Why is climate sensitivity so unpredictable?

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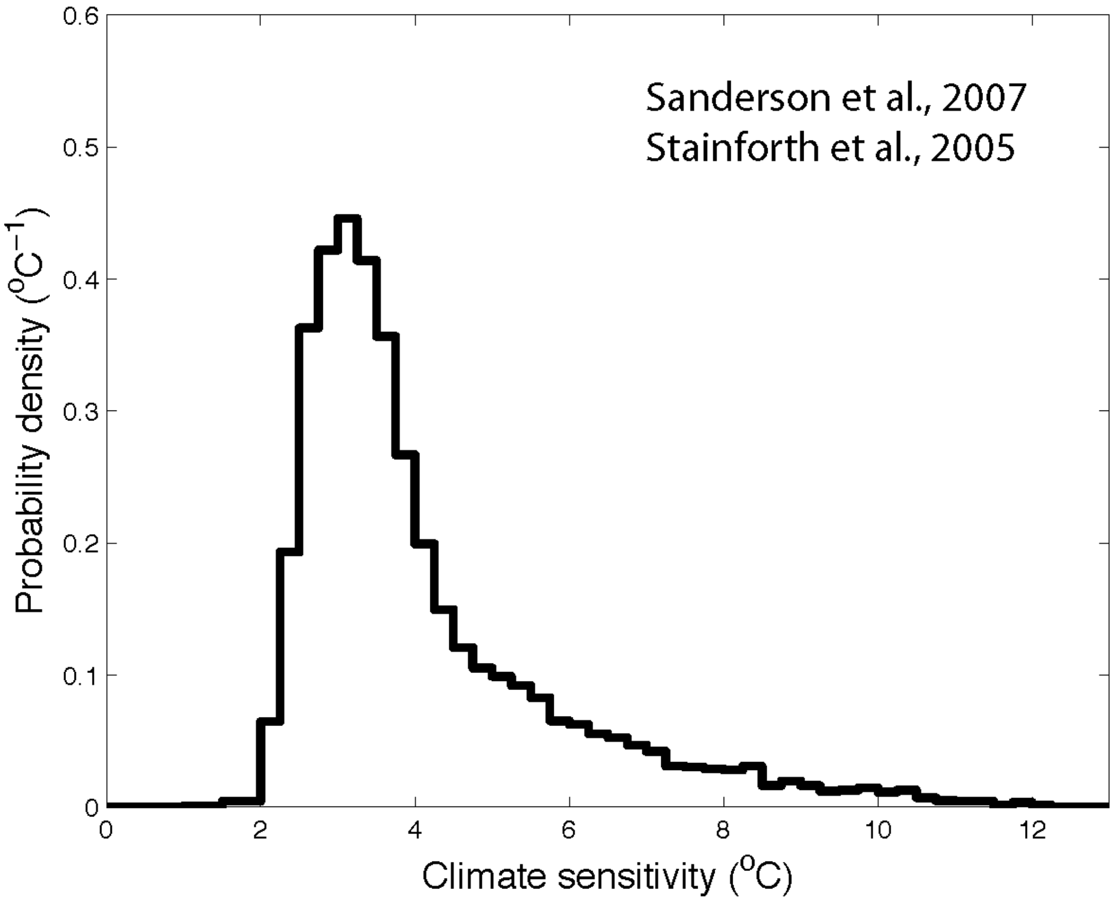
Climate sensitivity: an envelope of uncertainty

climateprediction.net 200,000+ integrations, 27,200,000 yrs model time(!);



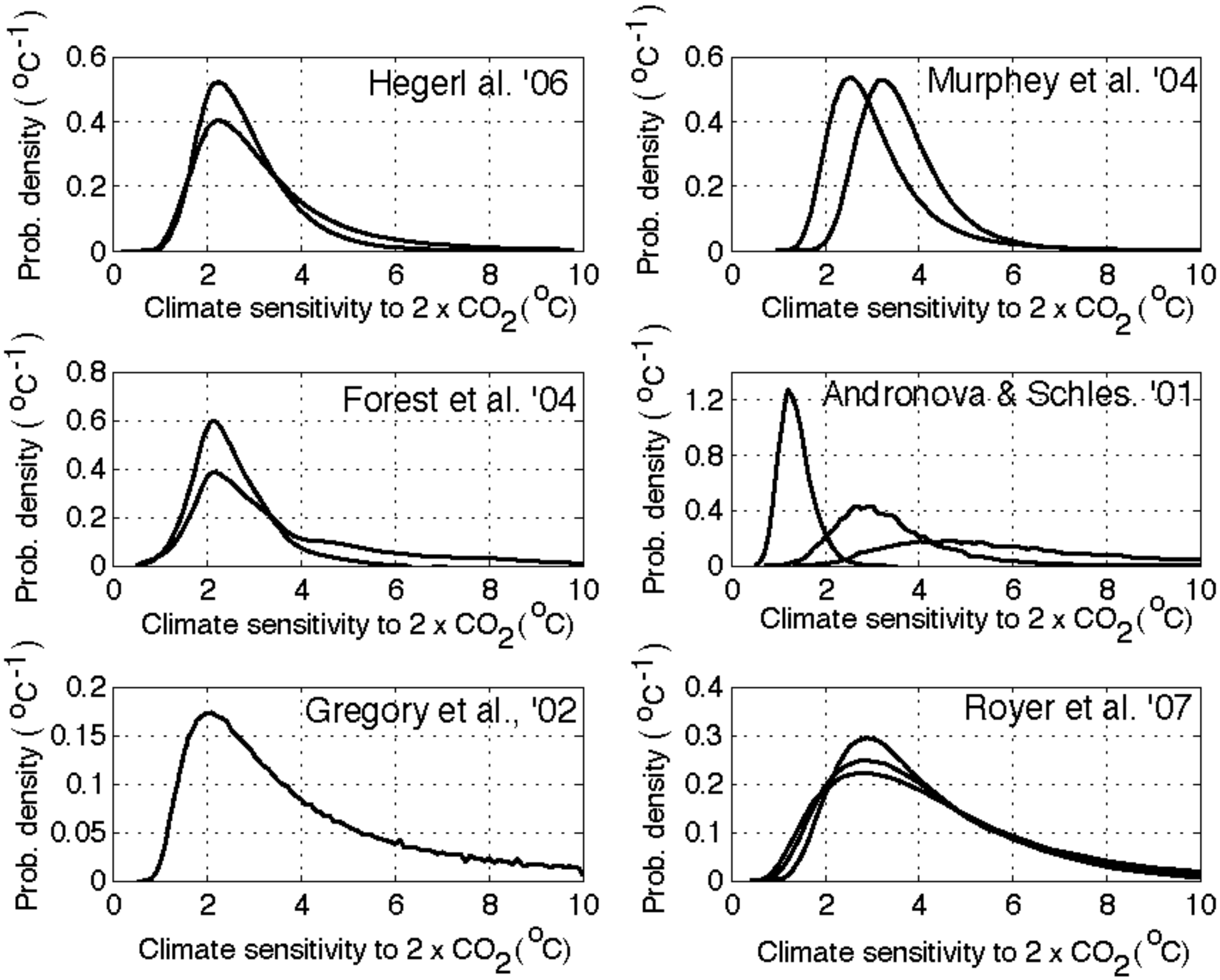
Eq^m. response of global, annual mean sfc. T to 2 x CO_2.

6,000 model runs, perturbed physics

Slab ocean, Q-flux 12 model params. varied

- Two questions:
    1. What governs the shape of this distribution?
    2. How does uncertainty in physical processes translate into uncertainty in climate sensitivity?

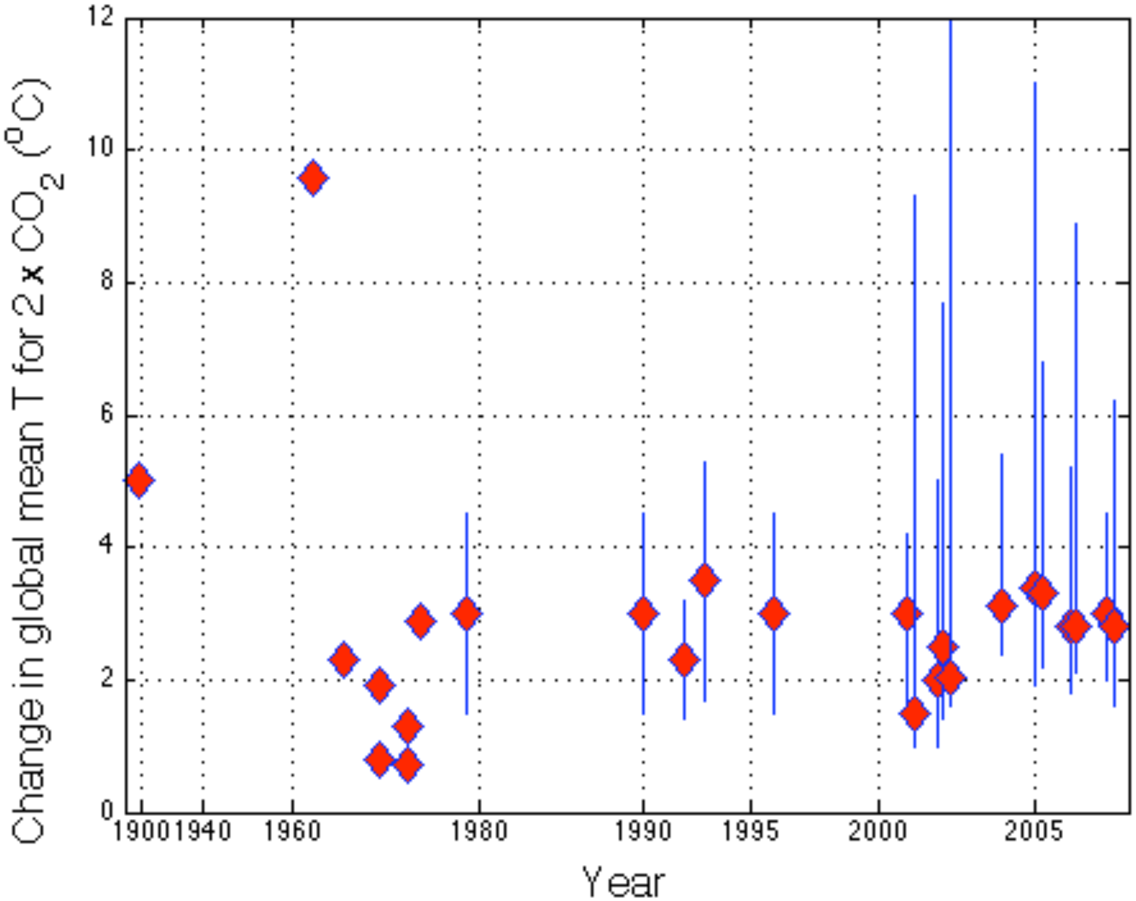
Climate sensitivity: an envelope of uncertainty



• Wide variety of models, methods, and reconstructions.

Climate sensitivity: estimates over time

Climate sensitivity $\equiv$ Equilibrium change in global mean, annual mean temperature given $CO_2 \rightarrow 2 \times CO_2$



1. Arrhenius, 1896
2. Moller, 1963
3. Weatherald and Manabe, 1967
4. Manabe, 1971
5. Rasool and Schneider, 1971
6. Manabe and Weatherald, 1971
7. Sellers, 1974
8. Weare and Snell, 1974
9. NRC Charney report, 1979
10. IPCC1, 1990
11. Hoffert and Covey, 1992
12. IPCC2, 1996
13. Andronova & Schlesinger, 2001
14. IPCC3, 2001
15. Forest et al., 2002
16. Harvey & Kaufmann, 2002
17. Gregory et al., 2002
18. Murphy et al., 2004
19. Piani et al., 2005
20. Stainforth et al., 2005
21. Forest et al., 2006
22. Hegerl et al. 2006
23. IPCC4, 2007
24. Royer et al., 2007

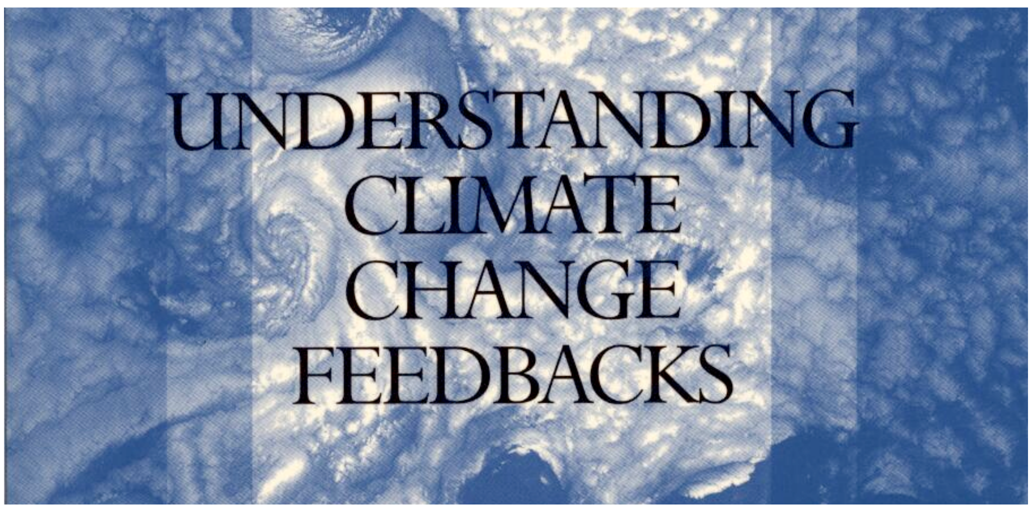
- Why is uncertainty not diminishing with time?

Feedback analysis:

Formal framework for evaluating the strength and relative importance of interactions in a dynamical system.

(Maxwell, 1863; Black, 1927; Hansen et al., 1984; Schlesinger & Mitchell, 1985)

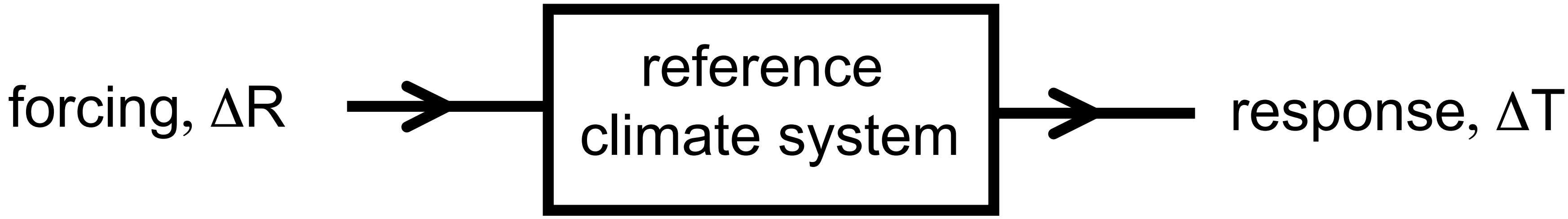
Confusion abounds….



U.S. National Research Council report, 2003

• gets definitions of feedbacks wrong…

Feedback analysis: basics



Climate sensitivity defined by: $\Delta T_0 = \lambda_0 \, \Delta R$

Reference climate system:

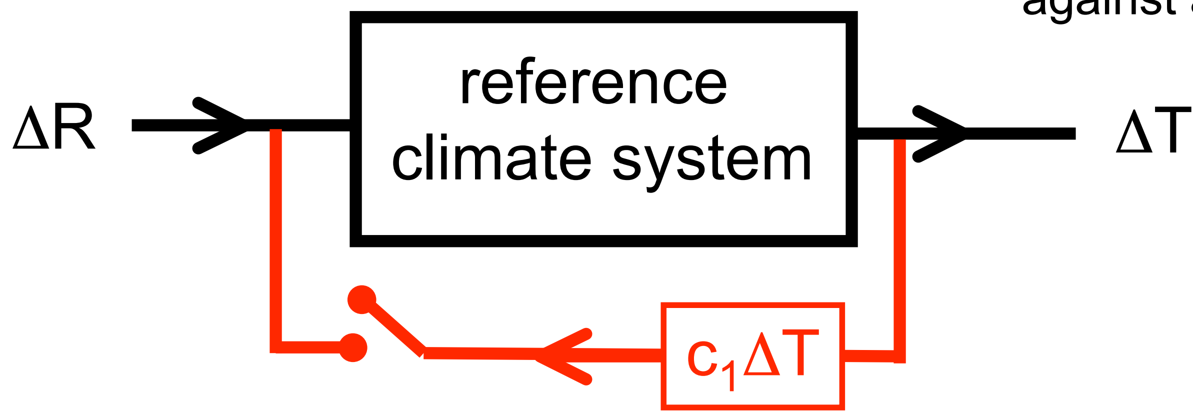
- Blackbody (i.e., no atmosphere).
- Terrestrial flux $= \sigma T^4$ (Stefan-Boltzmann)
- $\lambda_0 = (4\sigma T^3)^{-1} = 0.26$ K $(\mathrm{Wm}^{-2})^{-1}$

$\Rightarrow \Delta T_0 = 1.2\ ^{o}C$ for a doubling of CO_2

Feedback analysis: basics

- def^n: input is a function of the output

(n.b. Feedbacks are only meaningful when defined against a reference state.)



So now $$\Delta T = \lambda_0(\Delta R + \mathbf{c_1 \Delta T})$$

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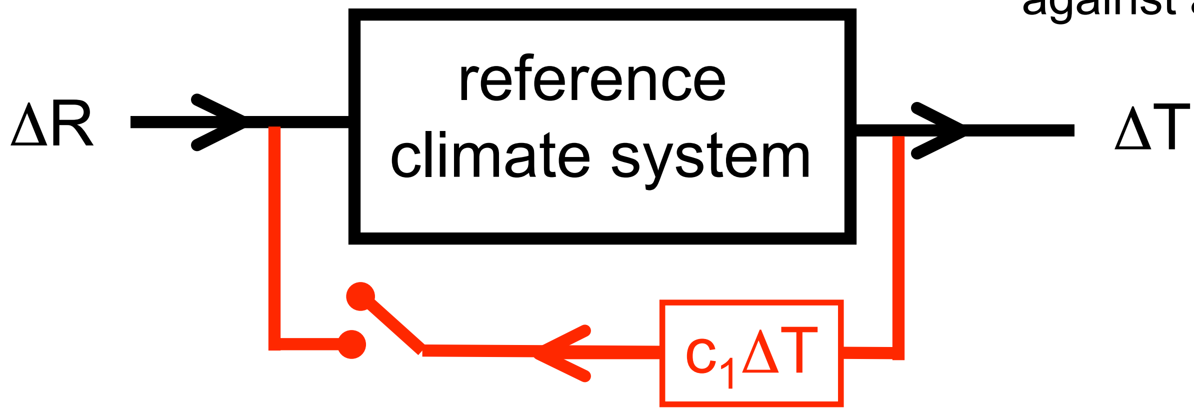

So now

$$\Delta T = \lambda_0(\Delta R + \boxed{c_1\Delta T})$$

Additional rad^n forcing due to system response to ΔR

Feedback analysis: basics

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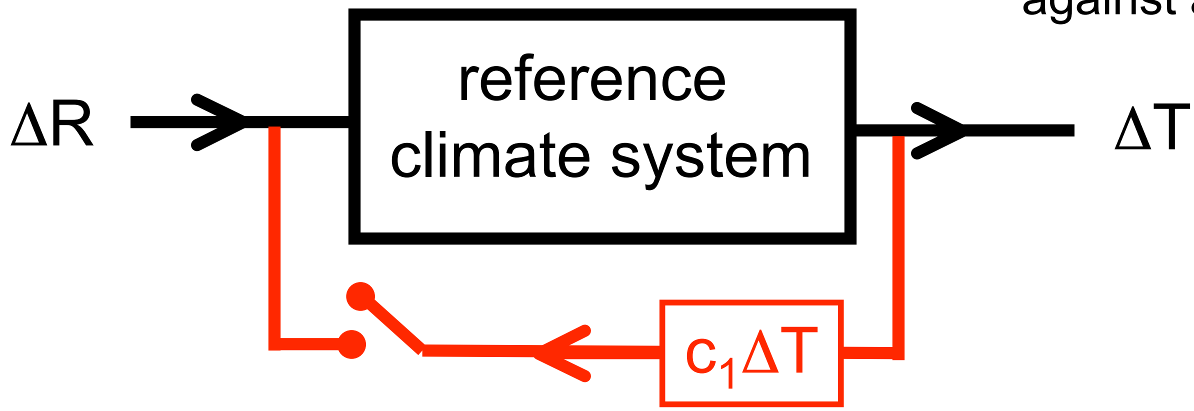


So now

$$\Delta T = \lambda_0(\Delta R + \boxed{c_1\Delta T})$$

Additional rad^n forcing due to system response to ΔR

Rearrange for ΔT

$$\Rightarrow \quad \Delta T = \frac{\lambda_0 \Delta R}{1 - c_1\lambda_0}$$

Feedback analysis: technobabble

$\boxed{\text{Feedback factor}}$: $f = c_1\lambda_0$ (f $\propto$ to fraction of output *fed back* into input)

$$\boxed{\text{Gain}} = \frac{\text{response with feedback}}{\text{response without feedback}} = \frac{\Delta T}{\Delta T_0}$$

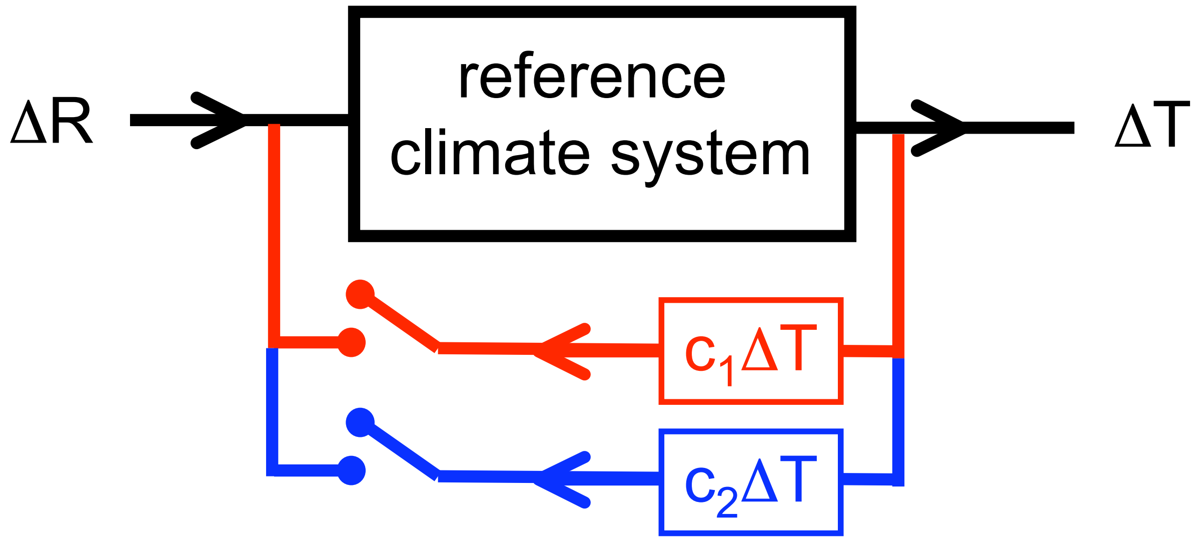
(Gain is proportion by which system has *gained*)

From before $$\Delta T = \frac{\lambda_0 \Delta R}{1 - c_1\lambda_0} = \frac{\Delta T_0}{1 - f}$$

And since $\Delta T = G\Delta T_0$:

$$\boxed{G = \frac{1}{(1 - f)}}$$

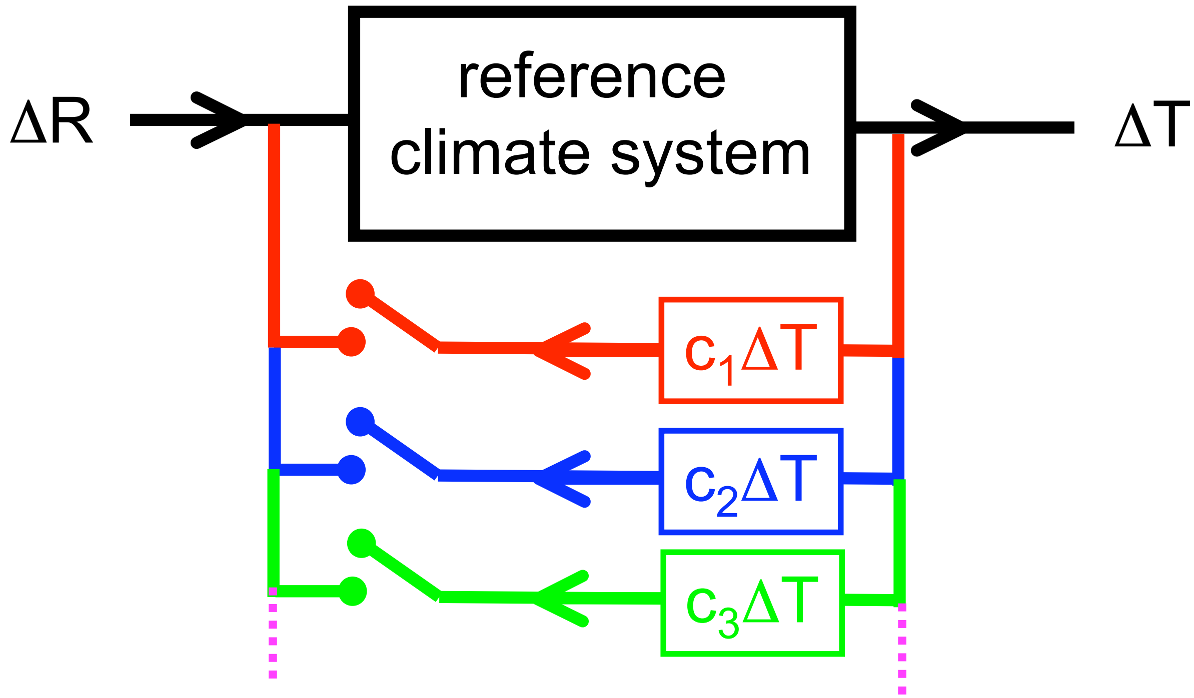
Feedback analysis: more than one feedback



Now have $$\Delta T = \lambda_0(\Delta R + \mathbf{c_1\Delta T} + \mathbf{c_2\Delta T})$$ (two nudges)

Gives: $$\Delta T = \frac{\lambda_0}{1 - c_1\lambda_0 - c_2\lambda_0}\Delta R$$

Feedback analysis: more than one feedback



And so in general for N feedbacks:

$$G = \frac{\Delta T}{\Delta T_0} = \frac{1}{1 - \sum_{i=1}^{N} f_i}$$

Climate feedbacks: calculating from models

Want to consider effect of variations in:
a) water vapor; b) clouds; c) sea-ice; d) snow cover; etc..

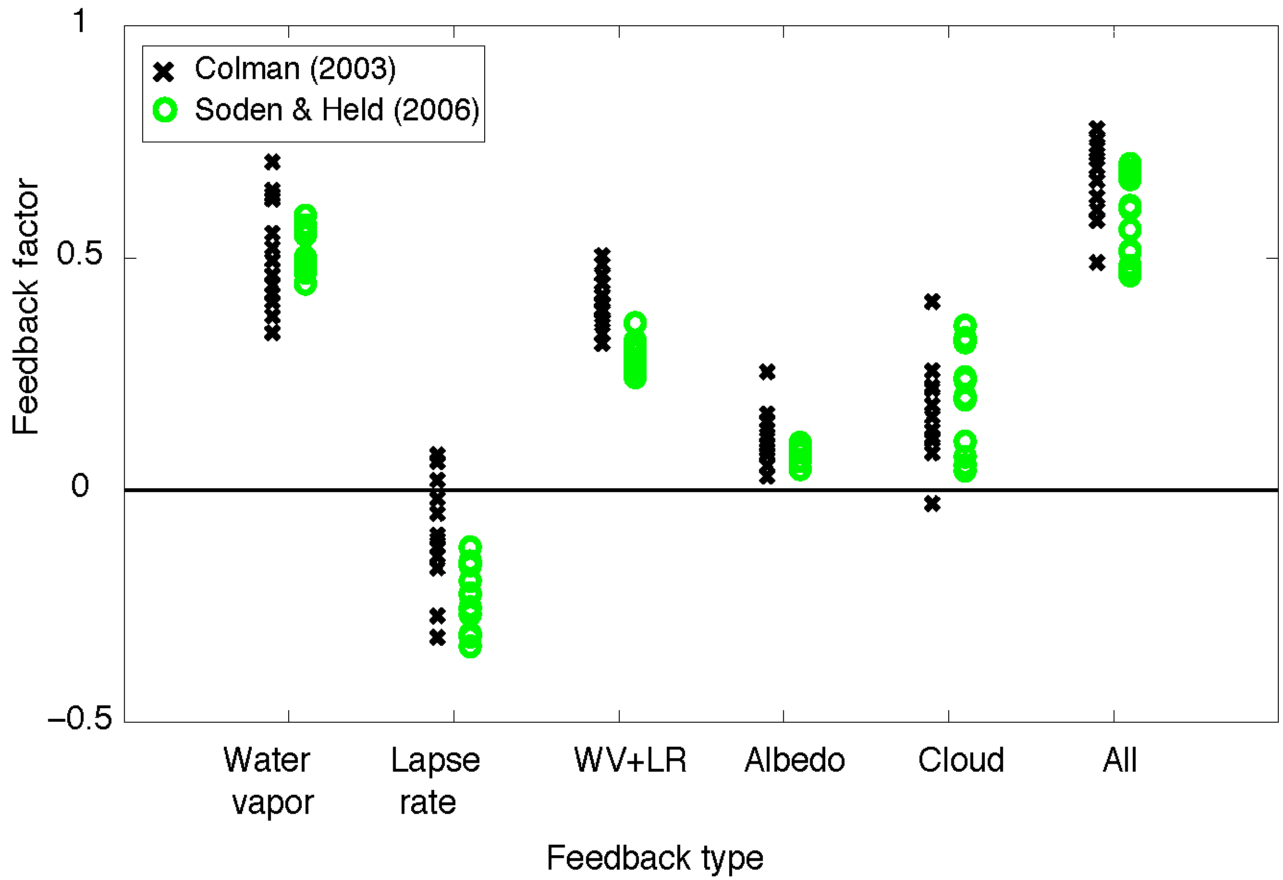
For i^{th} climate variable:
$$c_i \Delta T = \delta R\Big)_{j,\, j\neq i} = \frac{\partial R}{\partial \alpha_i}\Bigg)_{j,\, j\neq i} \frac{d\alpha_i}{dT} \Delta T$$

So feedback factors:
$$f_i \approx \lambda_0 \frac{\Delta R}{\Delta \alpha_i}\Bigg)_{j,\, j\neq i} \cdot \frac{\Delta \alpha_i}{\Delta T}$$

α_i - can be a lumped property (like clouds, sea ice, etc.),
- or individual model parameter (like entrainment coefficient)
- can also calculate spatial variations in f_i if desired.

Climate feedbacks: estimating from models

From suites of GCMS:



Individual feedbacks uncorrelated among models, so can be simply combined:

Soden & Held (2006):

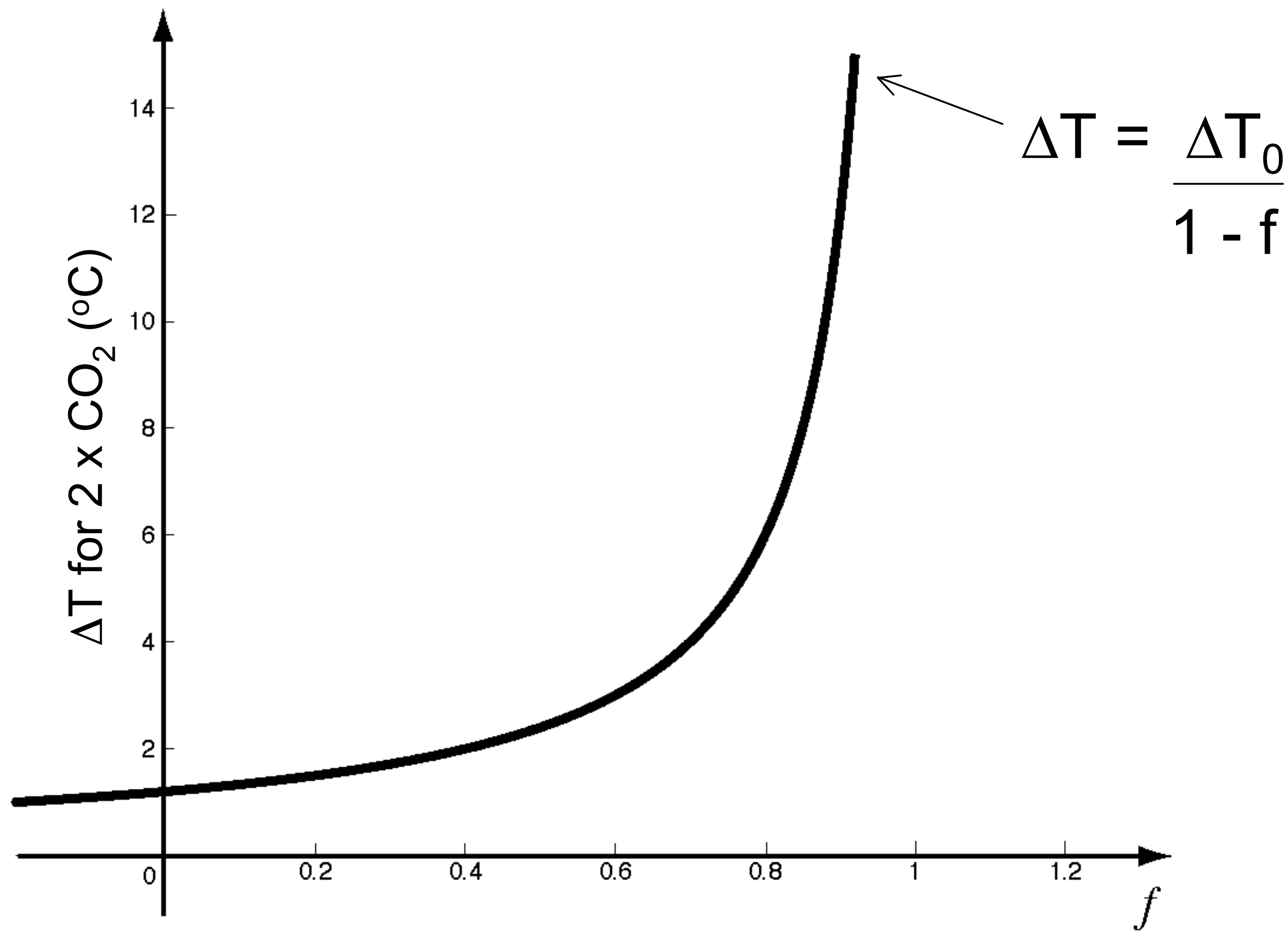
$\bar{f} = 0.62; \sigma_f = 0.13$

Colman (2003):

$\bar{f} = 0.70; \sigma_f = 0.14$

- How does this uncertainty in physics translate to uncertainty in climate sensitivity?

Uncertainty: it all depends on where you are.



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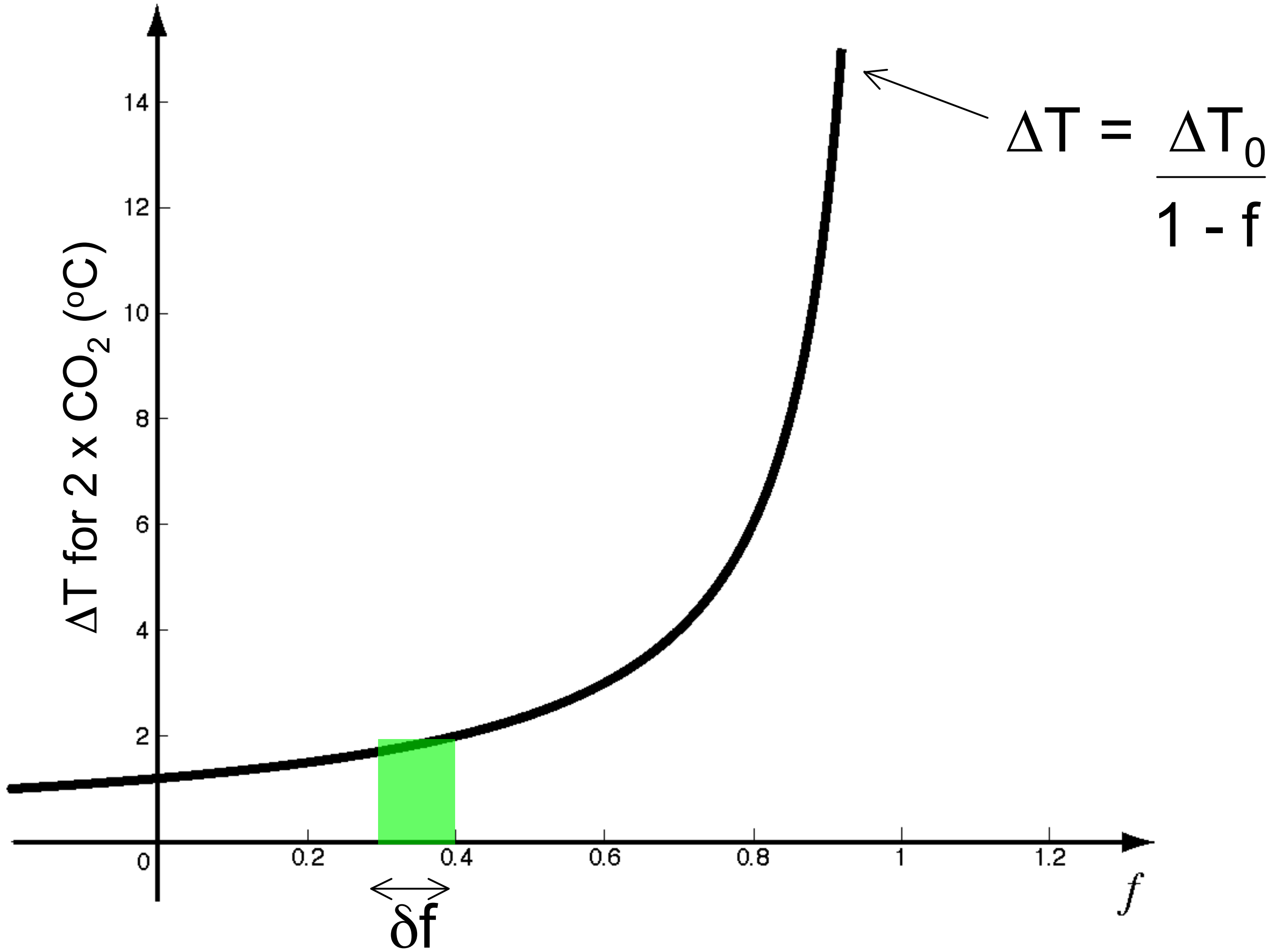

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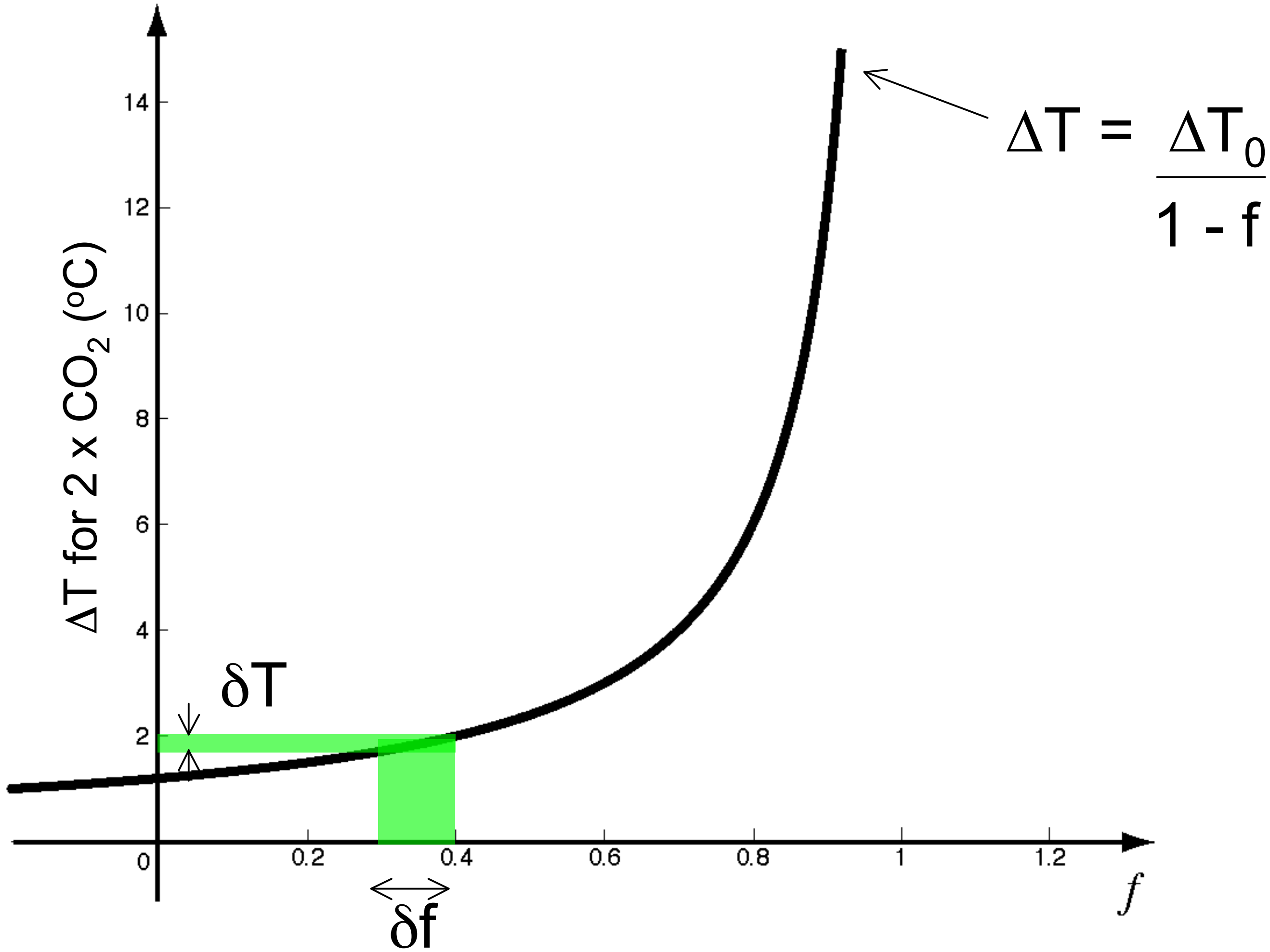

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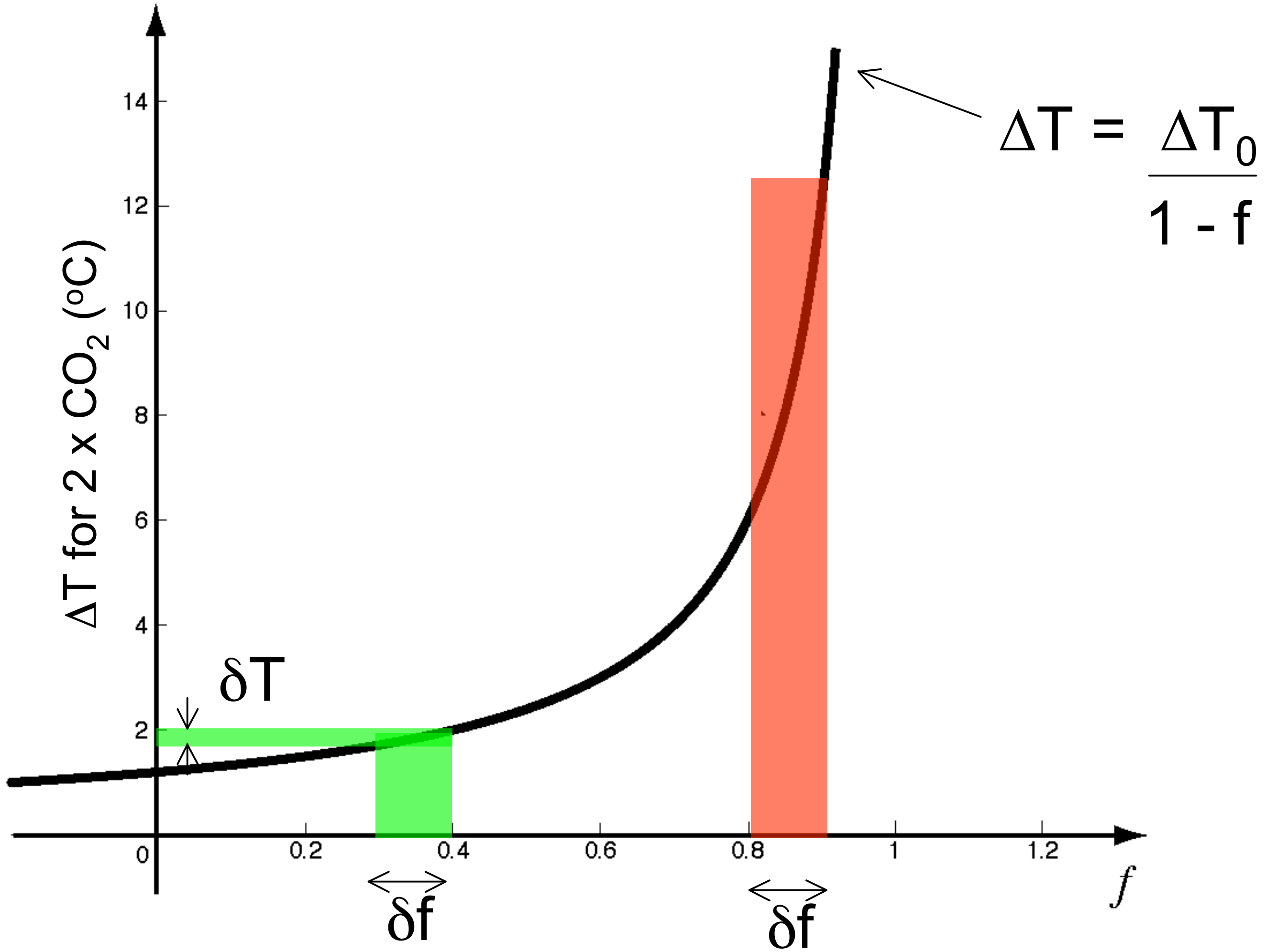

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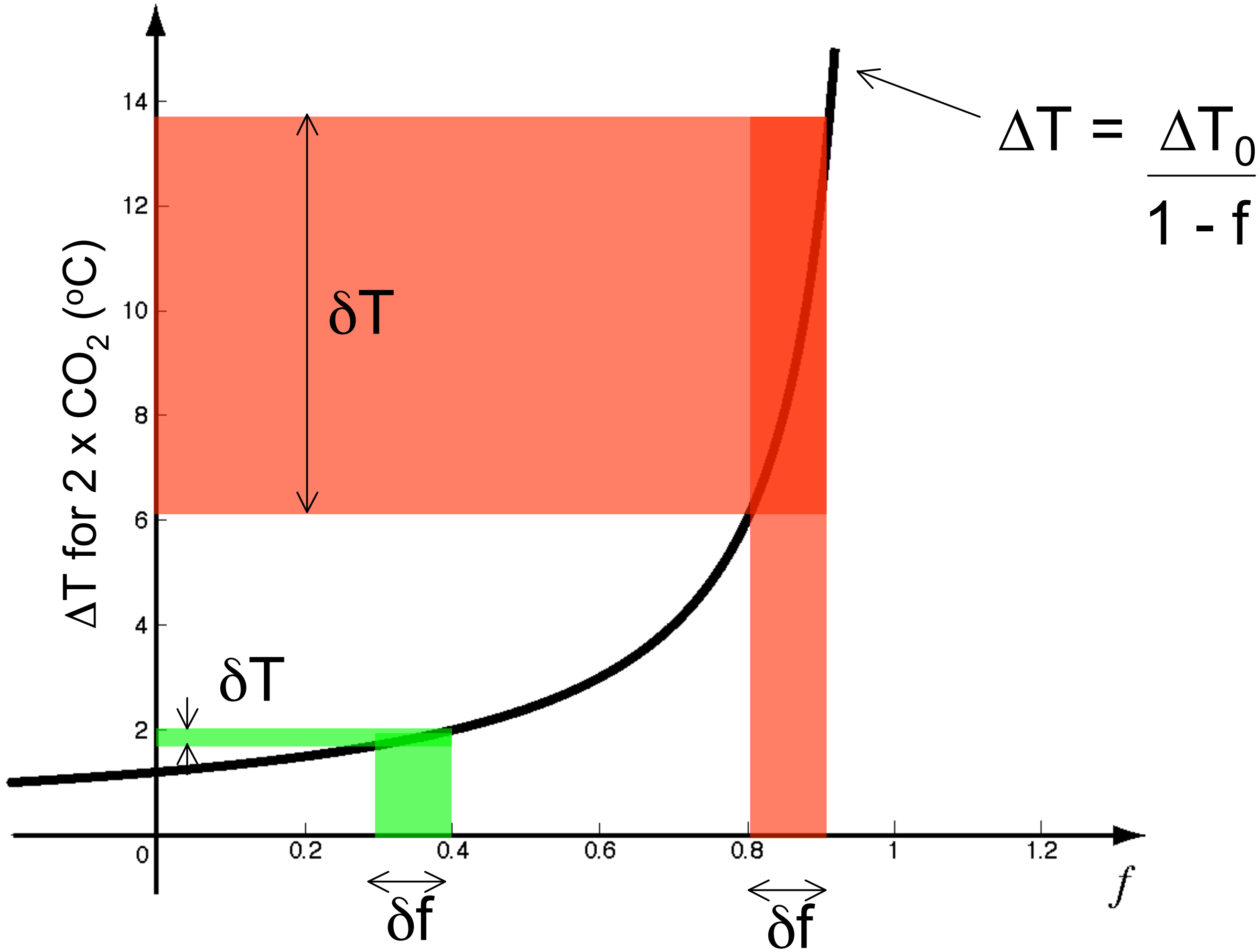

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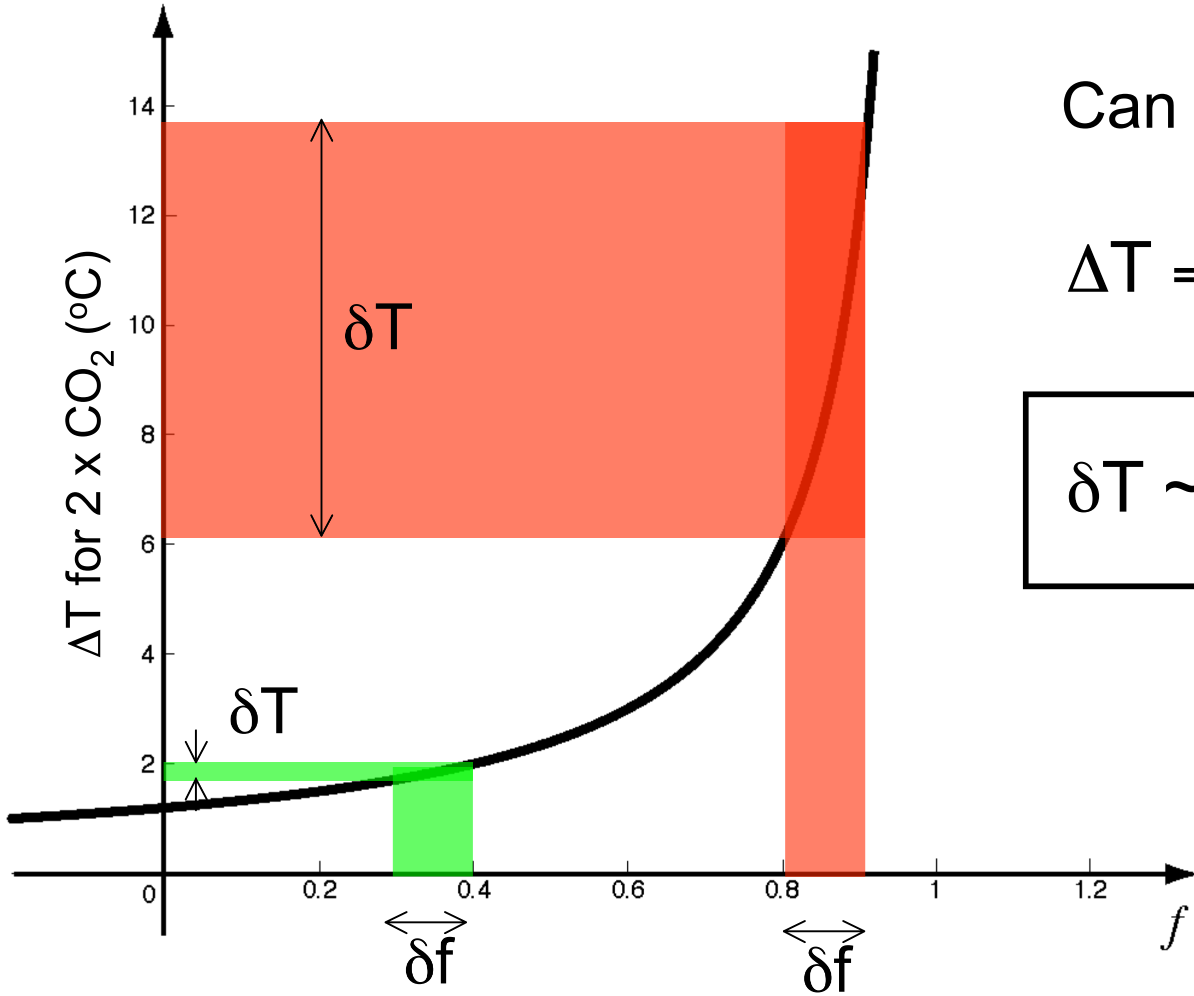


Can show:

$$\Delta T = G \cdot \Delta T_0$$

$$\boxed{\delta T \sim G^2 \cdot \Delta T_0 \cdot \delta \bar{f}}$$

• Uncertainty in climate sensitivity strongly dependent on the gain.

Climate sensitivity: the math

Let pdf of uncertainty in feedbacks $h_f(f)$: $h_f(f)$

Also have: $$\Delta T(f) = \frac{\Delta T_0}{1-f}$$

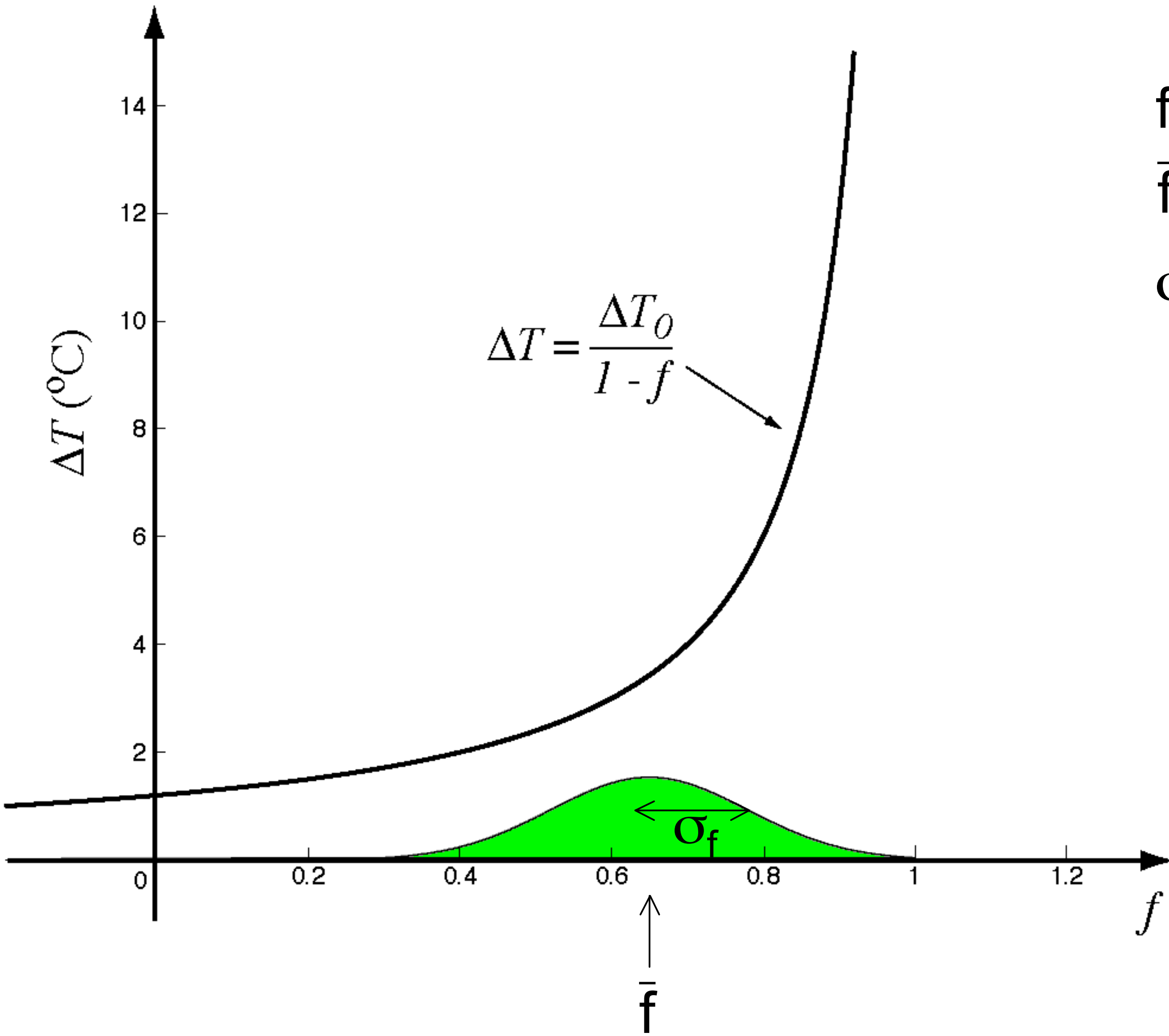
So can write: $$h_{\Delta T}(\Delta T) = h_f(f) \cdot \frac{df}{d(\Delta T)} = \frac{\Delta T_0}{\Delta T^2} \cdot h_f\left(1 - \frac{\Delta T_0}{\Delta T}\right)$$

Assume Gaussian h(f): $$h_f(f) = \frac{1}{\sigma_f \sqrt{2\pi}} \cdot \exp\left[-\frac{1}{2}\left(\frac{f-\bar{f}}{\sigma_f}\right)^2\right]$$

Gives

$$\boxed{h_{\Delta T}(\Delta T) = \frac{1}{\sigma_f \sqrt{2\pi}} \cdot \frac{\Delta T_0}{\Delta T^2} \cdot \exp\left[-\frac{1}{2}\left(\frac{1-\bar{f}-\Delta T/\Delta T_0}{\sigma_f}\right)^2\right]}$$

Climate sensitivity: the picture

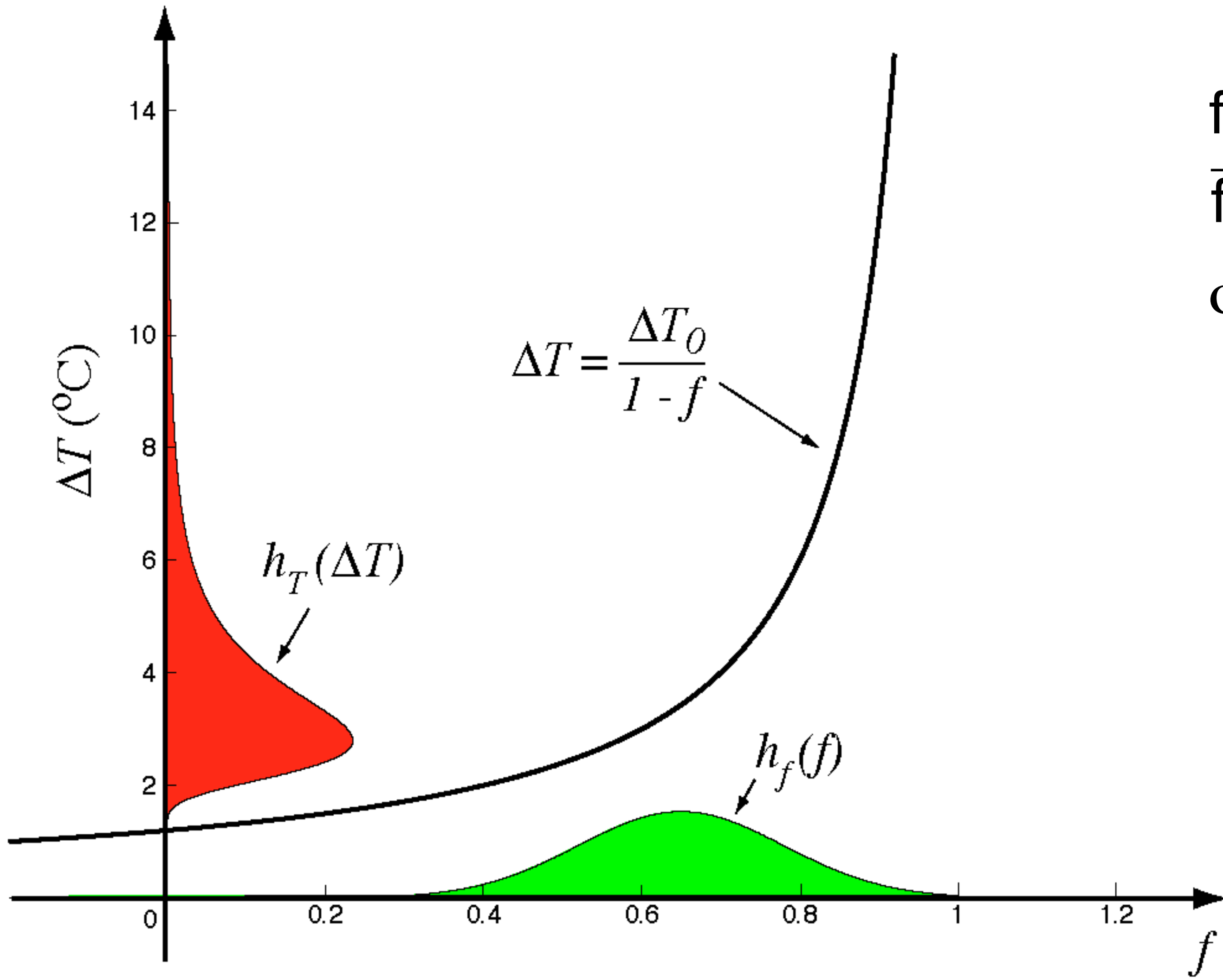


for:

$\bar{f} = 0.65$

$\sigma_f = 0.14$

Climate sensitivity: the picture



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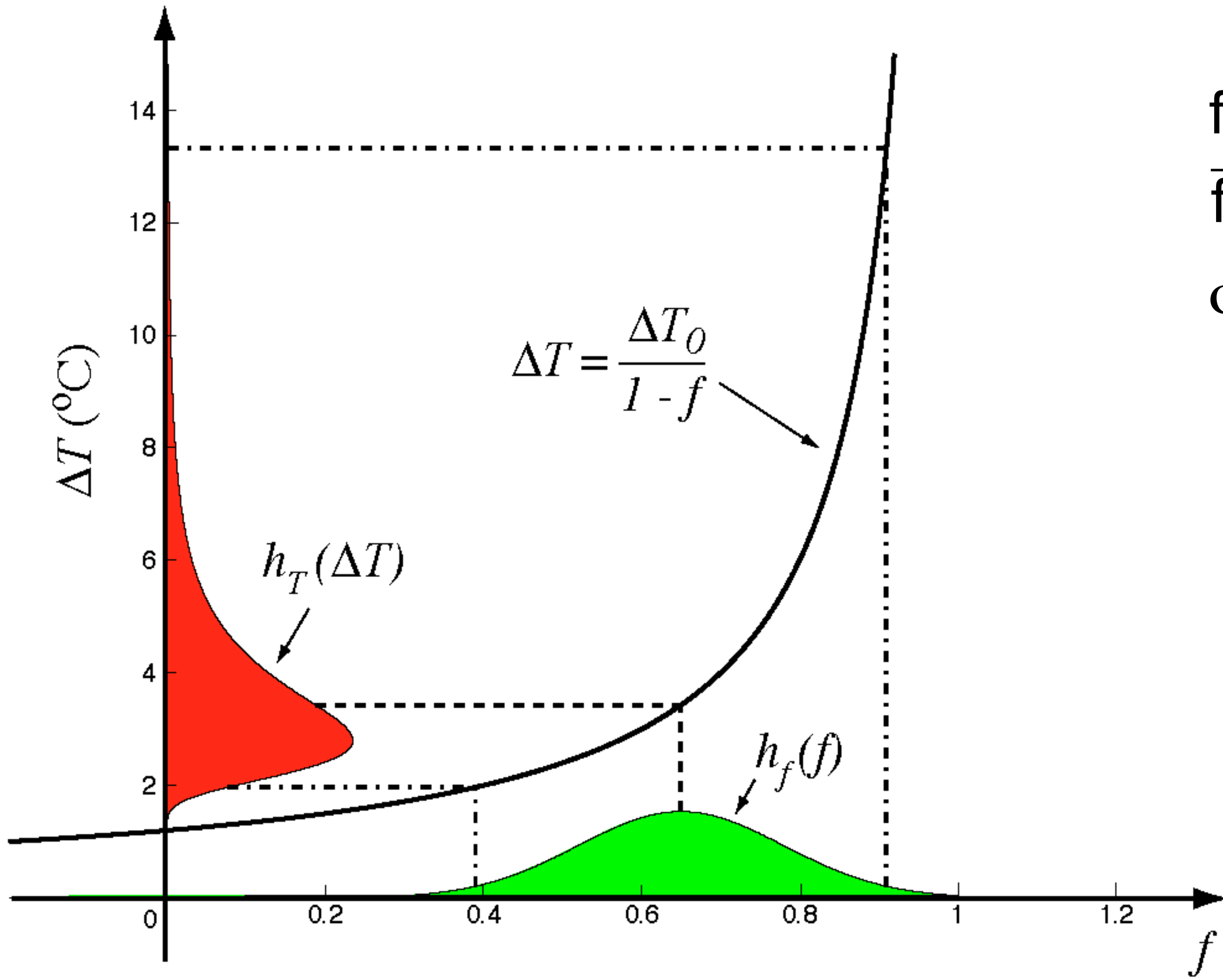
Climate sensitivity: the picture



for:

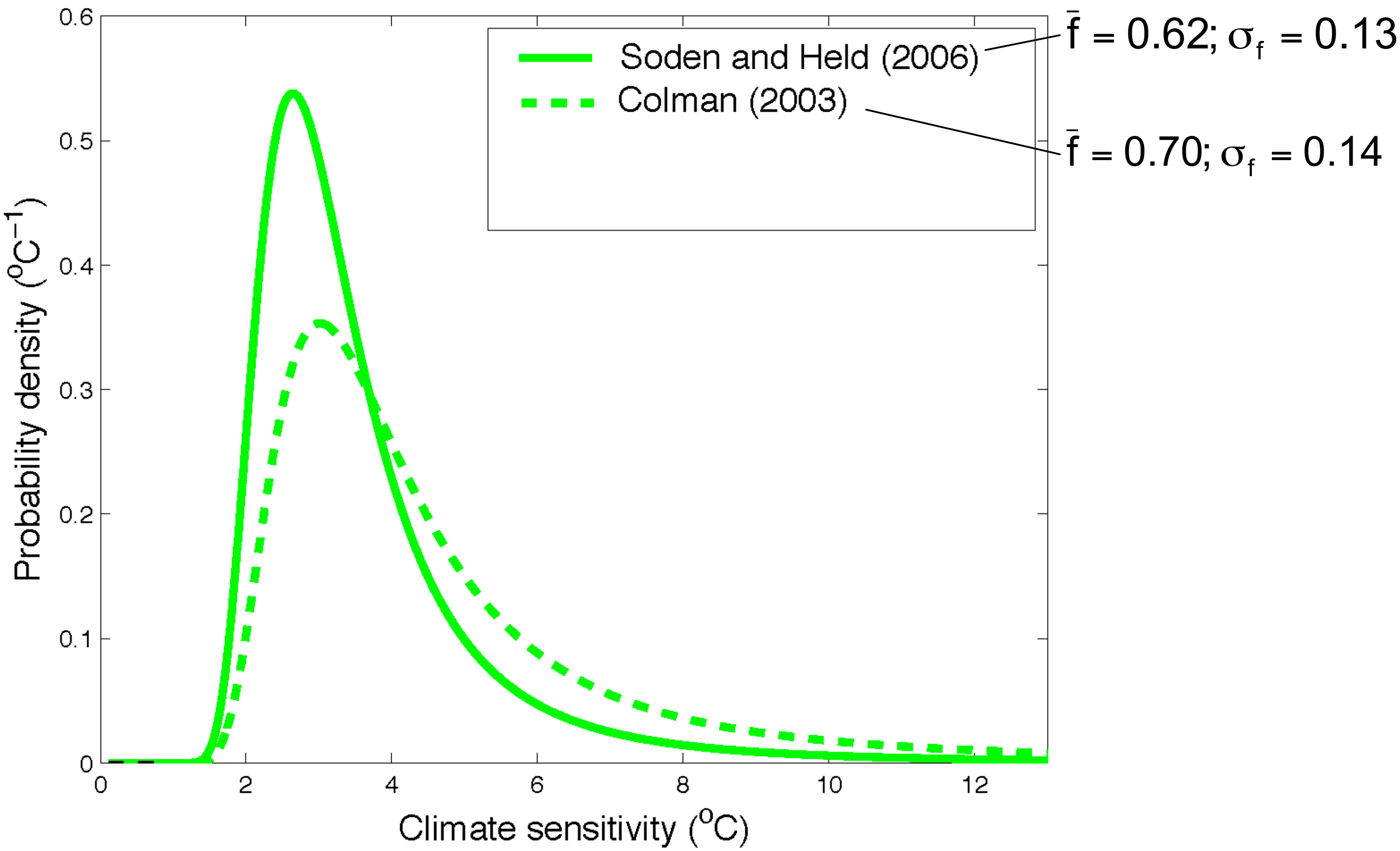
$\bar{f}$ = 0.65

σ_f = 0.14

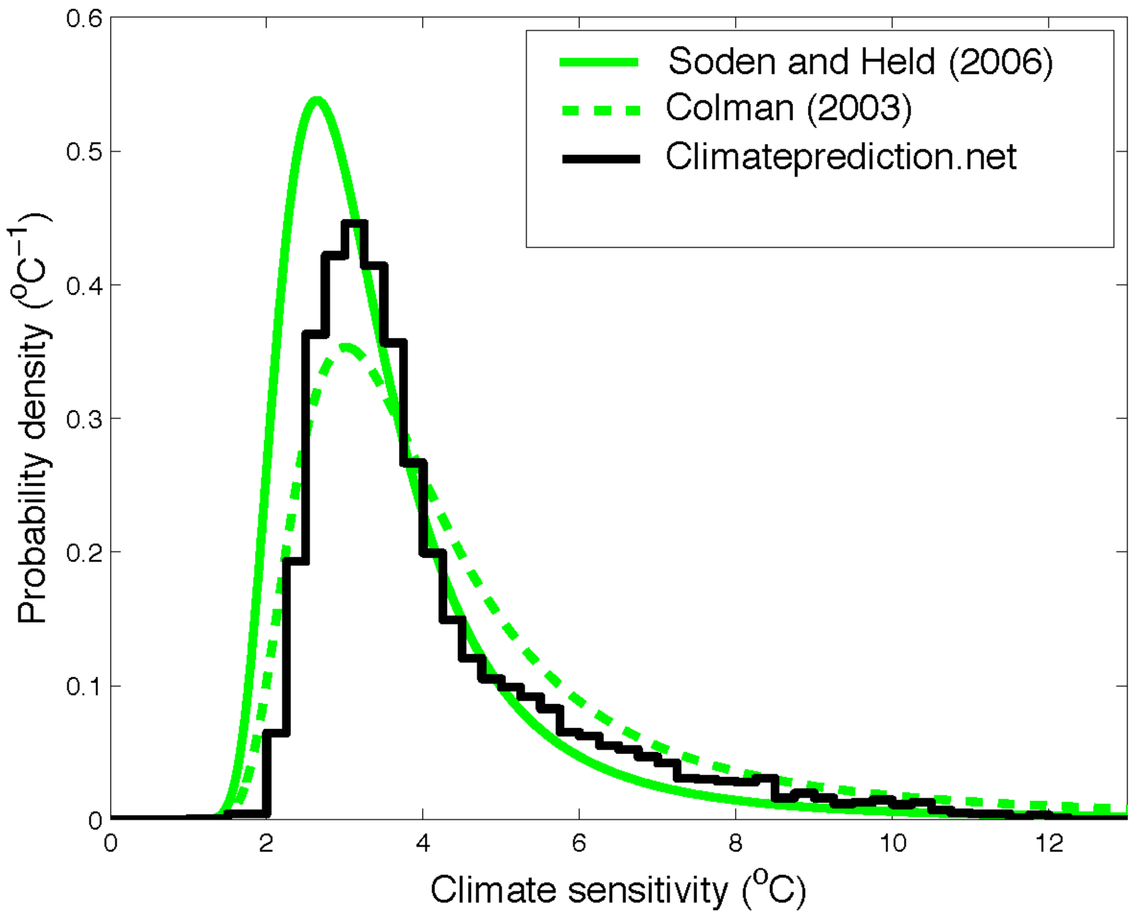
- Skewed tail of high climate sensitivity is inevitable!

<u>Climate sensitivity:</u>

GCM from linear sum of feedback factors



Climate sensitivity:
comparison with climateprediction.net



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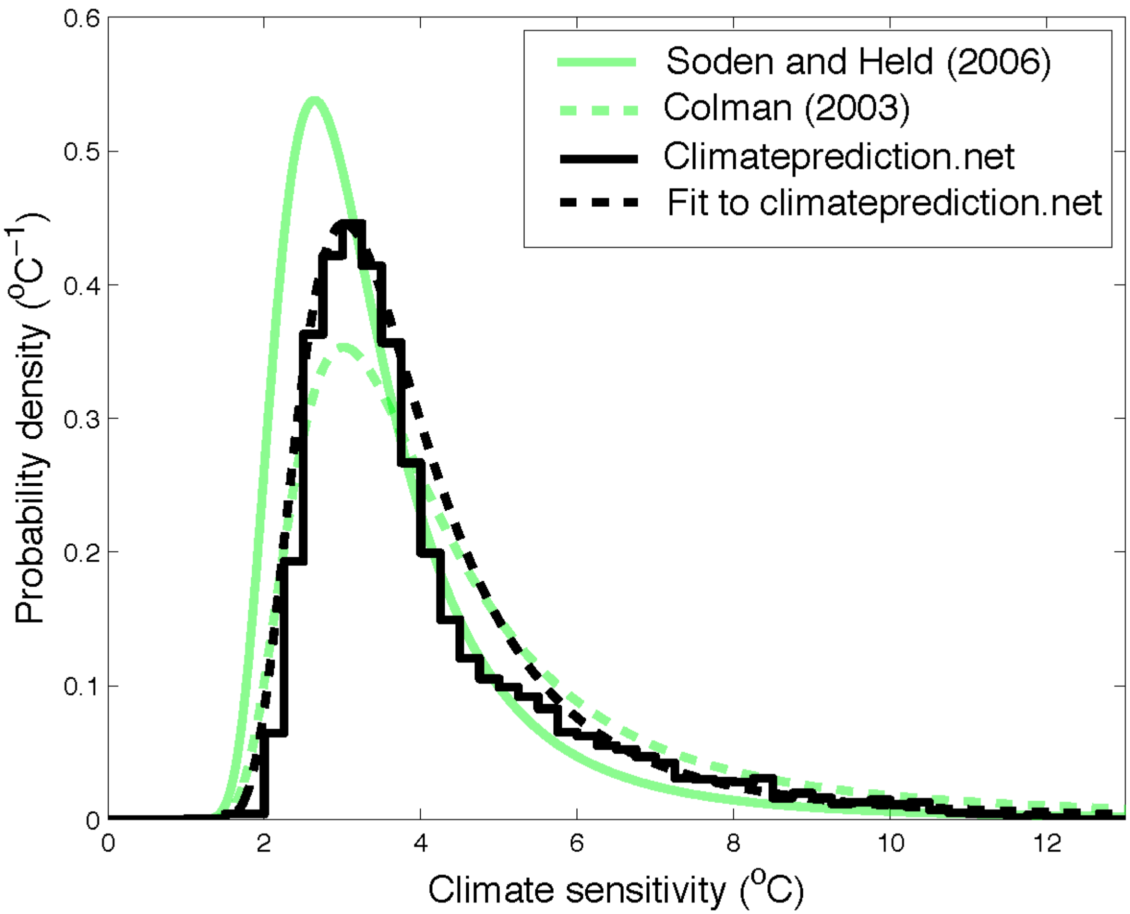
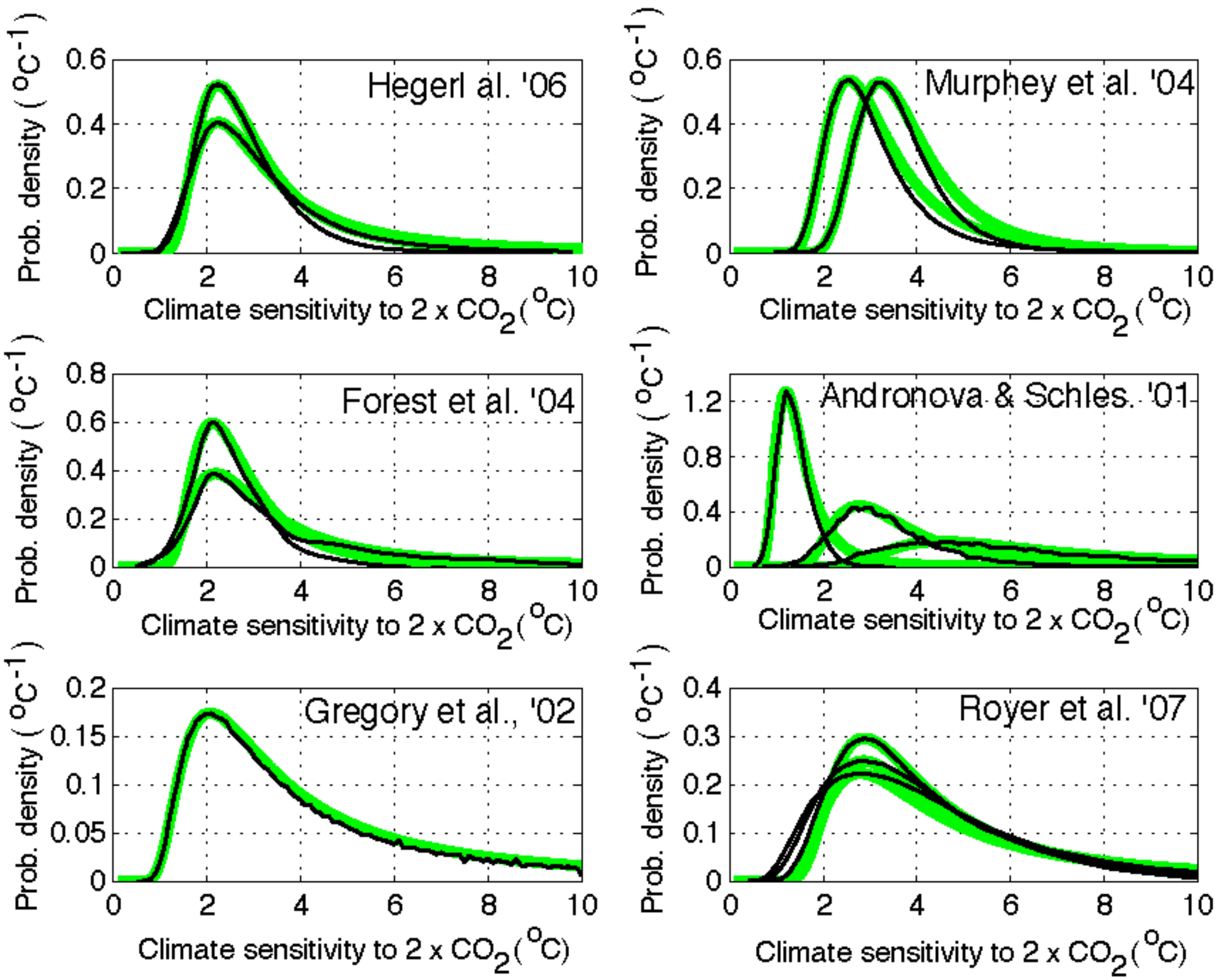


- GCMs produce climate sensitivity consistent with the compounding effect of essentially-linear feedbacks.

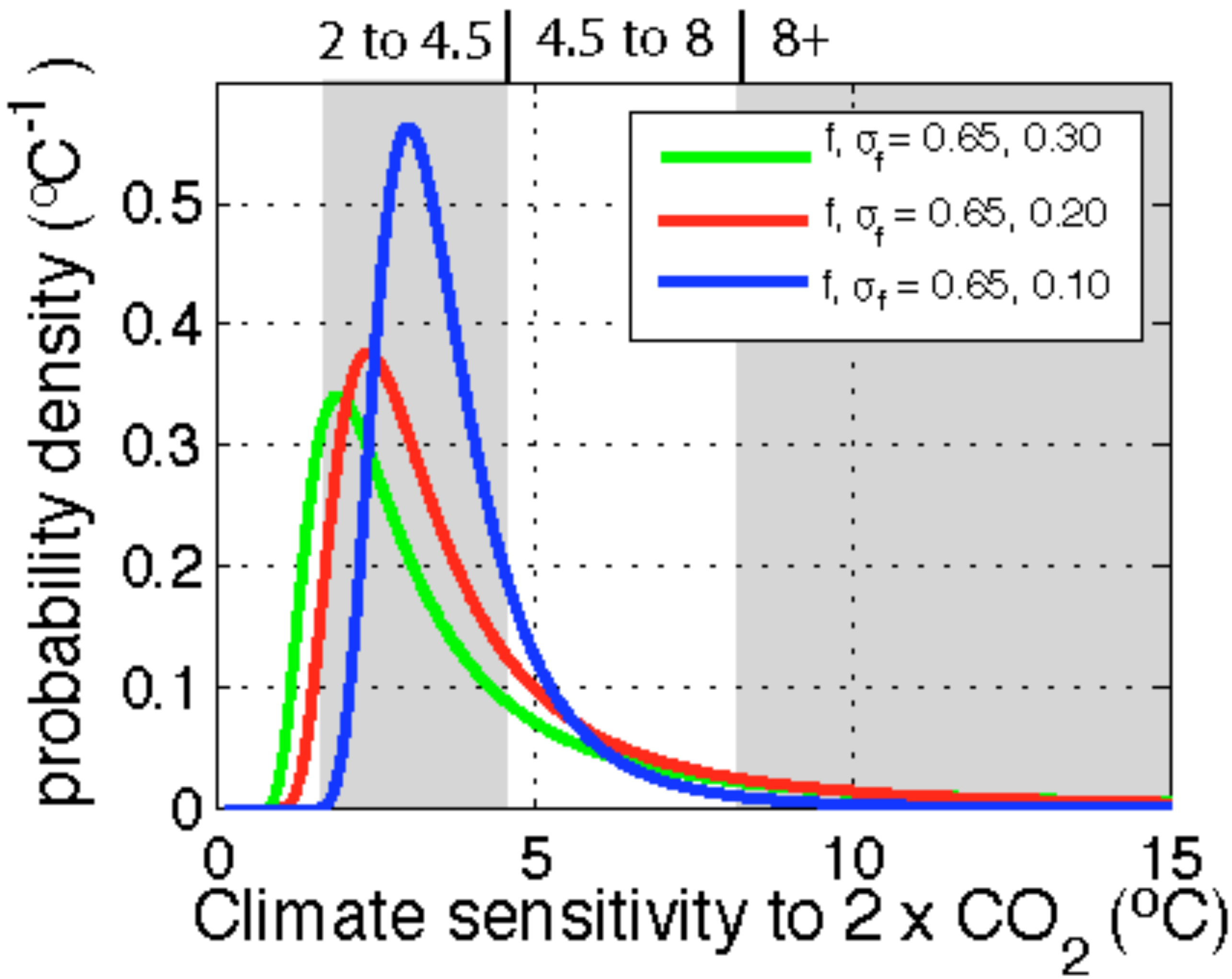
Climate sensitivity: comparison with studies



- $h_{\Delta T}(\Delta T)$ works pretty well.

Climate sensitivity: can we do better?

- How does uncertainty in climate sensitivity depend on σ_f?



Climate sensitivity: can we do better?

$\bar{f}, \sigma_f$ \ ΔT	2 to 4.5 ^oC	4.5 to 8 ^oC	> 8 ^oC
0.65, 0.3	29%	14%	13%
0.65, 0.2	43%	18%	12%
0.65, 0.1	55%	20%	8%
0.65, 0.05	95%	5%	0%

science is here

need to get here!

- Not much change as a function of σ_f

Climate sensitivity: can we do better?

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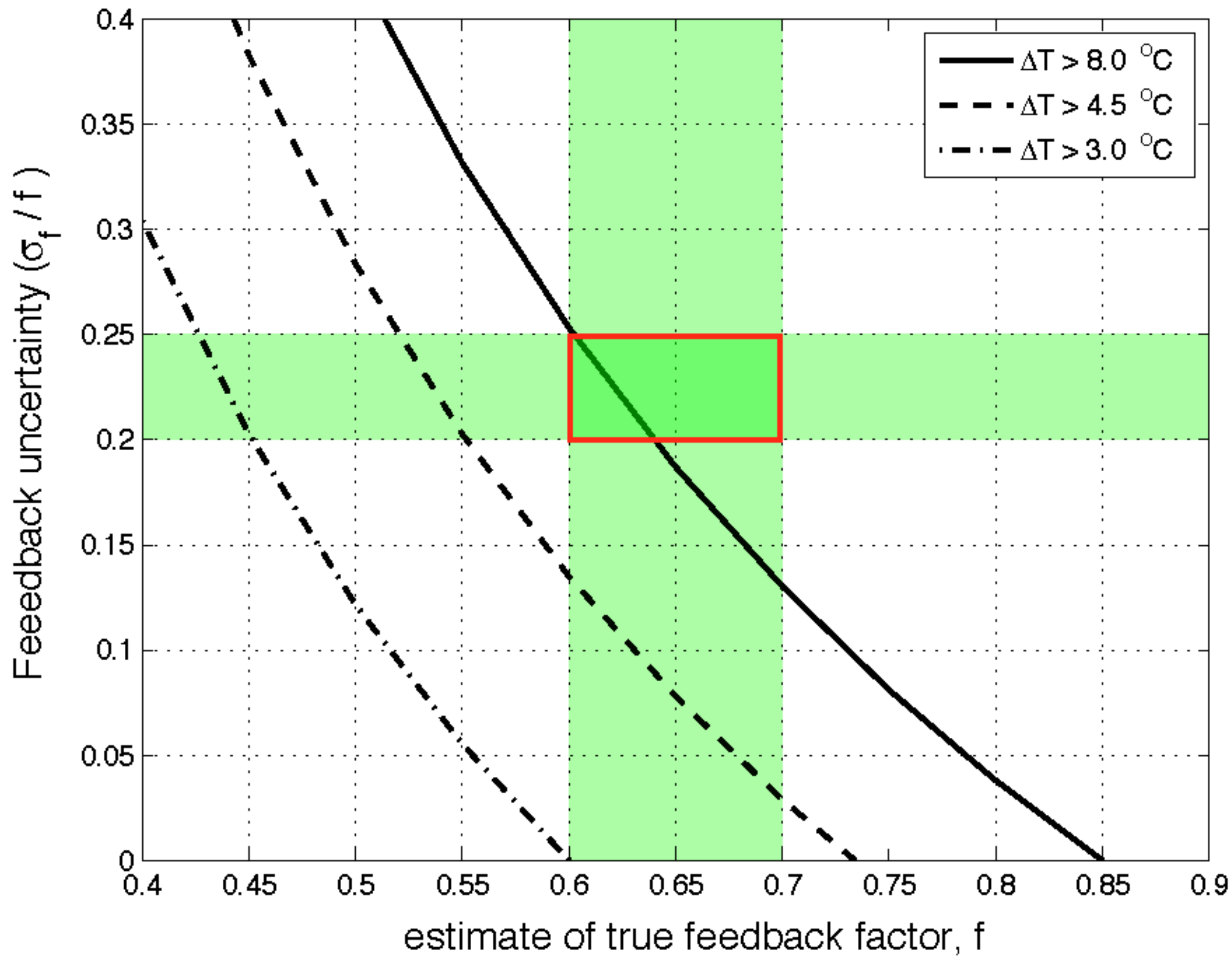
Climate sensitivity: can we do better?

• Combination of mean feedback and uncertainty at which a given climate sensitivity can be rejected.



• Need to get cross hairs below a given line to reject that ΔT with 95% confidence

Summary:

- Climate change is unpredictable because climate change is inescapable.

    Uncertainty is inherent is a system where the feedbacks are substantially positive.

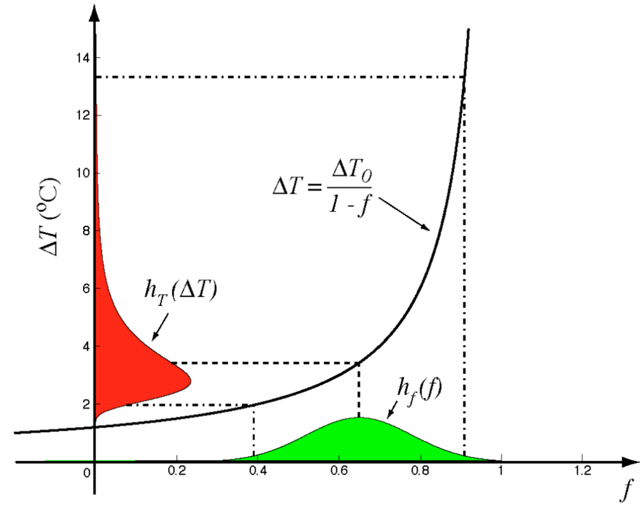
- The unpredictability of climate is predictable.

    Compounding effect of essentially linear feedbacks dominates system sensitivity.

- If you know the feedback factors, and their uncertainties, don’t need10^4 GCMs (or 10^7 model years!).

    Results suggest a simple relationship between forcing, feedbacks, and response

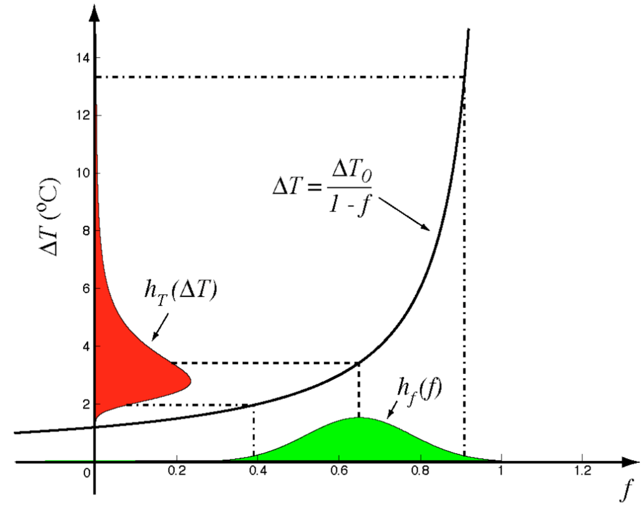
What's right about this?



- Very likely accounts for skewed tail of climate sensitivity pdfs.

- From a modeling perspective, reducing uncertainties model parameters have limited effect on reducing uncertainty in climate sensitivity.

What’s wrong about this?



- h(f) cannot strictly be Gaussian.

  not a big deal, any reasonable h(f) will do.

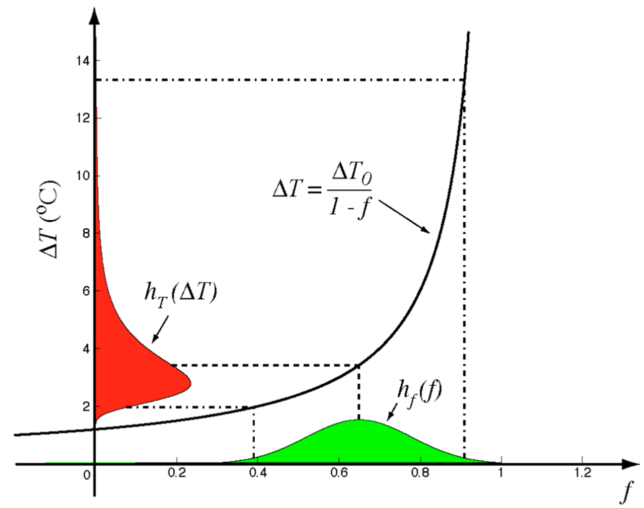
- feedback framework is a linear analysis

  in a very nonlinear world.

- conclusions come from a modeling perspective.

  o*bservations of what actually happens have not been used*!

<u>Where does our uncertainty in f come from?</u>



1. Ignorance?!

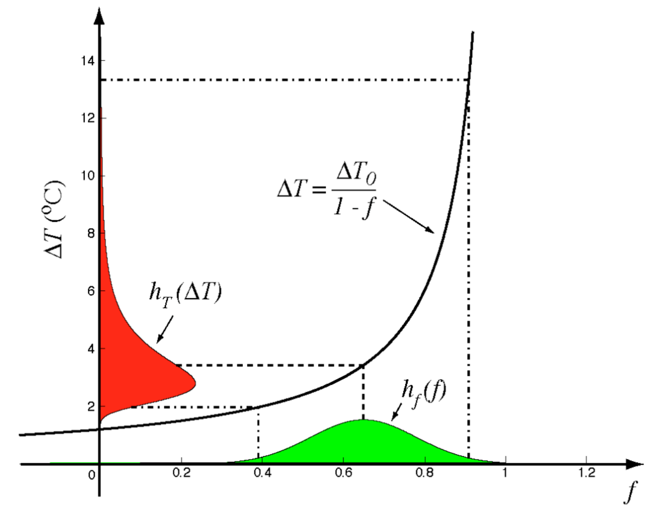
2. Nonlinearities in climate feedbacks

From basic analysis: $$\Delta R = \frac{dR}{dT}\Delta T + O(\Delta T^2)$$

But can take quadratic terms… $$\Delta R = \frac{dR}{dT}\Delta T + \frac{1}{2}\frac{d^2R}{dT^2}\Delta T^2 + O(\Delta T^3)$$

giving… $$\boxed{G = \frac{1}{1 - f - \frac{\Delta T}{2}\frac{df}{dT}}}$$

<u>Where does our uncertainty in f come from?</u>

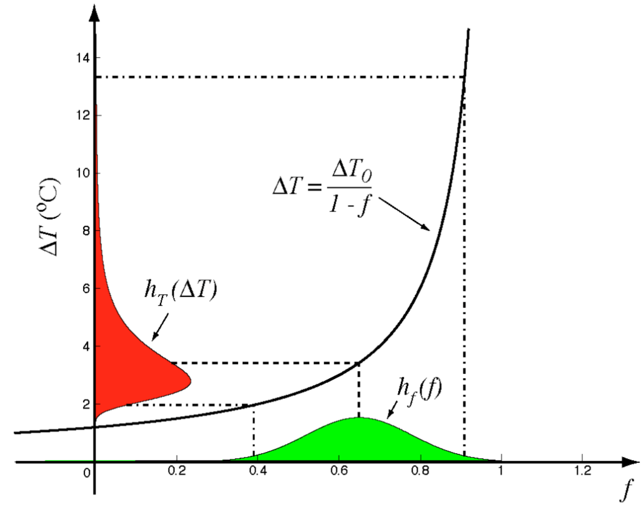


2. Nonlinearities in climate feedbacks.

- *Stefan-Boltzmann, Clausius-Clapeyron nonlinearities give δf ~0.02 for ΔT~ 4°C.*

- *Colman et al. (1997) nonlinearities in water vapor, clouds, and lapse rate feedbacks, giving δf ~0.1 for ΔT = 4°C.*

Where does our uncertainty in f come from?



3. Climate sensitivity varies with mean state.

- *Senior and Mitchell (2000) climate sensitivity <u>increases</u> 20% under a global warming scenario.*
- *Boer and Yu (2003) climate sensitivity <u>decreases</u> 10 to 20%.*
- *Crucifix (2006) different models have very different changes in sensitivity between LGM and modern climates.*

4. Chaotic climate system.

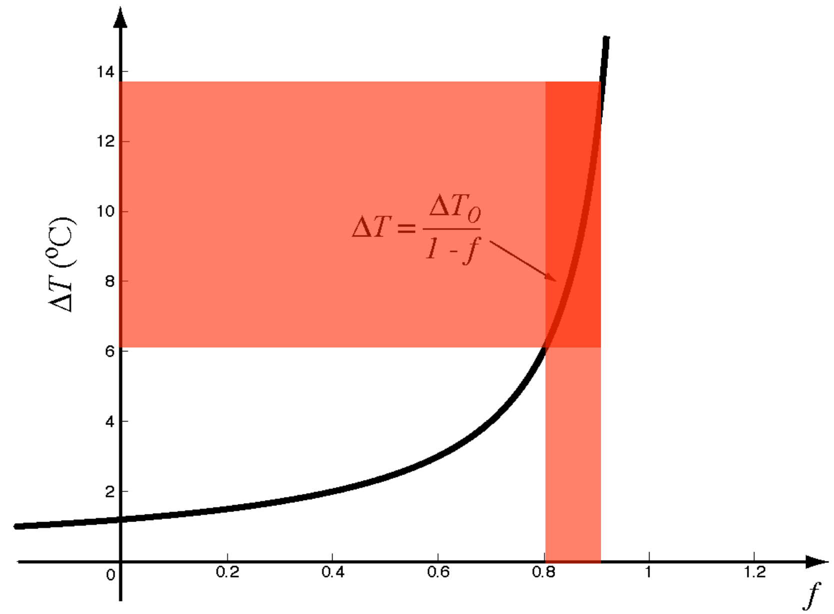
- *Lea et al. (2005); Knight et al. (2007) suggest small but identifiable effects.*

Other approaches:

Using observations

(Allen et al., 2007)

$$\lambda \sim \frac{\Delta T}{\boxed{\Delta R}} \sim \frac{\lambda_0}{1-\Sigma \boxed{f_i}}$$



Uncertainties in observables, ΔR, f_i, give only limited information about high end of the tail…

Combining different estimates

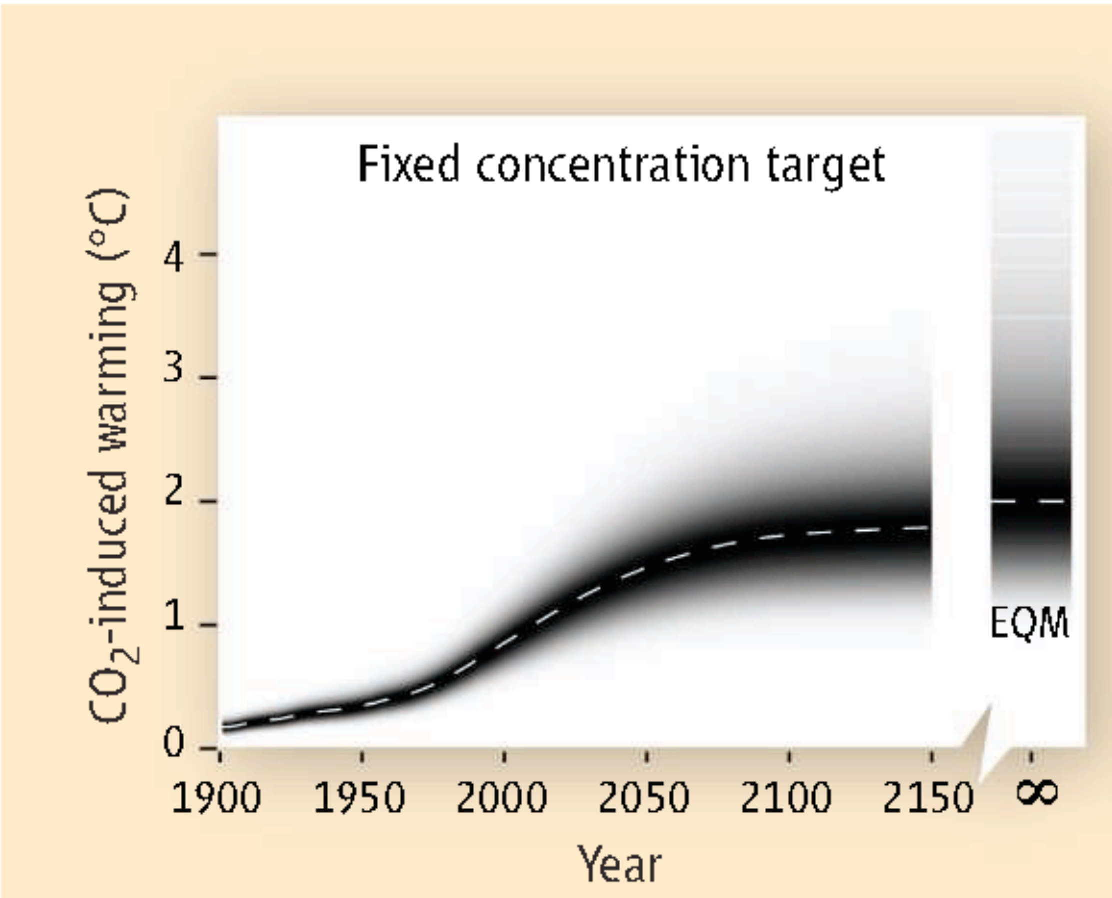
(e.g. Annan & Hargreaves, 2006; Crucifix, 2006; Sherwood & Forest, 2007)

Bayesian estimates:-

depends very sensitively on prior assumptions,

and the independence of different information.

Constraining climate sensitivity is not terribly relevant for projecting climate change…

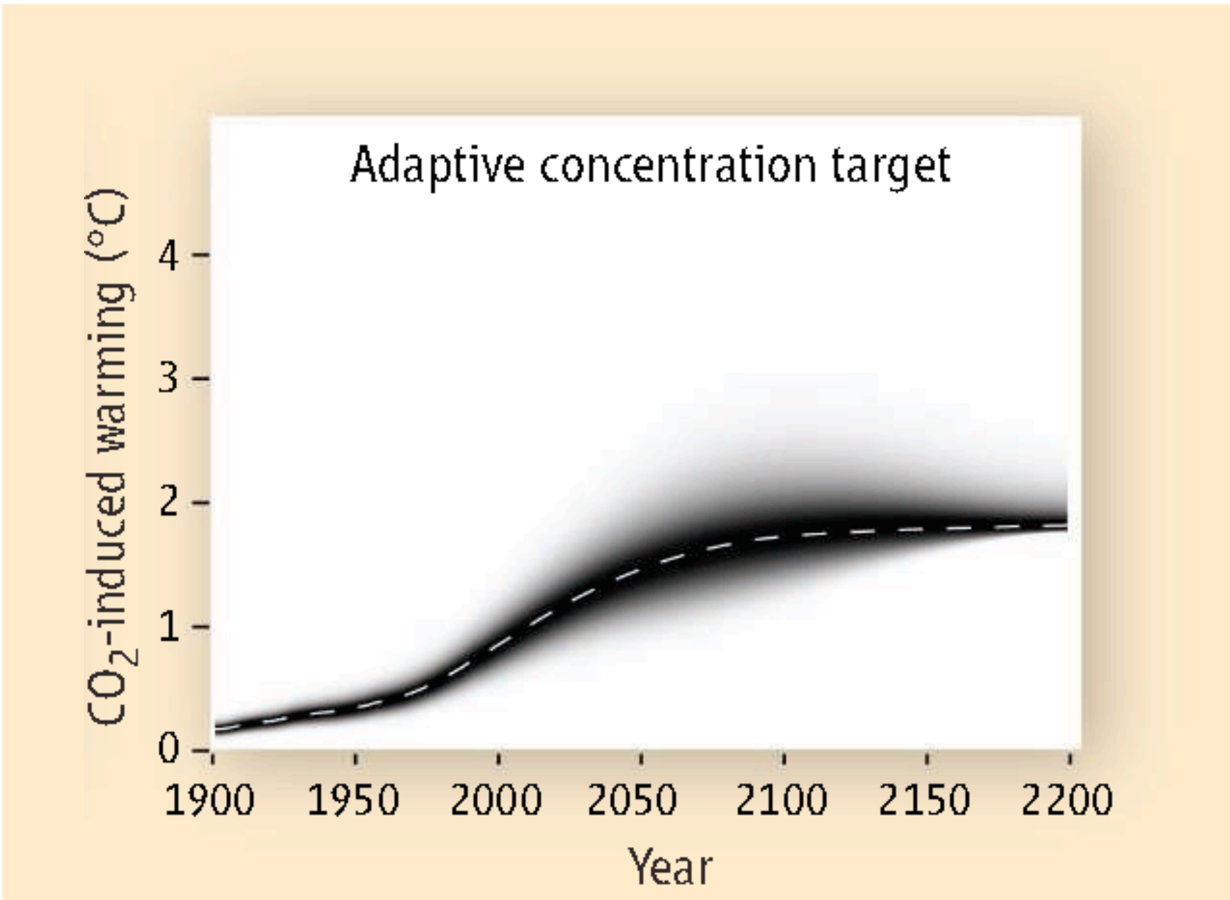


(Allen and Frame, 2007)

Stabilization target of 450 ppm at 2100

High end sensitivities take a long, long time to be realized…

Constraining climate sensitivity is not terribly relevant for projecting climate change…



(Allen and Frame, 2007)

Concentration target adjusted at 2050.

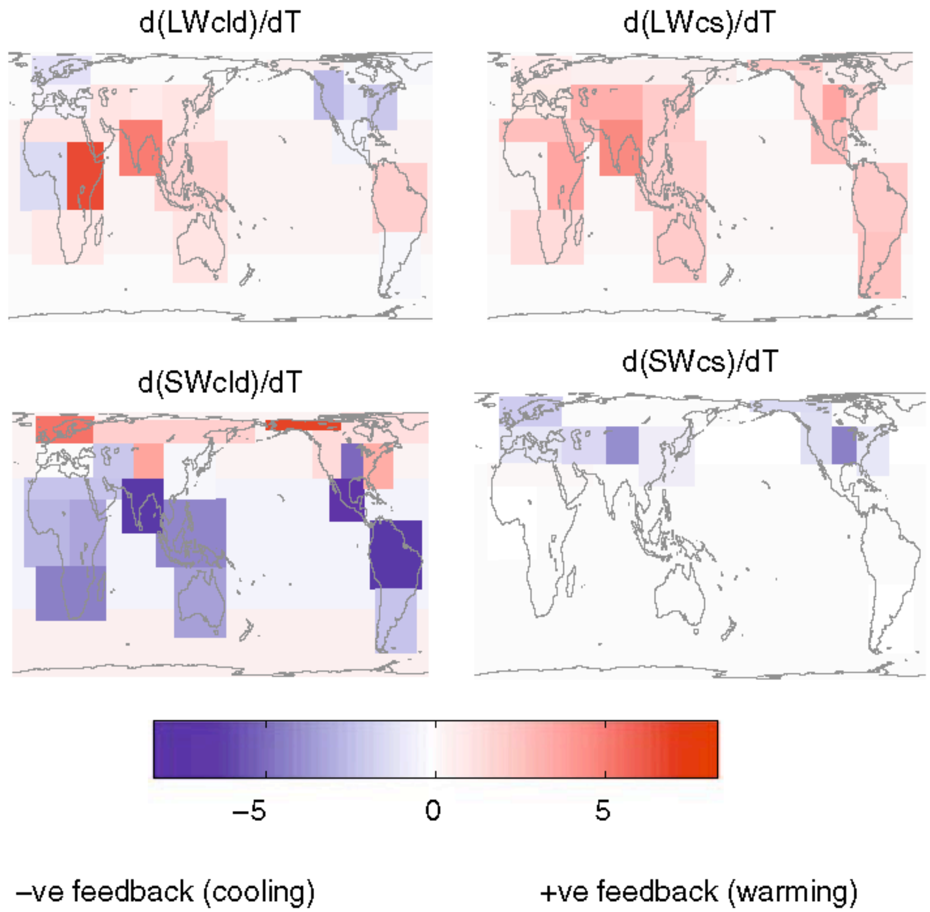
In the face of uncertain information, adaptation is the answer!

Spatial patterns of feedbacks

Sanderson et al., 2007

- **cloud entrainment parameter** has biggest impact on climate sensitivity in *climateprediction.net* ensemble.

- entrainment ↓, upper level moisture↑, clear sky greenhouse ↑



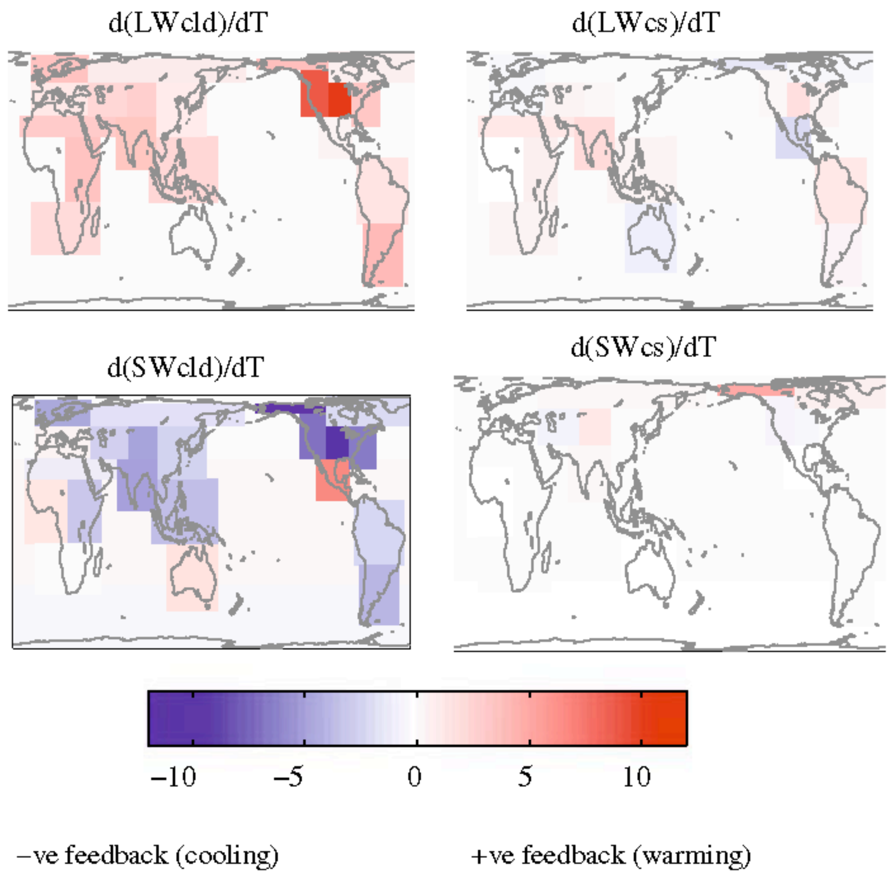
Surface rad^n tendencies assoc. with entrainment

<u>Spatial patterns of feedbacks</u>

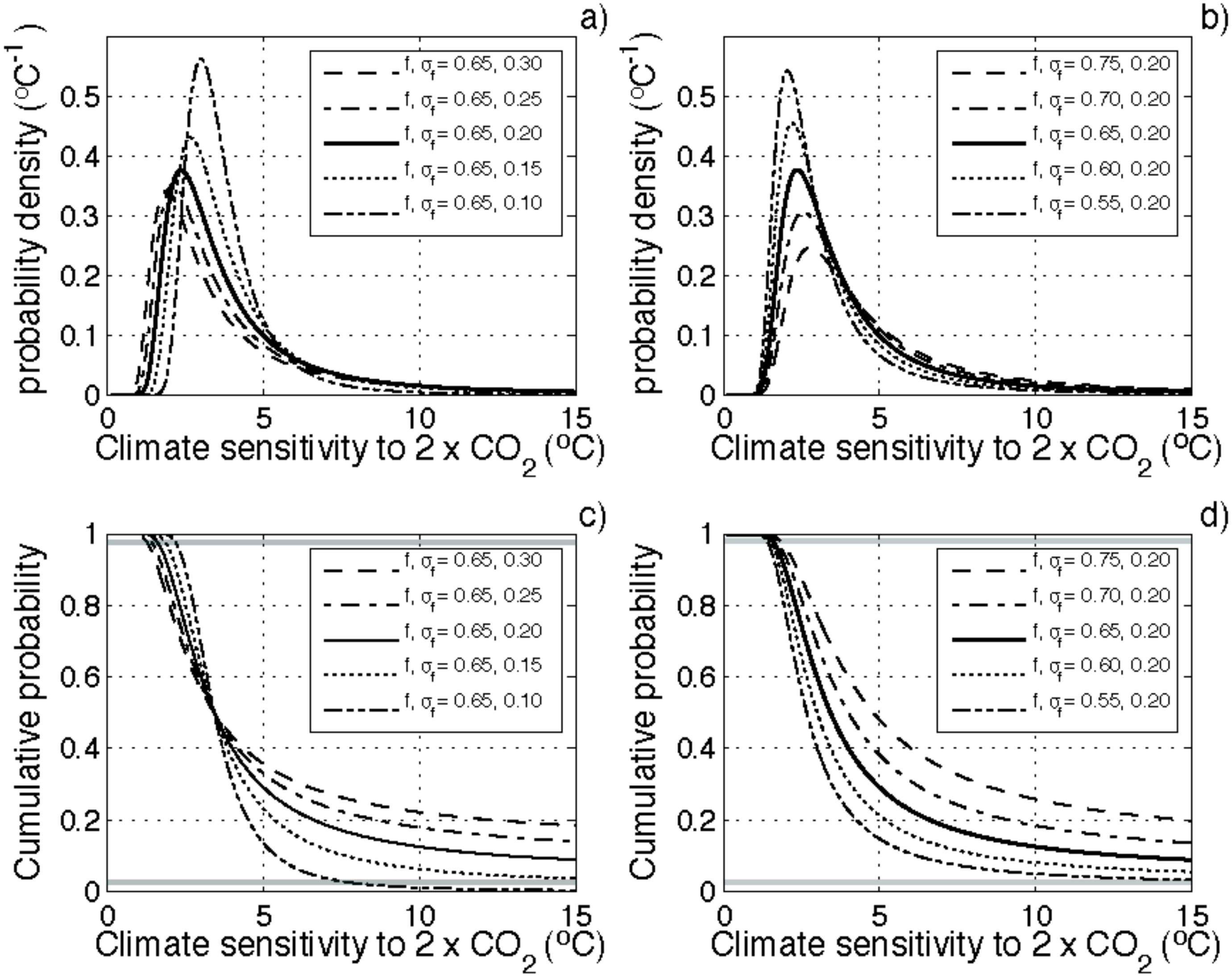
Sanderson et al., 2007

- **ice fall speed** has 2^{nd} biggest impact on climate sensitivity in *climateprediction.net* ensemble.

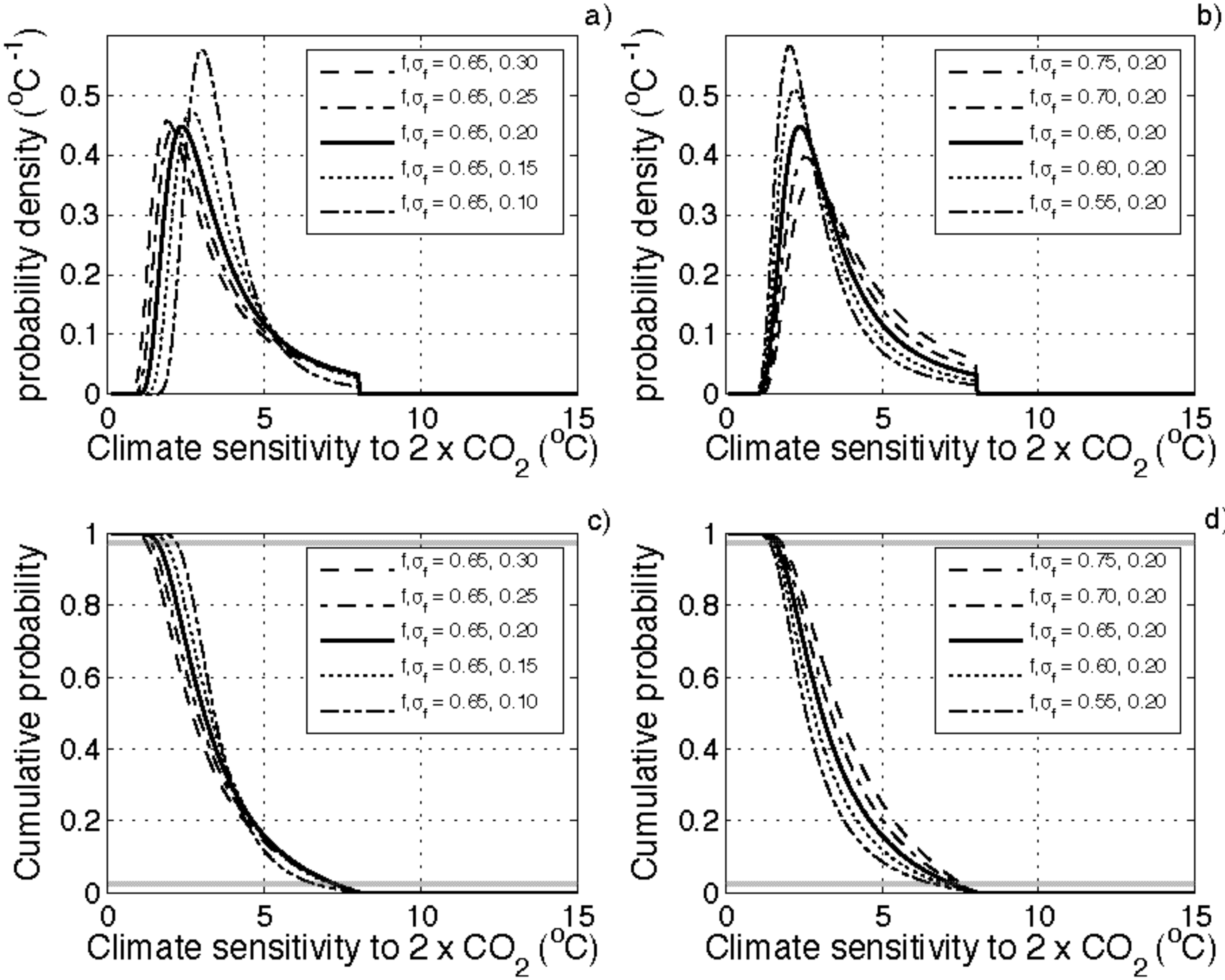
- fall speed ↓, clouds/humidity ↑, greenhouse effect↑



Surface rad^n
Tendencies
assoc. with
fall speed



a)
b)
c)
d)
probability density ($^oC^{-1}$)
Cumulative probability
Climate sensitivity to 2 x CO_2 (^oC)
f, σ_f= 0.65, 0.30
f, σ_f= 0.65, 0.25
f, σ_f= 0.65, 0.20
f, σ_f= 0.65, 0.15
f, σ_f= 0.65, 0.10
f, σ_f= 0.75, 0.20
f, σ_f= 0.70, 0.20
f, σ_f= 0.65, 0.20
f, σ_f= 0.60, 0.20
f, σ_f= 0.55, 0.20



a)
b)
c)
d)
probability density ($^oC^{-1}$)
Cumulative probability
Climate sensitivity to 2 x CO_2 (^oC)
0
5
10
15
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1
f,σ_f = 0.65, 0.30
f,σ_f = 0.65, 0.25
f,σ_f = 0.65, 0.20
f,σ_f = 0.65, 0.15
f,σ_f = 0.65, 0.10
f,σ_f = 0.75, 0.20
f,σ_f = 0.70, 0.20
f,σ_f = 0.60, 0.20
f,σ_f = 0.55, 0.20