# Tipping Points in the Earth System

***Hermann Held***

*Potsdam Institute for*
*Climate Impact Research (PIK)*

*Email: held@pik-potsdam.de*
*http://www.pik-potsdam.de*

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- Consequences for Earth System Management

# Tipping Points in the Earth System

(to be implemented after publication)

*(after Schellnhuber & Held 2001; Held et al. in prep.)*

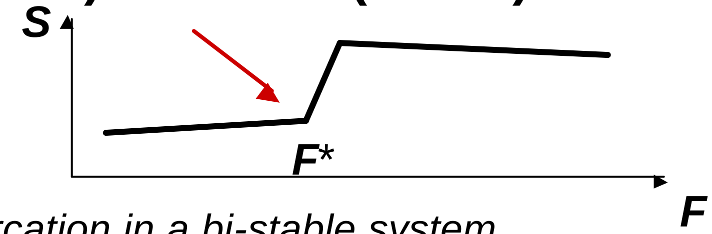
# Joint Characteristics of Tipping Points

- „Abrupt“ future effects,
- predominantly enforced by Climatic Change rather than natural variability
  - ⇒ e.g.
    - flips in ENSO-statistics
    - NOT: triggering of individual ENSO events
- Switches of at least subcontinental scale .

# Tipping Point Properties

- S = state variable (= sub-continental scale)
- F = forcing (linked to climate change)
- F* = critical forcing strength
- For an “imagined slow” forcing, F(t):

**dS/dF (F = F*) >> dS/dF (F < F*)**



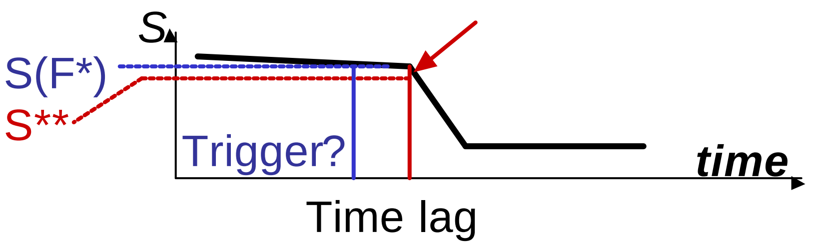

*Incorporates:*

- *Reaching bifurcation in a bi-stable system*
- *Non-linear change of a single equilibrium*
- *Lags in real system due to rapid forcing*

*(after H Held)*

# Tipping Point Properties (cont.)

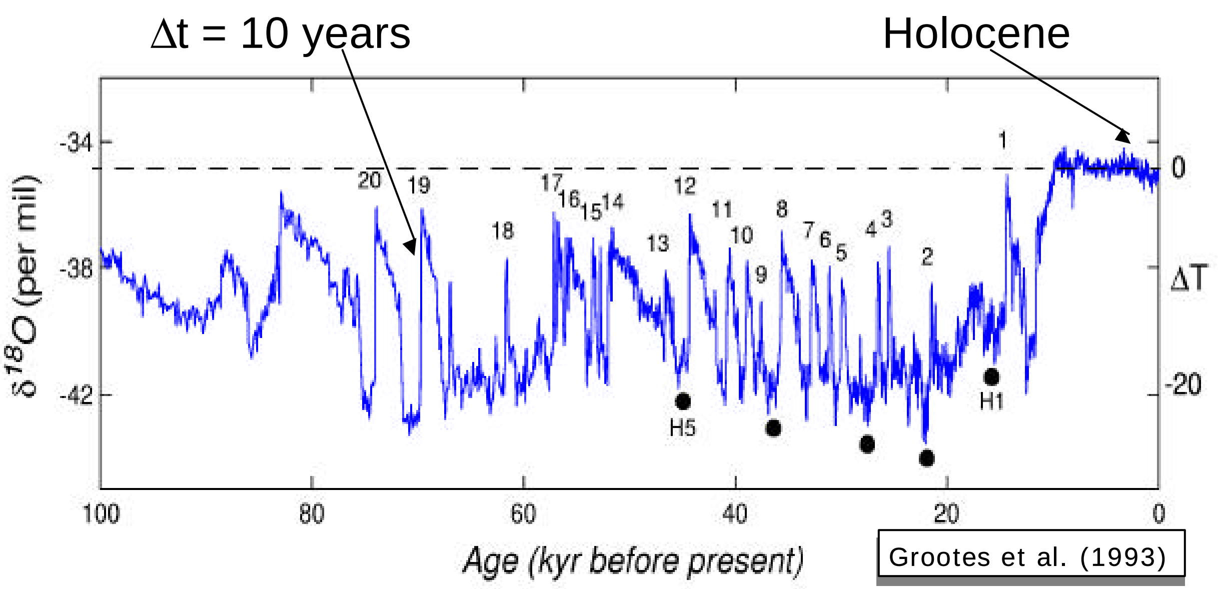
- Dynamical switch
  (time-series property)



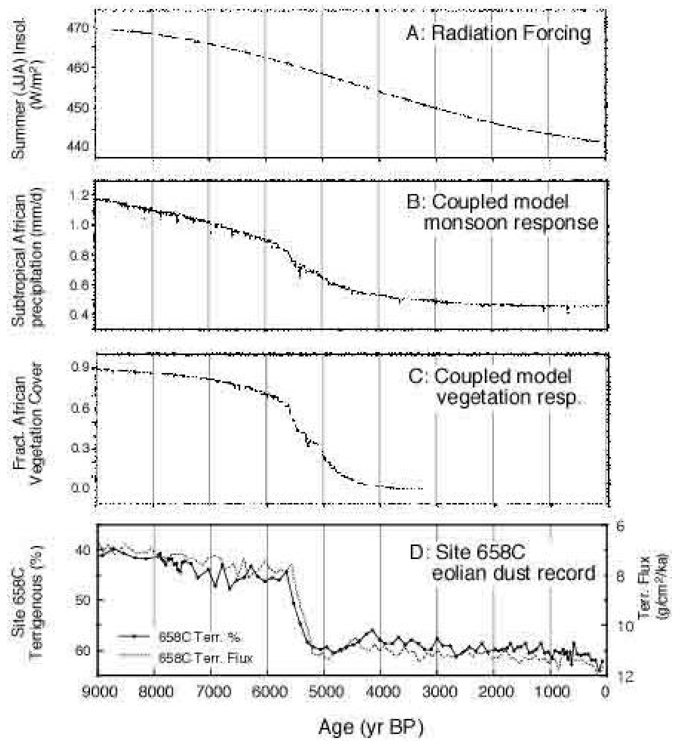

  - |dS/dt| (today) << |dS/dt| (S**)
  - For very slow forcing, S**=S(F*)

# Examples in Earth History

# Abrupt Temperature Changes @ Greenland



# Mid-Holocene Saharan Desertification




- Non-linear change in a single equilibrium
- Followed by the rise of “hydraulic societies” in Egypt, Mesopotamia…
- A tipping point in human systems linked to a tipping point in vegetation-climate?

De Menocal, P. J. *et al.* (2000). Quaternary Science Reviews 19: 347-361.

# West Antarctic Ice Sheet

Oppenheimer, Nature 1998)

- Triggered @ 2-4°C
- 4-6m Sea level rise
- Over 1000 yrs

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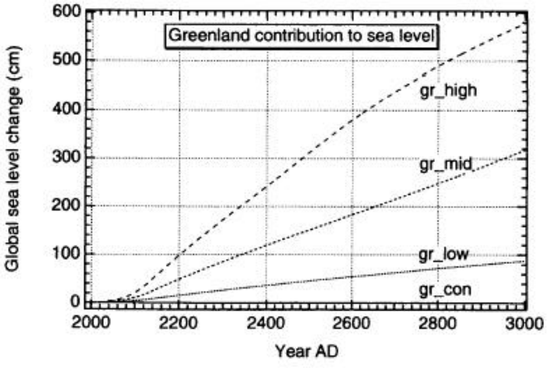
# Melting of Ice over Greenland

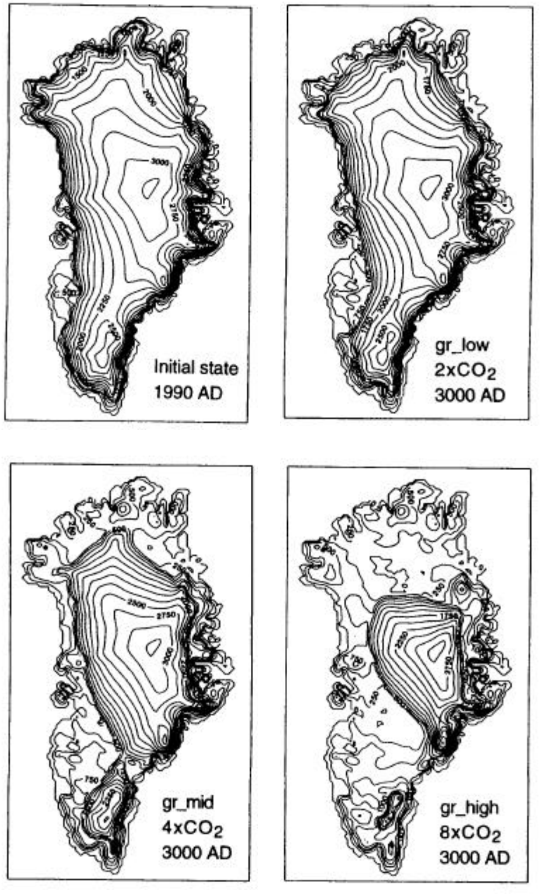
**Greenland ice sheet melt area increased on average by 16% from 1979 to 2002.**
**The smallest melt extent was observed after the Mt. Pinatubo eruption in 1992**

**Data from Konrad Steffen and Russell Huff, University of Colorado**

# Greenland melt and sea level change

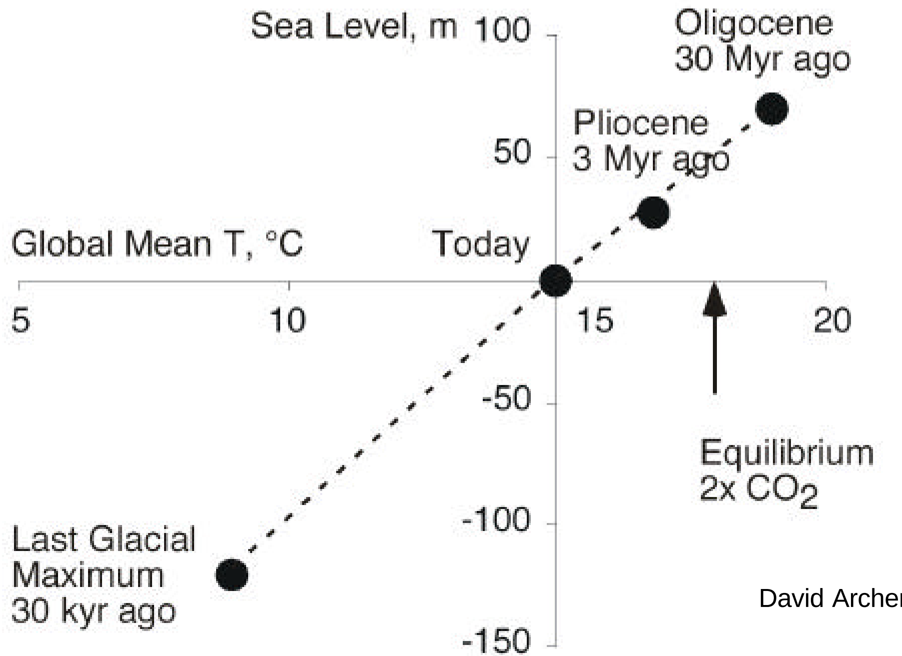



gr_con = control
gr_low = 2x$CO_2$
gr_mid = 4x$CO_2$
gr_high = 8x$CO_2$




Huybrechts, P. and J. De Wolde (1999). Journal of Climate **12**: 2169-2188.

# Past Sea Level vs. Temperature



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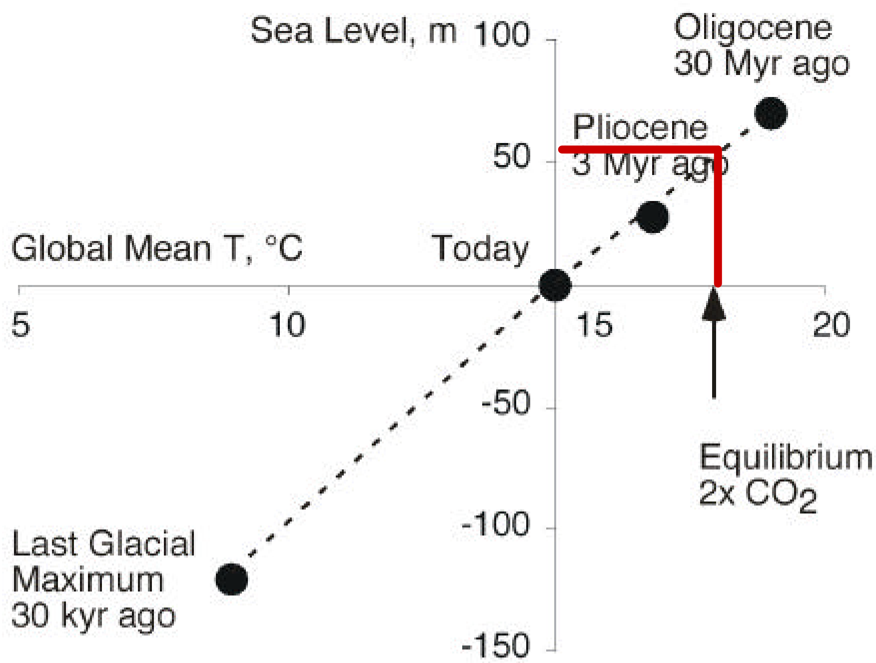


David Archer

- $\Rightarrow$ Potential of runaway effects
- Nonlinear & much faster decay
- „We need full stress-tensor-based ice models!“
- (R Alley @ EGU 2006, Vienna)

# Tipping Points in the Earth System

(to be implemented after publication)

*(after Schellnhuber & Held 2001; Held et al. in prep.)*

# Atmosphere-Land Surface Interactions

# Tipping Points in the Earth System

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# Amazon Forest Dieback

- **Many models show it, some don't – so it is a suspect but not convicted!**
- If climate becomes more "El Nino-like" (or more generally, a certain pattern of tropical SSTs) then possibility of Amazon die-back
- Chain of drivers: $CO_2$ – pattern of temp – precip - veg
- **Threshold: In GCMs happens at global warming of about 3-4 K**
- Also consider human activity – deforestation, forest fragmentation as **forcing** and as an influence on **sensitivity**, and also as a **feedback** (response of human systems to drying climate)
- Crossing threshold of deforestation first increasing precip then decreasing once past a certain fraction

# Permafrost Melt

- Threshold – annual mean temp of 5 or 7 °C but also depends on hydrology (autumn snow keeps warm)

## Tipping Points in the Earth System

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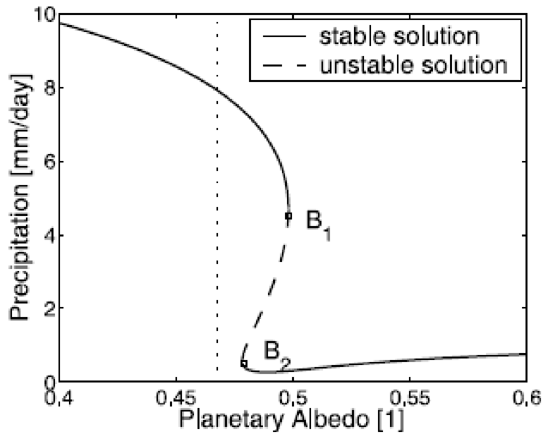
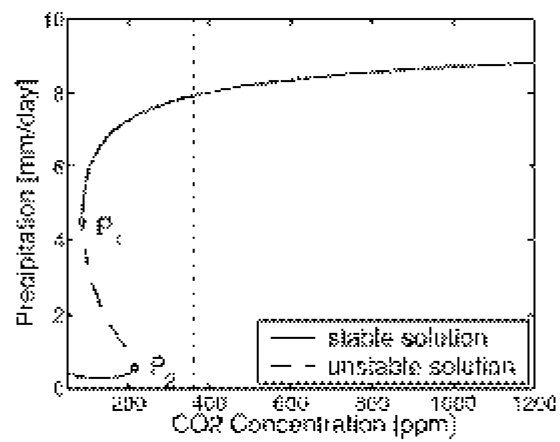
*(after Schellnhuber & Held 2001; Held et al. in prep.)*

# Indian Summer Monsoon




- Land cover change or aerosol forcing could trigger switch to arid regime
- $CO_2$ forcing would encourage return
- Potential “roller coaster” with huge social impacts

Zickfeld, K. *et al.* (2005). Geophysical Research Letters 32: L15707.

## Tipping Points in the Earth System

(to be implemented after publication)

*(after Schellnhuber & Held 2001; Held et al. in prep.)*

# CC-induced European Ozone Hole

- Global warming
- ⇒ stratospheric cooling
- ⇒ more stratospheric ice crystals
- ⇒ ozone depletion

*(Austin et al., 2003)*

# Known Temperature Threshold Intervals

(to be implemented after publication)

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*(after Schellnhuber & Held 2001; Held et al. in prep.)*


Direct $CO_2$ Impact:
Ocean Acidification
- ANOTHER AWAKENING GIANT

- How to measure the potential´s curvature?

# How to determine Curvature of Potential?

Theorie of Brownian Motion: Unified theorie of deterministic & stochastic forces (Einstein, 1905)

Responses to stochastic forces

Responses to deterministic forces

..are rooted in the same laws of mechanics

# Application for Shutdown of North Atlantic Thermohaline Circulation in CLIMBER-2

*After Held & Kleinen, GRL, 2004*

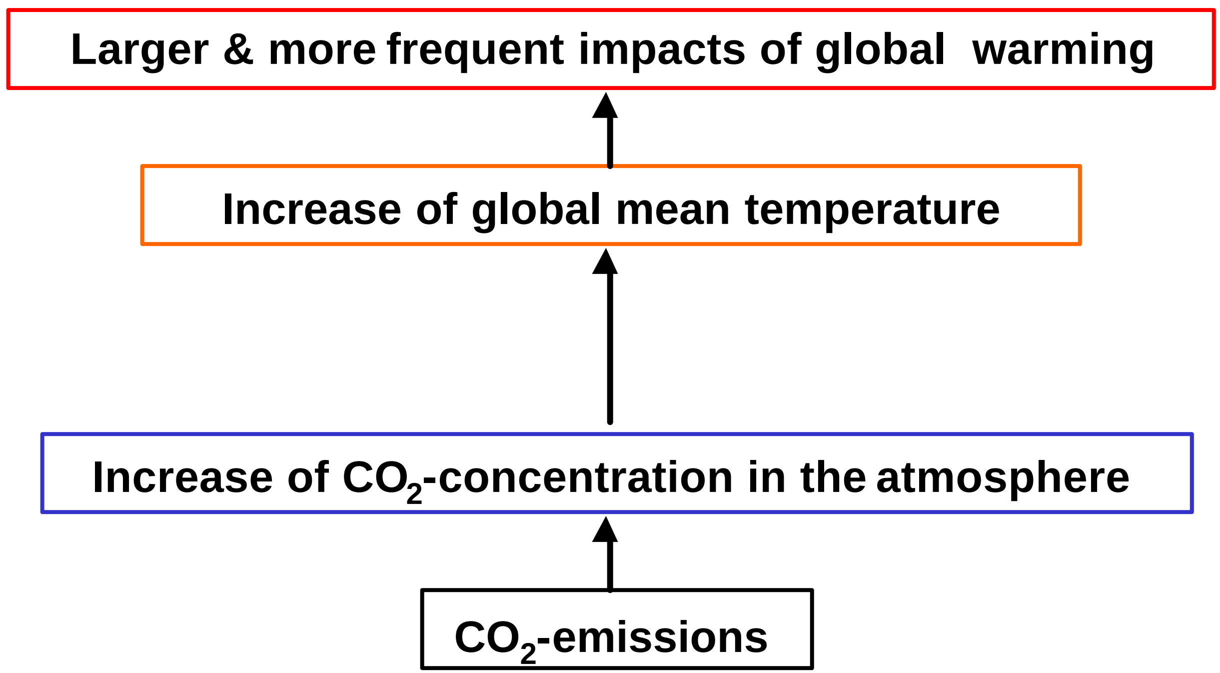
*No early warning*

(to be implemented after publication)

# Central Management Question

- Impacts of TPs on Adaptation/Mitigation strategy

# Key Factor Climate Sensitivity



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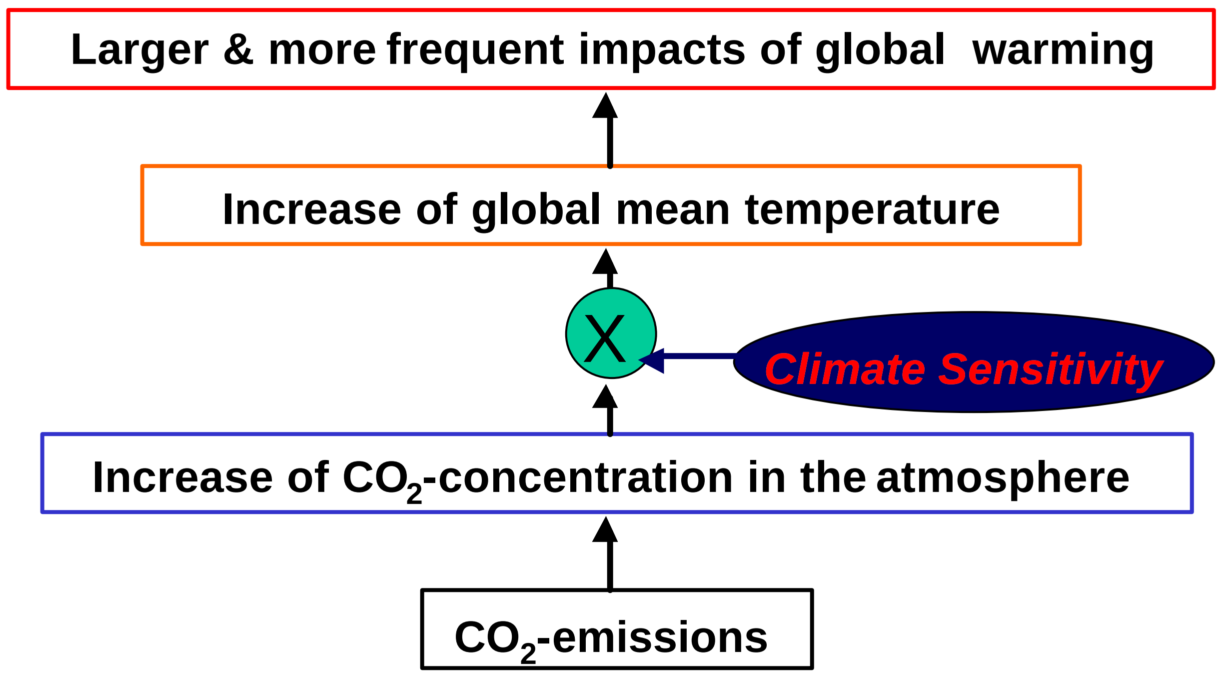
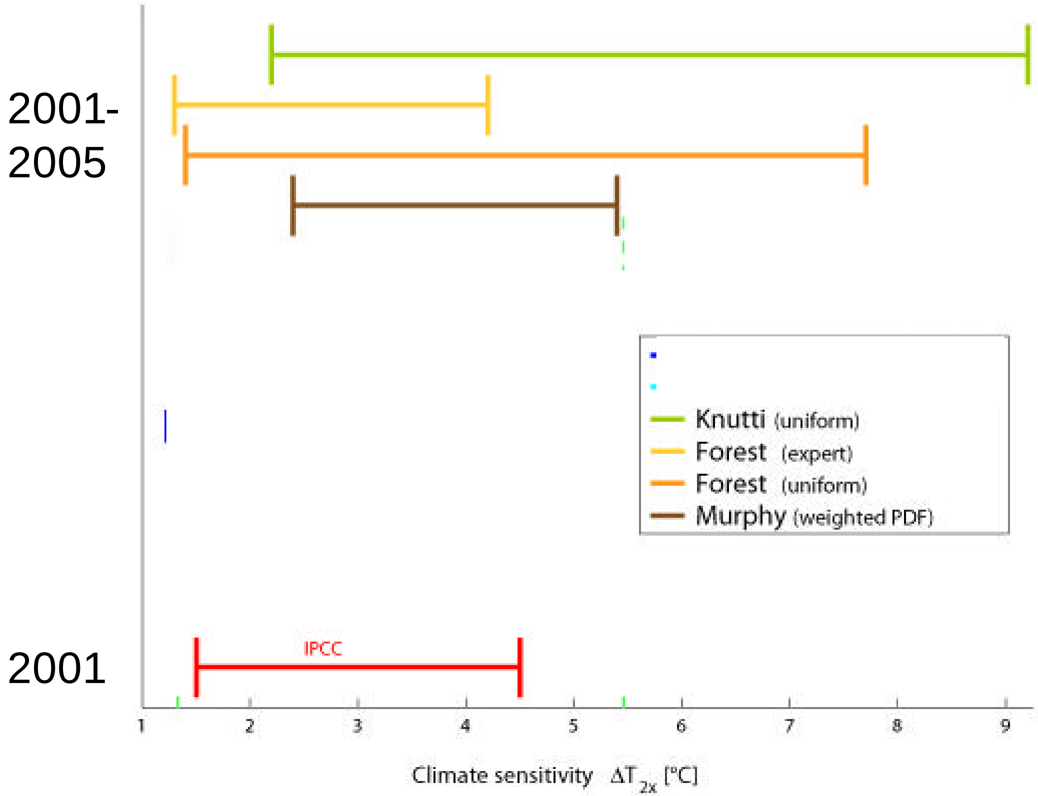


# Climate Sensitivity ® Impacts

(to be implemented after publication)

# CS: 5...95% Quantiles



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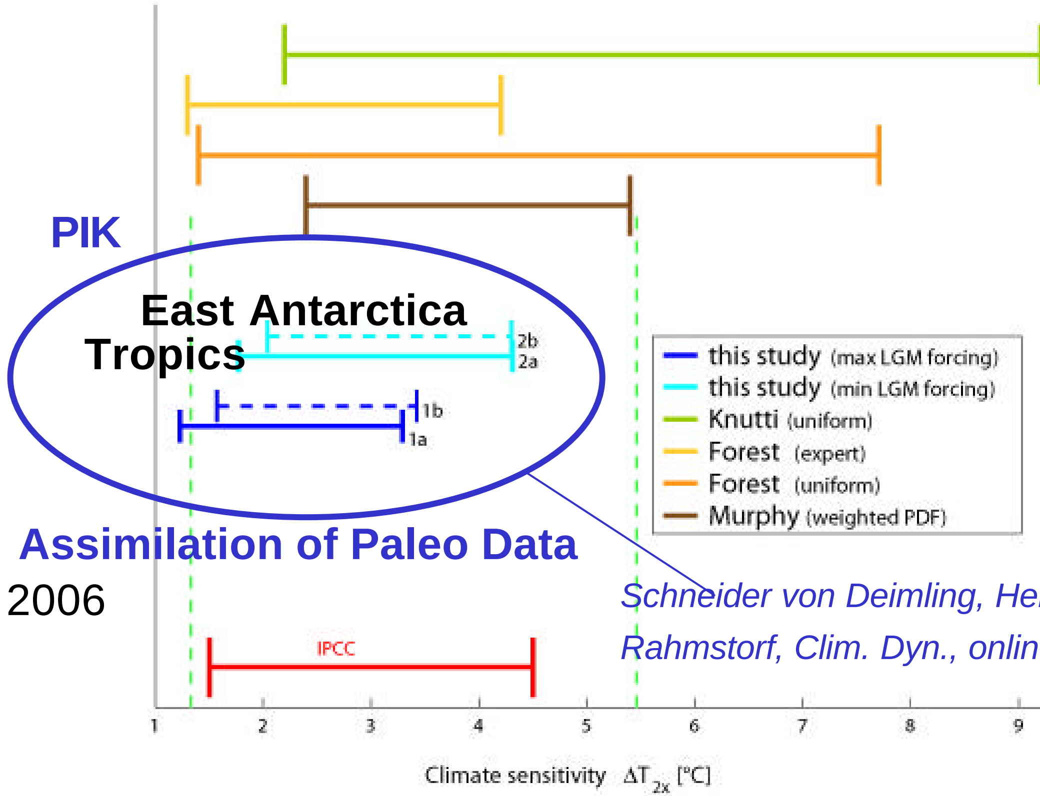


*Schneider von Deimling, Held, Ganopolski, Rahmstorf, Clim. Dyn., online*

# Summary

- A dozen Tipping Points identified
- Underrepresented in IPCC TAR
- Under several decision strategies:
  - Press for Mitigation
    & enhanced Adaptation costs