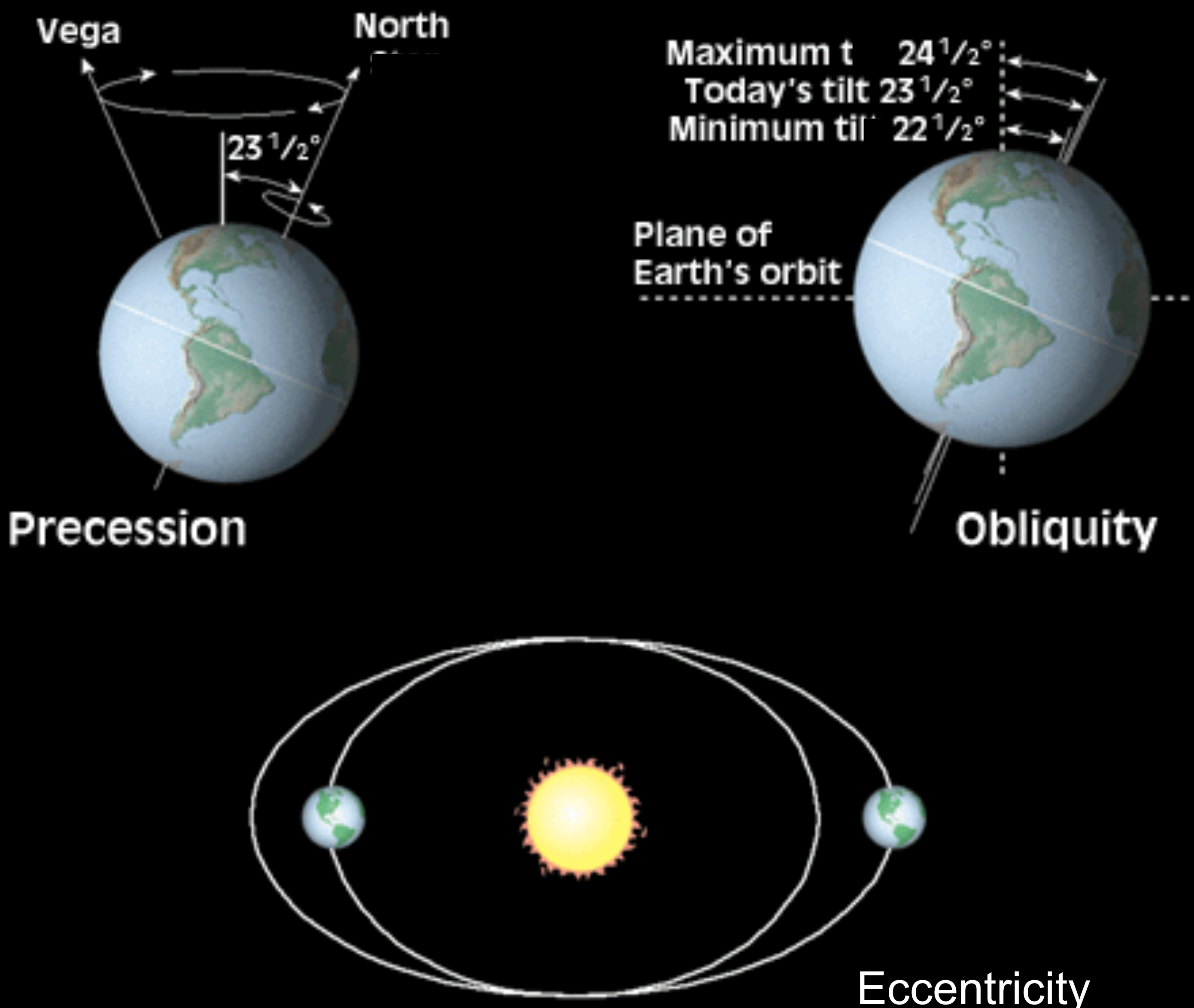
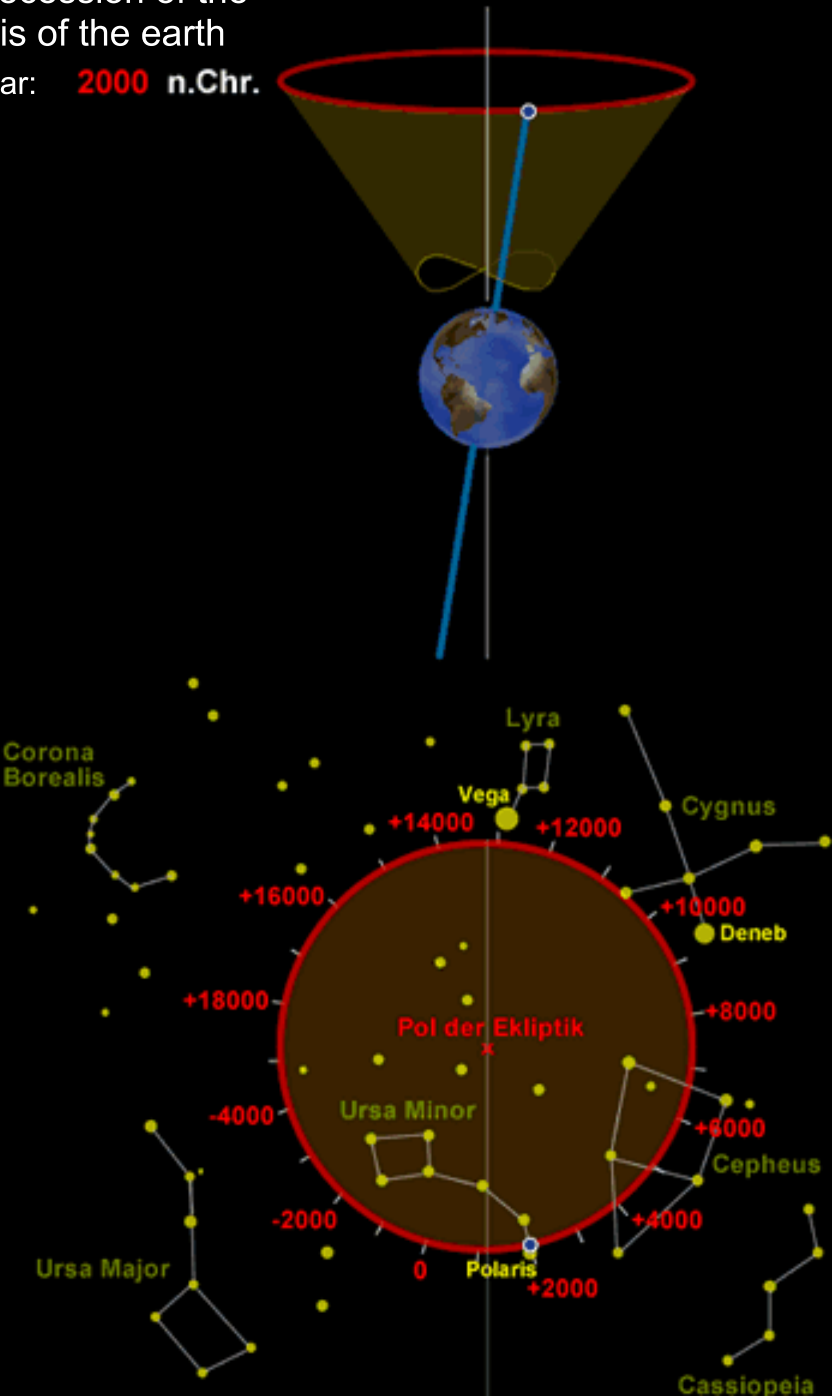


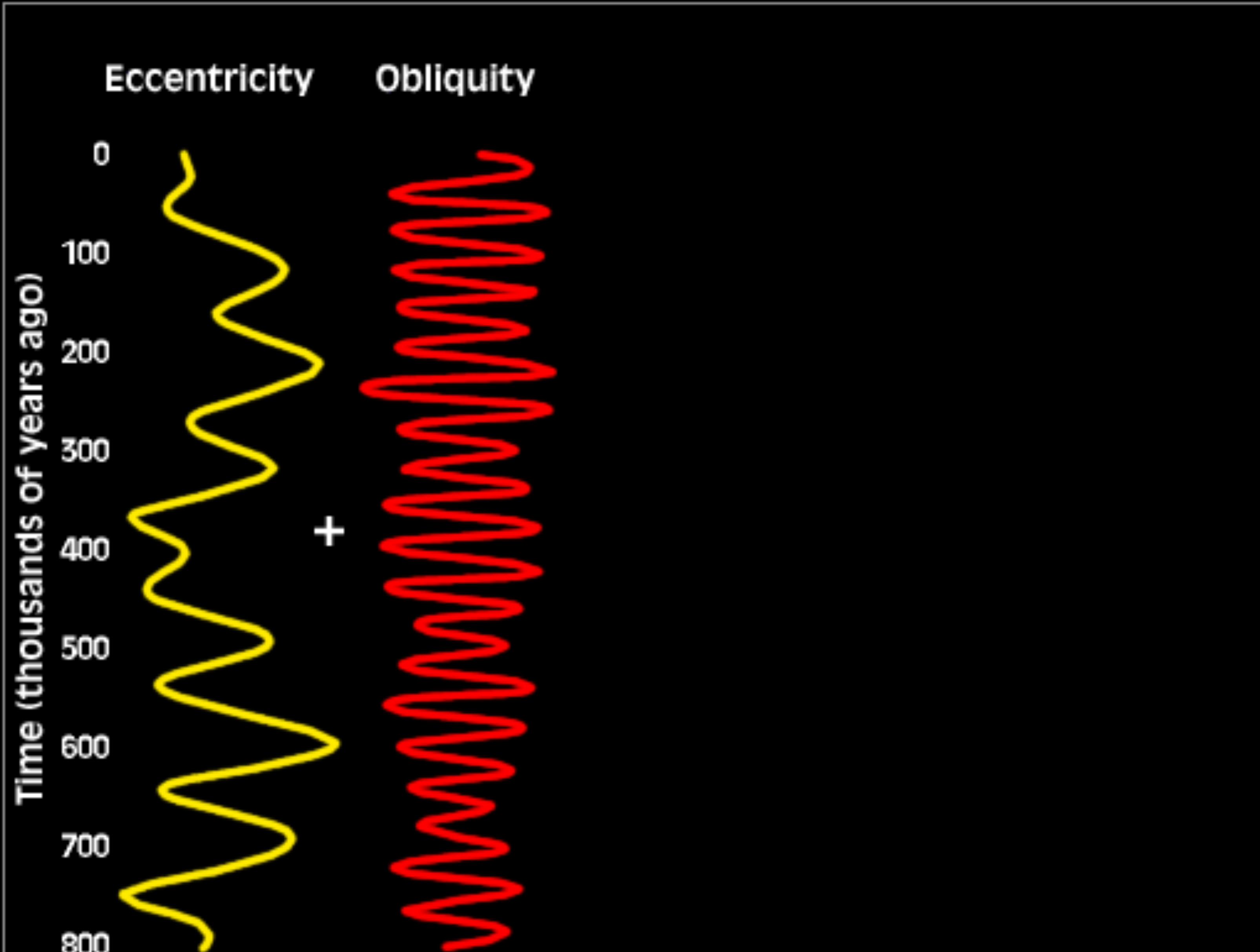
Vega
North
23 1/2°
Precession
Maximum t 24 1/2°
Today's tilt 23 1/2°
Minimum til 22 1/2°
Plane of
Earth's orbit
Obliquity
Eccentricity

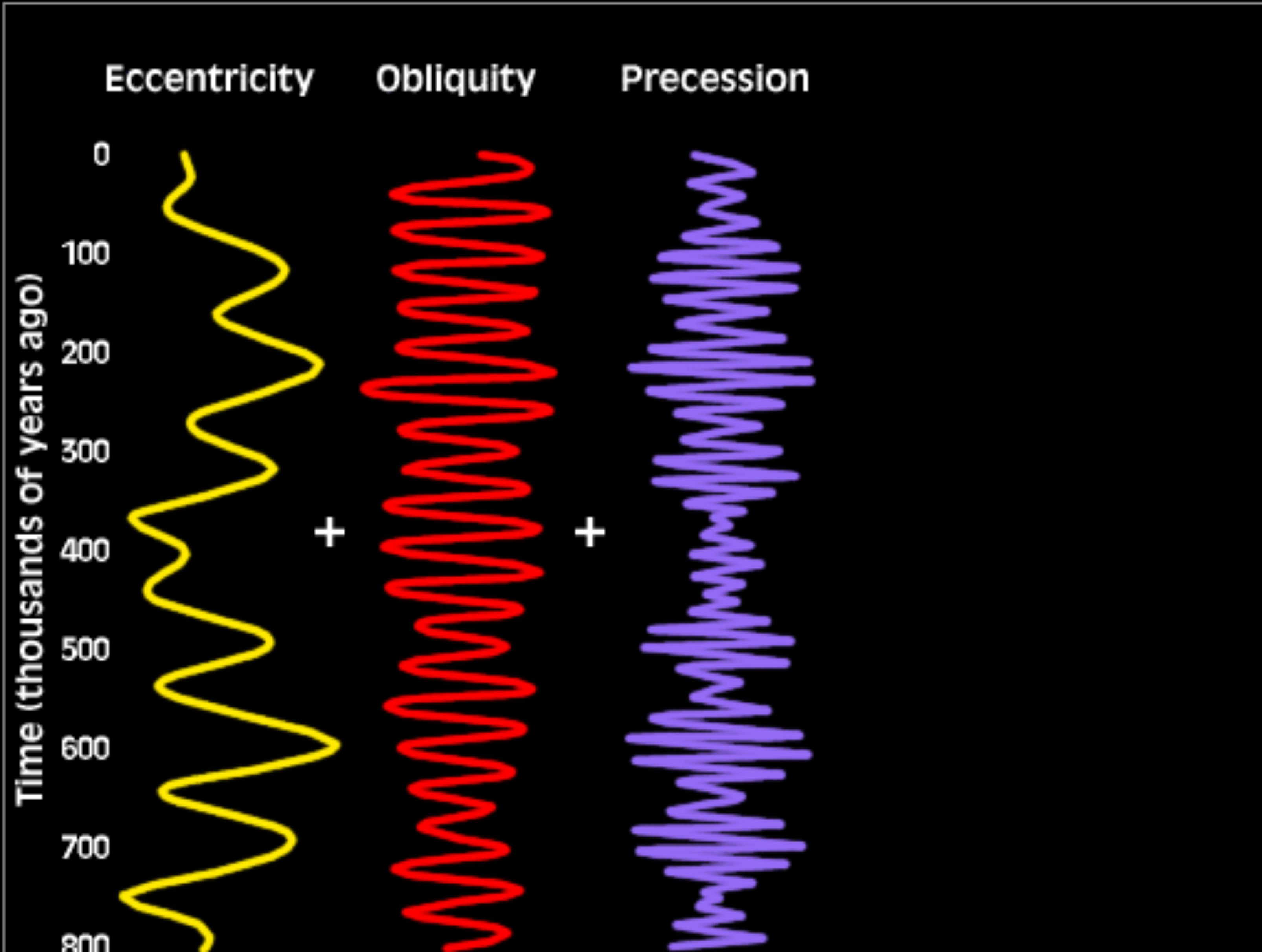
Precession of the axis of the earth

Year: 2000 n.Chr.

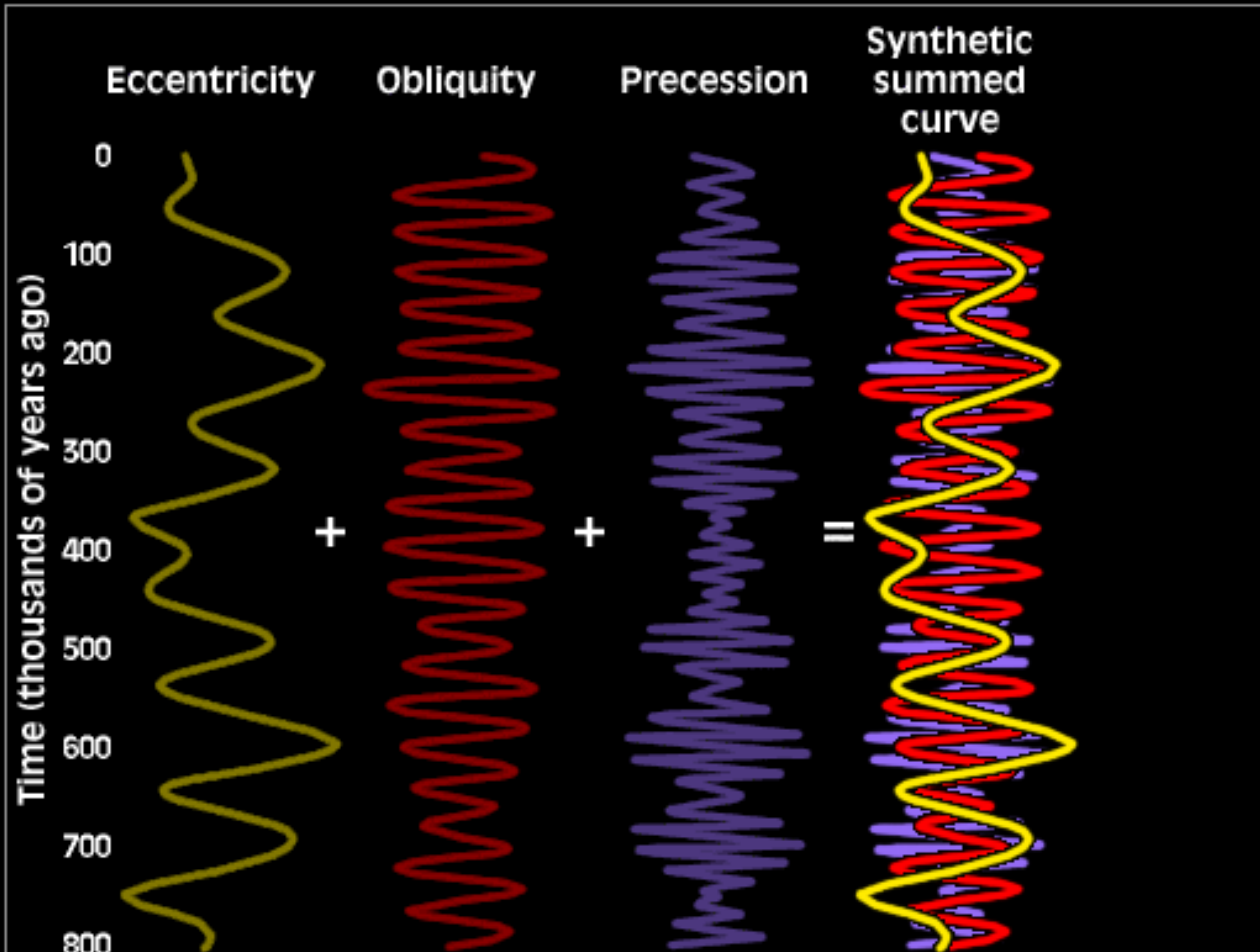



Eccentricity
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800


Eccentricity
Obliquity
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+



Eccentricity
Obliquity
Precession
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+
+

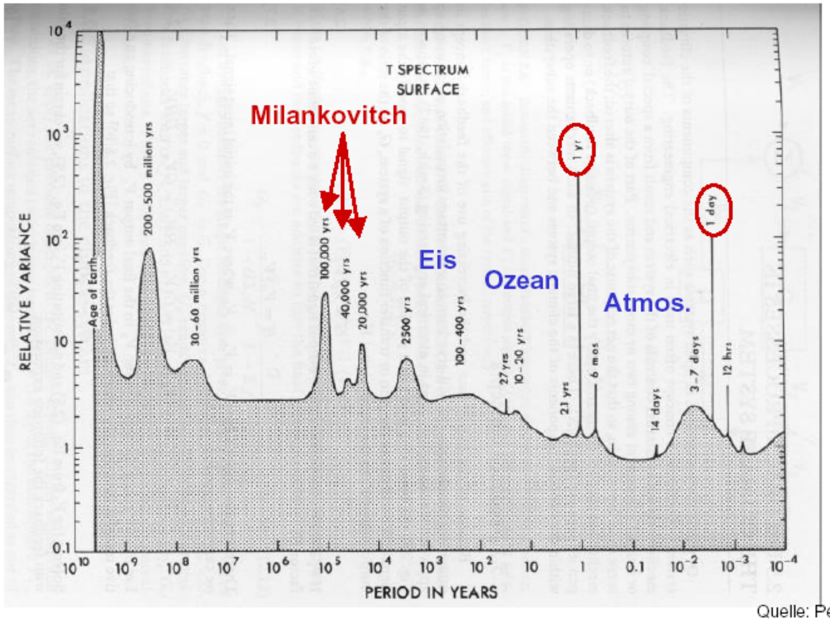


Eccentricity
Obliquity
Precession
Synthetic summed curve
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+
+
=

Orbital focing

- 20000, 40000, 100000 years
- 0.5, 1 year

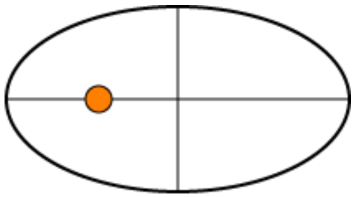
- Geometry of the Sun-Earth configuration



Quelle: Peixoto & Oort

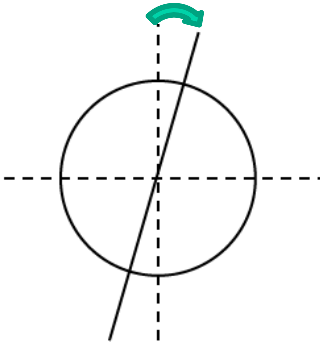
Orbital parameters

Excentricity



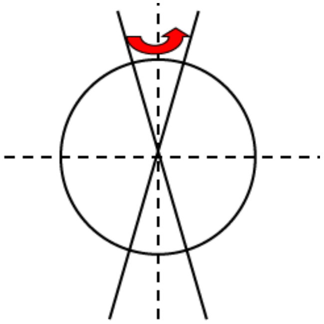
Periods:
100, 400 ky

Obliquity



Periods:
39, 41, 54 ky

Precession

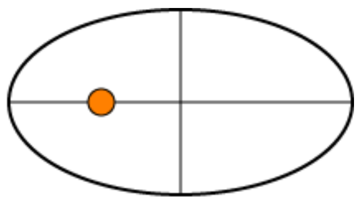


Periods:
19, 23 ky
Modulation Excentricity

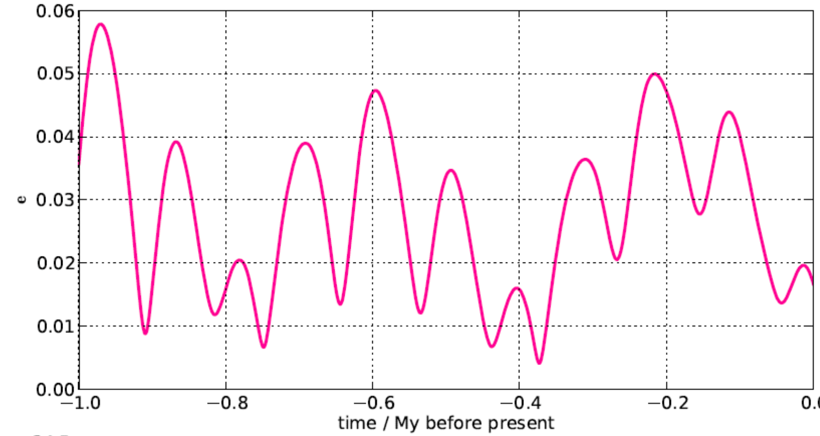
Orbital parameters

time

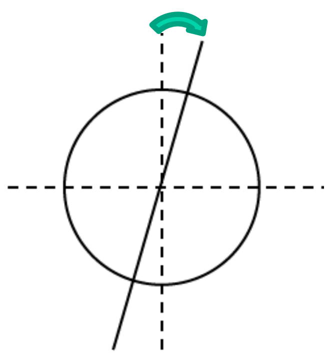
Excentricity



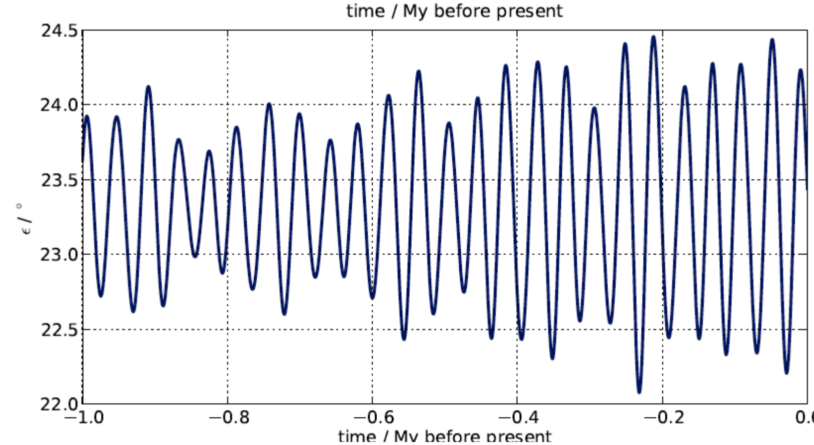
Periods:
100, 400 ky



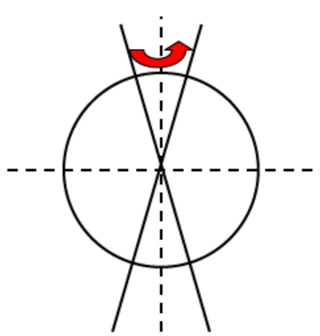
Obliquity



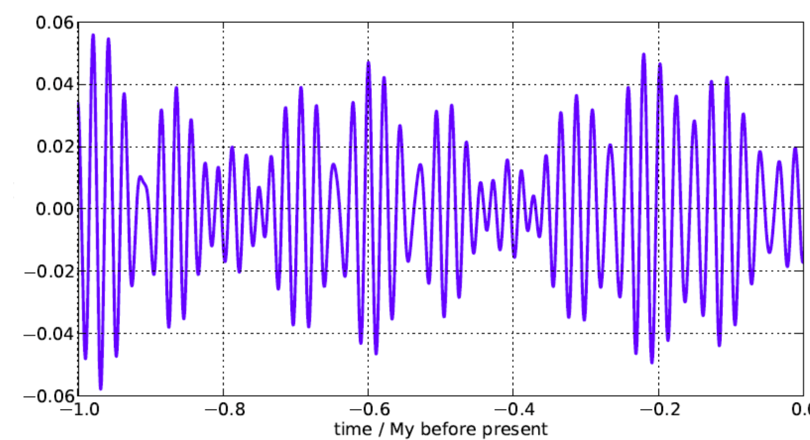
Periods:
39, 41, 54 ky
Modul. 1.2 My



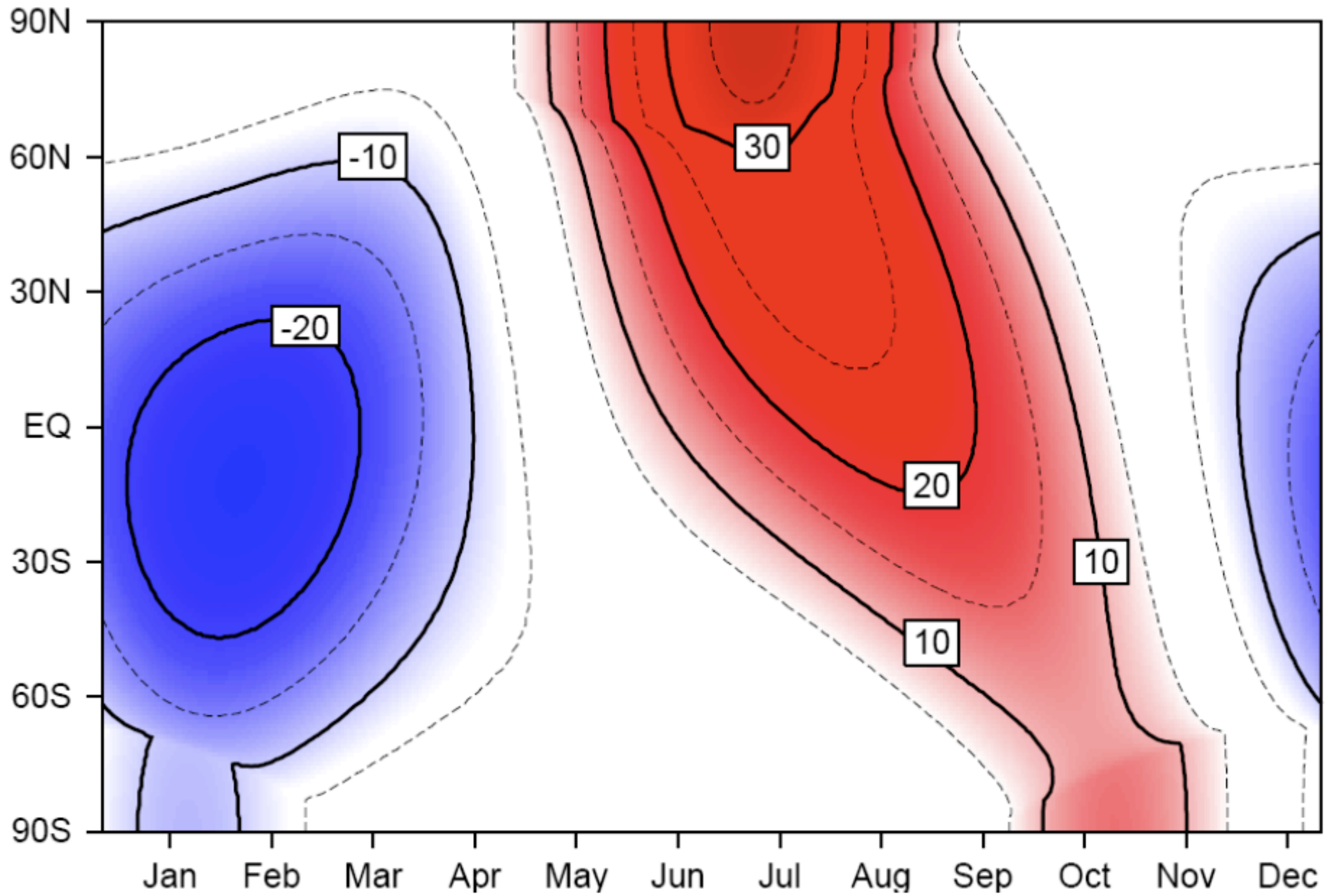
Precession



Periods:
19, 23 ky
Modul. Excentr

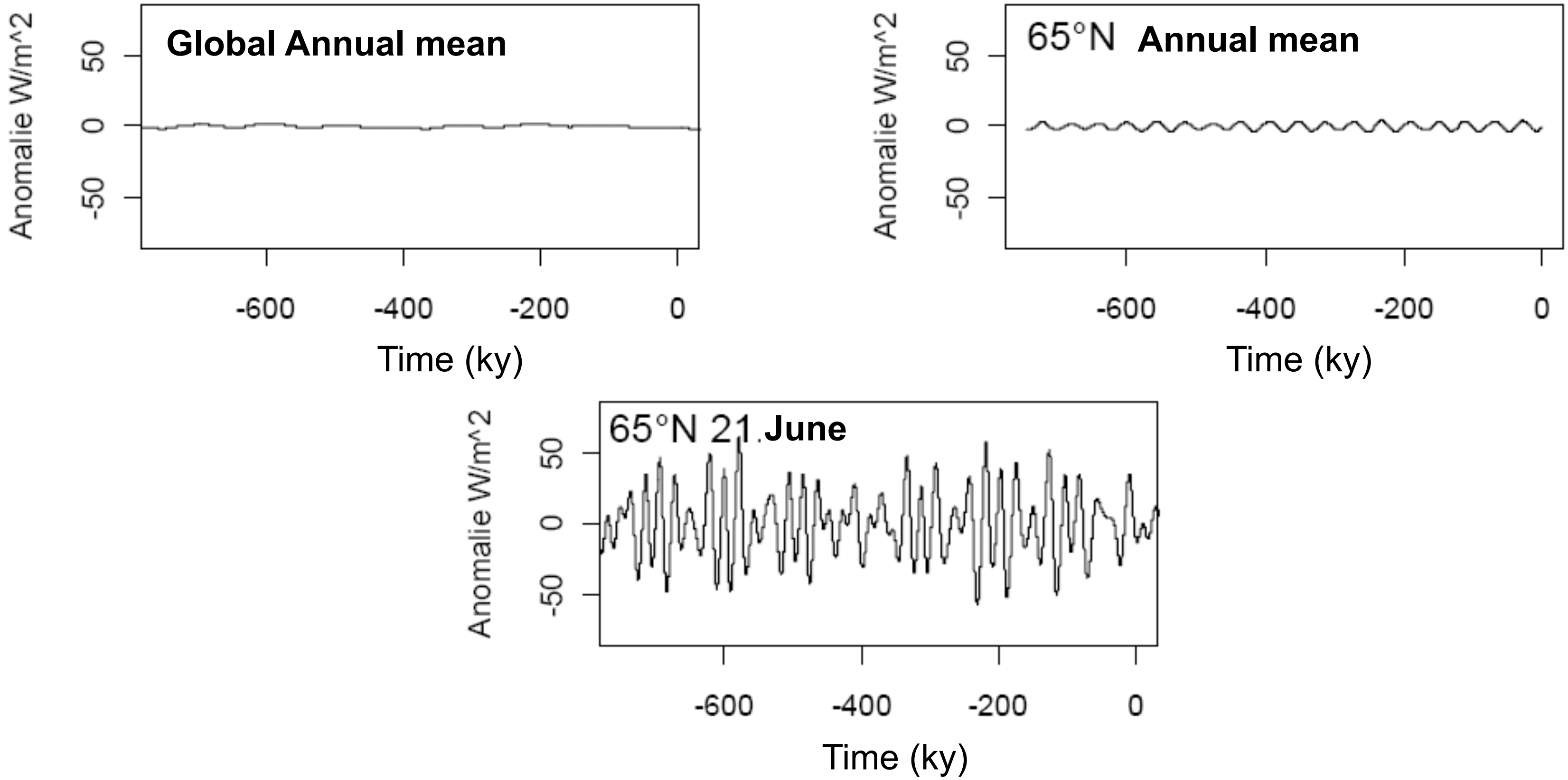


Insolation (6k minus present)



(after Berger, 1978)

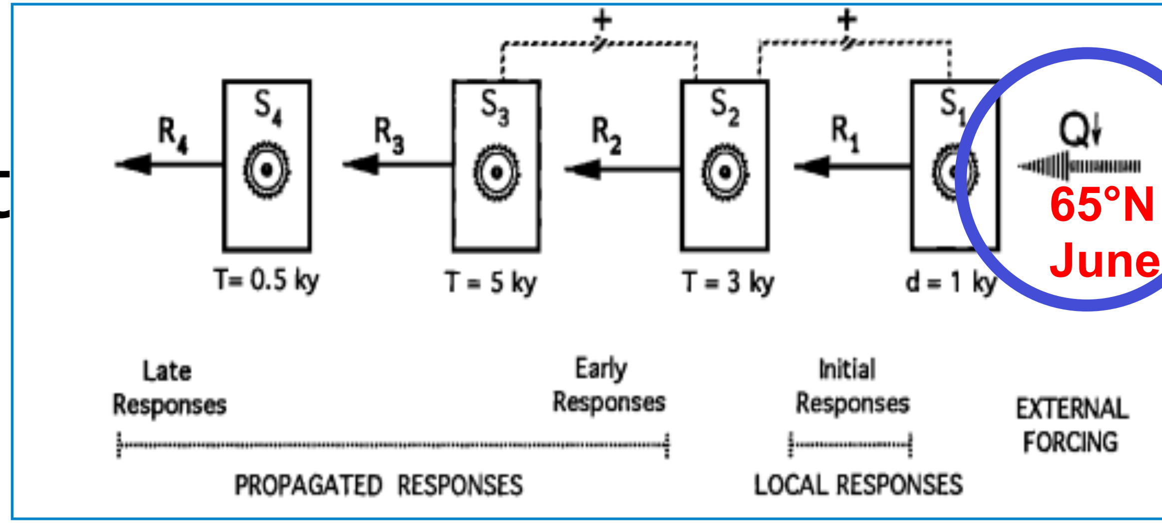
Resulting Effect



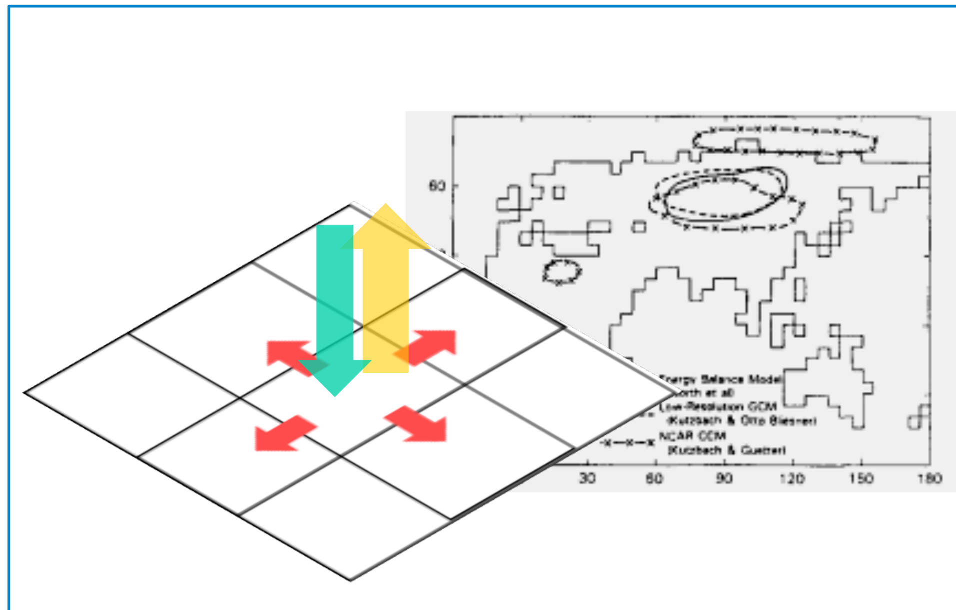
Non-linearities (selecting season and latitude) are important

Approaches to climate variations

- Global Concept (Imbrie 92)



- Local Model (Short et al., 91) 2D linear EBM



- Complex Models

  Computer

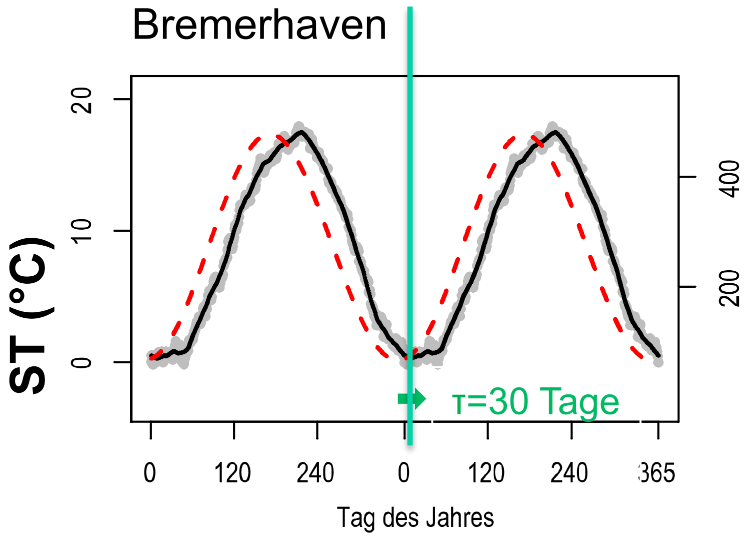
Template model

$$\text{Temperature}(x,t) = f[\text{insolation}(x,t)]$$

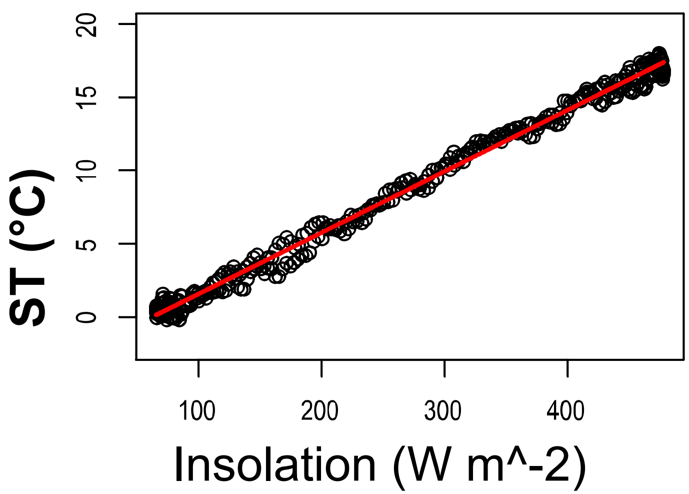
Assumption: f() is time independent

- Model: f() is based on present annual cycle.
- Idea: Apply this to the past

Annual cycle (NCEP, observations)



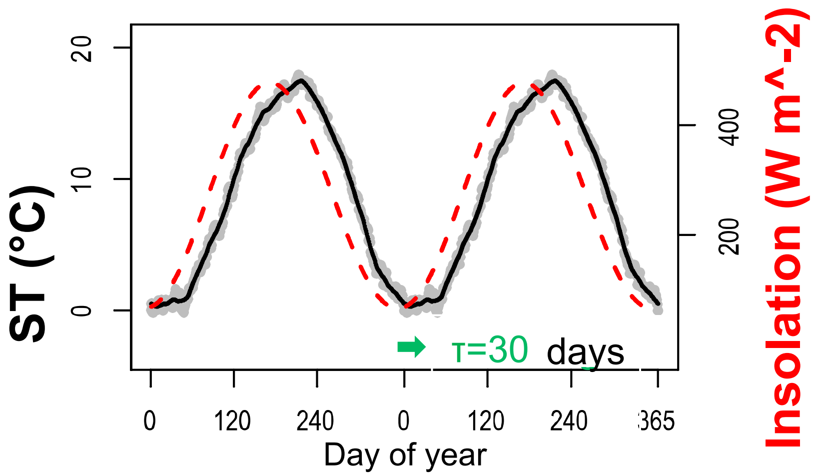
Insolation (W m^-2)



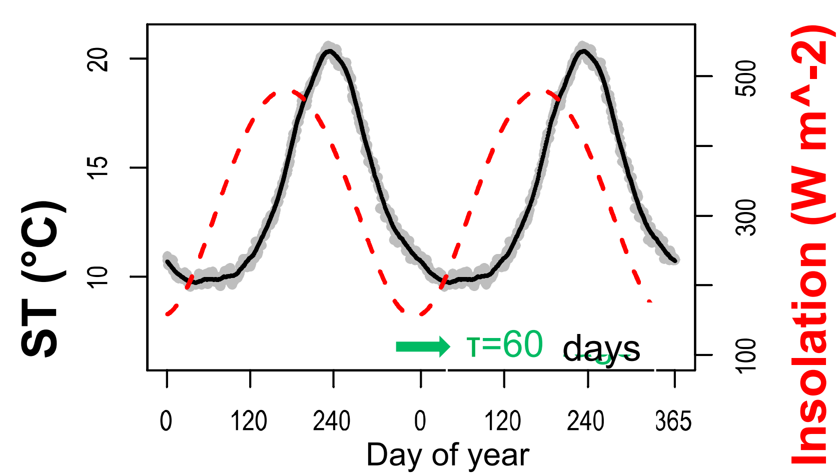
$$T_{surf}(t) = a_{lin} + b_{lin} I(t - \tau)$$

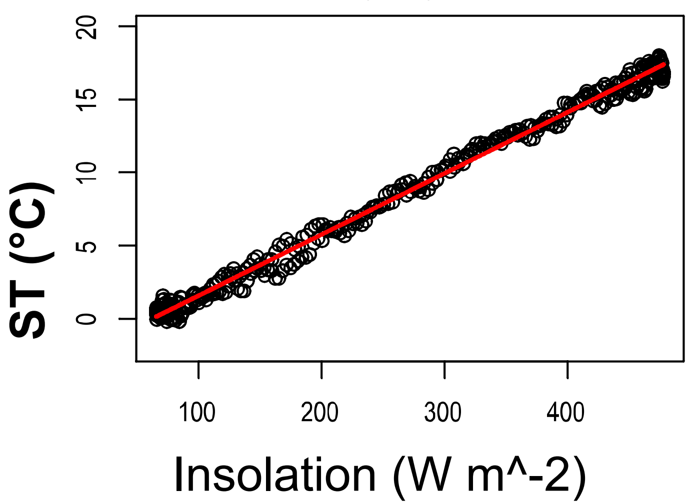
Annual cycle (NCEP, observations)

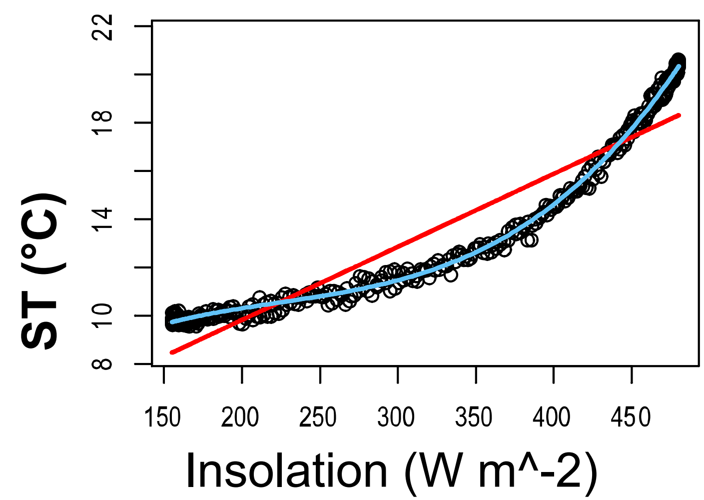
Bremerhaven



North Pacific Ocean (40°N 200°E)







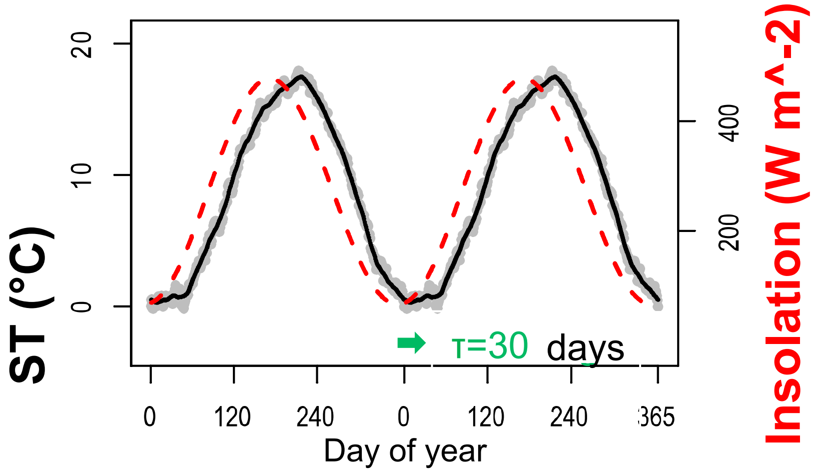
$$T_{surf}(t) = a_{lin} + b_{lin} I(t-\tau)$$

$$T_{surf}(t) = F(I(t-\tau))$$

$$F(I) = a + bI + cI^2 + dI^3$$

Annual cycle (NCEP)

Bremerhaven



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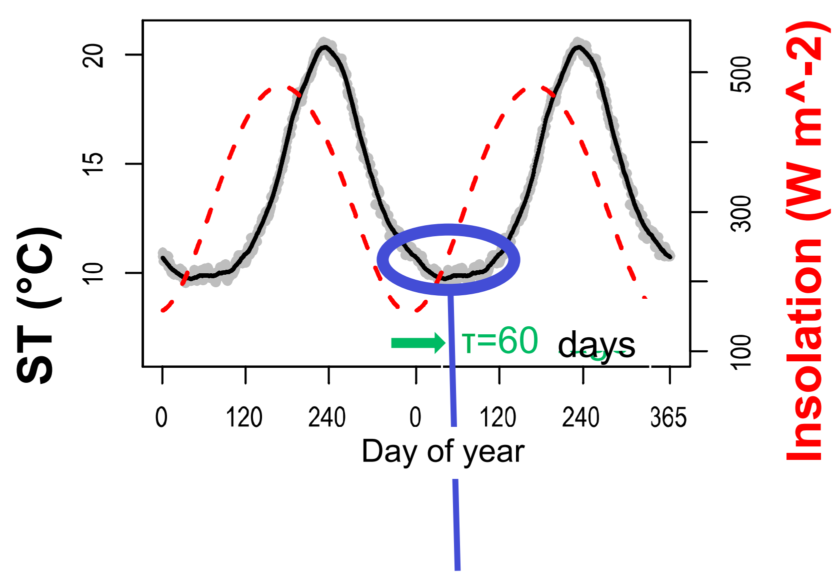
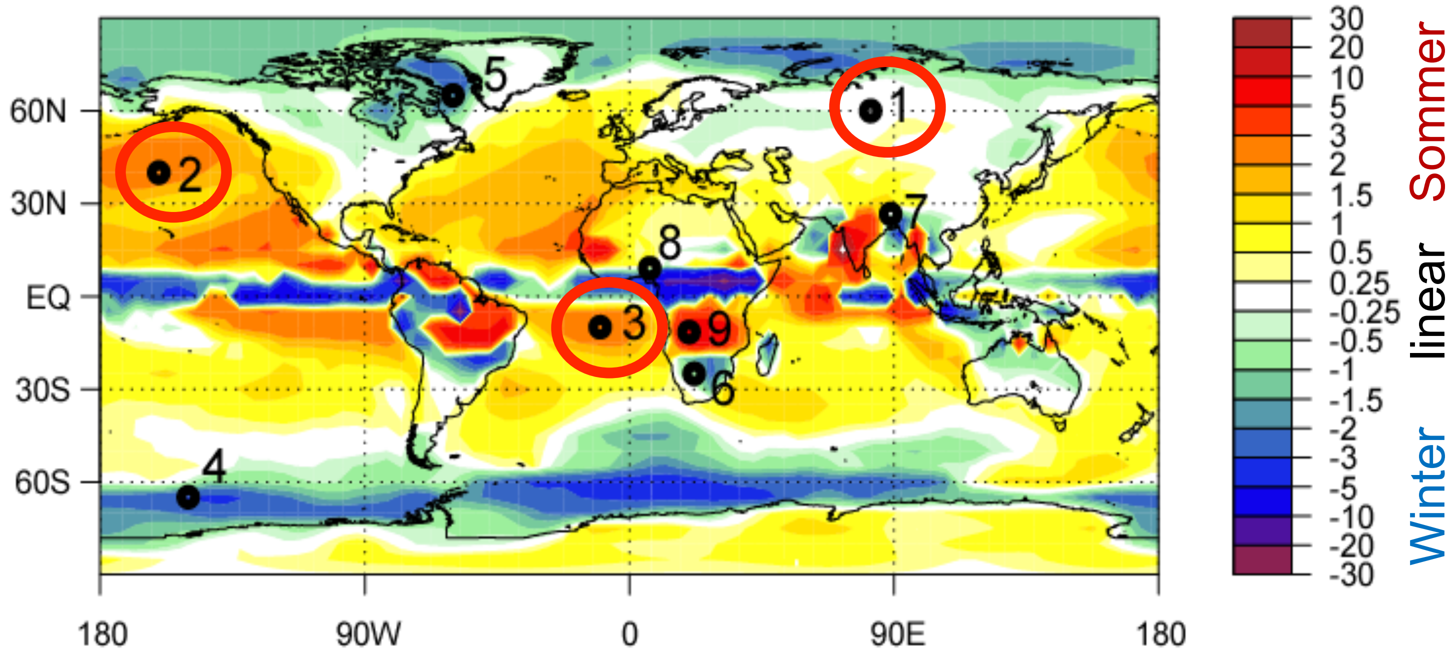


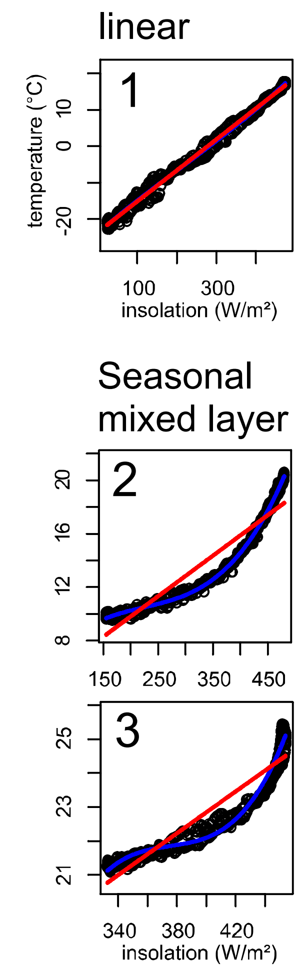
Linear Regime:
Extratropical continents

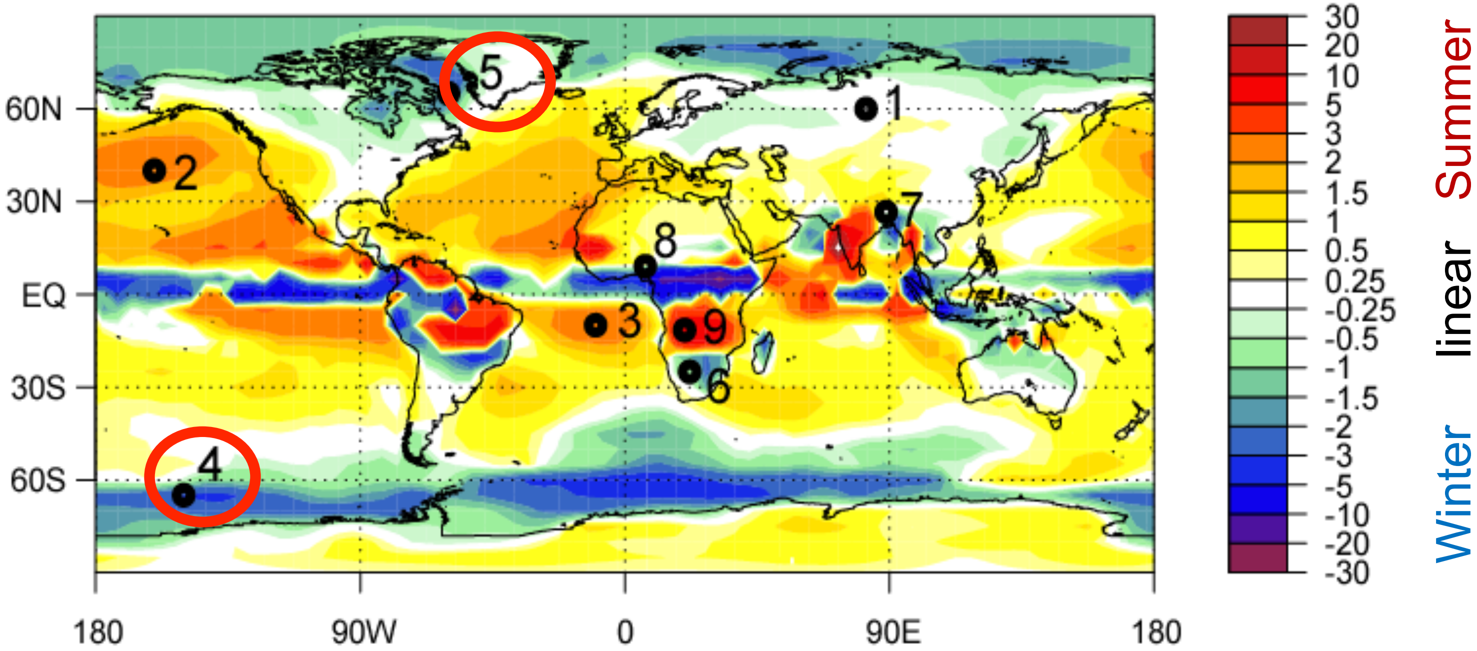
Non-linear Regime:
mixing during winter: Damping

Summer sensitive

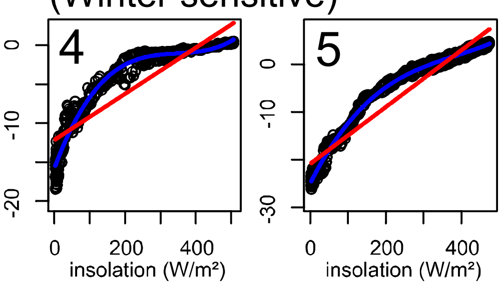
Seasonal Sensitivity

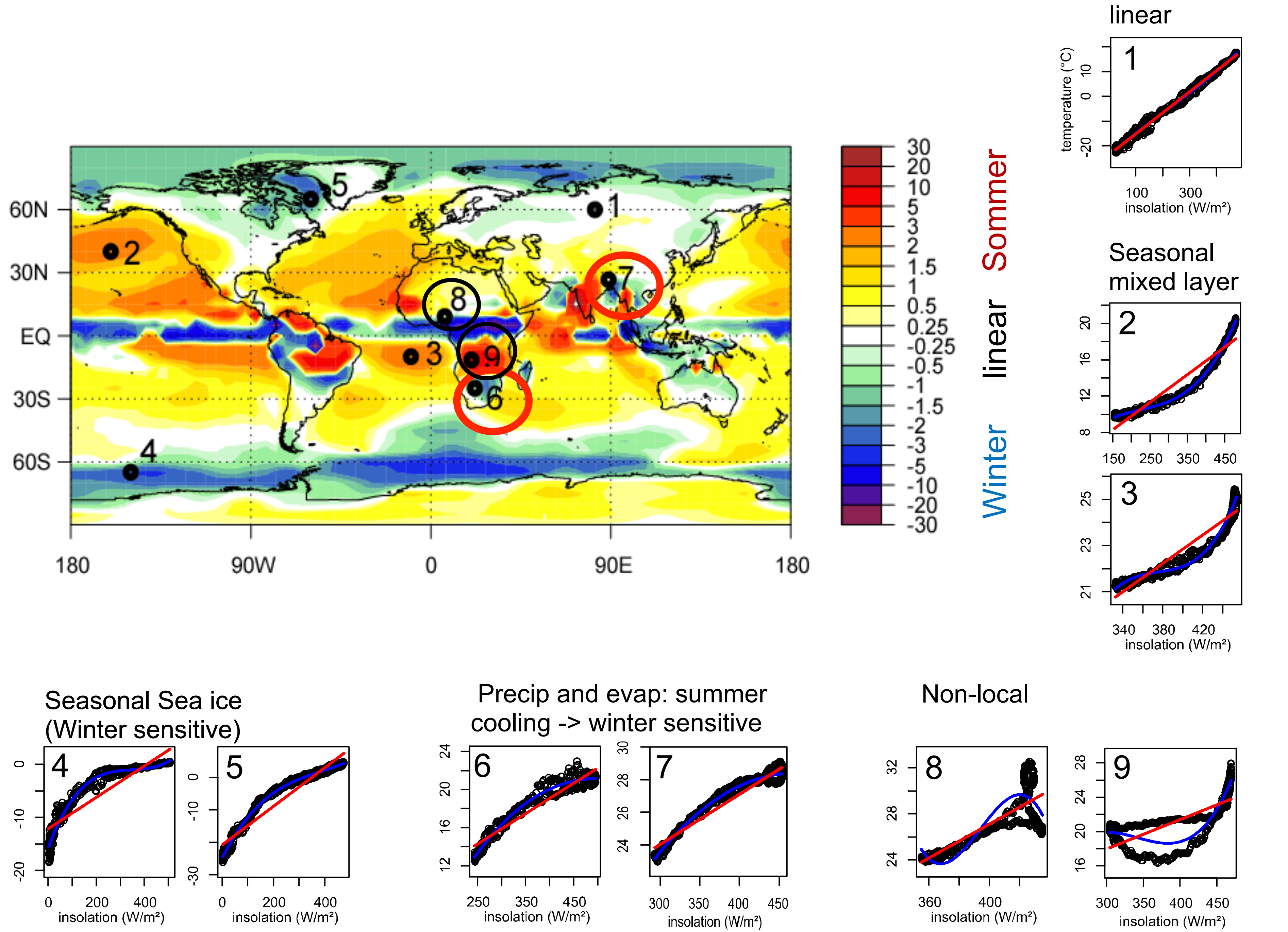






Seasonal Sea ice
(Winter sensitive)



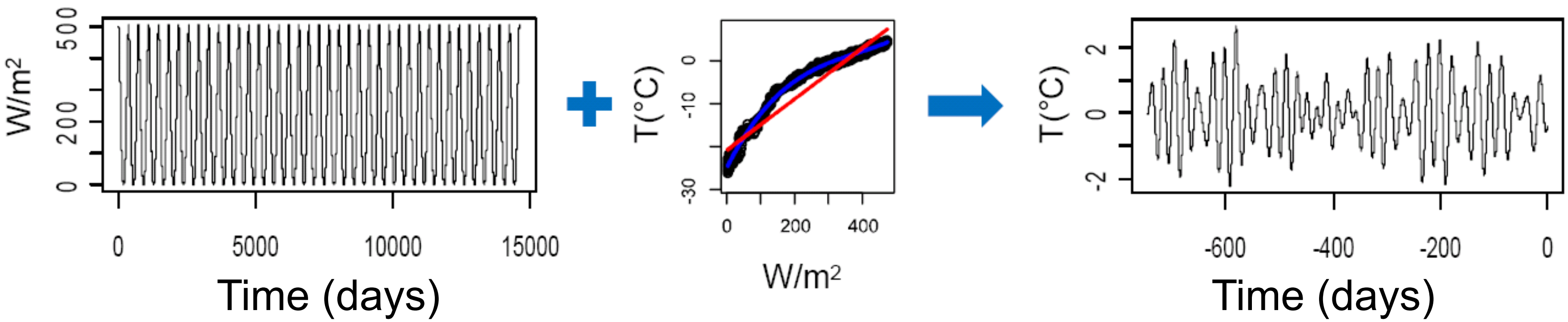


60N
30N
EQ
30S
60S
180
90W
0
90E
180
1
2
3
4
5
6
7
8
9
30
20
10
5
3
2
1.5
1
0.5
0.25
-0.25
-0.5
-1
-1.5
-2
-3
-5
-10
-20
-30
Sommer
linear
Winter
linear
temperature (°C)
insolation (W/m²)
Seasonal mixed layer
Seasonal Sea ice (Winter sensitive)
Precip and evap: summer cooling -> winter sensitive
Non-local

Template model: seasonal cycle -> Astronomical

Seasonal Sensitivity

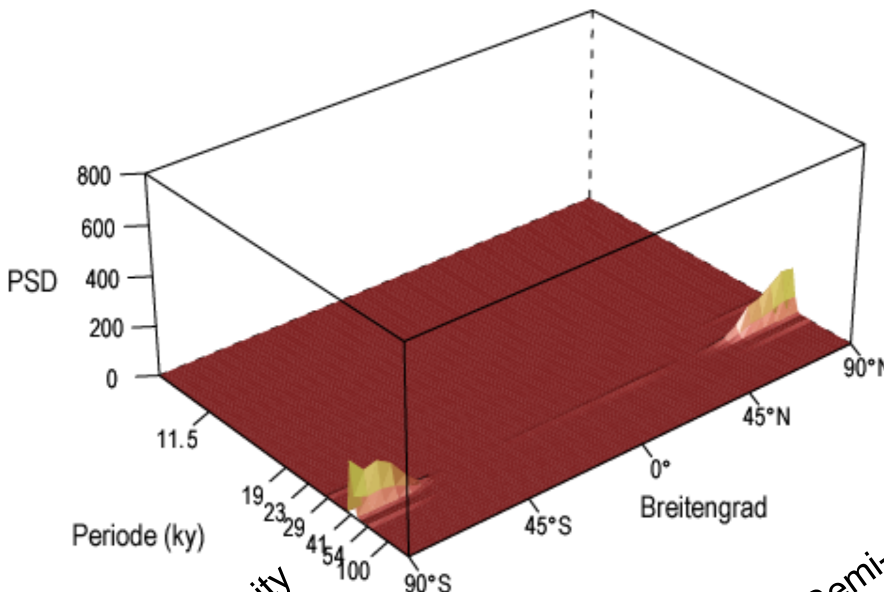
Local,daily insolation | transfer function temperature | expected annual



Laepple and Lohmann, Paleoceanography 09

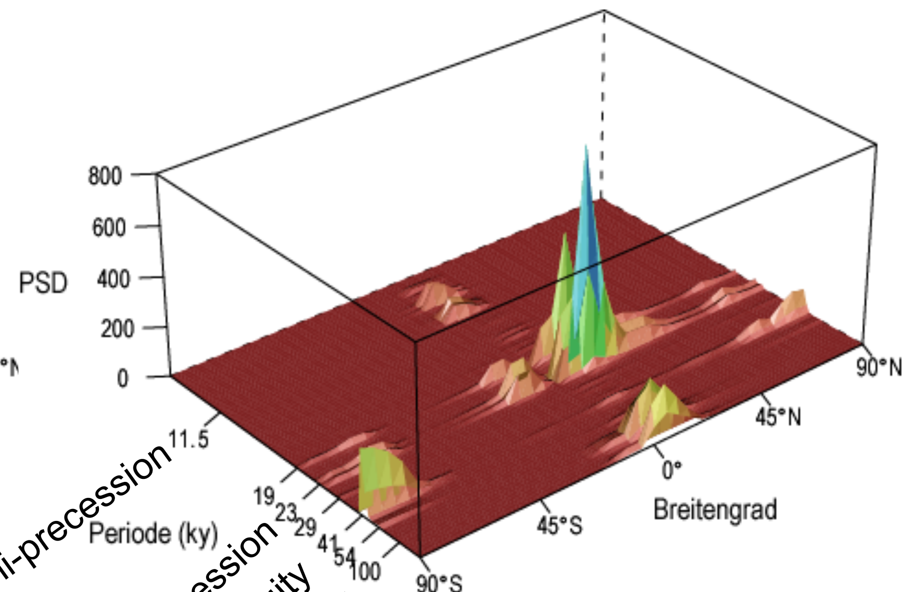
Temperature spectra 750ka

- Linear Model



Obliquity
~40ky

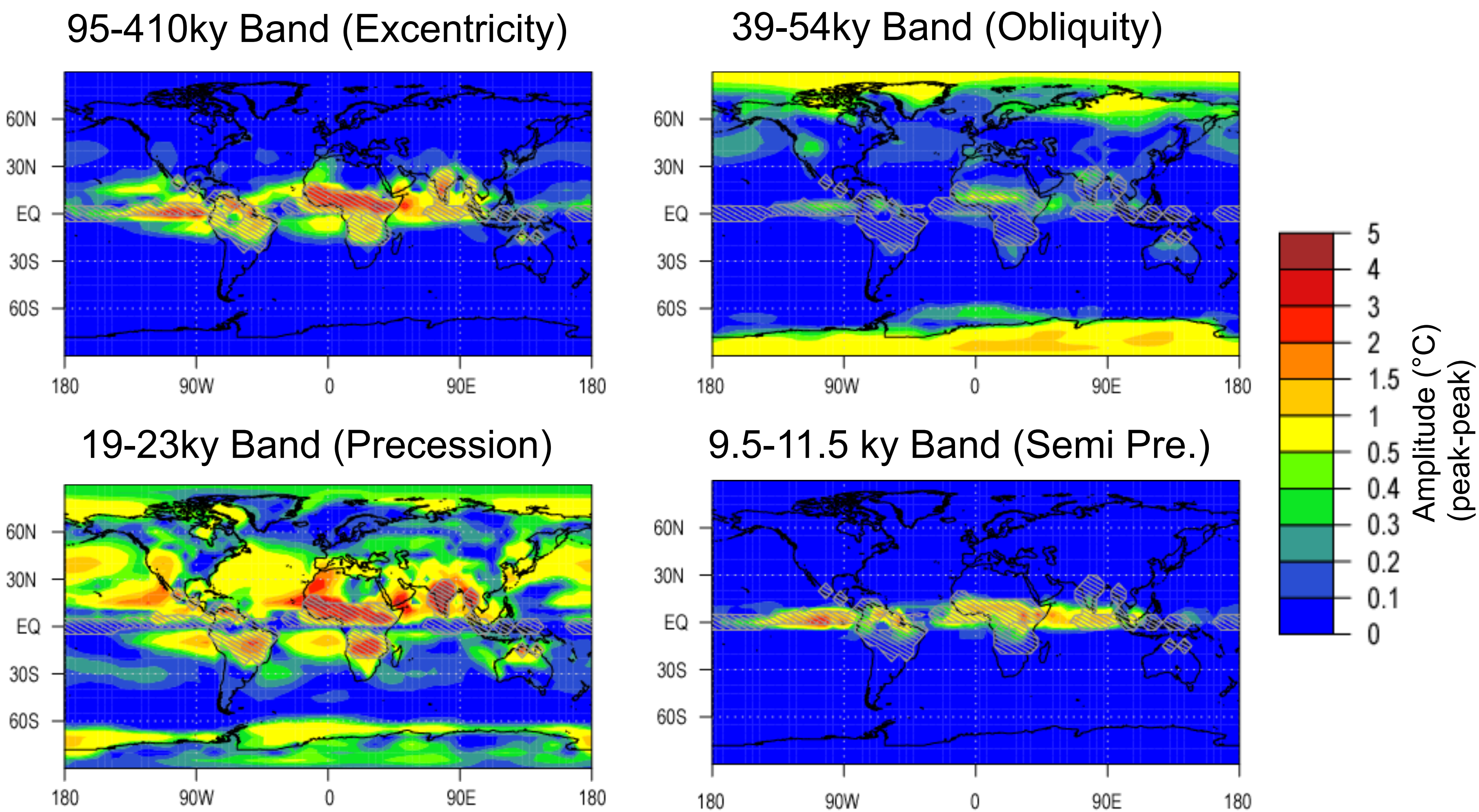
- Non-linear Model



Semi-precession
10ky
Precession
20ky
Obliquity
40ky
Excentricity
100ky

Already template model (fast feedbacks only) -> complex variability

Regional Temperature spectra



- Spatial temendence !

- In (Sub)tropics: lokal 100ky cycle, Semi-precession

GCM-Setup

- **Include now: Feedbacks, advection etc**
- **Earth System model COSMOS (MPI)** under interglacial background conditions, but varying orbital parameters
- 10,000 year long run represents the **last million years** accelerated by a factor of 100 (Lorenz & Lohmann, 2004)

GCM-Setup

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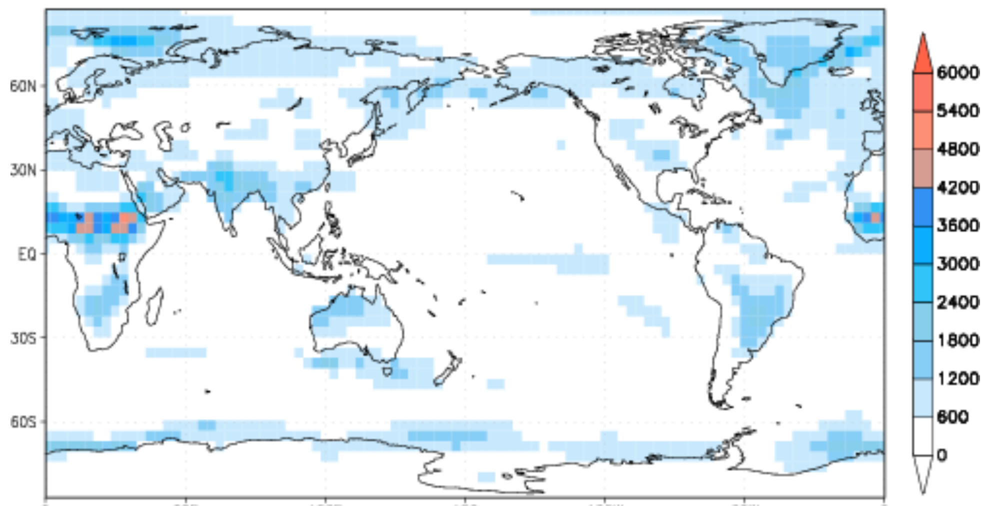
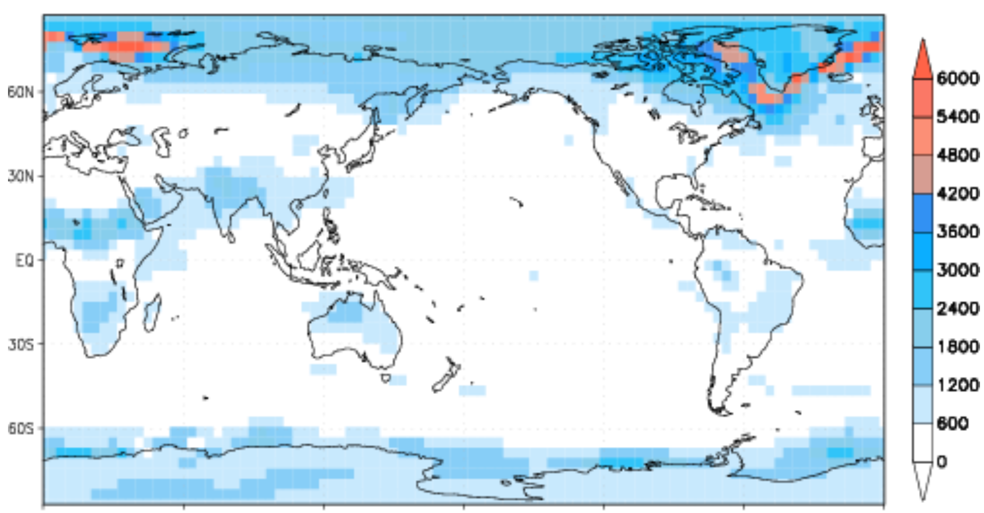
- **Earth System model COSMOS** under interglacial background conditions, but varying orbital parameters
- 10,000 year long run represents the **last million years** accelerated by a factor of 100 (Lorenz & Lohmann, 2004)

Now: 0.7 years of computer time (SX-8) instead of 3 seconds

Regional Temperature spectra

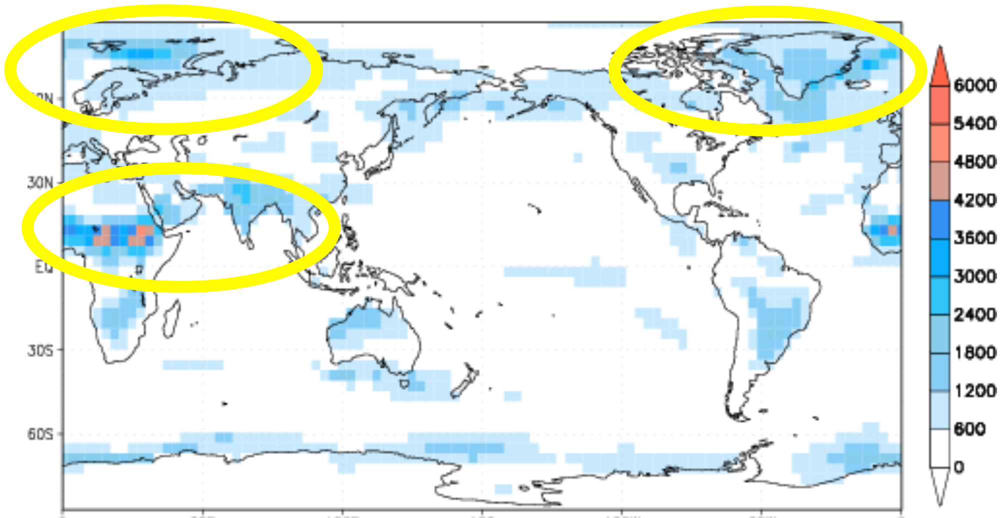


17-27ky Band (Precession)



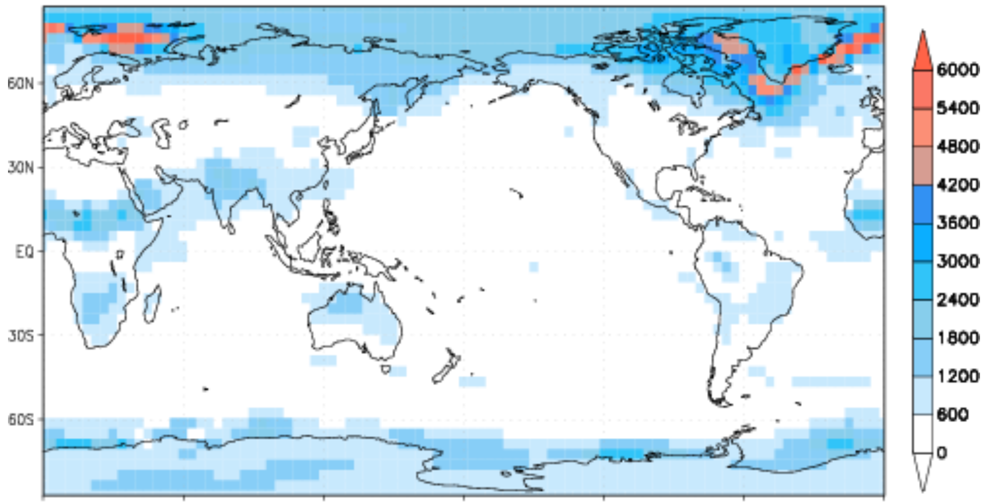
35-45 ky Band (Obliquity)

Regional Temperature spectra



17-27ky Band (Precession)

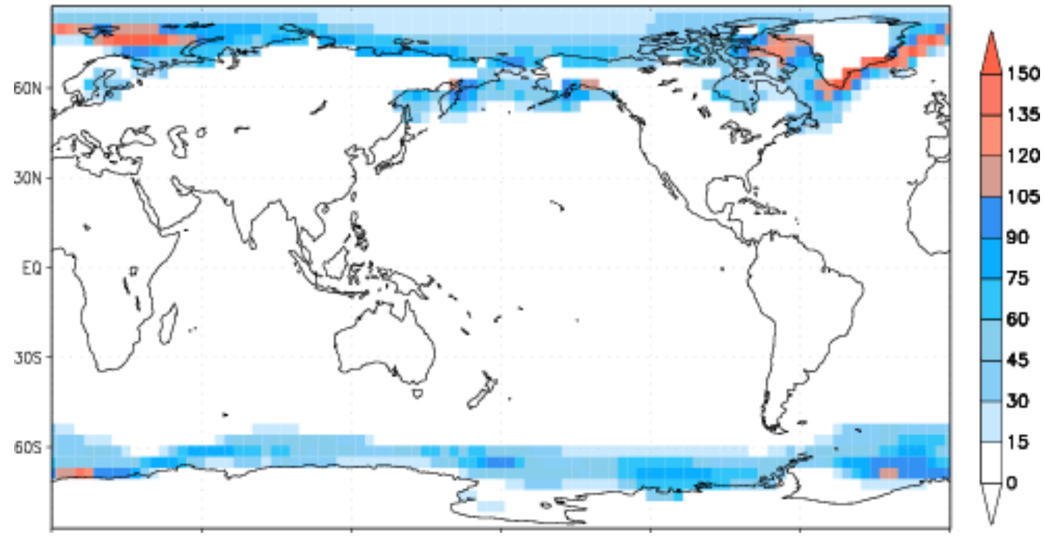
related to nonlinearities or seasonal biases



35-45 ky Band (Obliquity)

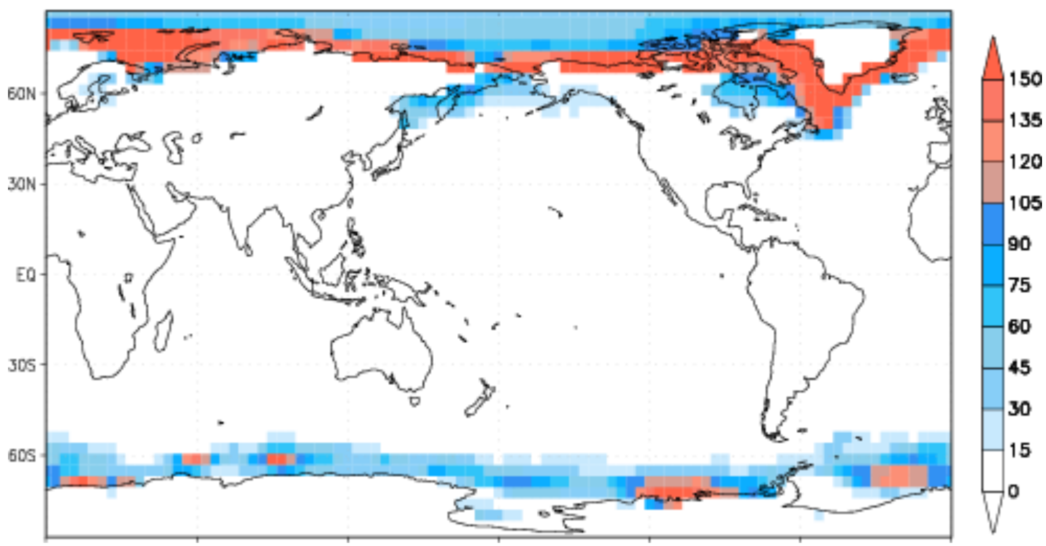
Similarities to the template model, but long-term feedbacks!

Sea ice cover



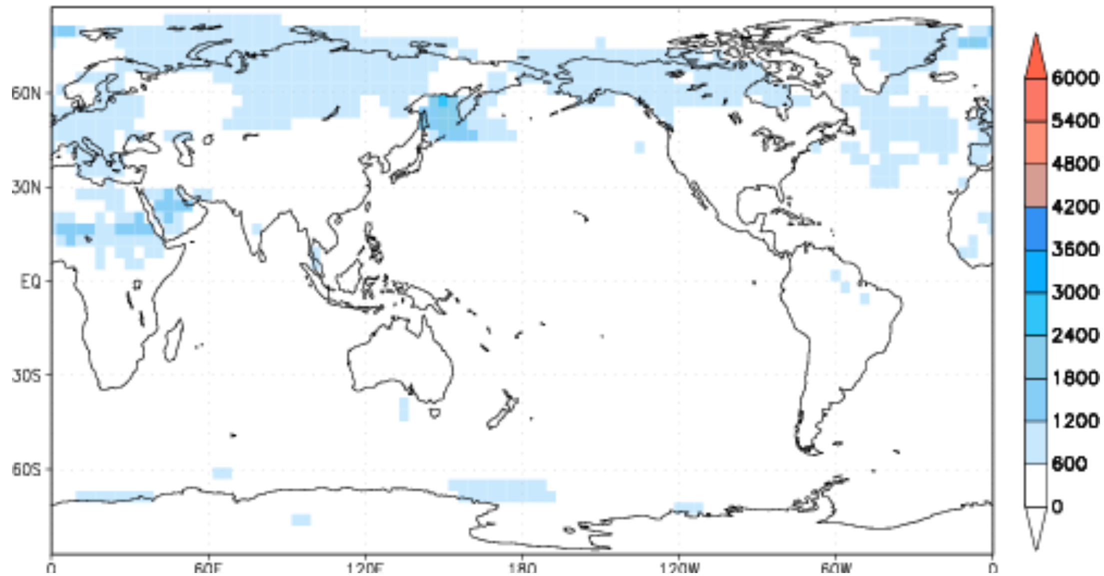
17-27 ky Band (Precession)

Nonlinearity
Affects large-scale ocean



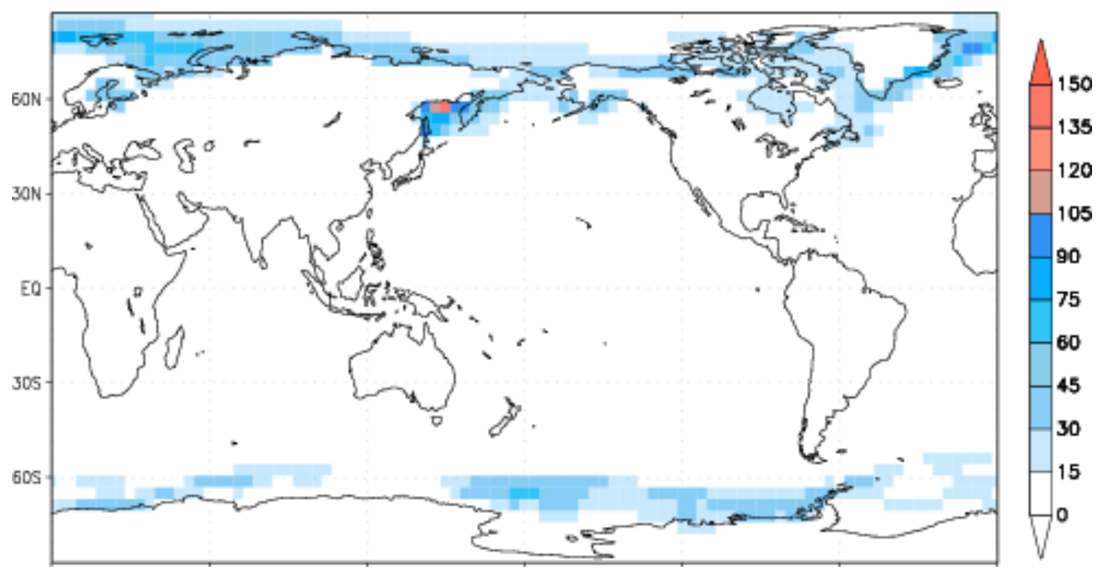
35-45 ky Band (Obliquity)

Regional Temperature spectra



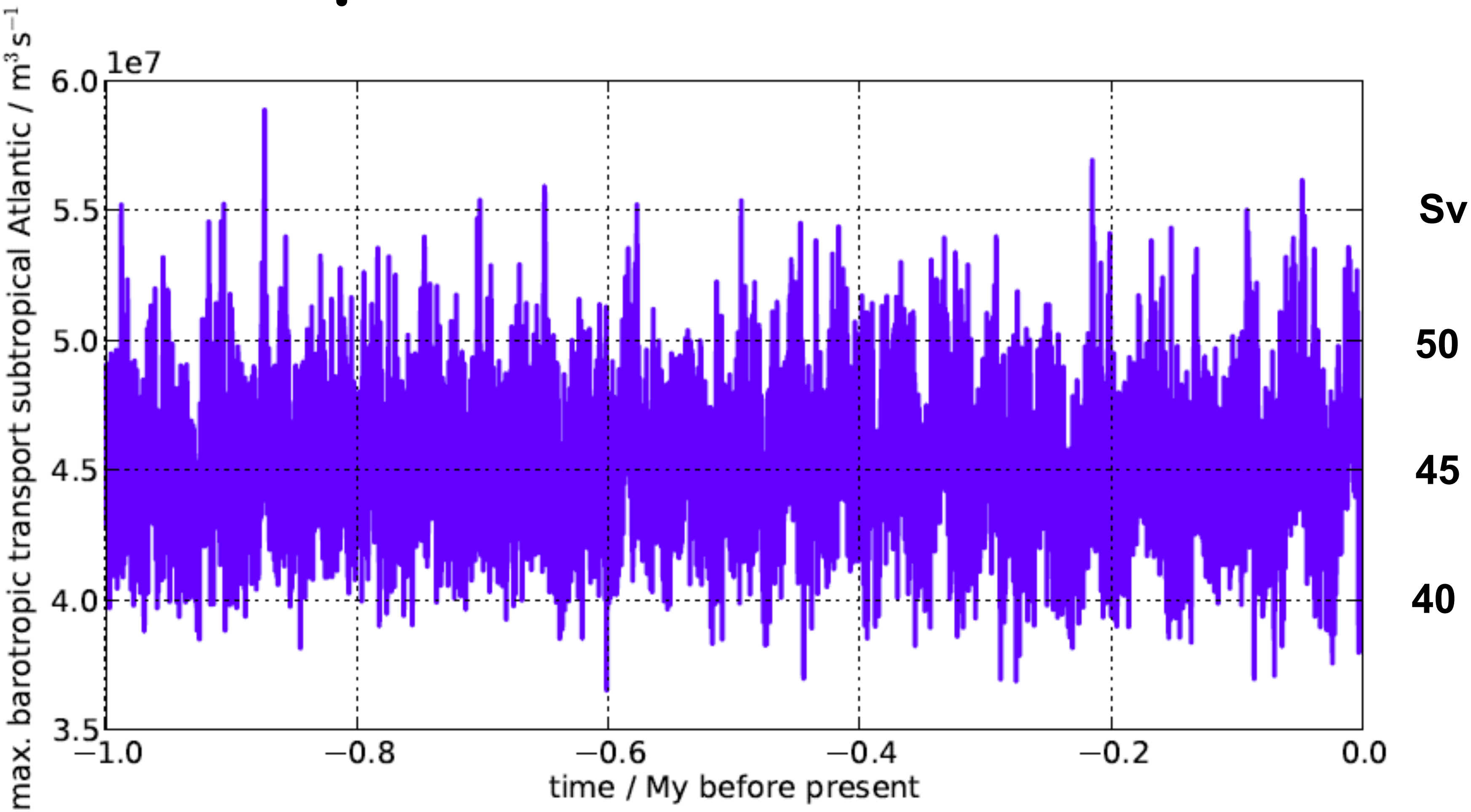
96-106 ky

Temp

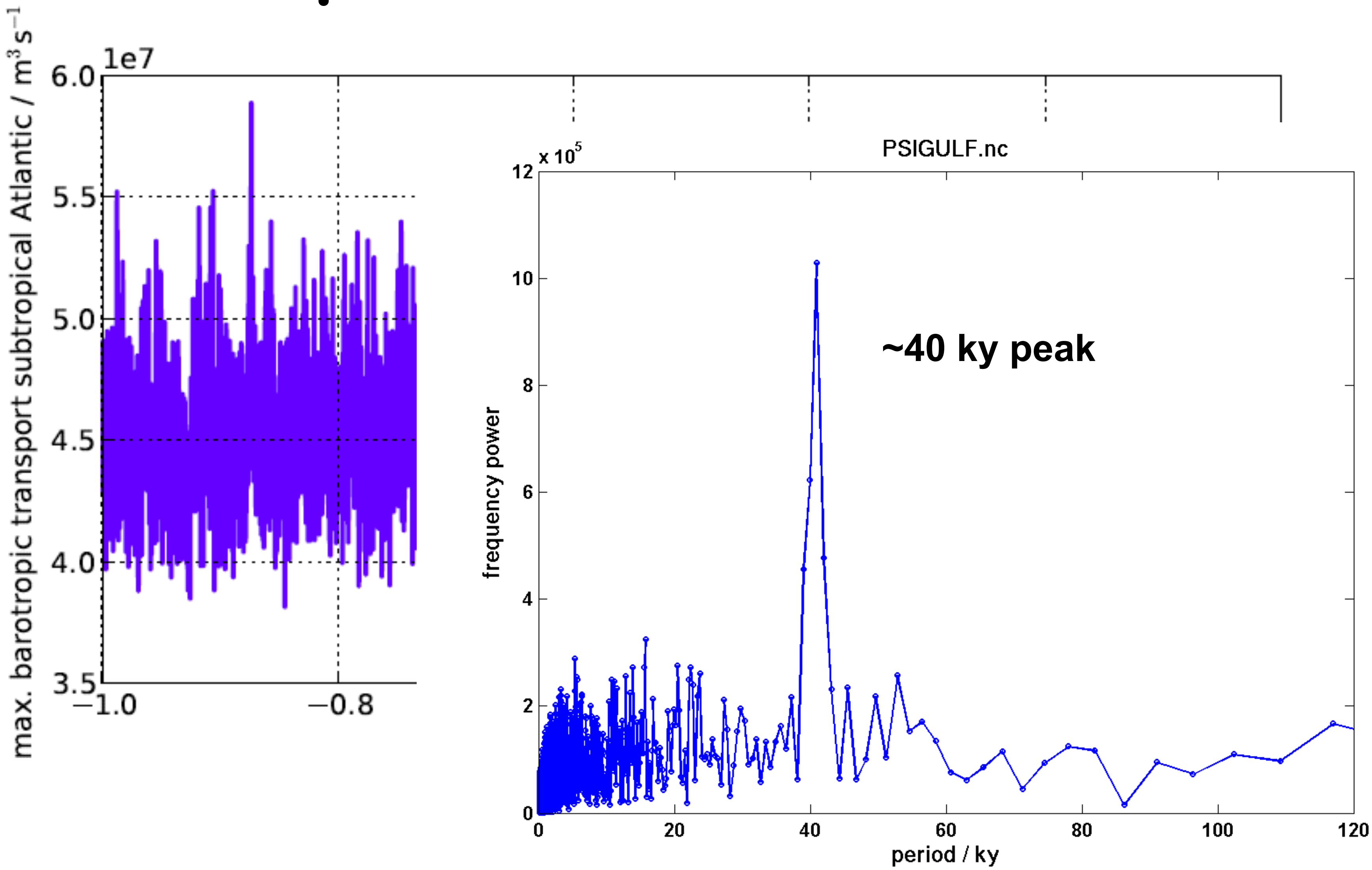


Sea ice

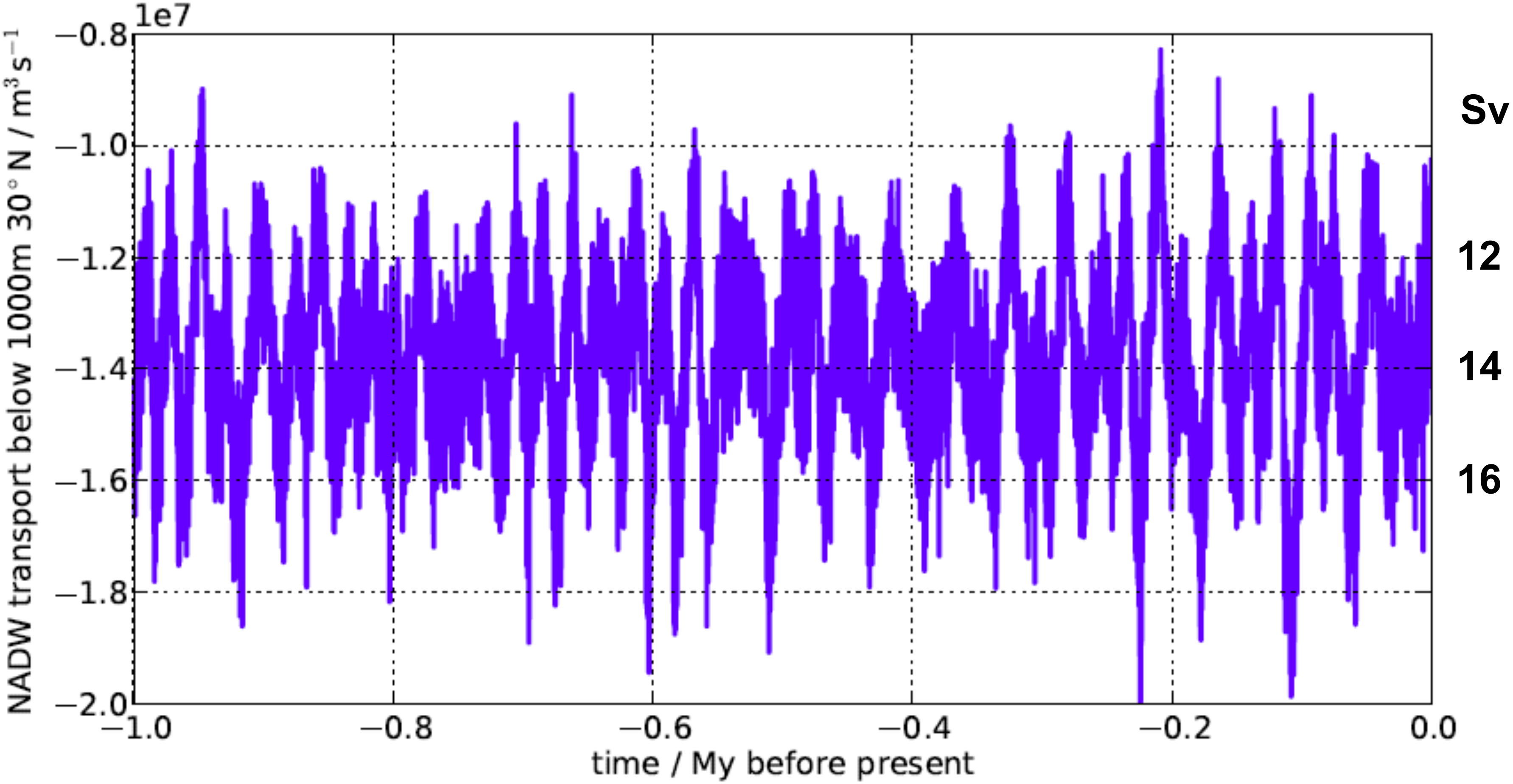
Orbital Variations: Mass transport of the Gulf Stream



Orbital Variations: Mass transport of the Gulf Stream

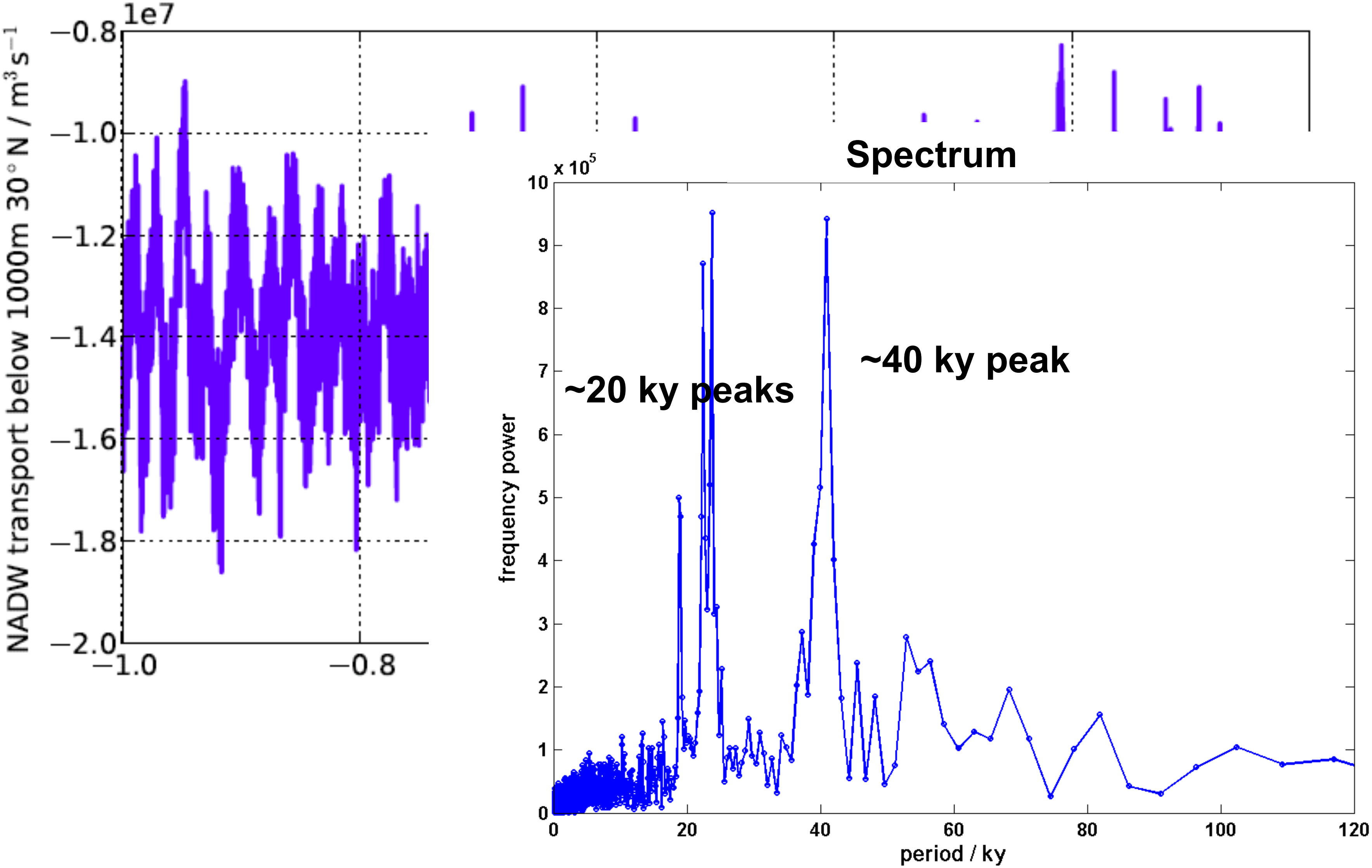


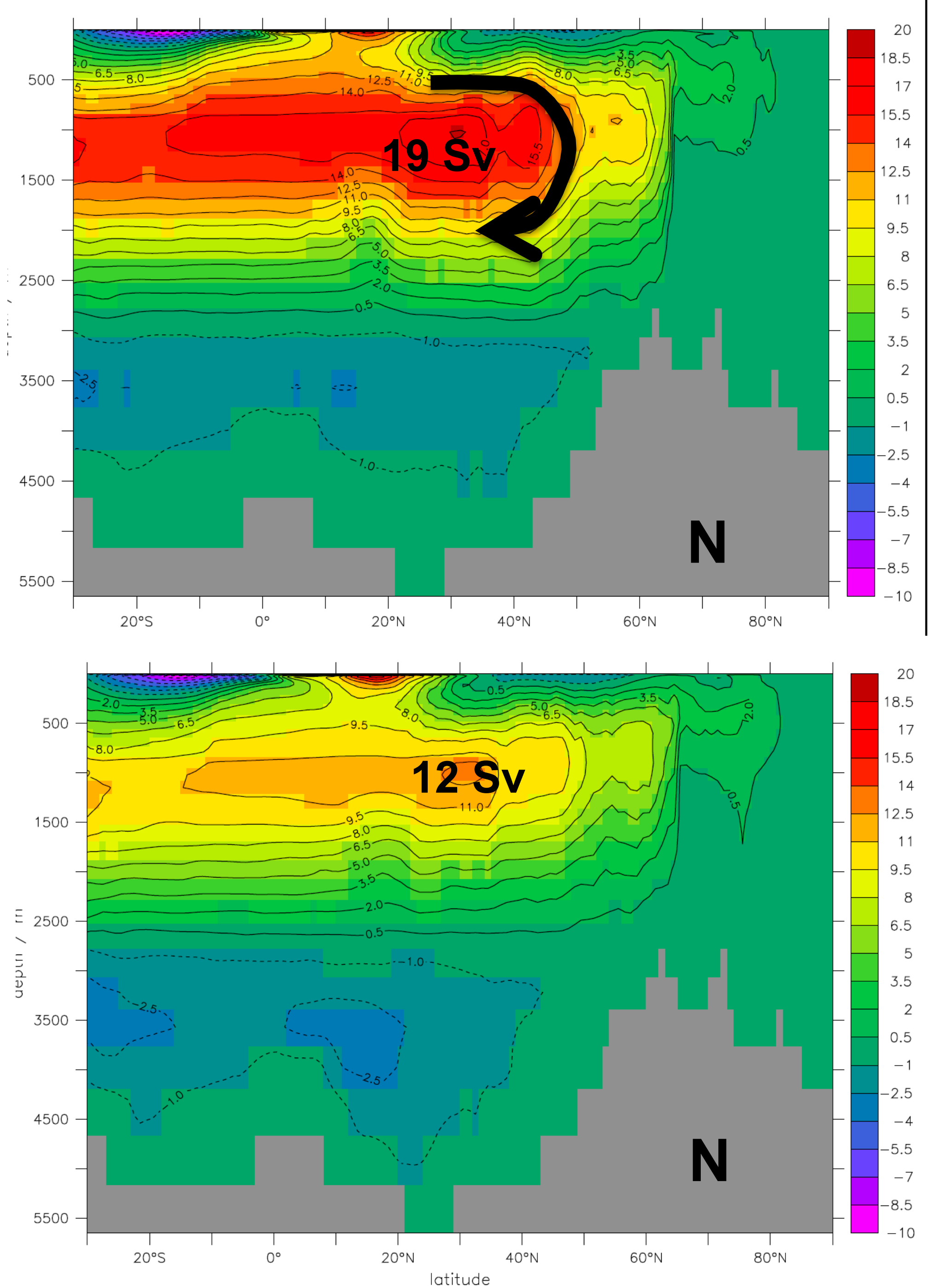
NADW



1e7
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
time / My before present
NADW transport below 1000m 30° N / m³s⁻¹
Sv
12
14
16

NADW


1e7
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
−1.0
−0.8
NADW transport below 1000m 30° N / m³ s⁻¹
Spectrum
x 10⁵
frequency power
period / ky
0
20
40
60
80
100
120
1
2
3
4
5
6
7
8
9
10
~20 ky peaks
~40 ky peak



Strong/deep

&

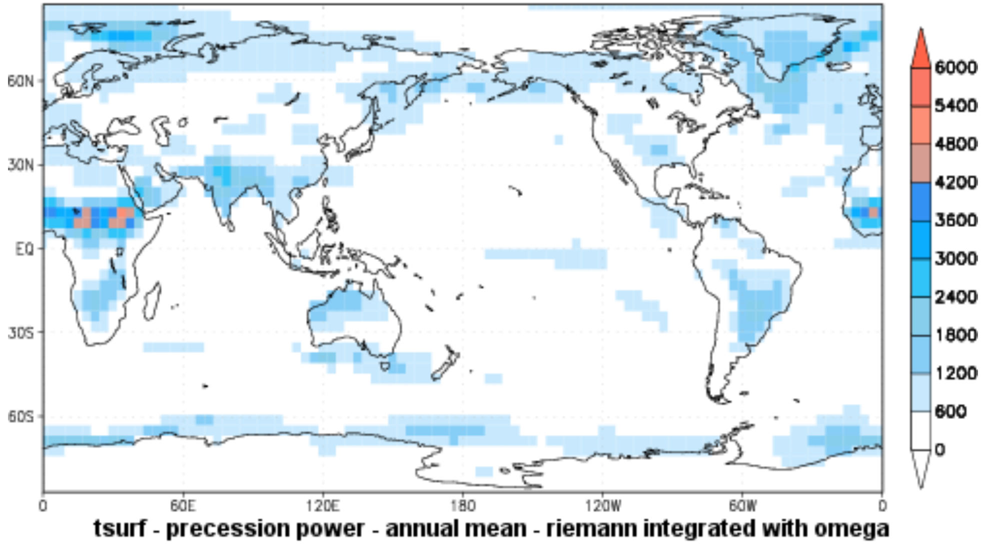
Weak/shallow

NADW

Conclusions

- **Precessional response is related to nonlinearities/seasonal biases in the climate system (atmosphere & ocean)**

What can we learn from the recent climate (seasonality, non-linearities) and the climate on orbital time scales?



`Ocean: significant energy in the 20 kyr precession band, but the atmosphere does not.‘

Conclusions

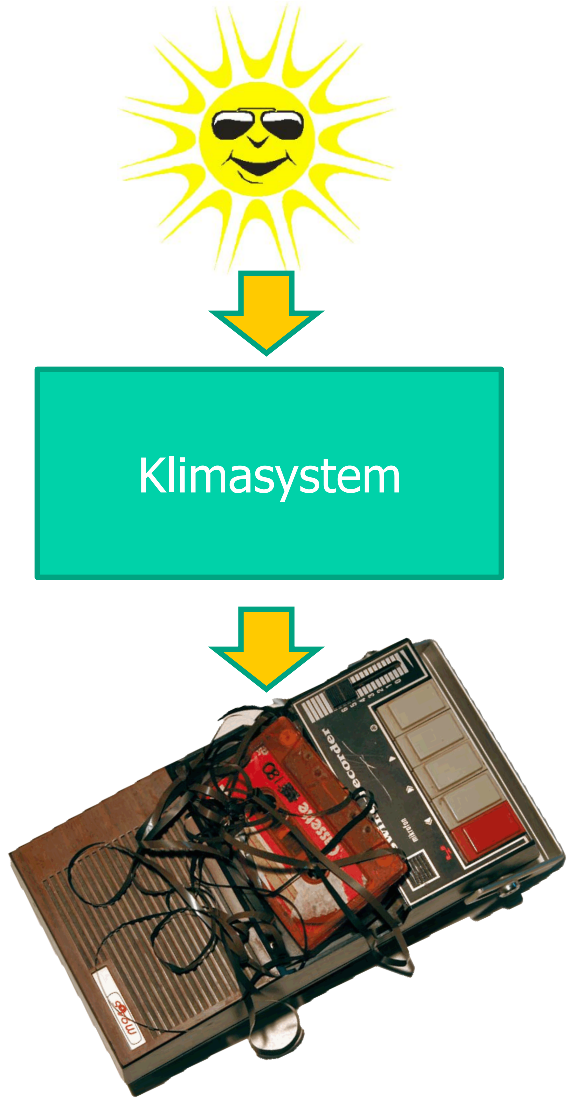
- **Precessional/eccentricity response is related to <u>nonlinearities/seasonal biases</u> in the climate system (atmosphere & ocean & ice)**

- **Temperature variability is dominated by precession, at high latitudes by obliquity.**

- **Ocean circulation**

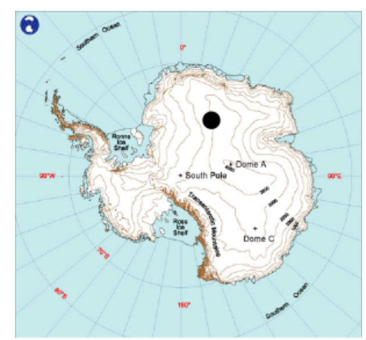
Wind-driven: obliquity (more a linear response),
Deepwater form./AMOC: precessional & obliquity peaks nonlinearities & seasonal biases linked to sea ice

Recorder Problem: Antarctic



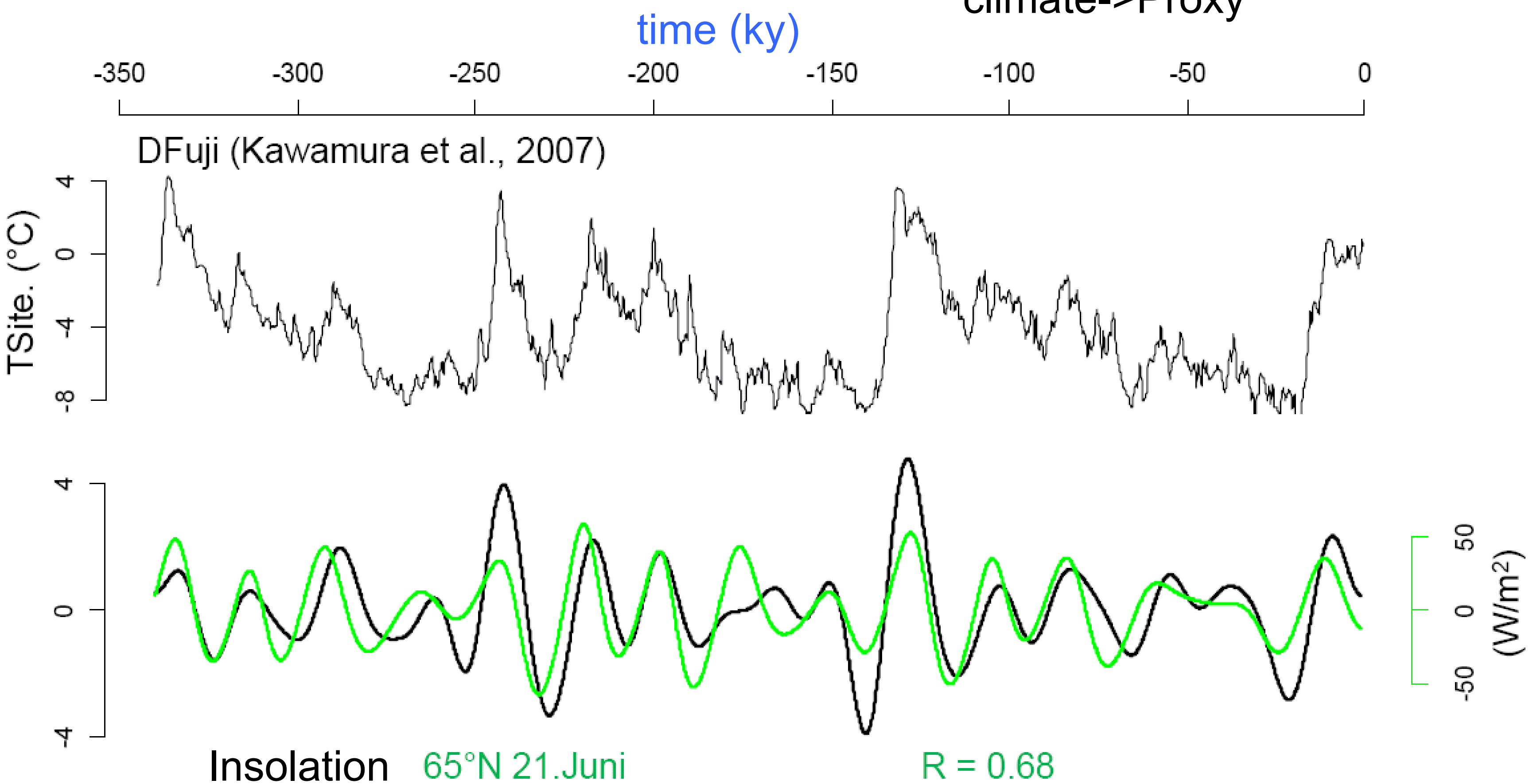
Antarctic ice cores

z.B.



Laepple, Werner, Lohmann, Nature 2011a

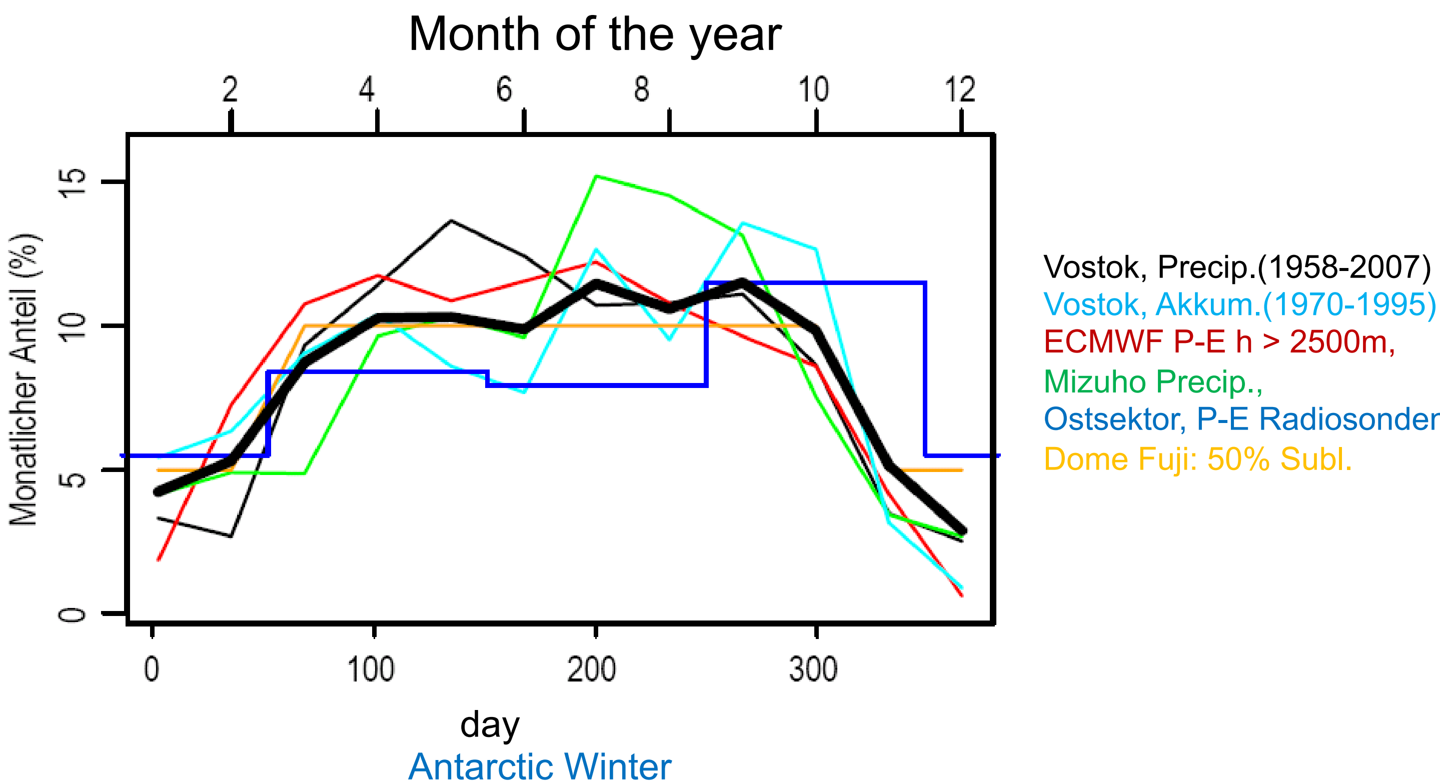
climate->Proxy

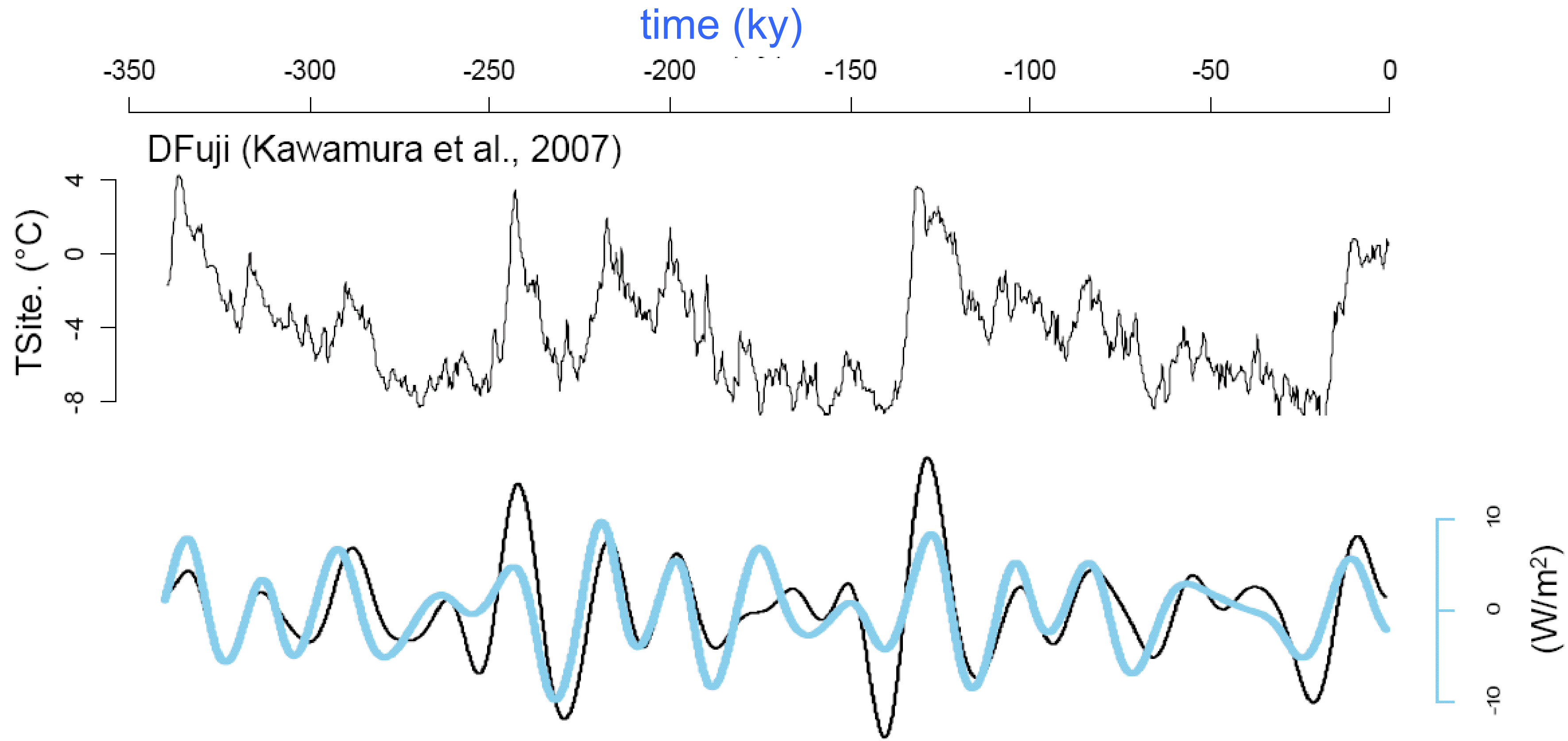


Ice core peoples' conclusion: Imbrie is right.
South triggered by the North, but how??

Isotope signal weighted with accumulation

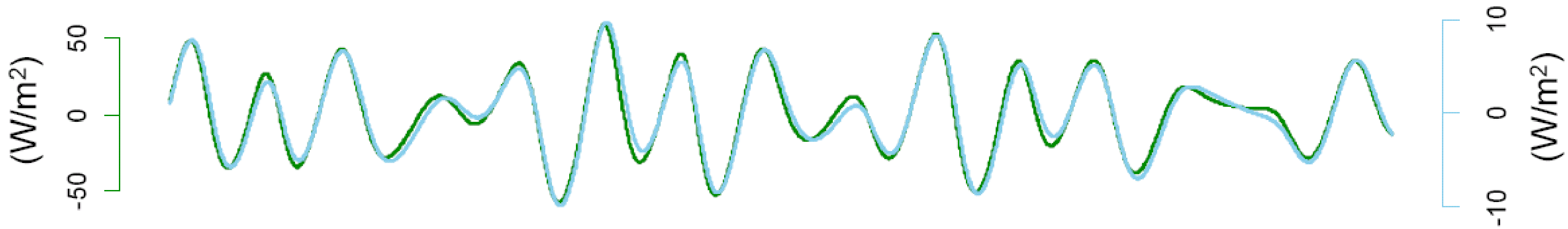
$$T_{isotopic}(t) = \frac{\int_{Sample} T(t) * Accum(t)dt}{\int_{Sample} Accum(t)dt}$$





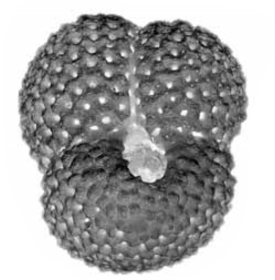
Insolation 77° S accumulation weighted R=0.71

Comparison: Insolation 65°N June; 77° S accumulation weighted R=0.71



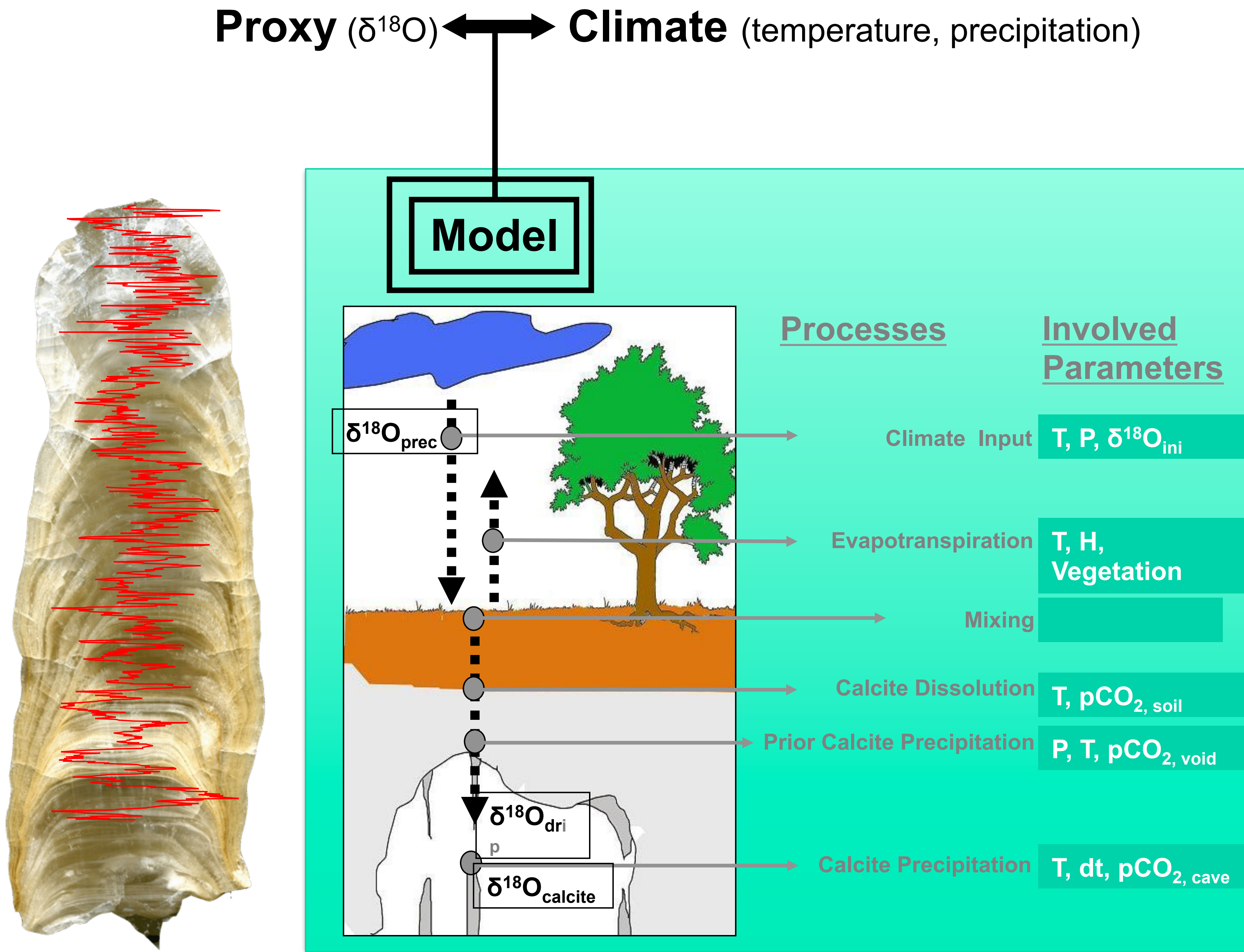
Conclusions (II)

- Modellers: do not believe in data, recorder system!



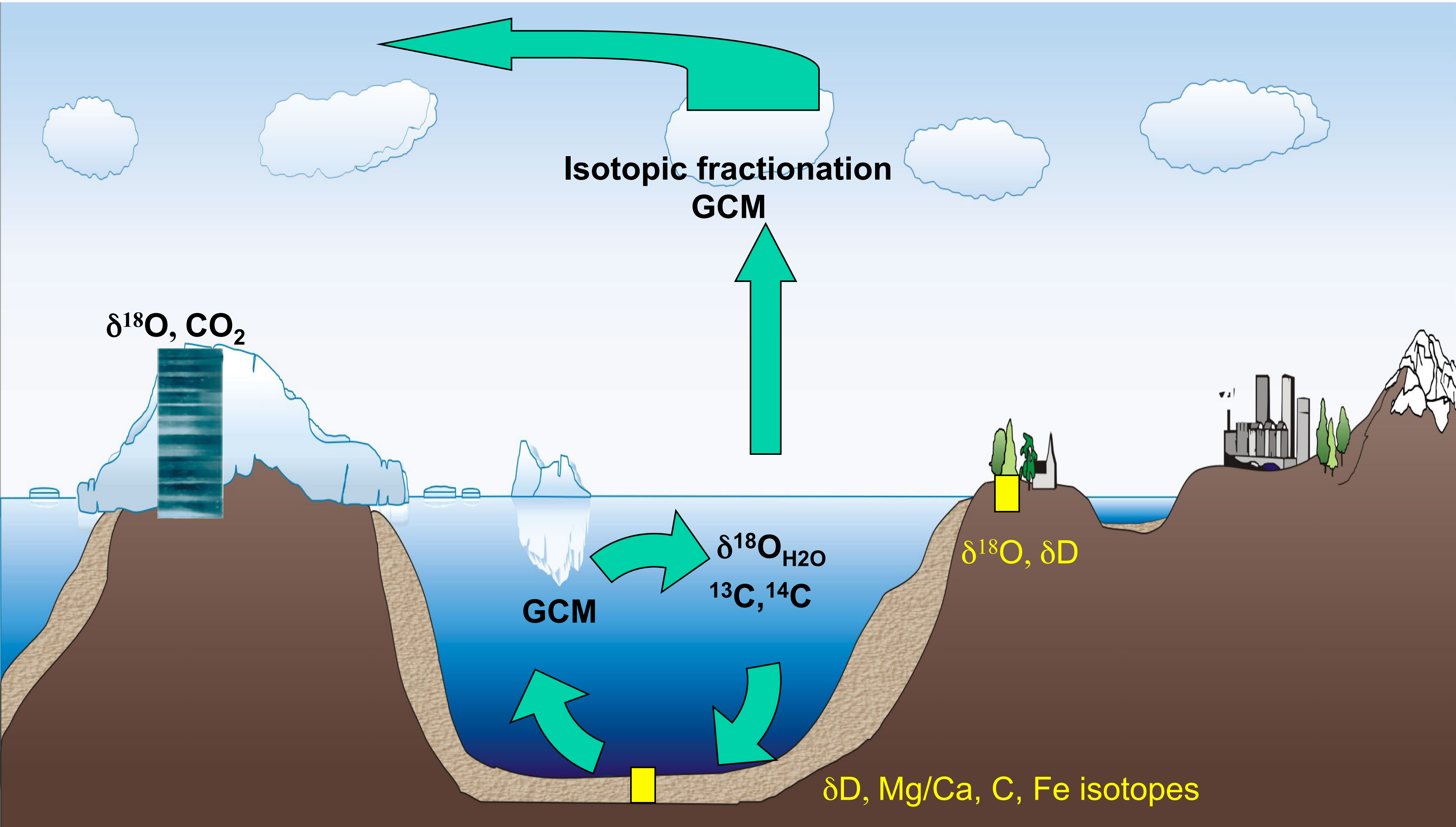
- Data people: check the assumptions in the models, mechanisms!

- Common Model-Data-Interpretation

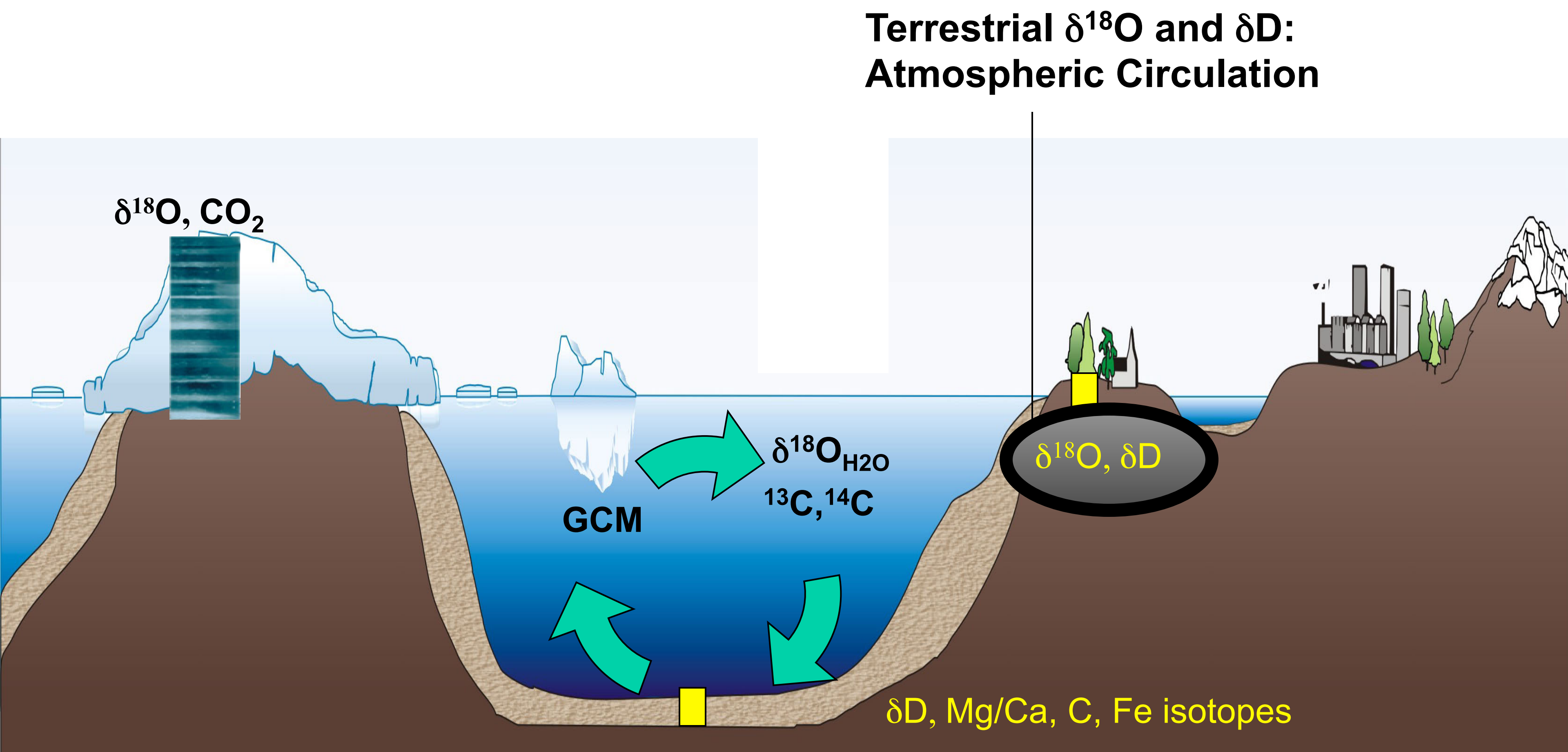


Proxy ($\delta^{18}O$)
Climate (temperature, precipitation)
Model
Processes
Involved Parameters
$\delta^{18}O_{prec}$
Climate Input
T, P, $\delta^{18}O_{ini}$
Evapotranspiration
T, H, Vegetation
Mixing
Calcite Dissolution
T, $pCO_{2, soil}$
Prior Calcite Precipitation
P, T, $pCO_{2, void}$
$\delta^{18}O_{drip}$
$\delta^{18}O_{calcite}$
Calcite Precipitation
T, dt, $pCO_{2, cave}$

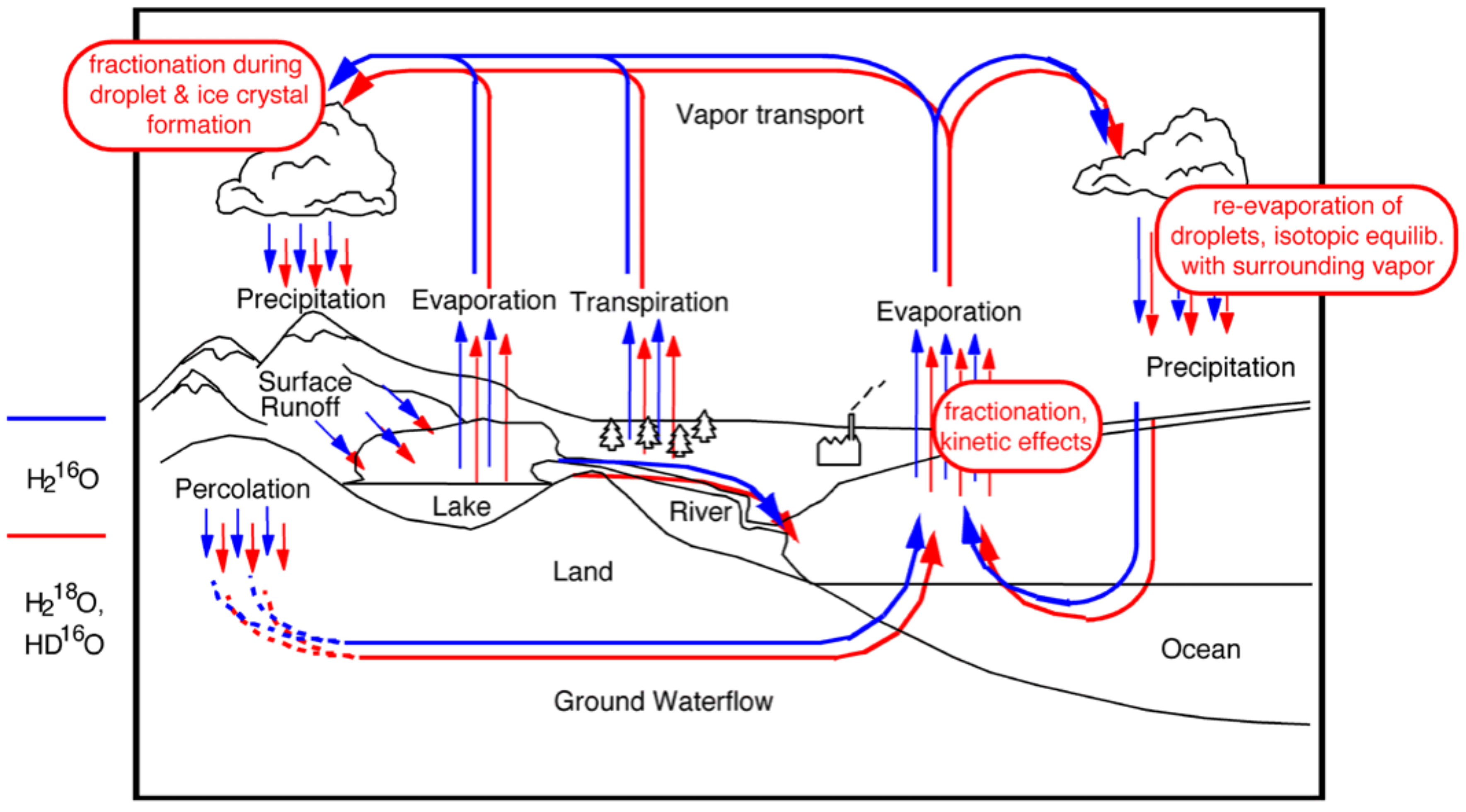
Climate Archives & Erth System Models



Climate Archives & Models

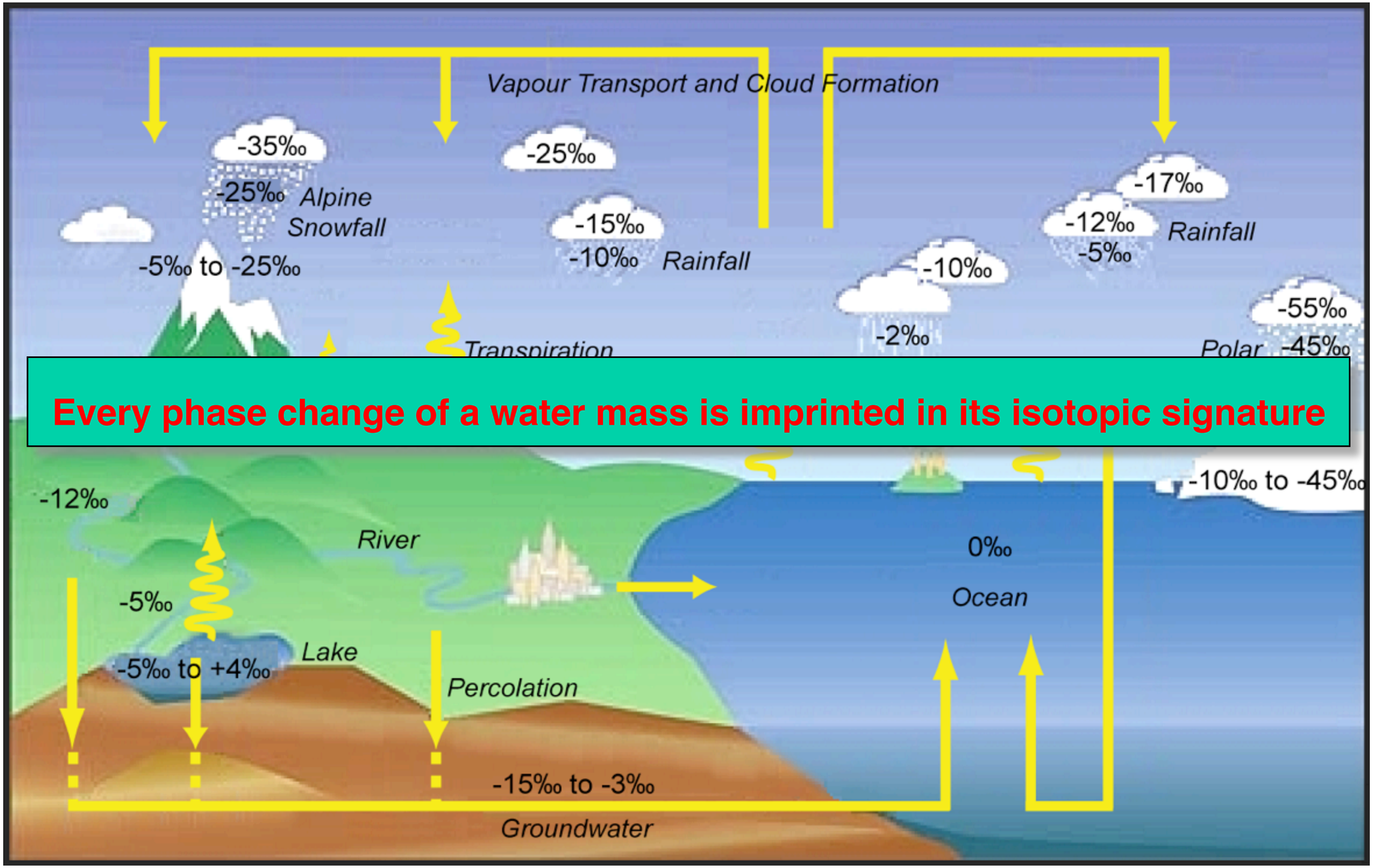


Isotopes: Realisation in General Circulation Models (GCMs)



Werner (2000): ECHAM4

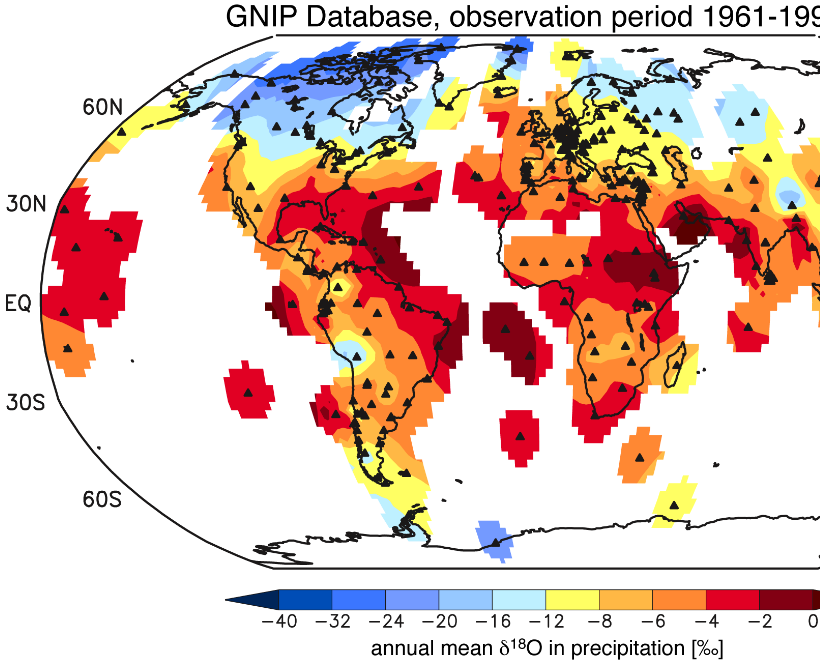
$\delta^{18}O$ Signal in the Hydrological Cycle



Scheme of typical isotope depletion in various parts of the hydrological cycle

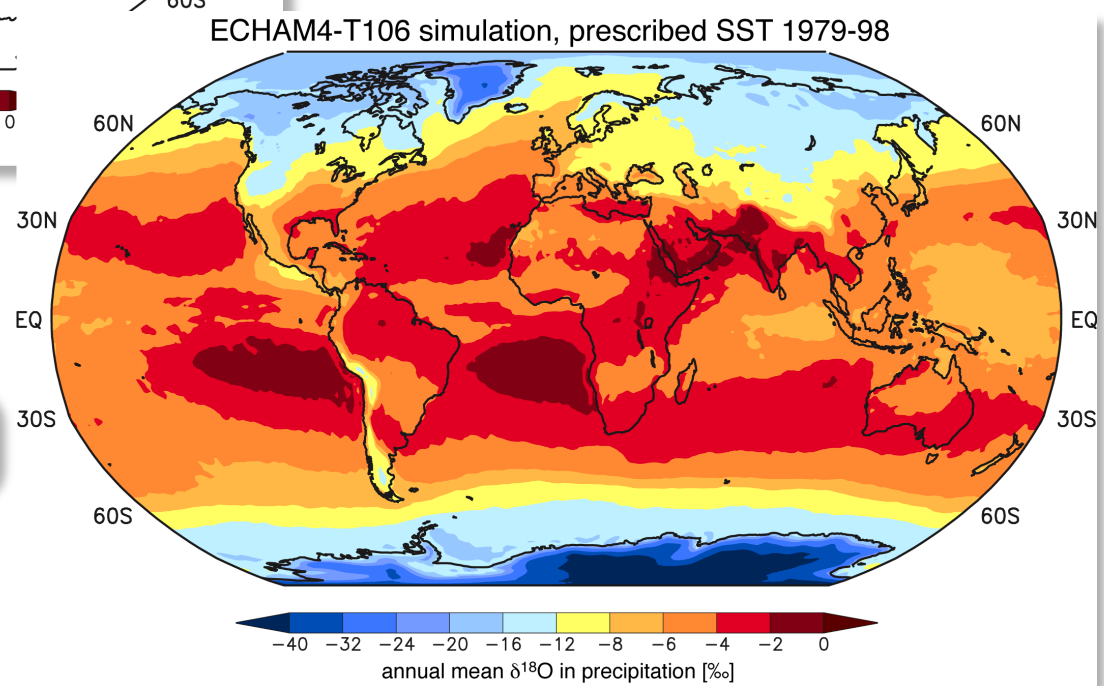
[plot adapted from the GNIP brochure, IAEA, 1996]

$\delta^{18}O$ Signal in Precipitation
Observations vs. Simulation



GNIP Observations

[data source: GNIP Database, IAEA/WMO, 2001]

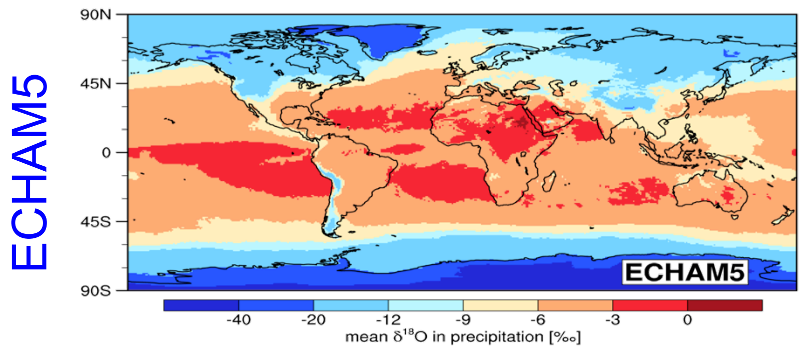


ECHAM-4 Simulation

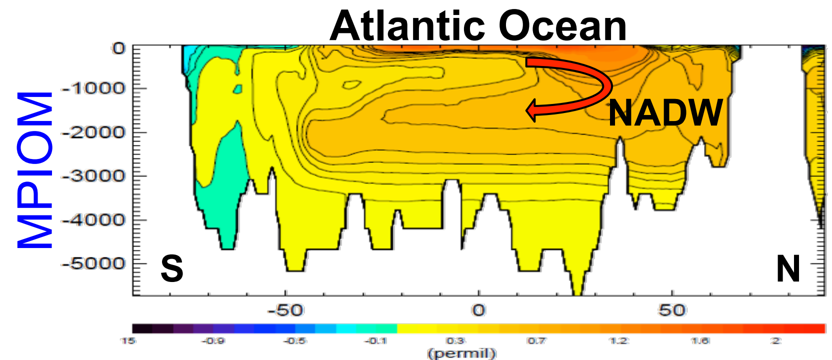
Werner et al., 2002

New development

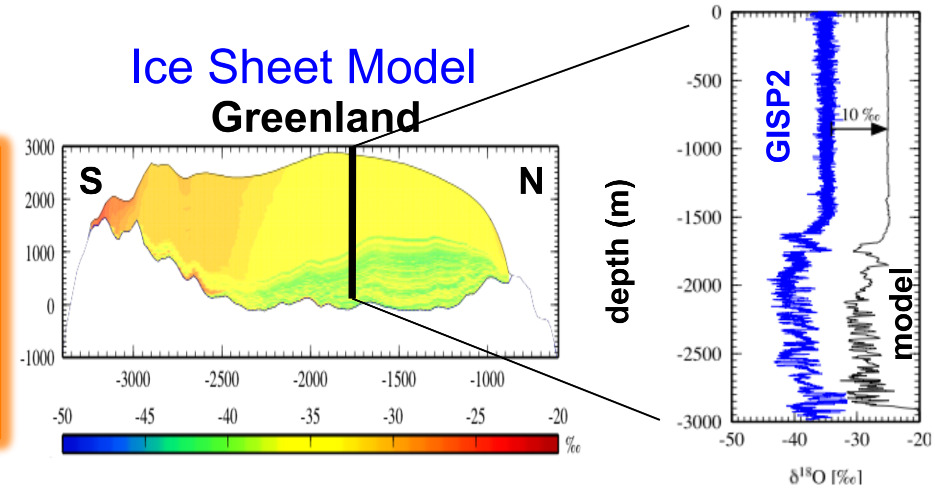
Simulation of $\delta^{18}O$ in Atmosphere, Ocean, and Ice Sheets



Werner et al., 2011



Xu, PhD Thesis



Explicit modelling of element cycles and proxies:

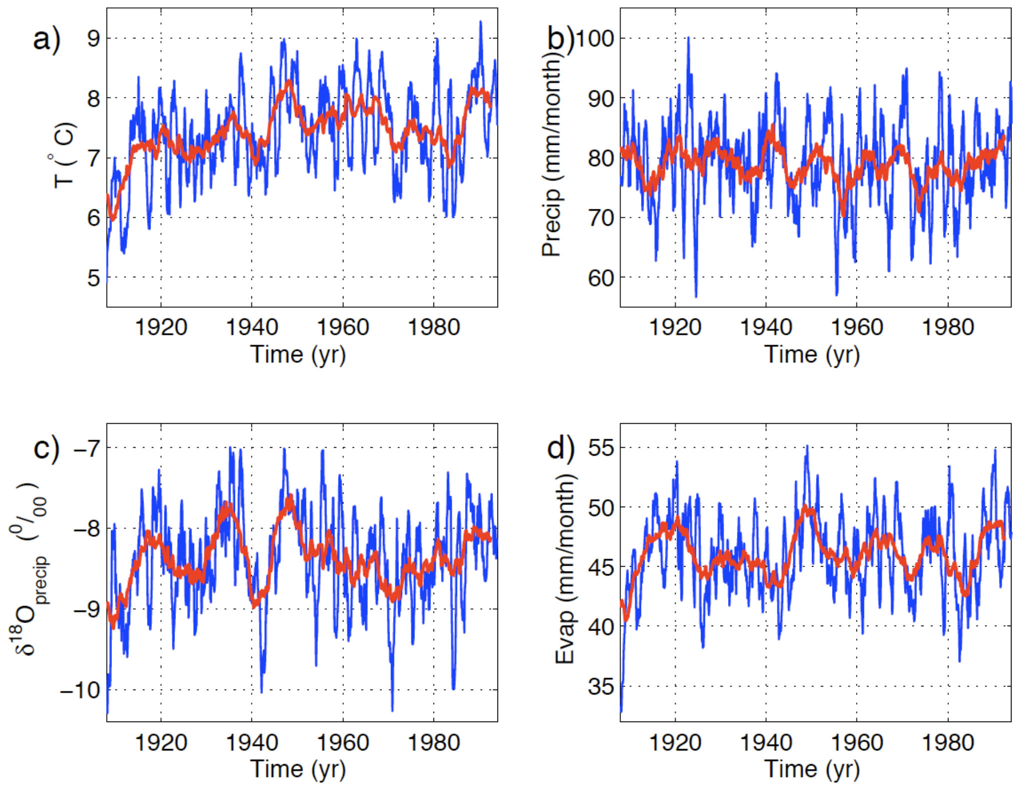
Improved interpretation of various paleoclimate records

Goelles et al., 2014

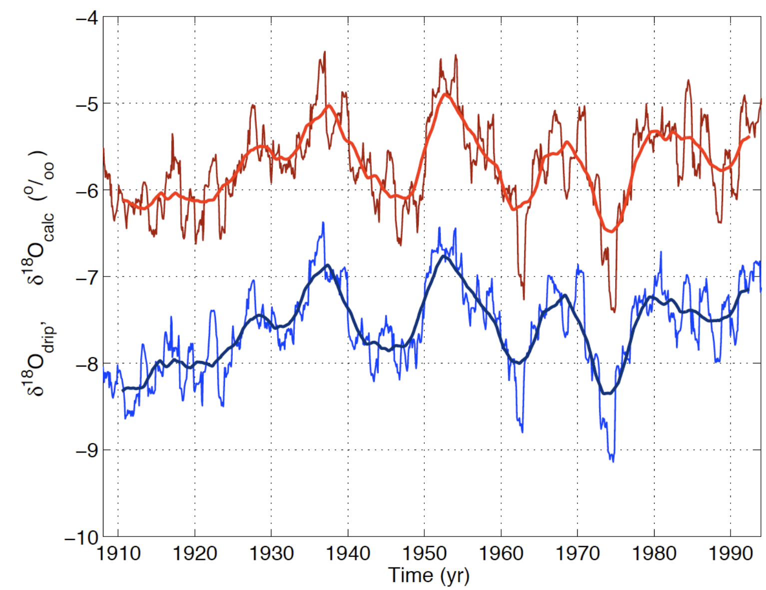
Noisy Proxies: Stalagmites

(Bunker cave, Western Germany)

Simulated Climate



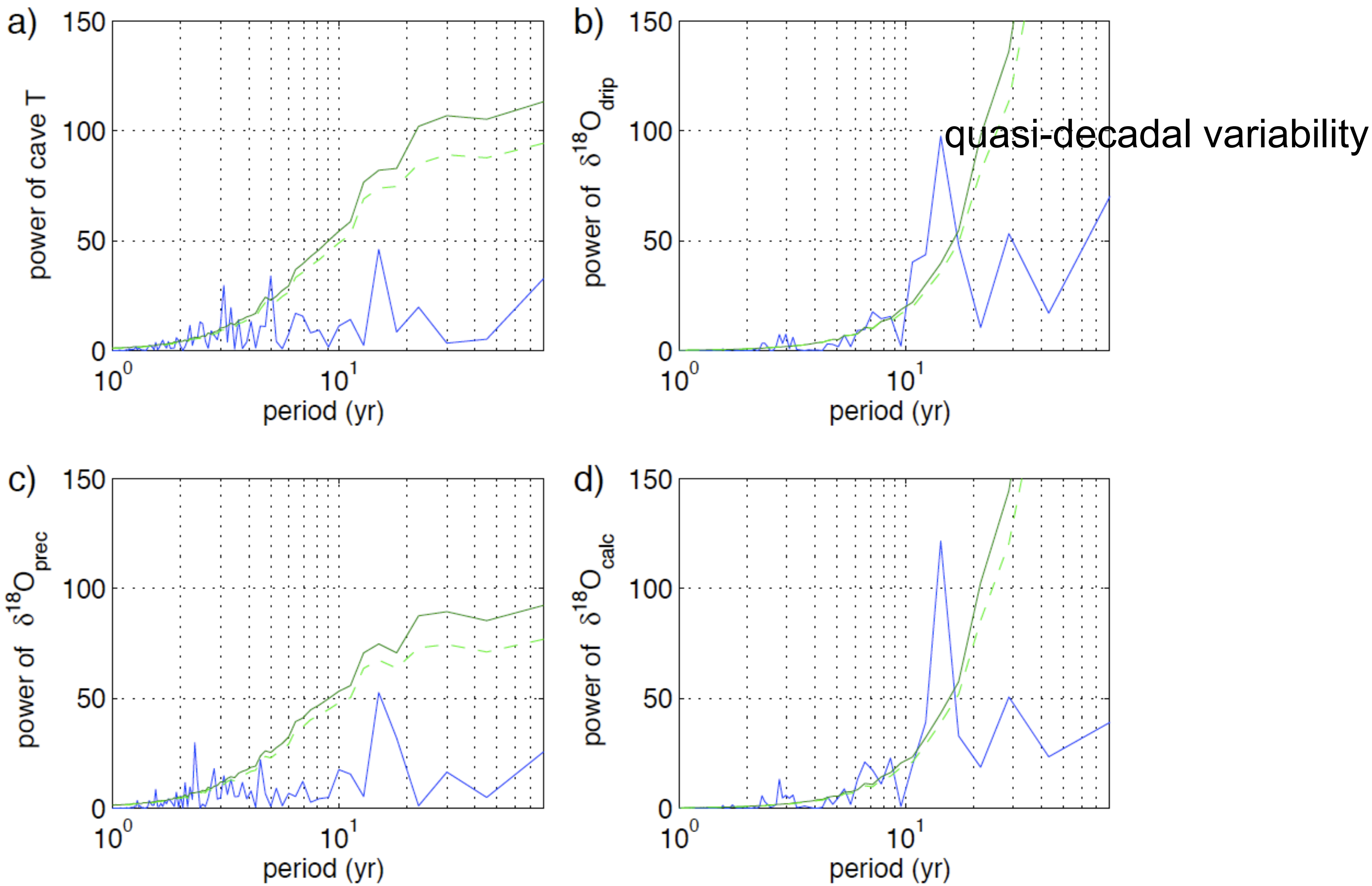
Simulated Recorder



Lohmann et al., 2013b, Climate of the Past

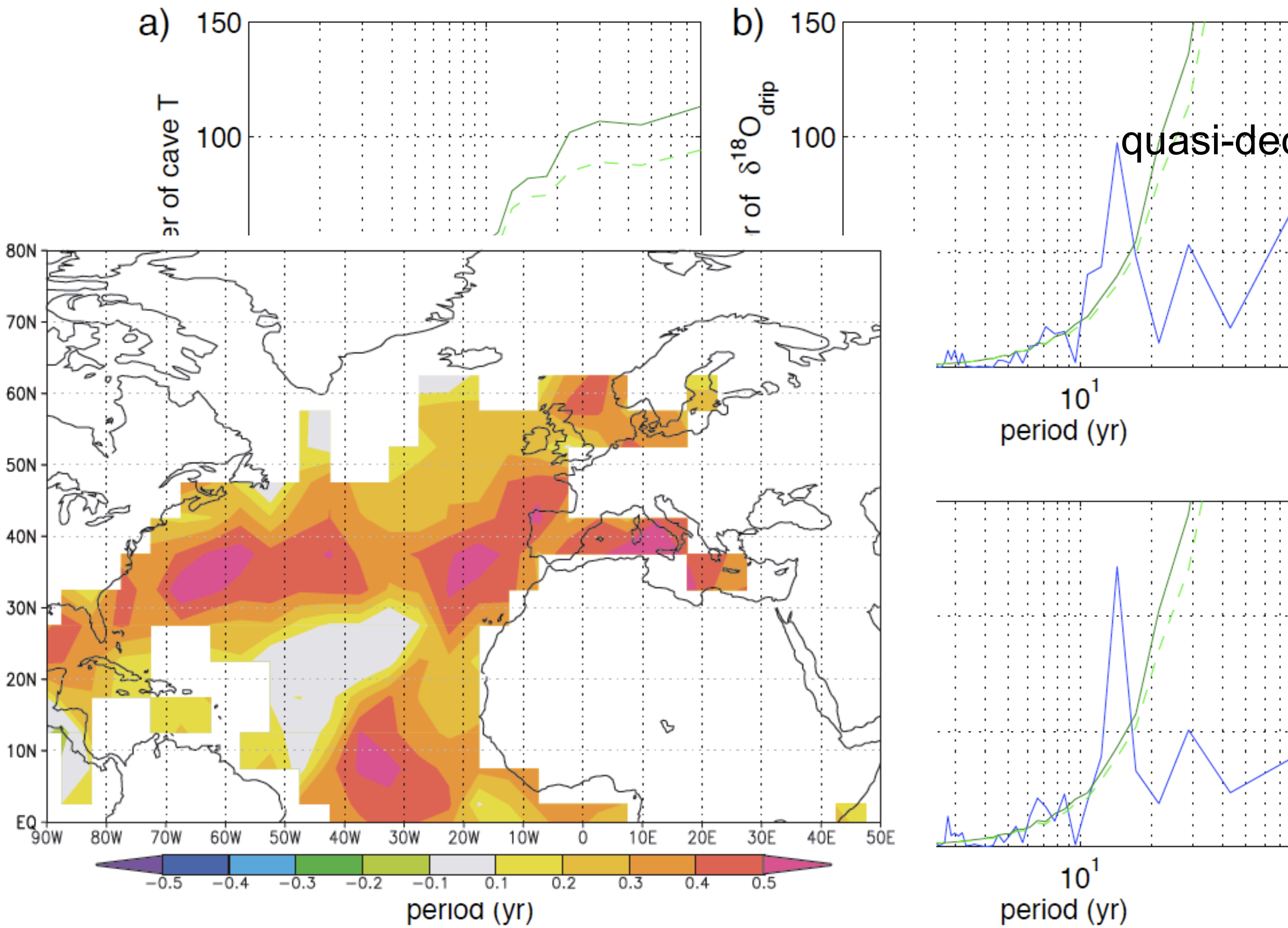
Spectra

Climate | **Recorder**

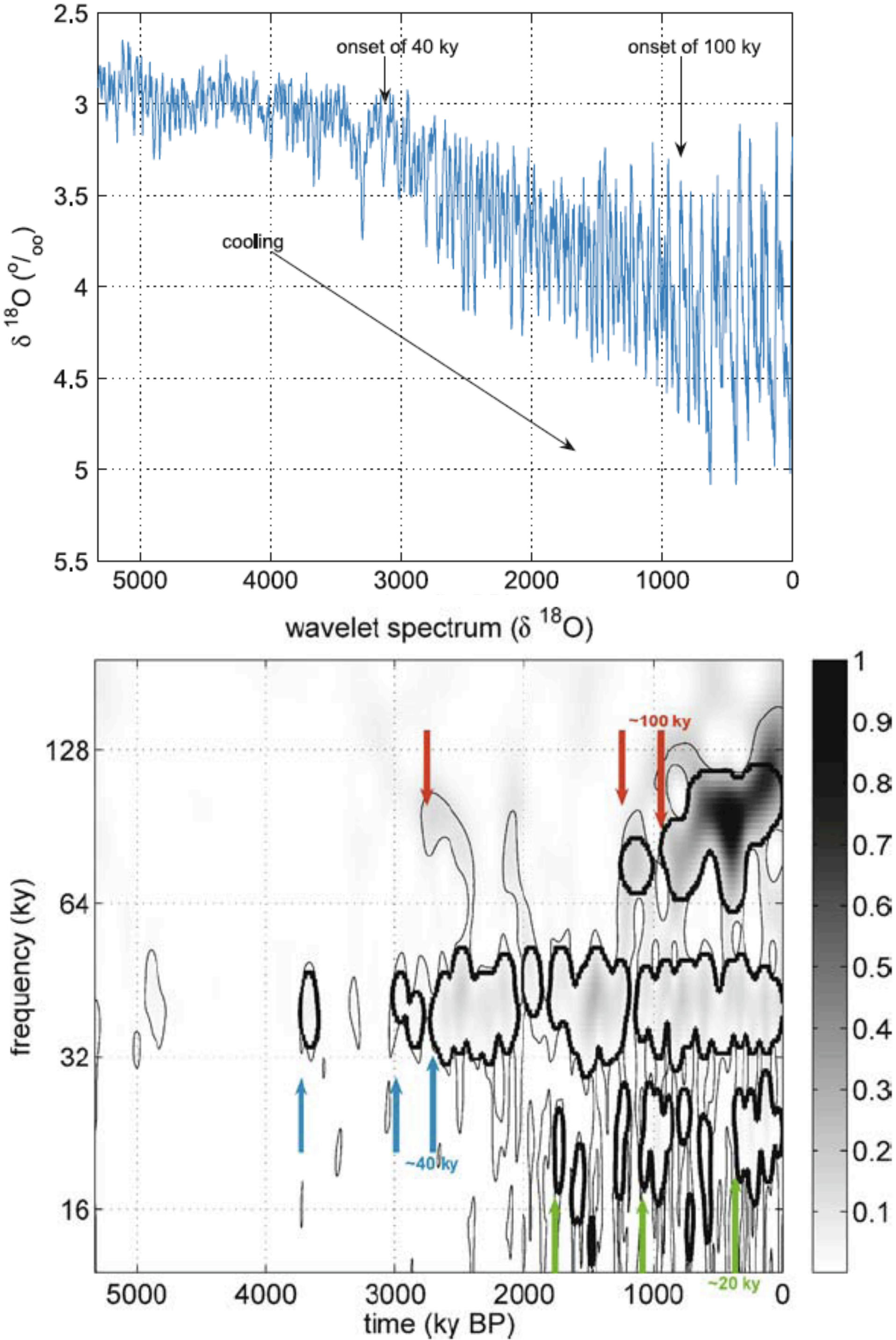


Spectra

Climate   Recorder

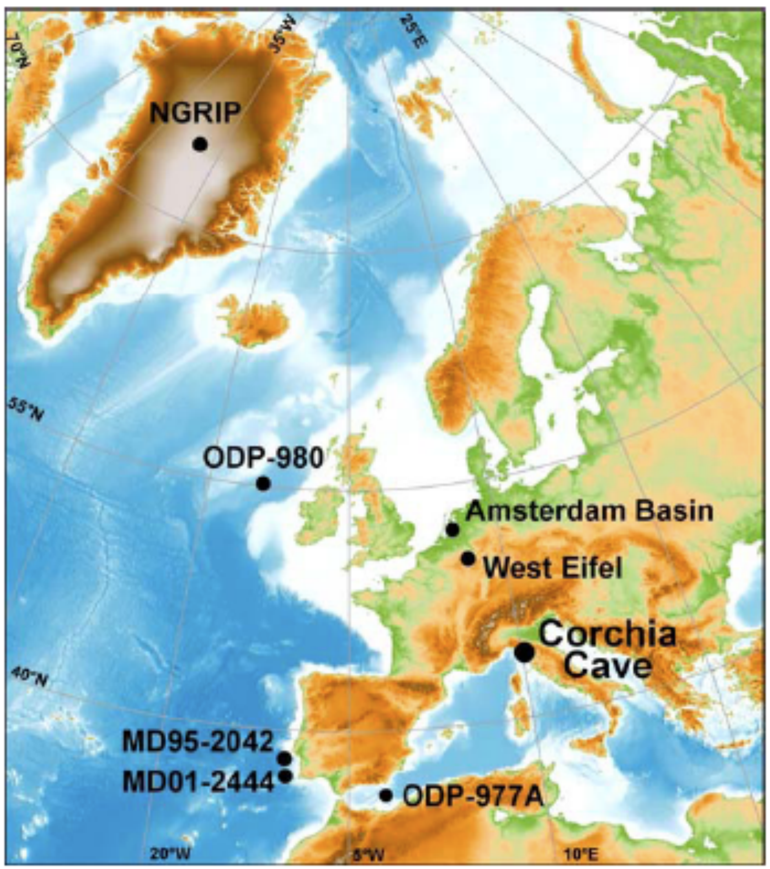


Ice ages

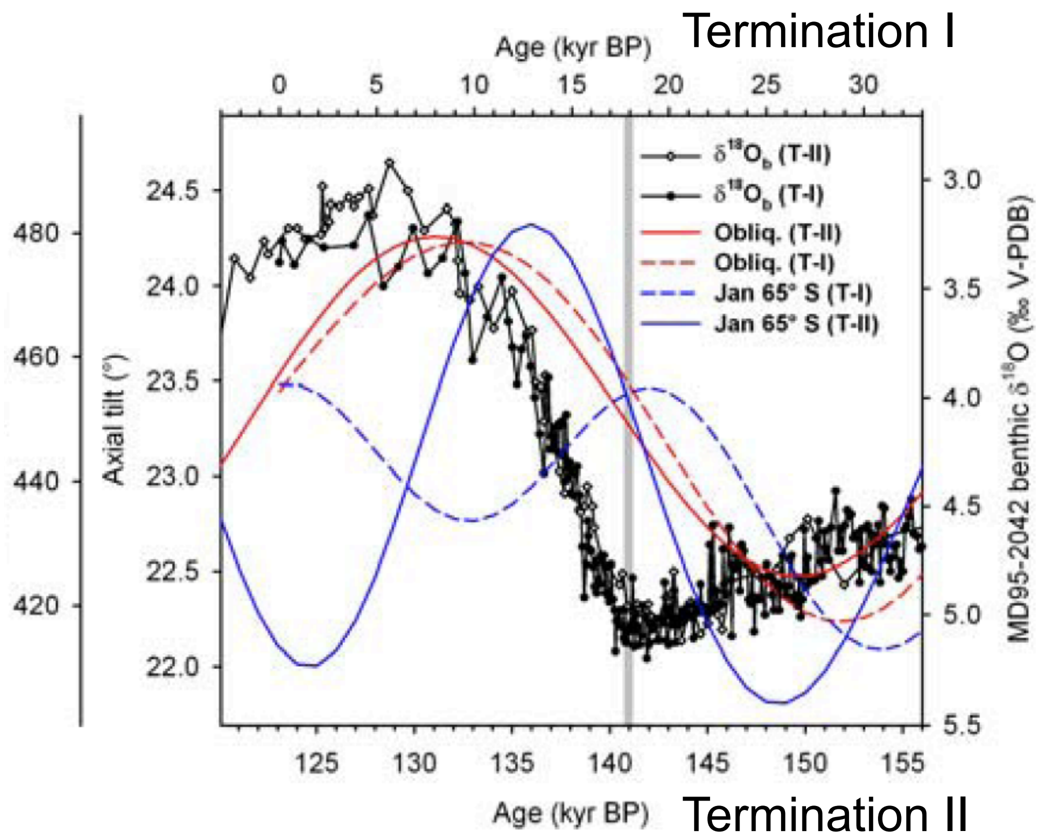


onset of 40 ky
onset of 100 ky
cooling
$\delta^{18}O$ (‰)
wavelet spectrum ($\delta^{18}O$)
~100 ky
~40 ky
~20 ky
frequency (ky)
time (ky BP)

A precise chronology of North Atlantic palaeoclimate:Terminations



Drysdale et al. 2009, Science



Terminations: Obliquity, not 65°N or 65°S
123 kyr age difference: 3 obliquity cycles

Conclusions (III)

- Main forcing 40,000 years
- Unsolved 100,000 year cycle
- Conceptual and full models needed

Exploring the Milankovich Cycles

http://profhorn.meteor.wisc.edu/wxwise/climate/milankovich.html

Calculating Insolation

http://www.imcce.fr/langues/fr/presentation/equipes/ASD/insola/earth/online/