# A probabilistic analysis of cumulative carbon emissions and long-term planetary warming

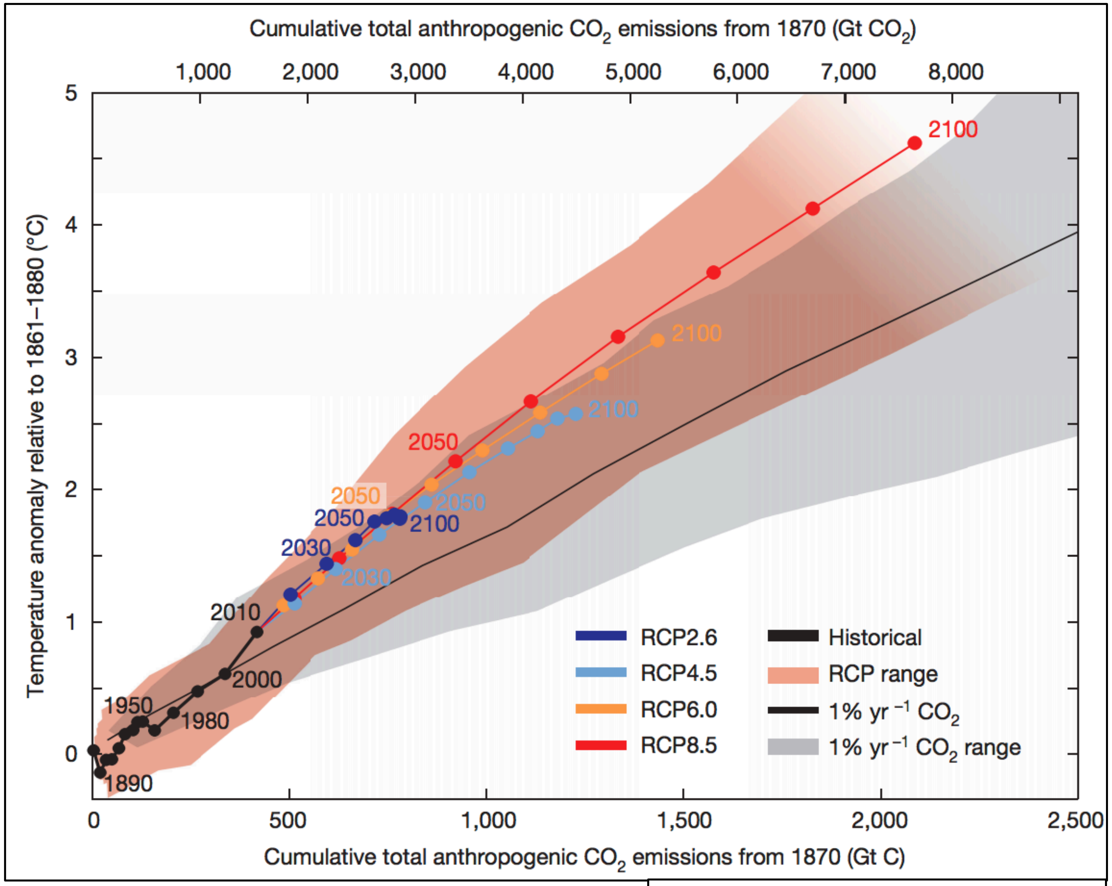
*Fyke and Matthews, 2015, ERL Special Issue: Focus on Cumulative Emissions, Global Carbon Budgets and the Implications for Climate Mitigation Targets*

Jeremy Fyke[1], Damon Matthews[2], David Huard[3]

# Synopsis

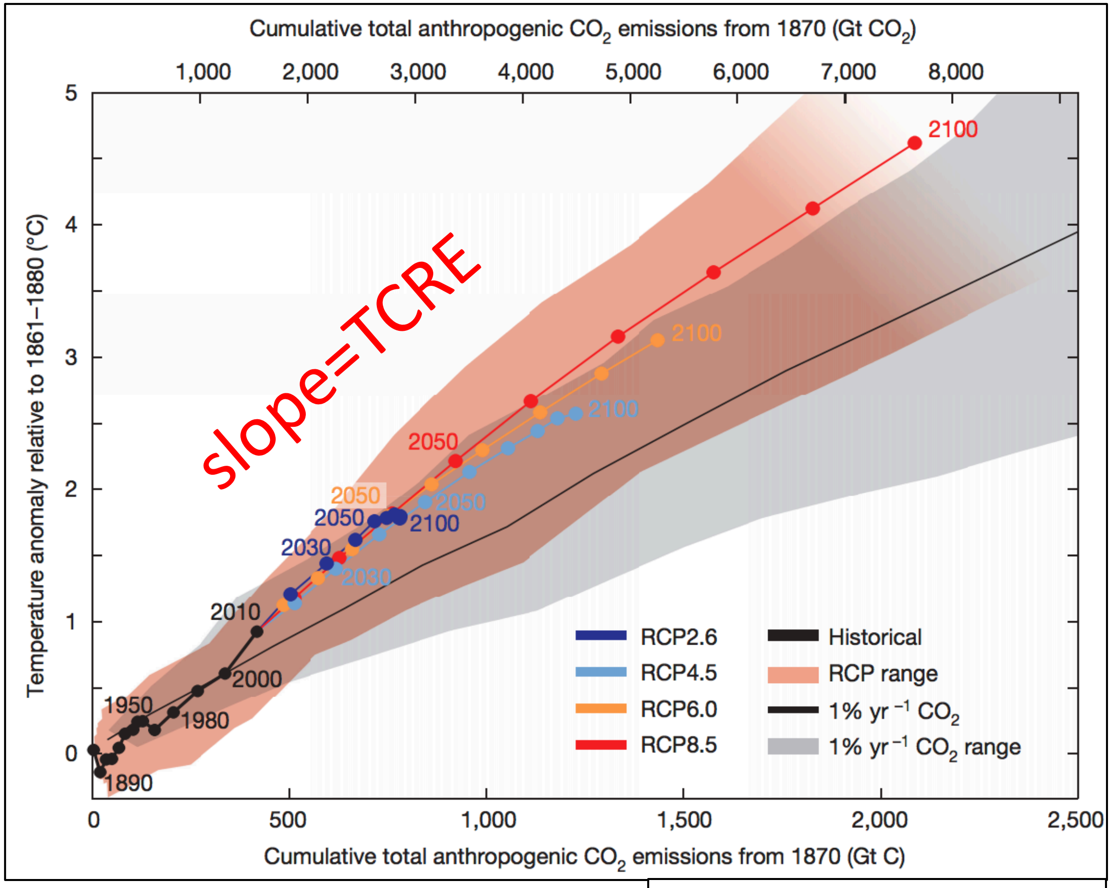
- Introduction: Why care about cumulative carbon emissions?
- Methods: Cumulative Emissions Projection Model (CEPM)
- Demonstration: $10^5$-member parametric uncertainty ensemble
- Discussion: relation to mitigation/adaptation policy

# Introduction: Why care about cumulative carbon emissions?




IPCC AR5, Chapter 12

# Introduction: Why care about cumulative carbon emissions?




IPCC AR5, Chapter 12

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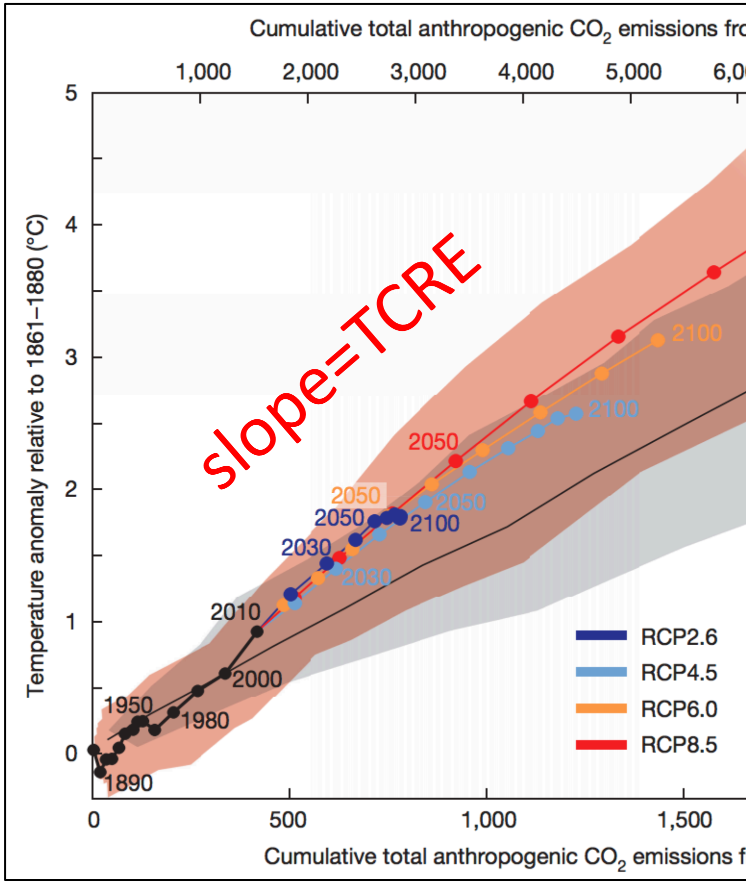
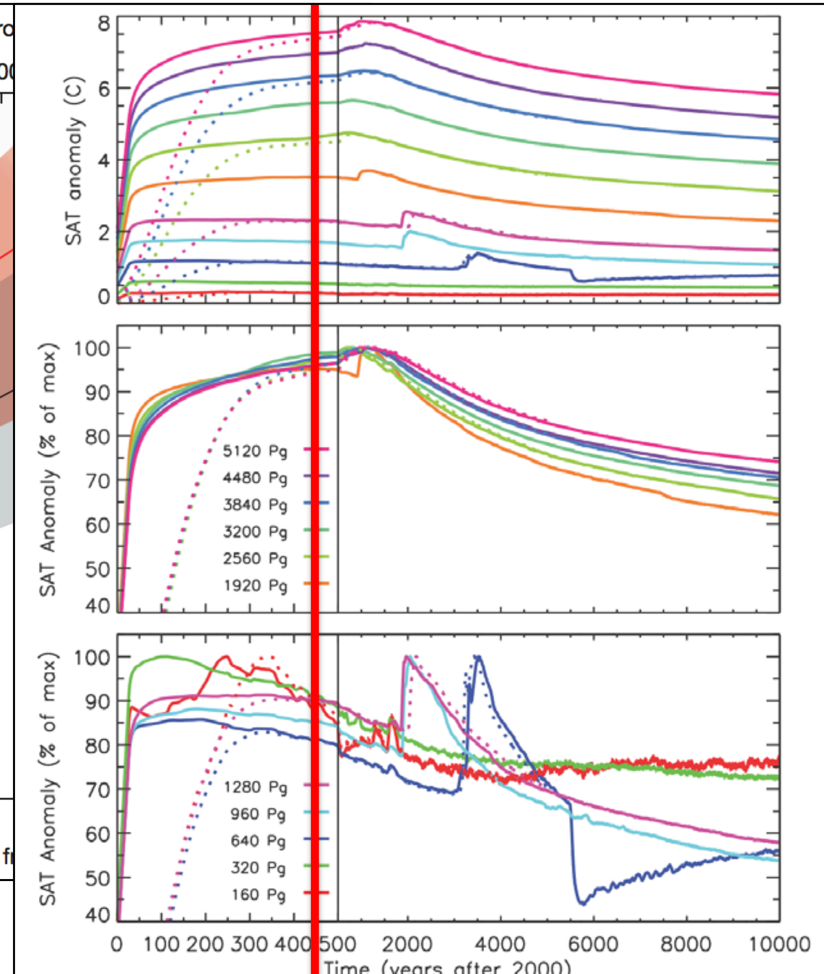
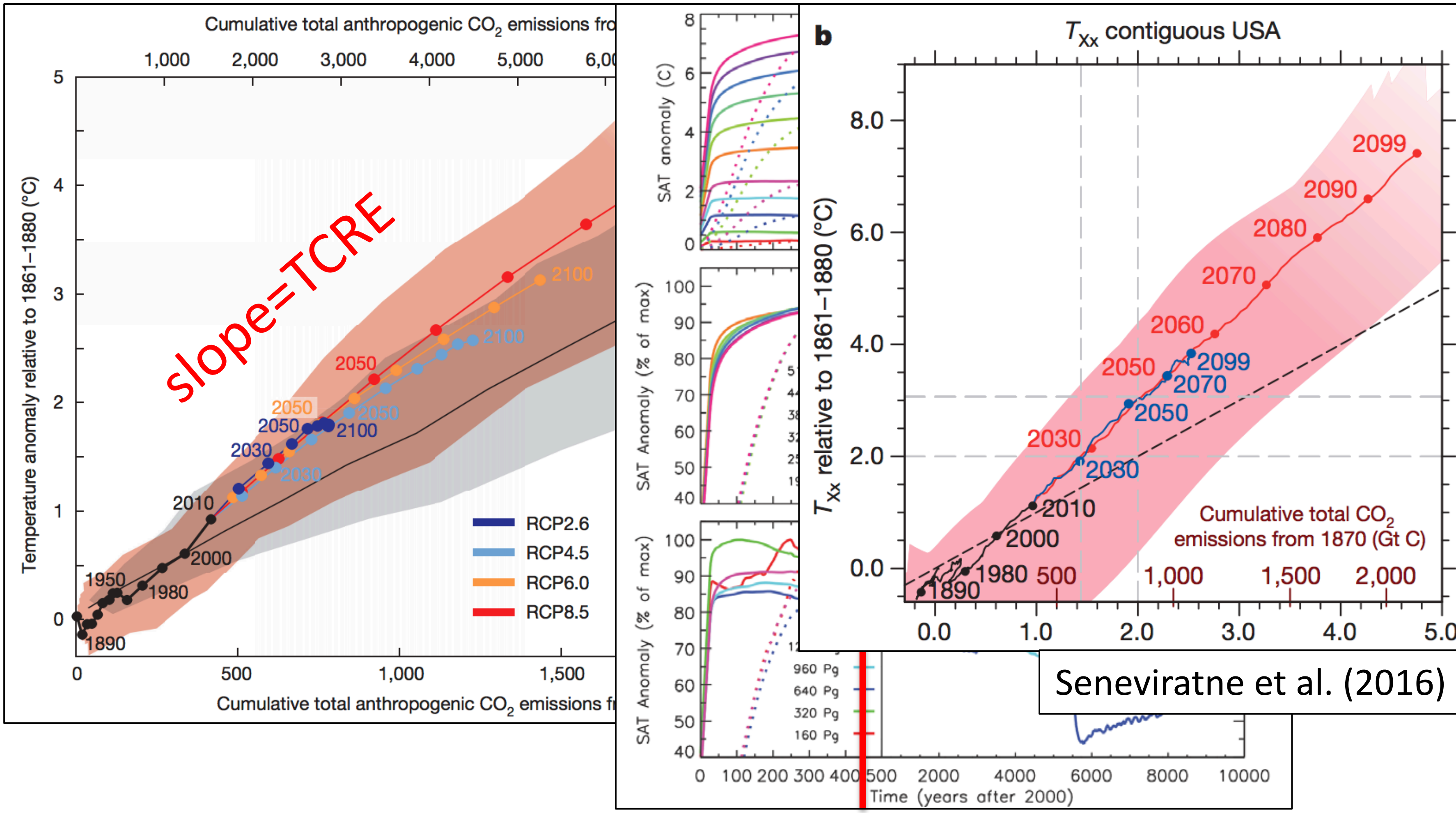



Eby et al. (2009)

# Introduction: Why care about cumulative carbon emissions?




Seneviratne et al. (2016)

# Introduction: Why care about cumulative carbon emissions?

- Consequences of linear T/CE relationship:
  - Every tonne of emitted C contributes same amount of warming ~no matter when emitted (scaling via TCRE)
  - Avoiding temperature thresholds implies finite C budgets
  - Global net emissions must end at some time ($t=t_{e=0}$)
  - Maximum change realized at $t=t_{e=0}$
  - large fraction of maximum change persists for $10^3$ years
  - Projections over [1850 $t(t<t_{e=0})$] miss some fraction (perhaps large) of climate response to anthropogenic activity

# Introduction: Why care about cumulative carbon emissions?

- Motivation:
  - Generate cumulative carbon emission/warming projections to $t=t_{e=0}$
  - Provide risk-assessment-tractable (i.e. probabilistic) cumulative carbon emission/warming projections
  - Relate cumulative emissions/warming projections to mitigation/adaptation policy

# Methods: Cumulative Emissions Projection Model (CEPM)

"Reduced-complexity" model based on numerical solution of ODE representing geological carbon reserve volume

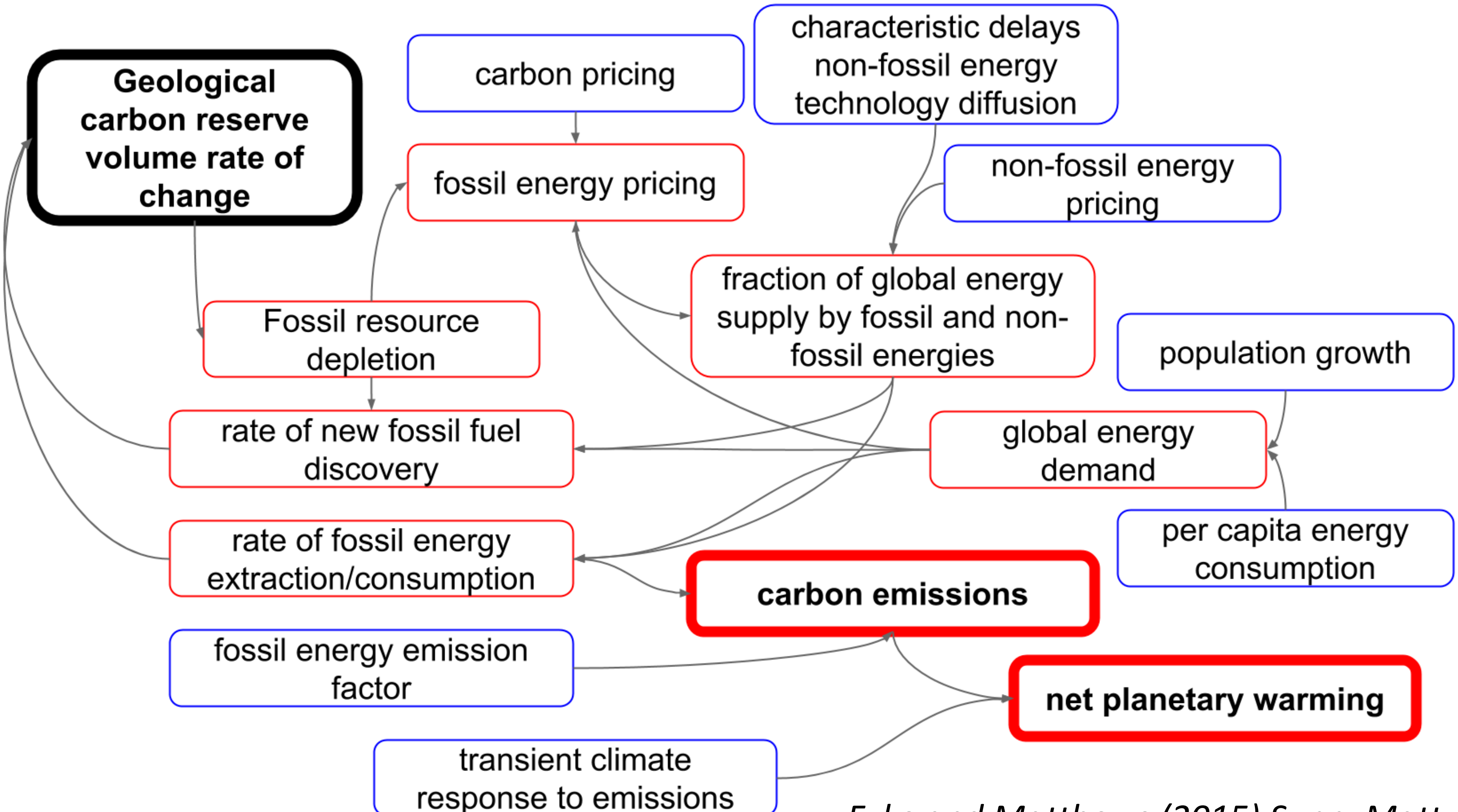
$$\frac{dV_{ff}}{dt} = D_{ff}(t) - C_{ff}(t)$$

Rate of carbon discovery

Rate of carbon extraction/combustion

*Fyke and Matthews (2015) Supp. Matt.*
*https://github.com/JeremyFyke/CEPM*

# Methods: Cumulative Emissions Projection Model (CEPM)



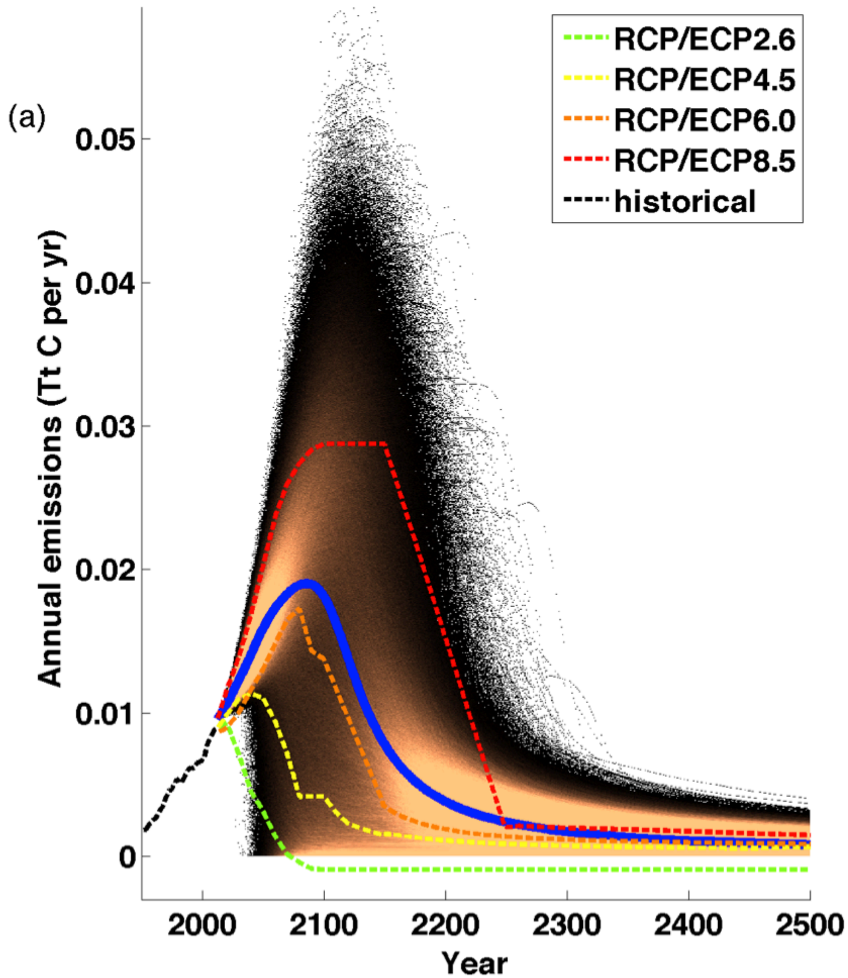

*Fyke and Matthews (2015) Supp. Matt.*
*https://github.com/JeremyFyke/CEPM*

# Demonstration: $10^5$-member parameter sensitivity ensemble

- Latin hypercube sampling ->$10^5$ prognostic simulations swathing 17D parameter space

| | Symbol | Units | Mean/$\sigma$ |
|---|---|---|---|
| Initial fossil fuel reservoir reserves | $V_{ff}(0)$ | Tt C | 1.5/0.23[1] |
| Maximum fossil fuel resources | $V_{ff_{max}}$ | Tt C | 5.1/1.3[1] |
| Initial fossil fuel cost | $Pr_{ff}(0)$ | \$/brl oil | 75/12[2] |
| Fossil energy emission factor trend | $T_{Eff}$ | g C/J/yr | $8.0\times10^{-8}/1.0\times10^{-8}$[3] |
| Final fossil energy emission factor | $E_{ff_f}$ | g C/J | $2.1\times10^{-5}/2.6\times10^{-6}$[3] |
| Initial non-fossil energy unit cost | $Pr_{nff}(0)$ | \$/MWh | 400/50[4] |
| Minimum non-fossil energy unit cost | $Pr_{nff_{min}}$ | Fraction of initial cost | 0.2/0.05[3] |
| Maximum carbon price | $S_{ff_{max}}$ | \$/tonne C | 300/180[5] |
| Carbon tax price | $T_{S_{ff}}$ | \$/tonne C/yr | 7.5/1.2[5] |
| E-folding time of non-fossil energy cost decline | $T_{nff}$ | Yr | 15/2.5[4] |
| Maximum population | $P_{max}$ | Billion people | 11/0.68[6] |
| Population increase rate | $P_{inc}$ | %/yr | 0.019/0.002[7] |
| Maximum per-capita energy consumption | $De_{pc_{max}}$ | GJ/yr | 200/32[8] |
| Per- capita energy consumption increase | $De_{pc_{inc}}$ | %/yr | 0.01/0.0022[8] |
| Fossil to non-fossil energy transfer delay | $B$ | Unitless | 0.6/0.2[3] |
| Fossil to non-fossil energy transfer fade strength | $C$ | Unitless | −5/0.5[3] |
| Transient climate response to emissions | TCRE | °C/Tt C | 1.6/0.42[9] |

# Demonstration: $10^5$-member parameter sensitivity ensemble




- Median projected emissions most similar to RCP6.0
- Ensemble largely bracketed by RCP4.5/RCP8.5

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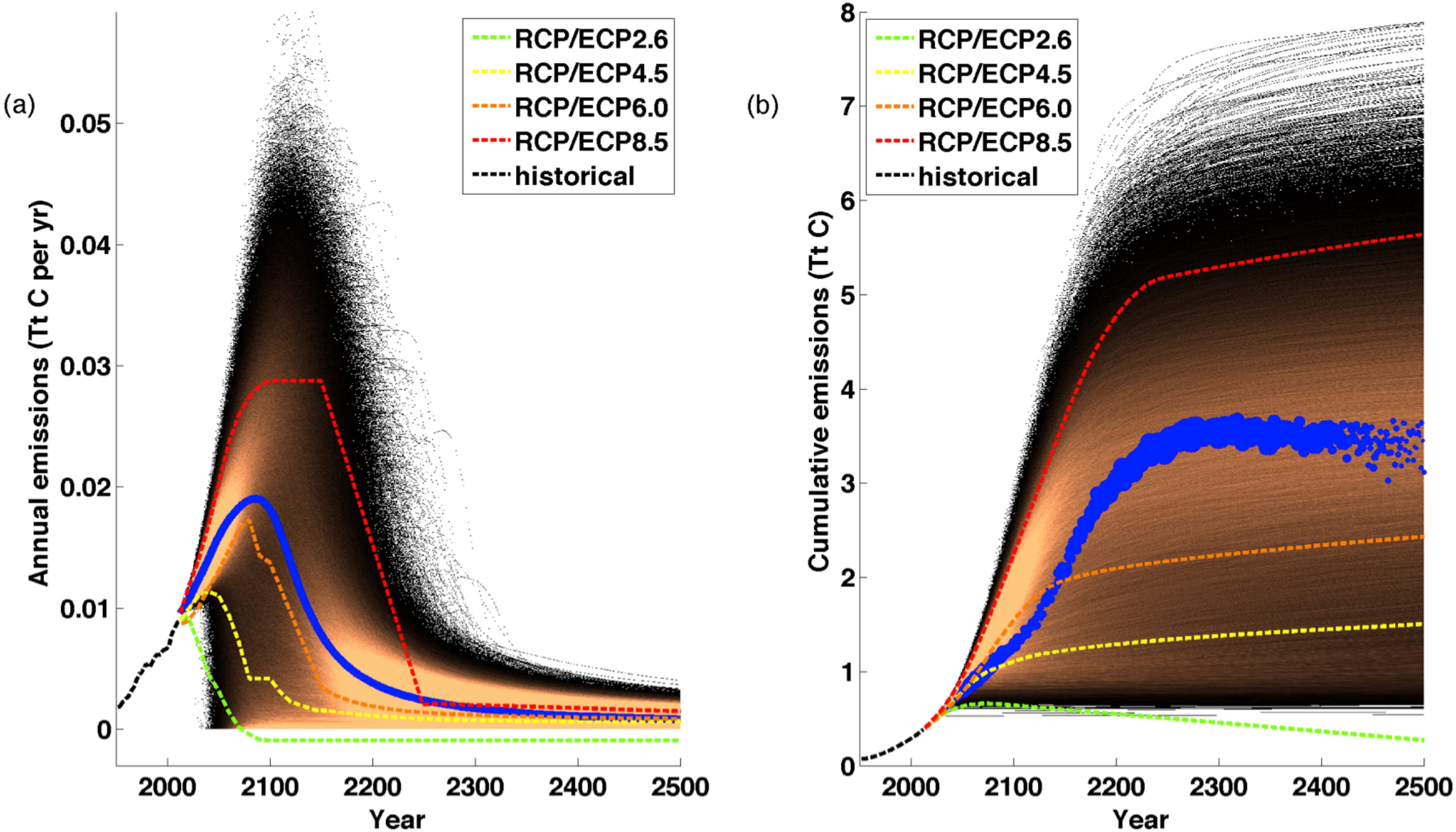


- Cumulative emissions integrate emission curves
- Year-mean net CE increases to ~2300

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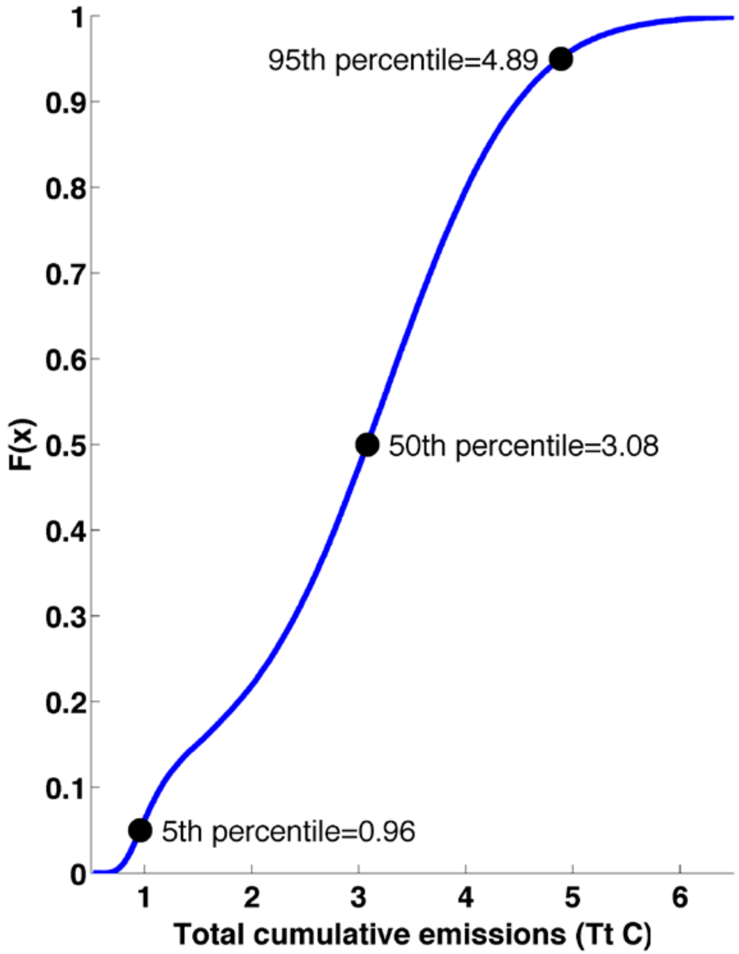


- CDFs of ensemble output -> probabilistic estimates of total CE…

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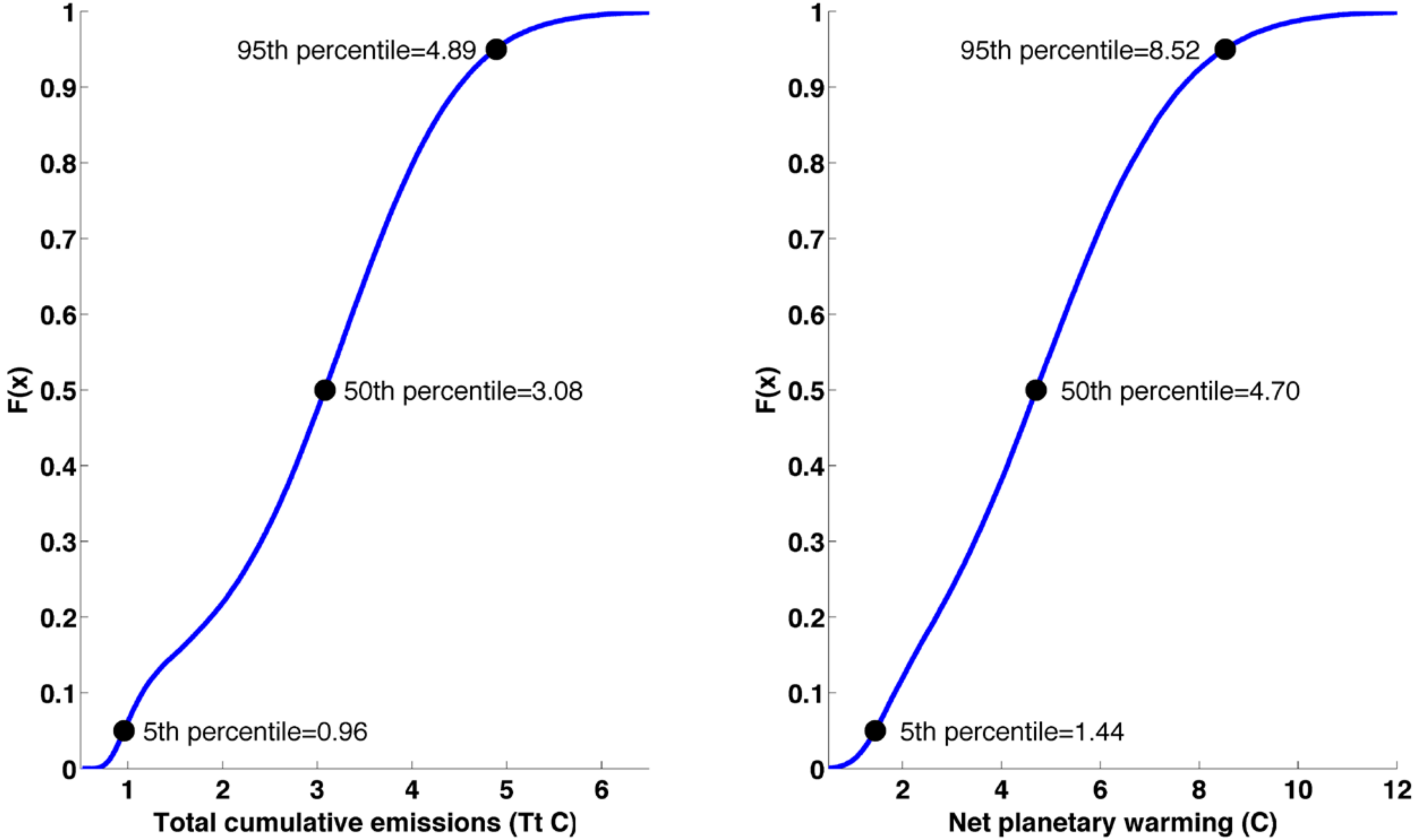


- CDFs of ensemble output -> probabilistic estimates of total CE, total anthropogenic warming…

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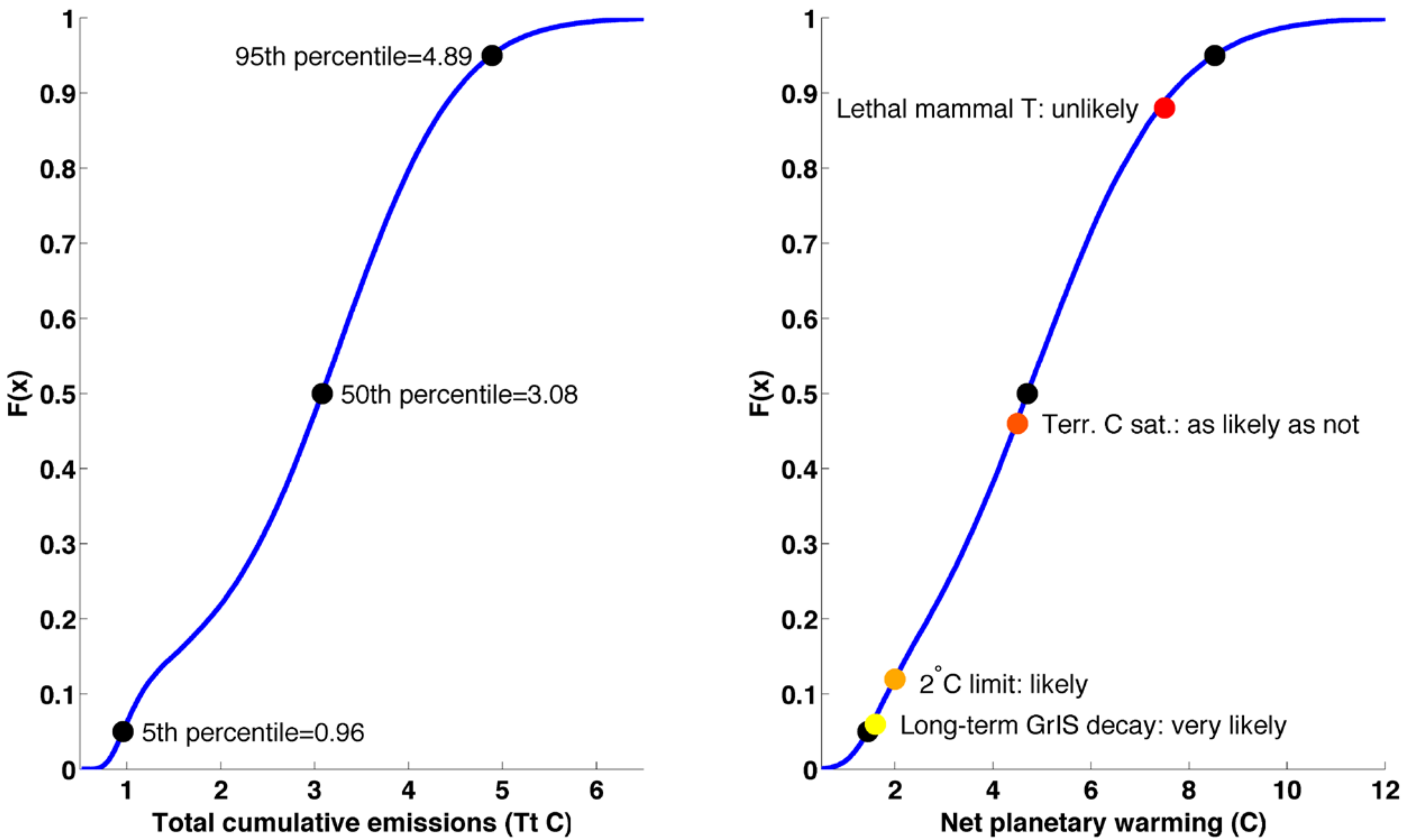
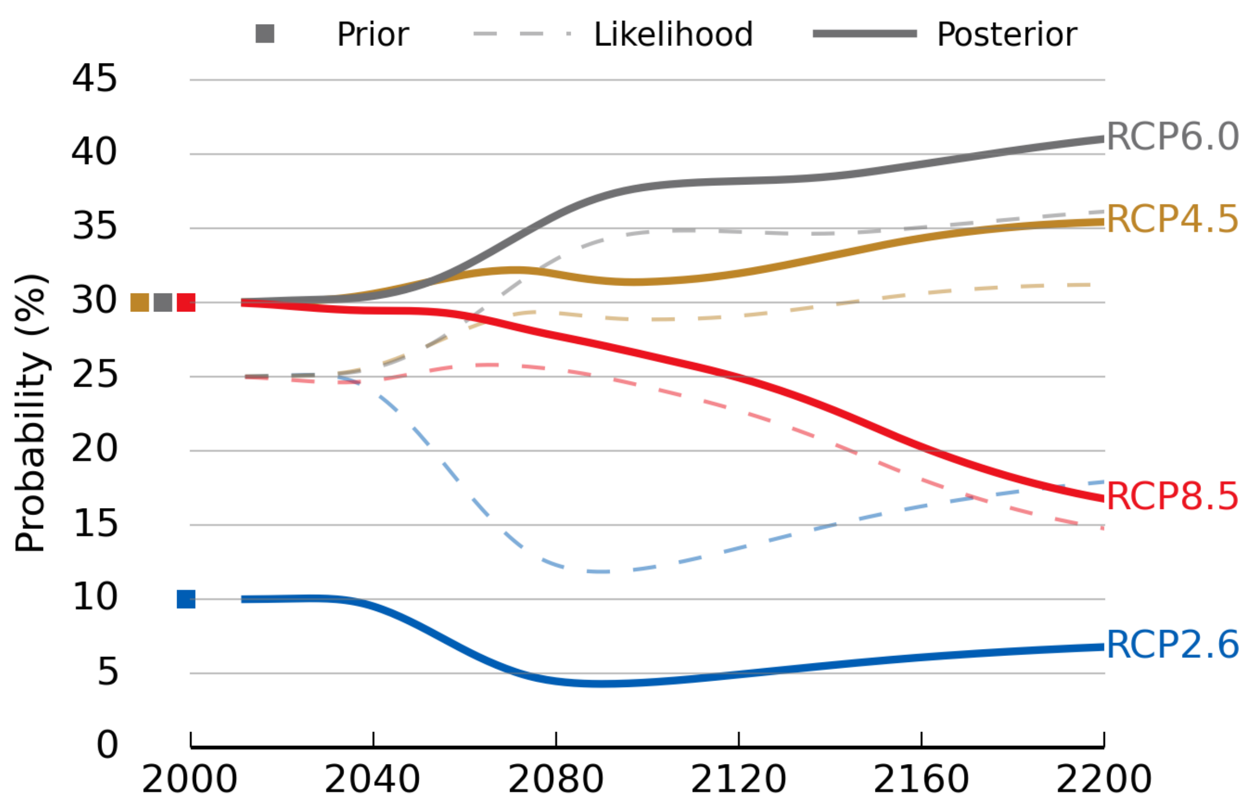



- CDFs of ensemble output -> probabilistic estimates of total CE, total anthropogenic warming and climate threshold "IPCC likelihoods"

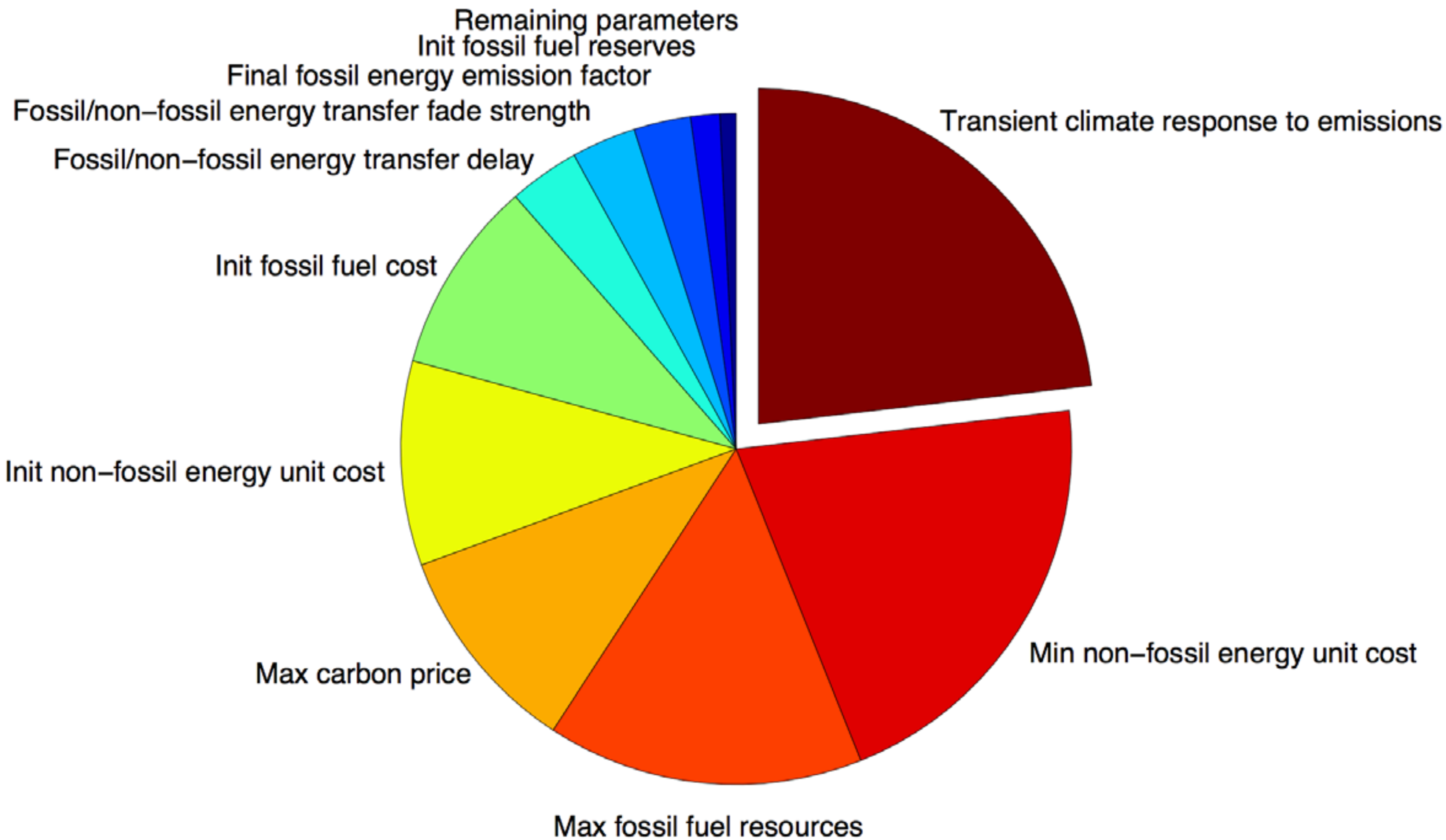
# Demonstration: $10^5$-member parameter sensitivity ensemble



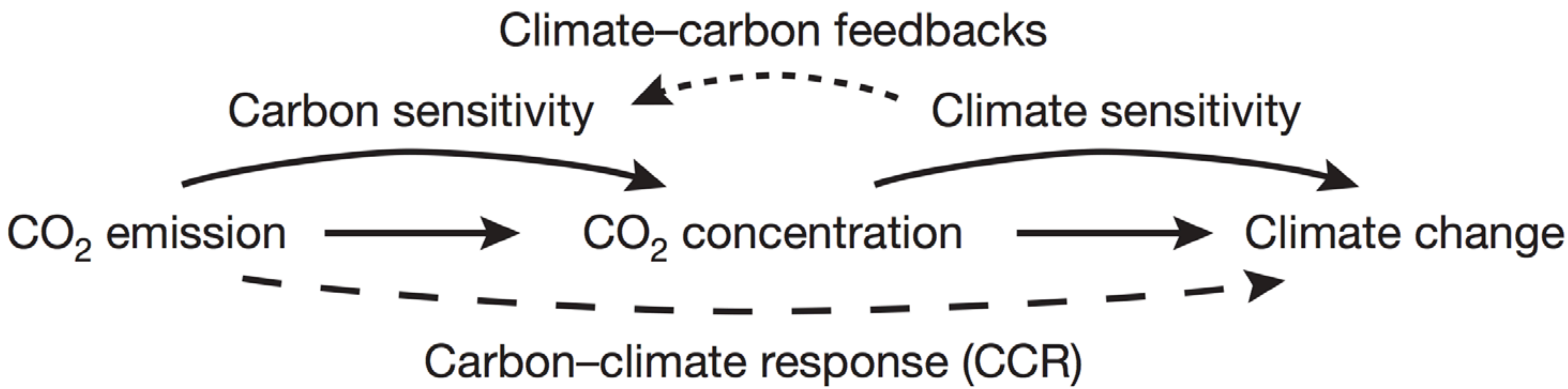

- If distribution of CEPM emission time series taken as data for use in Bayesian framework -> estimate of time-evolving RCP scenario posterior probabilities (*dependent on prior choice*; *D. Huard*)

# Conclusions

- TCRE a powerful metric for relating cumulative carbon emissions to net warming
- Maximum warming only attained at point of zero emissions
- CEPM developed for long-term cumulative carbon emissions/net warming projections
- Large ensemble of CEPM simulations demonstrates:
  - Probabilistic estimates of cumulative emissions/net warming
  - Assessments of threshold-crossing likelihoods
  - Likelihoods of RCP scenarios
- ***CEPM 'demonstrative': for sake of understanding full Earth System response to human activity, we encourage more probabilistic cumulative carbon emission approaches in IAMs***




- Normalizing parameter ranges and performing multiple linear regression -> assessments of most-effective policies for reducing $dT_{e=0}$ (*different than reducing* $dT_{2100}$*!*)


Climate–carbon feedbacks
Carbon sensitivity
Climate sensitivity
CO2 emission
CO2 concentration
Climate change
Carbon–climate response (CCR)