POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

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nagra aus verantwortung

Evolution of the climate in the next Million years:

A Simple Model for Glacial Cycles
and
Impact of fossil fuel CO_2

Leibniz Association

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Objectives

- Generate a **Process-based Simple Model** to describe the Temporal Natural Evolution of the Climate System as forced by Changes in Incoming Insolation only

Forcing:	Summer Maximum Insolation at 65°N	(**f**)
Climate System Variables to Model:	Northern Hemipshere (NH) Continental Ice-Volume	(**v**)
	Atmospheric CO_2 concentration	(**CO_2**)
	Global Mean Temperature Anomaly	(**dT**)

- Use the Model to **predict the Evolution of the Climate System in the Next 1 Million years**, including the effect of Anthropogenic CO_2 Emissions

Model Description

- Process-based Simple Model
- 3 Equations with 3 unknown variables: **v**, **CO2**, **dT**
    - **v** is non-dimensional (normalized to vary between [0,1])
    - **CO2** is measured in ppm
    - **dT** is measured in C
- For time-scales longer than 1000 years

Model Description

Equation (1): Temporal Evolution of NH Continental Ice-Volume (**v**)

$$\boxed{\frac{dv}{dt}=\frac{b_1 v+b_2 v^{3/2}+b_3(f-\bar{f})+b_4\log(CO2)}{1+b_5 v_{memory}}+b_6}$$

$$v_{memory}(t)=\frac{\delta}{T}\int_{t-T}^{t} v(\tau)\,d\tau$$

$T=30\,kyr$

$\delta=1\ if\ \frac{dv}{dt}<0$

$\delta=0\ otherwise$

Ice-growth / Ice-melting depends on:

- Magnitude of the current Ice-Volume (through linear and a 3/2 power terms)
- Orbital Forcing
- log(CO2)
- Memory Term: Registering the magnitude of the Ice-Volume in the previous 30 kyr

Note: - v must be non negative at all times
- Before -400 kyr v must be larger than 0.05 (in Normalized units)

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Model Description

Equation (2): Temporal Evolution of Atmospheric CO2 Concentration (CO2)

$$\boxed{CO2 = c_1 dT + c_2 v + c_3 min\left(\frac{dv}{dt}, 0\right) + c_4}$$

CO2 evolution depends on:

- dT term: Solubility, Ocean Circulation and Deep Ocean Ventilation effects
- V term: Salinity, vegetation Covered Area and Iron Fertilization effects
- Atlantic Meridional Overturning Circulation changes (term that is only active when melting occurs i.e. dv/dt < 0)

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Model Description

Equation (3): Temporal Evolution of Global Mean Temperature Anomaly (dT)

$$\boxed{dT = d_1 v + d_2 \log\left(\frac{CO2}{278}\right)}$$

dT evolution depends on:

- Ice-volume
- log(CO2)

Model Description

Model:

(1) $$\frac{dv}{dt} = \frac{b_1 v + b_2 v^{3/2} + b_3 (f - \bar{f}) + b_4 \log(CO2)}{1 + b_5 v_{memory}} + b_6$$

$$v_{memory}(t) = \frac{\delta}{T} \int_{t-T}^{t} v(\tau)\, d\tau$$

$T = 30\, kyr$

$\delta = 1 \; if \; \frac{dv}{dt} < 0$

$\delta = 0 \; otherwise$

(2) $$CO2 = c_1\, dT + c_2 v + c_3 \min\left(\frac{dv}{dt}, 0\right) + c_4$$

(3) $$dT = d_1 v + d_2 \log\left(\frac{CO2}{278}\right)$$

Number of Model Parameters: 12

3 Conditions on the Parameters

Pre-industrial conditions:	if v=0 & CO2 = 278 ppm → dT = 0 C
Last Glacial Maximum conditions:	if v=1 & CO2 = 194 ppm → dT = -5 C
Climate Sensitivity:	if CO2 = 2 x Pre-industrial CO2 → dT = [2,4] C

→ 9 Parameters left to adjust

Model Description

Model:

(1) $$\boxed{\frac{dv}{dt}=\frac{b_1 v+b_2 v^{3/2}+b_3(f-\bar{f})+b_4\log(CO2)}{1+b_5 v_{memory}}+b_6}$$

$$v_{memory}(t)=\frac{\delta}{T}\int_{t-T}^{t} v(\tau)\,d\tau$$

$T=30\,kyr$

$\delta=1\ if\ \frac{dv}{dt}<0$

$\delta=0\ otherwise$

(2) $$\boxed{CO2=c_1 dT+c_2 v+c_3 min\left(\frac{dv}{dt},0\right)+c_4}$$

(3) $$\boxed{dT=d_1 v+d_2\log\left(\frac{CO2}{278}\right)}$$

Fit of the Model:

Use of **Paleo Data from the last 800 kyr as Learning Set**

Approach: **Non-Linear Optimisation Problem** with Constraints

1. Optimisation target: Maximise correlation between **v** and **paleo data v**
2. Constraint: v (Pre-industrial ... +20 kyr) < ε, being ε small (No Glacial Inception in the next 20kyr permitted)

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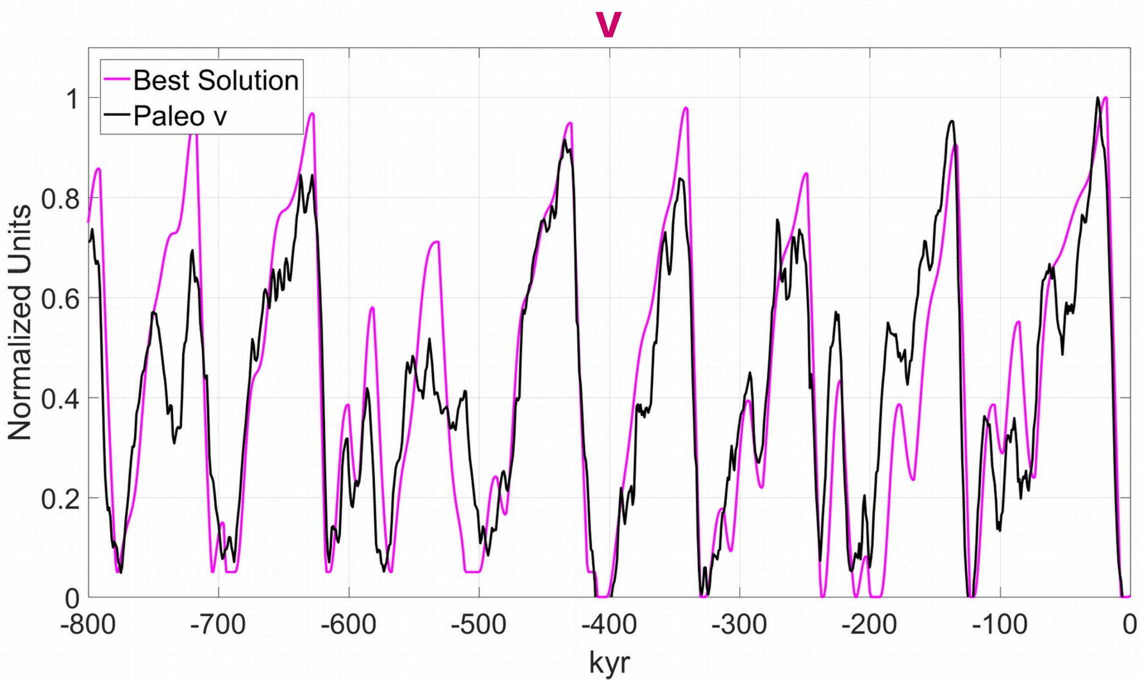
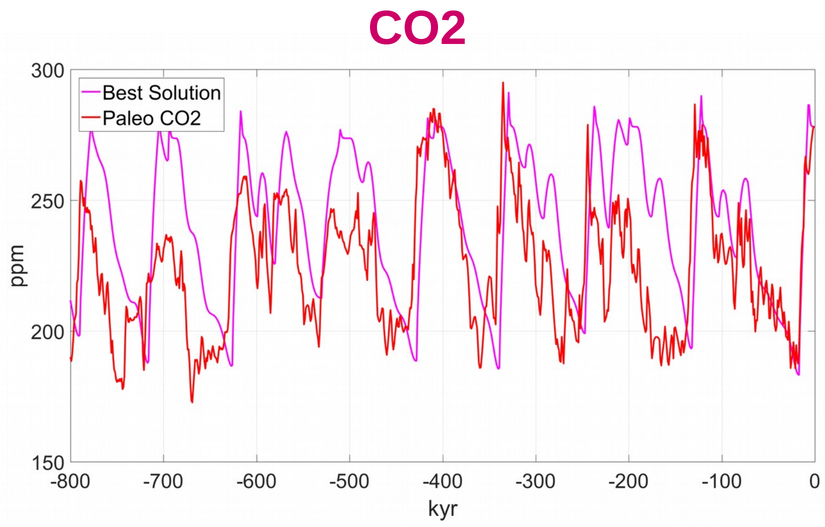
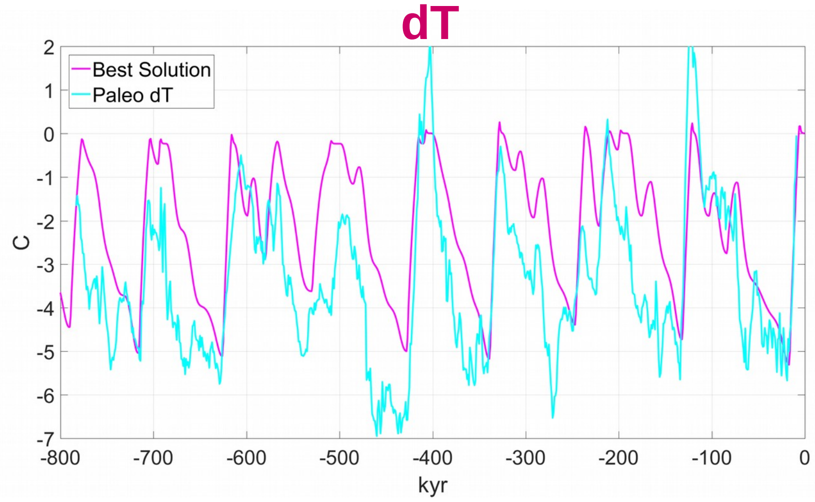
Model Performance: Comparison with Paleodata last 800 kyr

Best Solution







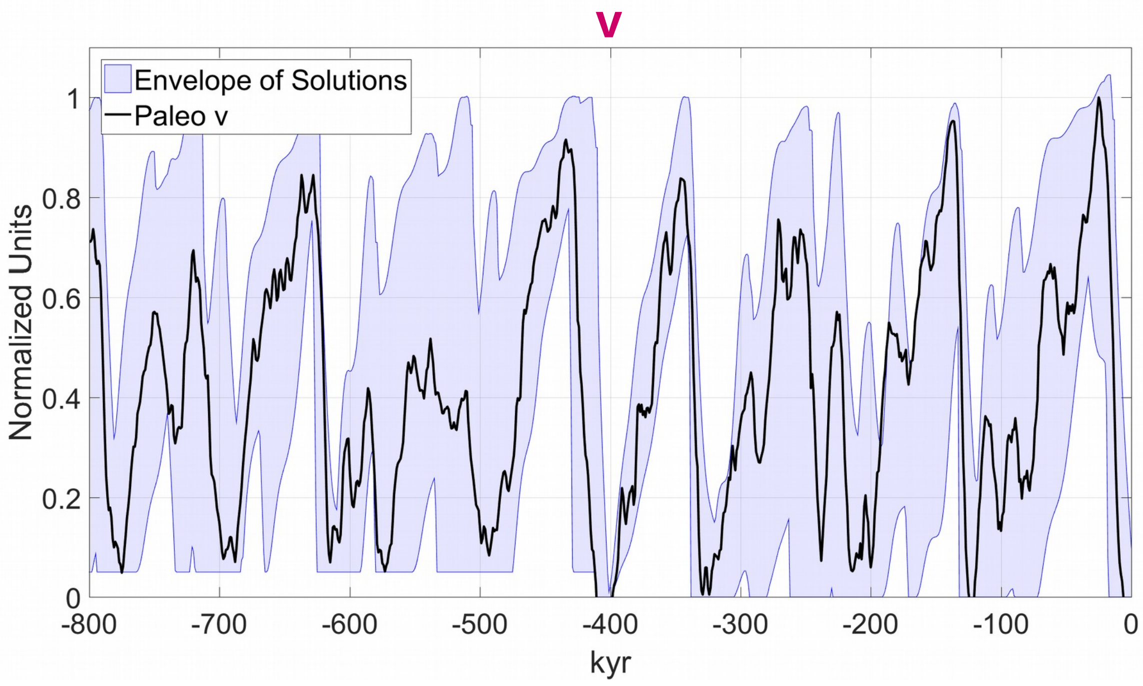
The model is able to reproduce the Natural Temporal Evolution of the Climate System

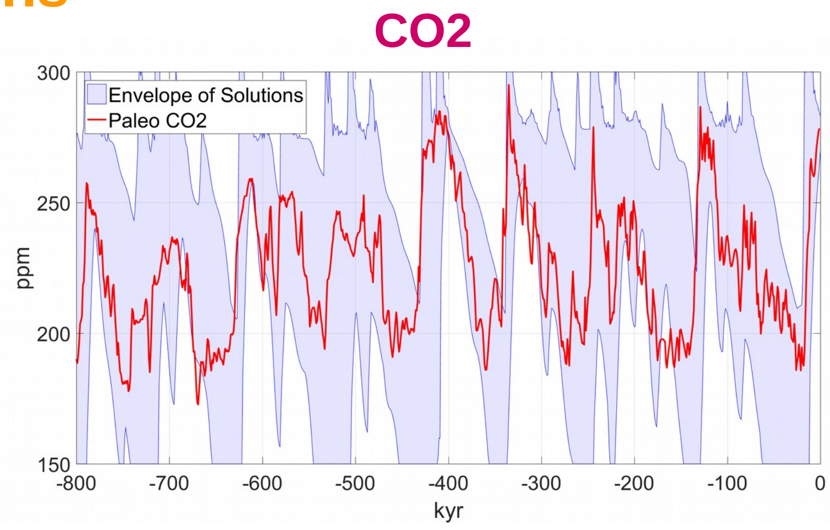
Correlation between v and Paleo v	= 0.87
Correlation between CO_2 and Paleo CO_2	= 0.60
Correlation between dT and Paleo dT	= 0.61

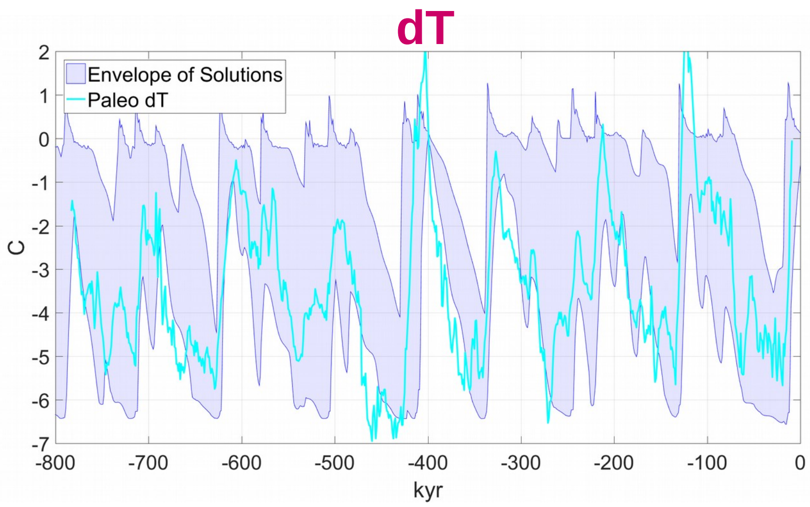
*for references on the Paleo Data Sources please see the information provided in the last slide

Model Performance: Comparison with Paleodata last 800 kyr

Ensemble of Accepted Solutions







Ensemble Accepted Solutions: Those with correlation between v and Paleo Data v >= 0.7 (**N = 353**)

Mean Correlation between v and Paleo v	= 0.76
Mean Correlation between CO2 and Paleo CO2	= 0.50
Mean Correlation between dT and Paleo dT	= 0.56

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Model Performance: Estimation of Prediction Skill

- The Model has high skill when Validated against the same data used for Learning (Apparent Skill)
- Estimation of Prediction Skill:

Separate Data into independent **Learning** and **Validation** Sets

- Learning: paleo data in period [-800,-400] kyr // Validation: paleo data in period [-400,0] kyr
- Learning: paleo data in period [-400,0] kyr // Validation: paleo data in period [-800,-400] kyr

Loss in Skill from Learning to Validation:

Mean Correlation between v and paleo v in Validation Period = **0.49**

Mean Correlation between CO_2 and paleo CO_2 in Validation Period = **0.37**

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Model Prediction: Next 1 Milion Years

We add to the Model **Anthropogenic CO2 Emissions**:

(1) $$\frac{dv}{dt}=\frac{b_1 v+b_2 v^{3/2}+b_3(f-\bar{f})+b_4\log(CO2)}{1+b_5 v_{memory}}+b_6$$

$$v_{memory}(t)=\frac{\delta}{T}\int_{t-T}^{t} v(\tau)\,d\tau$$

$T=30\,kyr$

$\delta=1\ if\ \frac{dv}{dt}<0$

$\delta=0\ otherwise$

(2) $$CO2=c_1 dT+c_2 v+c_3 min\left(\frac{dv}{dt},0\right)+c_4+CO2_{Anthropogenic}$$

(3) $$dT=d_1 v+d_2\log\left(\frac{CO2}{278}\right)$$

Anthropogenic Emissions:

- Delta Pulse at Present

$$CO2_{Anthropogenic}(t)=E\sum_{i=1}^{5}\alpha_i * e^{-t/\tau_i} \qquad \alpha_i=\alpha_i(E) \quad \tau_i=\tau_i(E)$$

Following Lord et al. (2016)
α and τ polynomials of degree 3

- Magnitude of Cummulative Emission E

E = 500 Pg: Already emitted
E = 3000 Pg: Maximum Expected total Emissions in the next 200-300 years

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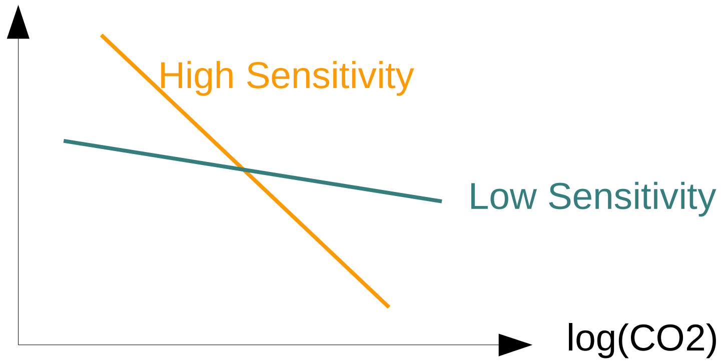
Model Prediction: Next 1 Milion Years

- We show the results of the **Ensemble of Accepted Solutions (N = 353)**

- For each Accepted Solution we calculate the dependency of the Critical Insolation on CO2 levels (as in Ganopolski et al., 2016)

$$Insolation_{critical} = \alpha \log(CO2) + \beta$$



- We separate the solutions into those with **High Sensitivity (N_{High} = 324)** or **Low Sensitivity (N_{Low} = 29)**

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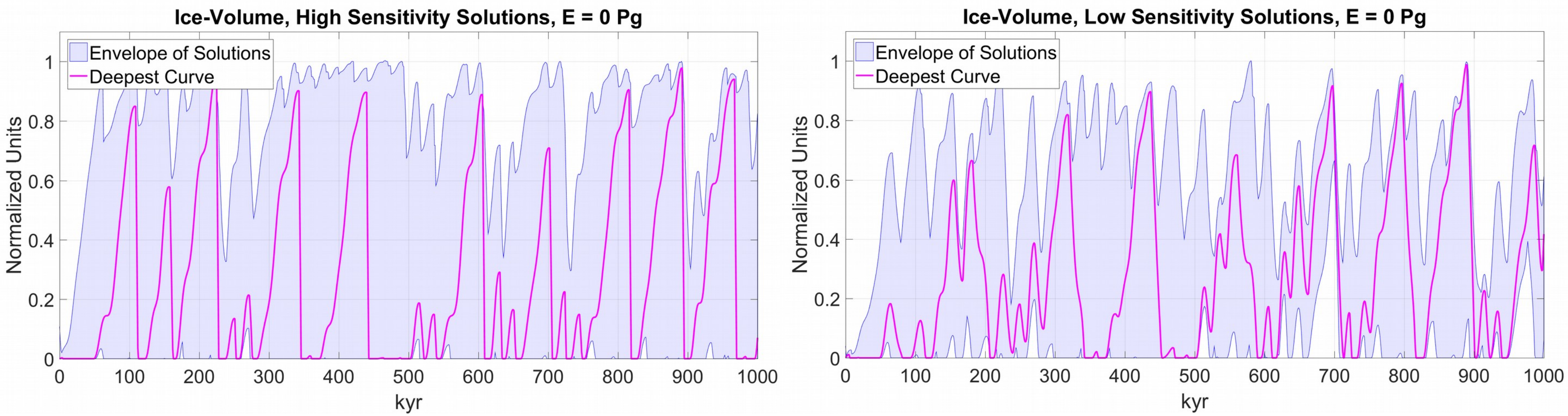
Model Prediction: Next 1 Milion Years



Natural Scenario (E = 0)

- High Sensitivity Solutions:
  - Next 1 Myr: Large Uncertainty
  - Next Glacial Inception: Likely in ~50 kyr
- Low Sensitivity Solutions:
  - Next 1 Myr: Large Uncertainty
  - Next Glacial Inception: Likely in ~120 kyr

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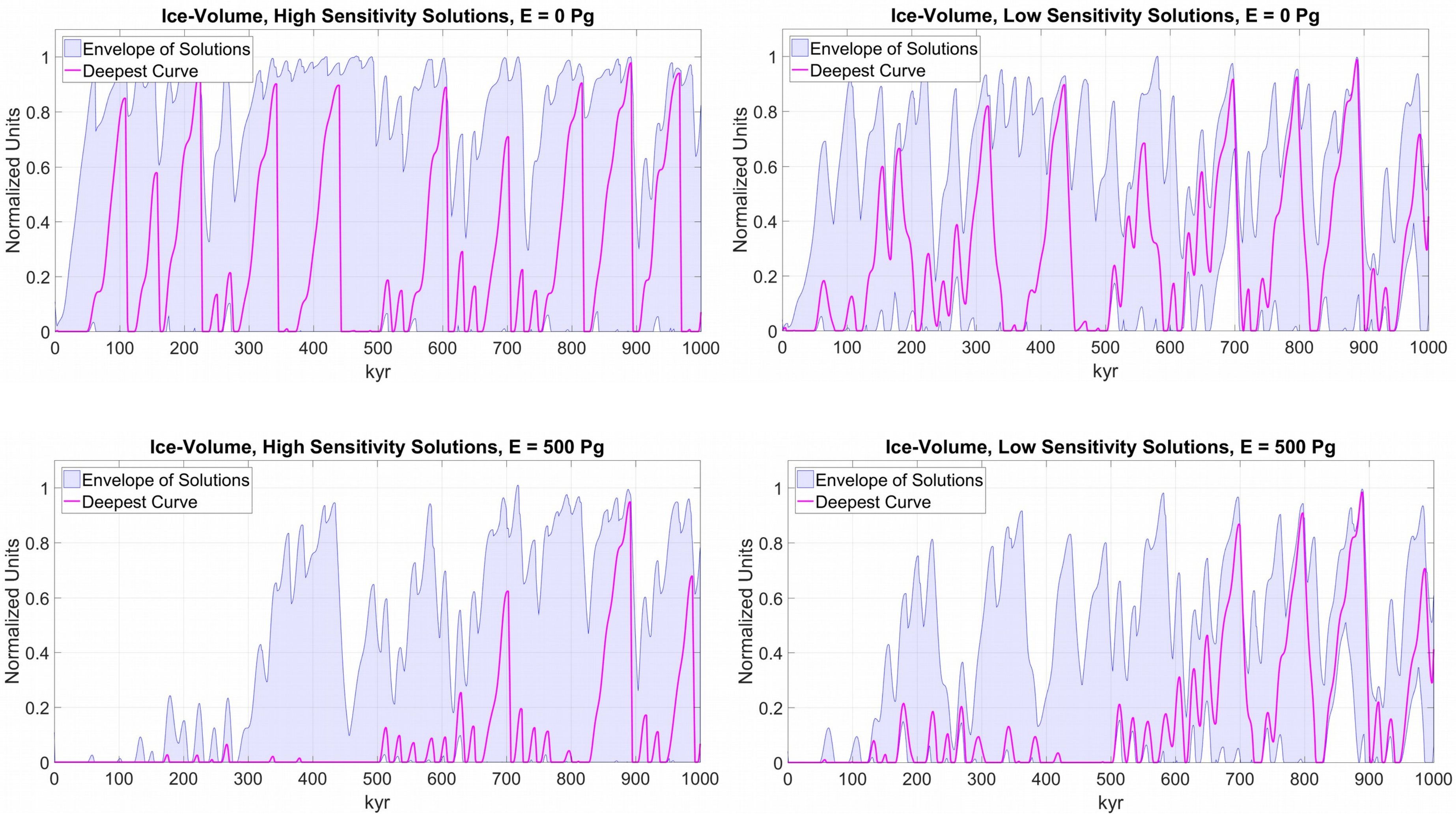
*Deepest curve: „Most central curve“ in the Ensemble, following López-Pintado and Romo (2006)

Model Prediction: Next 1 Milion Years



Natural Scenario (E = 0)

- High Sensitivity Solutions:
  - Next 1 Myr: Large Uncertainty
  - Next Glacial Inception: Likely in ~50 kyr
- Low Sensitivity Solutions:
  - Next 1 Myr: Large Uncertainty
  - Next Glacial Inception: Likely in ~120 kyr

Emissions Scenario (E = 500 Pg)

- High Sensitivity Solutions:
  - Next 300 kyr: Conditions significantly different from Natural, Low Uncertainity of almost ice-free conditions
- Low Sensitivity Solutions:
  - Next 120 kyr: Conditions significantly different from Natural, Low Uncertainity of almost ice-free conditions

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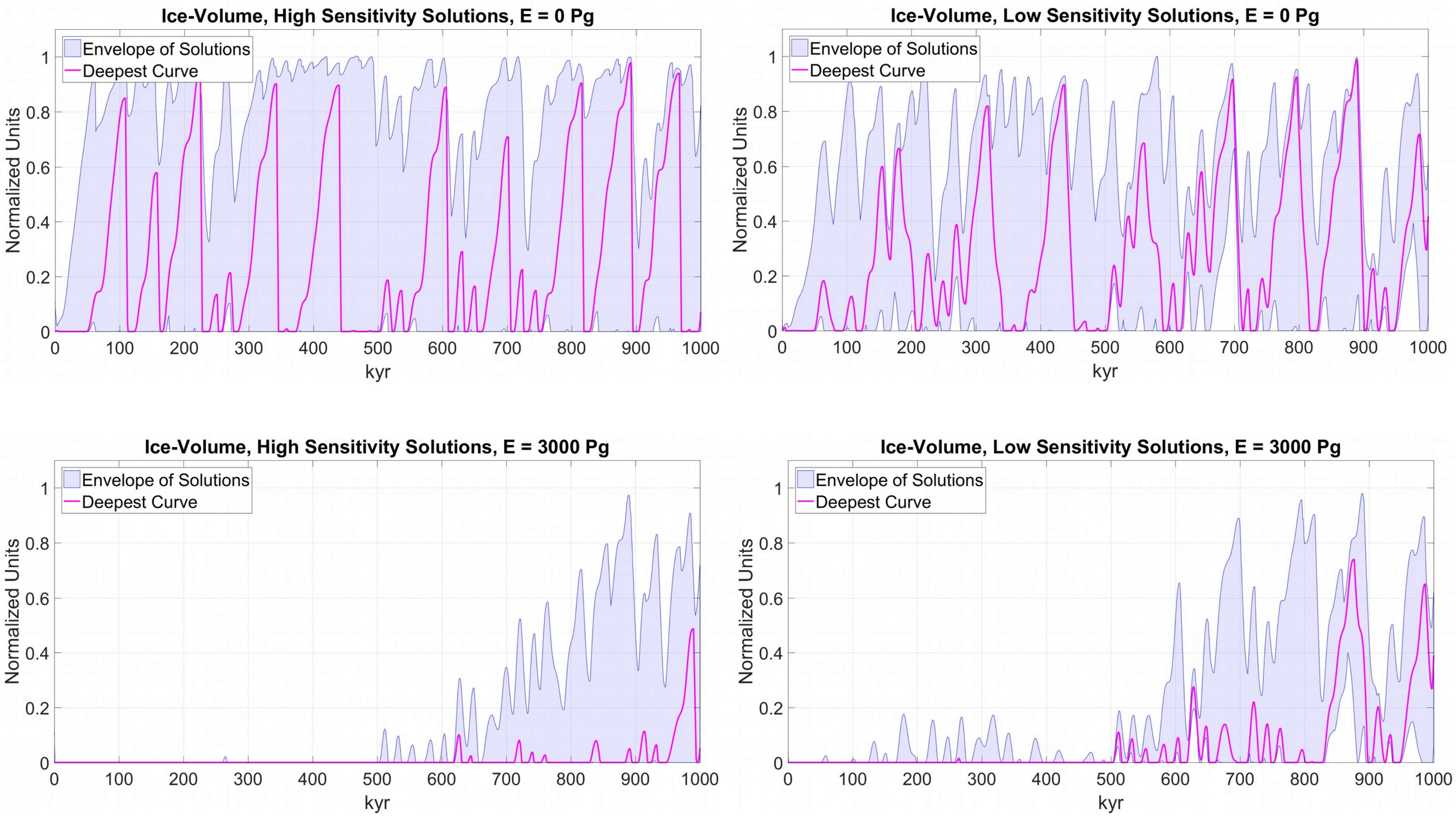
*Deepest curve: „Most central curve“ in the Ensemble, following López-Pintado and Romo (2006)

Model Prediction: Next 1 Milion Years



Natural Scenario (E = 0)

- High Sensitivity Solutions:
  - Next 1 Myr: Large Uncertainty
  - Next Glacial Inception: Likely in ~50 kyr
- Low Sensitivity Solutions:
  - Next 1 Myr: Large Uncertainty
  - Next Glacial Inception: Likely in ~120 kyr

Emissions Scenario (E = 3000 Pg)

- High Sensitivity Solutions:
  - Next 700 kyr: Conditions significantly different from Natural evoultion Low Uncertainity of almost ice-free conditions
- Low Sensitivity Solutions:
  - Next 550 kyr: Conditions significantly different from Natural evoultion. Low Uncertainity of almost ice-free conditions

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*Deepest curve: „Most central curve“ in the Ensemble, following López-Pintado and Romo (2006)

Summary and Conclusions

- The **Model is successful** in reproducing the Natural Evolution of the Climate System in the **last 800 kyr**
- The **Model is skillful** in **Predictive Mode** (when evaluated with data in an independent Validation Set)
- For the Future:
  - **Natural Scenario**:
    - Large Uncertainty in the Next 1 Myr: Indication that the past does not constraint the future of the Climate Evolution subject only to Orbital Forcing
    - Next Glacial Inception: Most likely to occurr in ~50 kyr from now
  - **Anthropogenic Emissions Scenarios**:
    - Even already achieved CO_2 Anthropogenic Emissions (500 Pg) are capable of affecting the Climate Evolution for long periods: Significantly different from Natural behaviour in, at least, the next 120 kyr
    - High CO_2 Anthropogenic Emissions (3000 Pg or larger): Significantly different from Natural behaviour in, at least, the next 550 kyr

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Thanks!

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References

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