The shape of things to come:

Why is climate sensitivity so unpredictable,
and who cares anyway?

Gerard Roe & Marcia Baker

Dept of Earth and Space Sciences,
University of Washington
Seattle, WA.

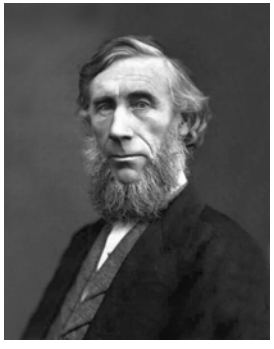
Disclaimer

This presentation represents the views of the presenter and has neither been reviewed nor approved by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views or policies of theU.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Climate change: not a new problem

Joseph Fourier, 1827:

On the temperatures of the terrestrial sphere and interplanetary space.



John Tyndall, 1860s:

“The solar heat possesses. . . the power of crossing an atmosphere; but, when the heat is absorbed by the planet, it is so changed in quality that the rays emanating from the planet cannot get with the same freedom back into space. Thus the atmosphere admits of the entrance of the solar heat, but checks its exit; and the result is a tendency to accumulate heat at the surface of the planet.”

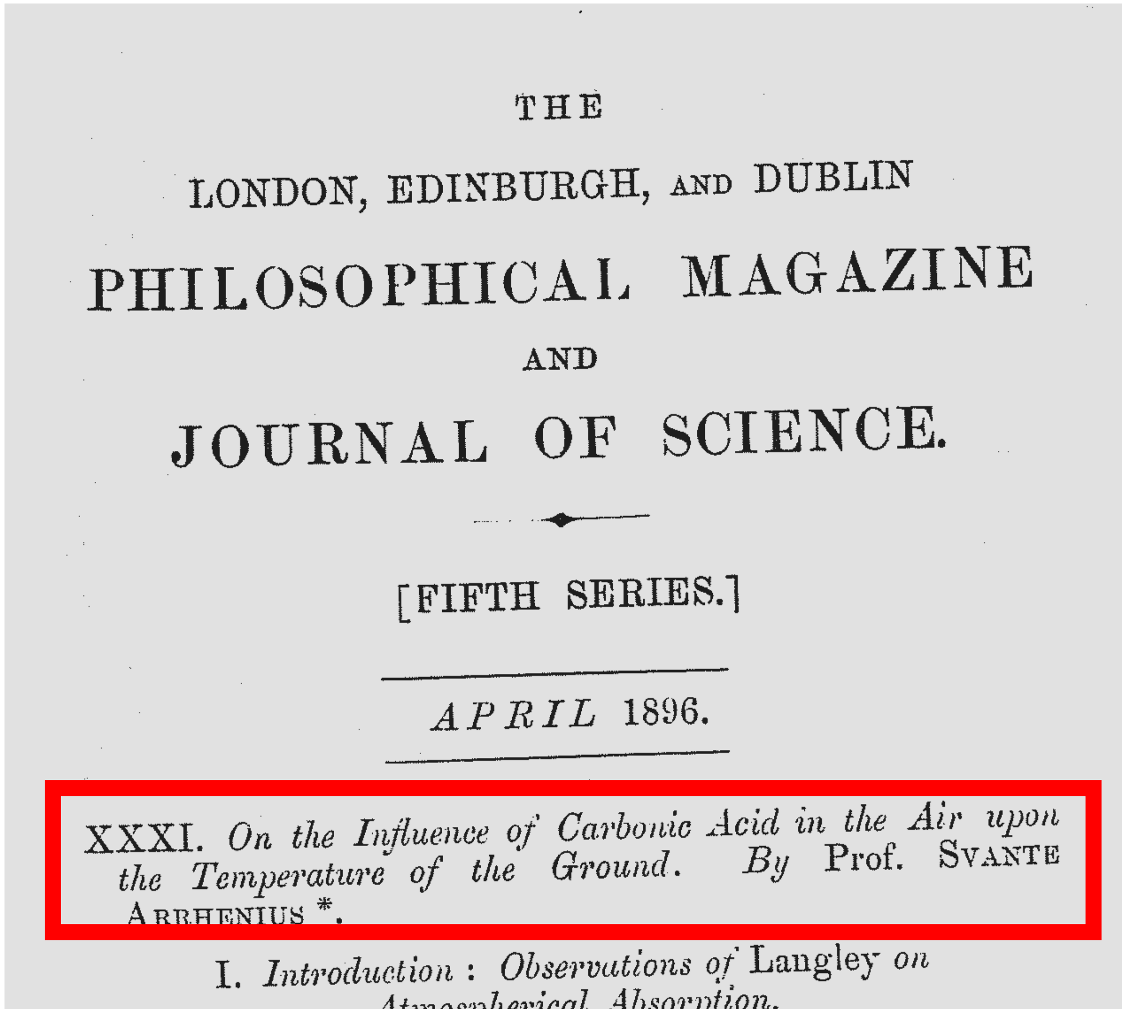
Samuel Langley, 1870s+

- Measurement of the direct effect of sun spots on terrestrial climates. *Monthly Notices Roy. Astron. Soc, 1876.*
- On the amount of atmospheric absorption. *Amer. Journ. Sci.,1883.*
- On hitherto unrecognized wavelengths. *Amer. Journ. Sci.,1886.*

Also Pouillet (1838); De Marchi (1895); Milankovitch (1924)…

Climate change: not a new problem

Svante Arrhenius,1896:



THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

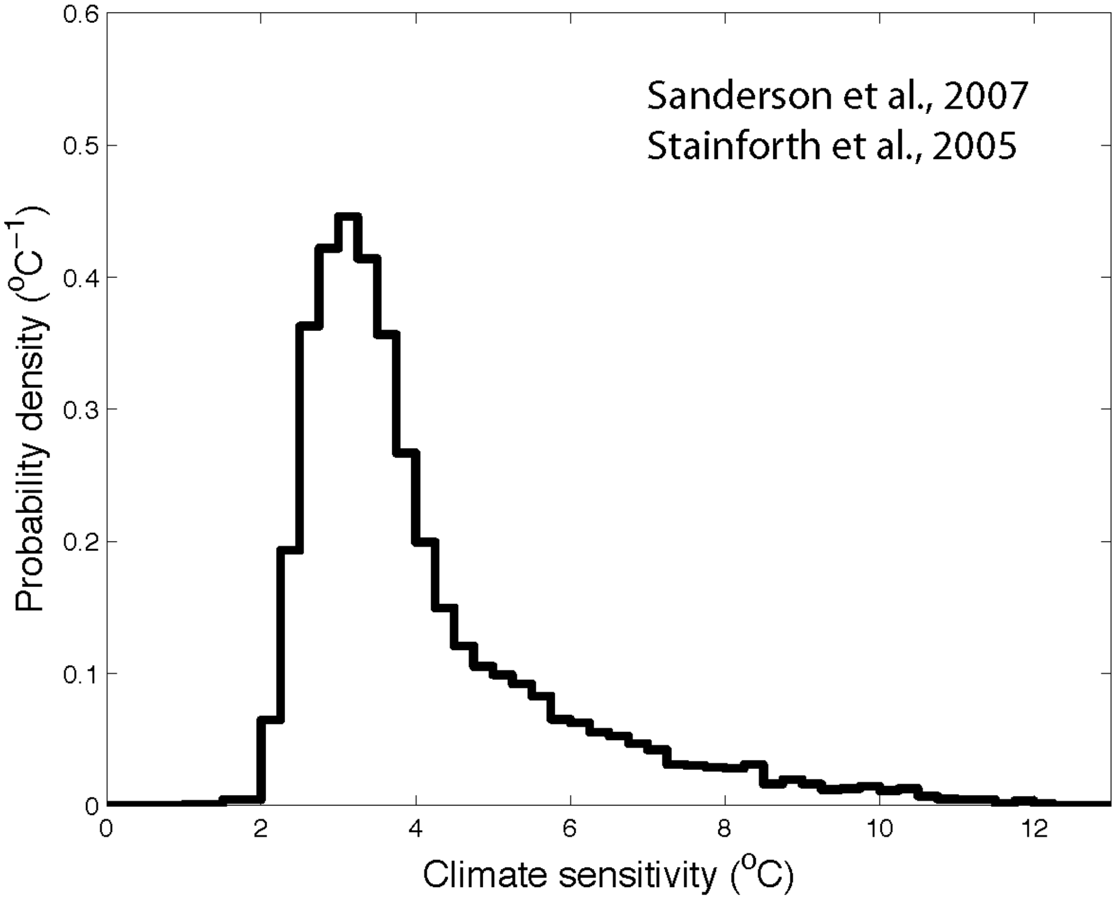
APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

I. *Introduction: Observations of* Langley *on Atmospherical Absorption.*

Climate sensitivity: an envelope of uncertainty

climateprediction.net 200,000+ integrations, 31,400,000 yrs model time(!);



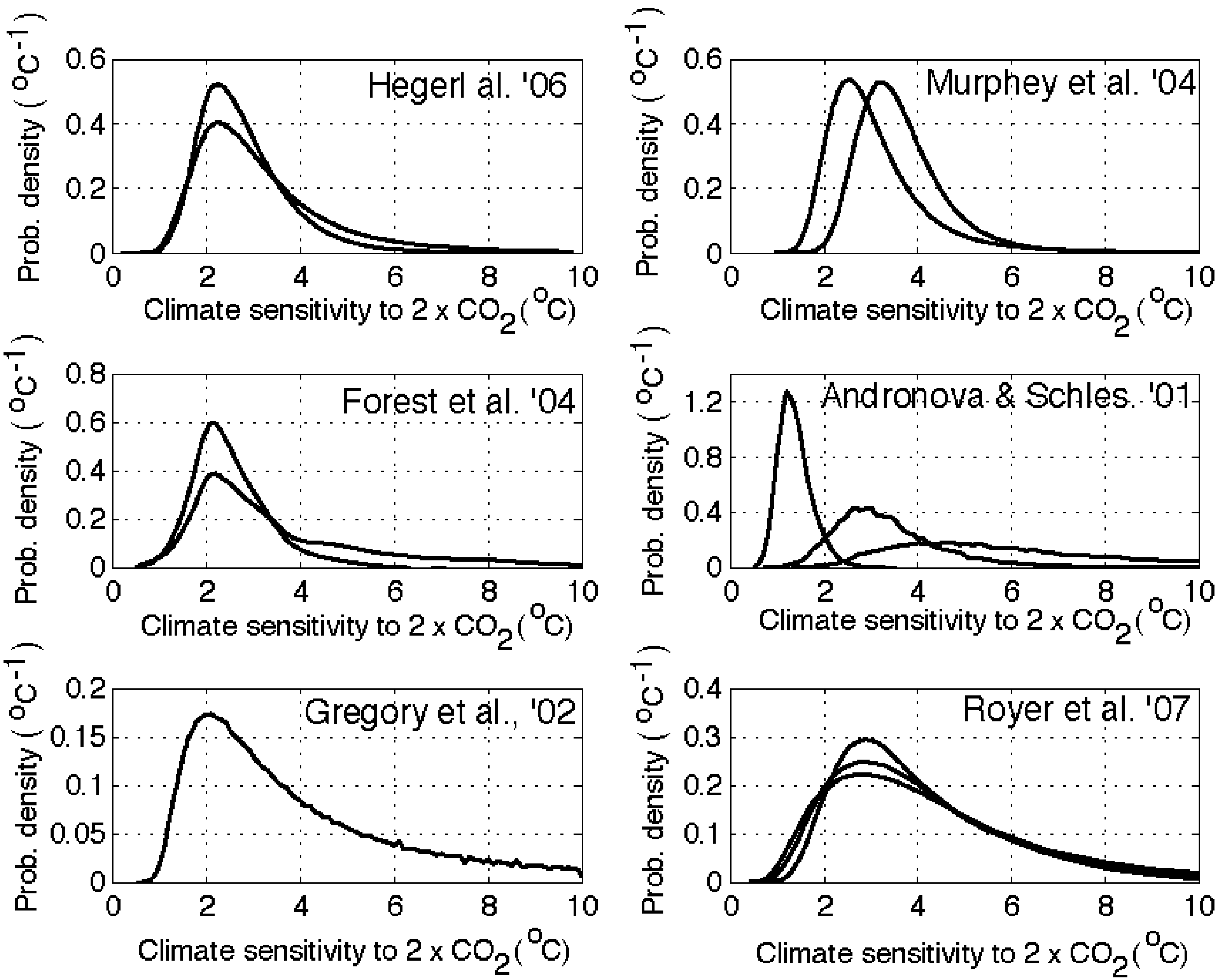
Eq^m. response of global, annual mean sfc. T to 2 x CO_2.

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?

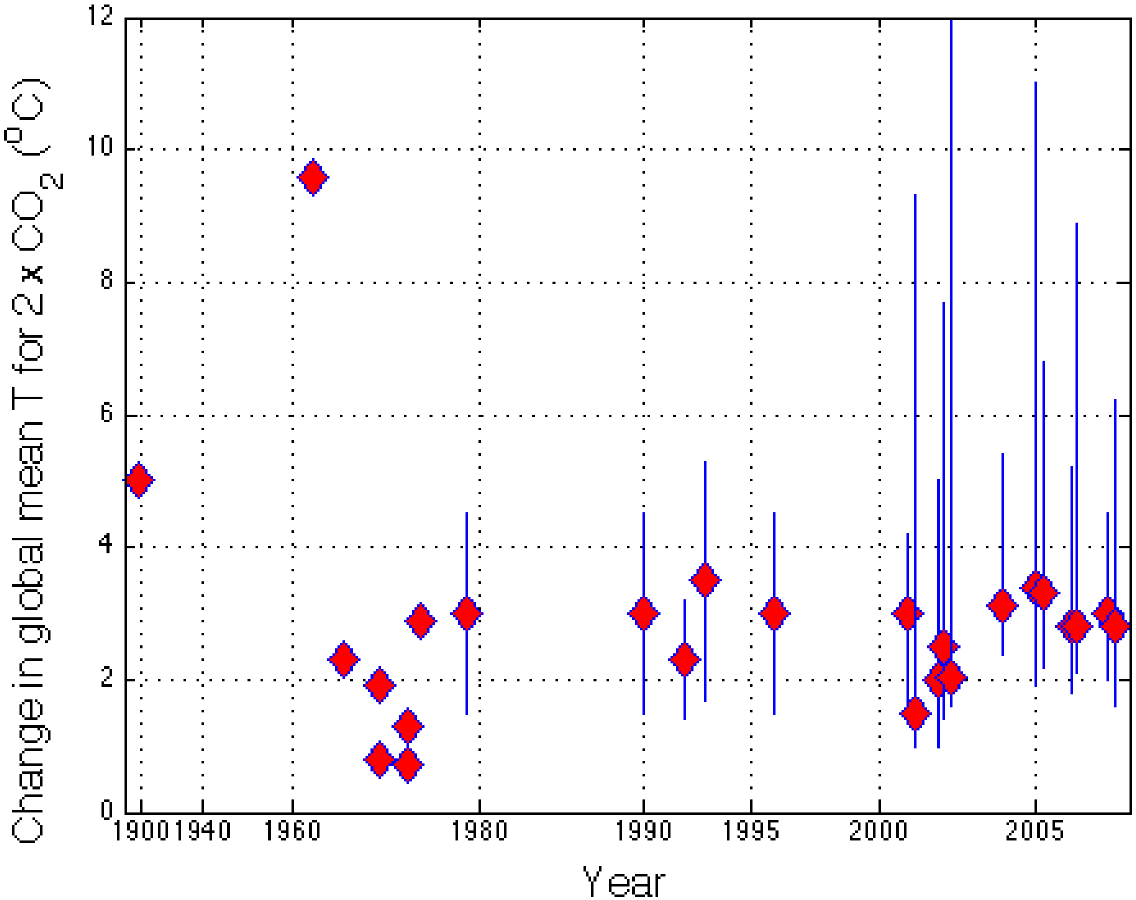
Climate sensitivity: an envelope of uncertainty



• Wide variety of models, methods, and reconstructions.

Climate sensitivity: estimates over time

Climate sensitivity ≡ 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?

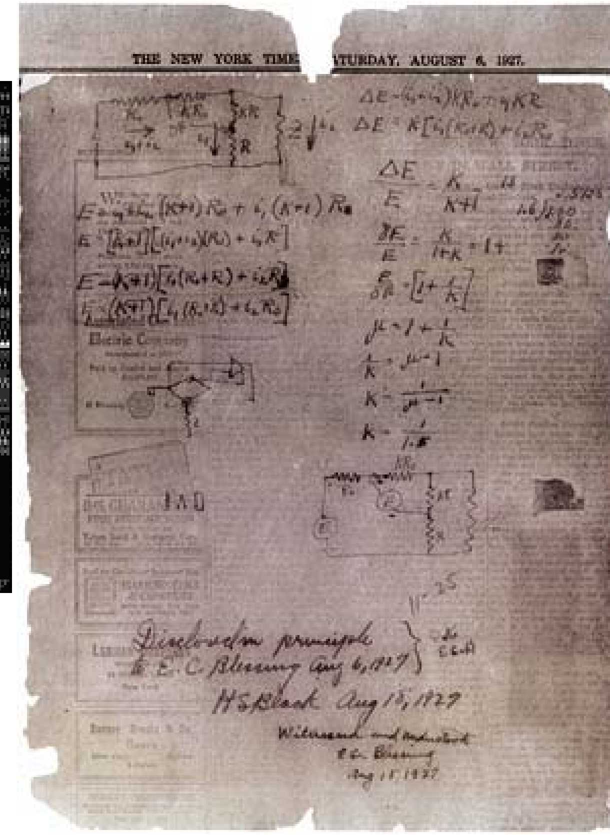
Need feedback analysis!

- introduced concept of negative feedback.

- got the idea on Lackawanna ferry on his way to work.

- took nine years to get granted a patent.

Harold S. Black
(1898-1983)



Original notes scribbled on NY Times

"Our patent application was treated in the same manner one would a perpetual motion machine" Black, H.S. IEEE Spectrum, 1977

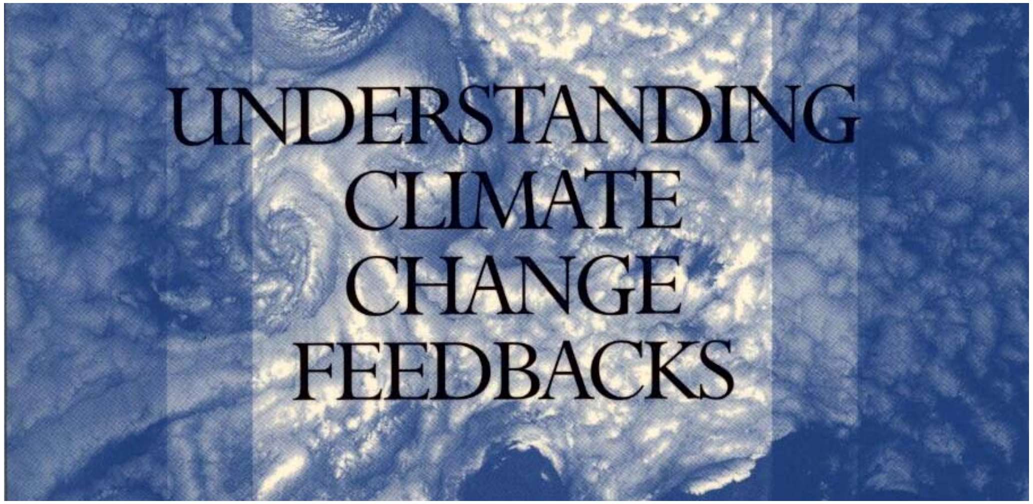
• Formalized framework for the evaluation of interactions in dynamical systems.

Feedback analysis:

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

(Maxwell, 1863; Black, 1927; Cess, 1975; Charney et al., 1979; 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 *parameter* defined by: $\Delta T_0 = \lambda_0 \Delta R$

Reference climate system:

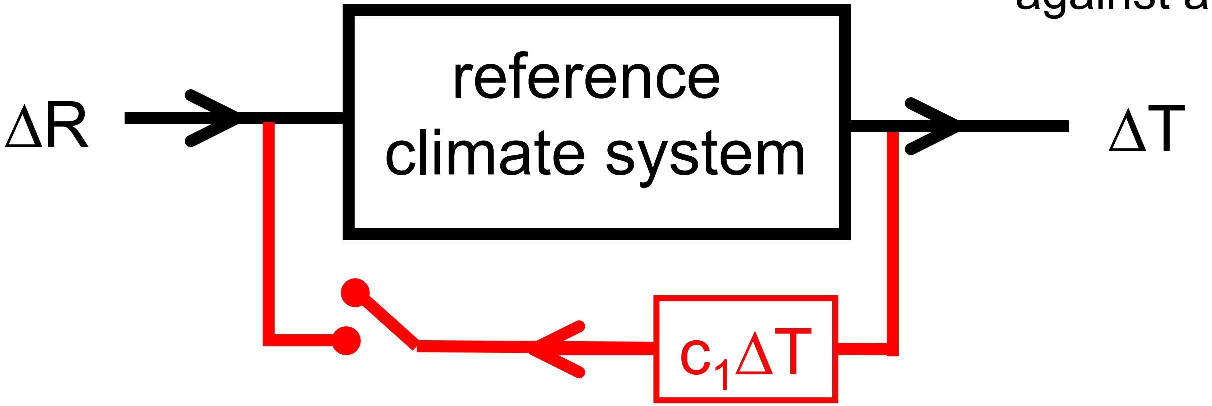
- Blackbody (i.e., no atmosphere).
- Terrestrial flux $= \sigma T^4$ (Stefan-Boltzmann)
- $\lambda_0 = (4\sigma T^3)^{-1} = 0.26$ K $(Wm^{-2})^{-1}$

$\Rightarrow \Delta T_0 = 1.2\ ^oC$ 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.)



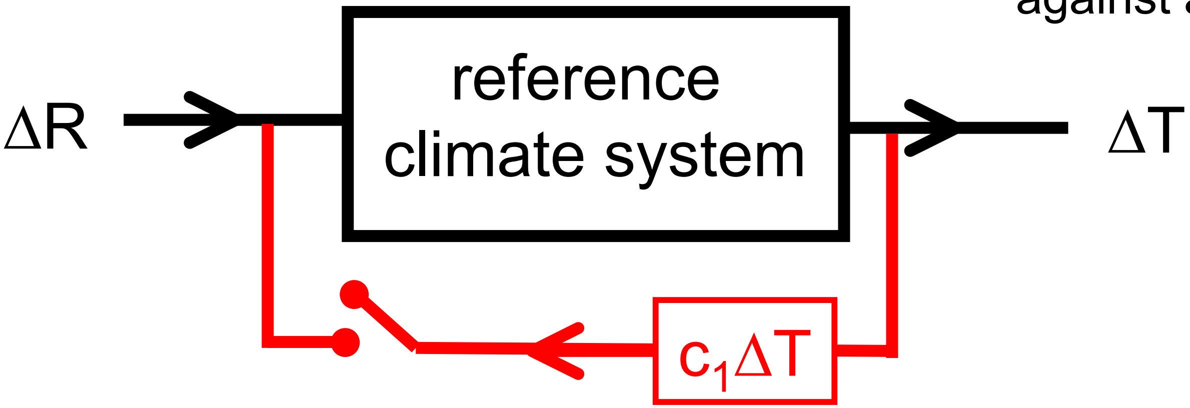
So now

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

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

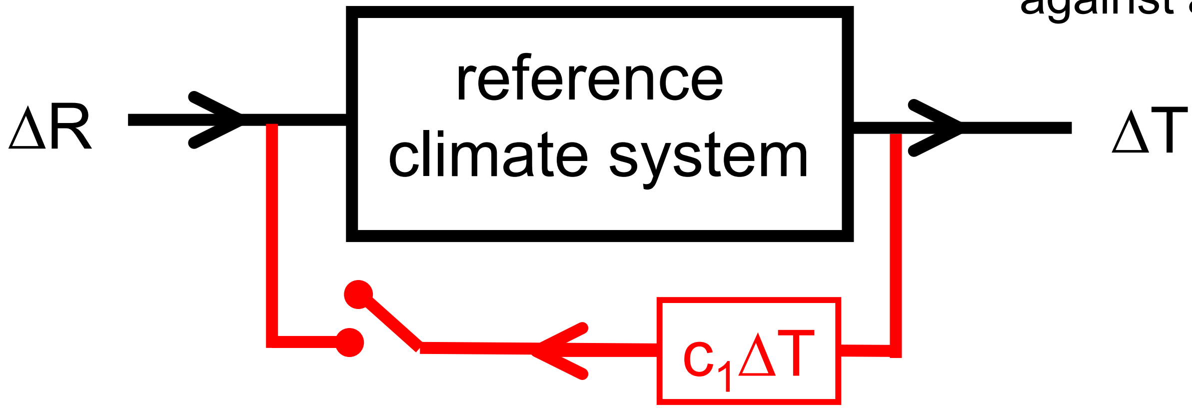
$$\Delta T = \lambda_0(\Delta R + c_1 \Delta T)$$

Additional rad^n forcing due to system response to ΔR

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

$$\Delta T = \lambda_0(\Delta R + c_1\Delta T)$$

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

Feedback factor: $f = c_1\lambda_0$

(f $\propto$ to fraction of output *fed back* into input)

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

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

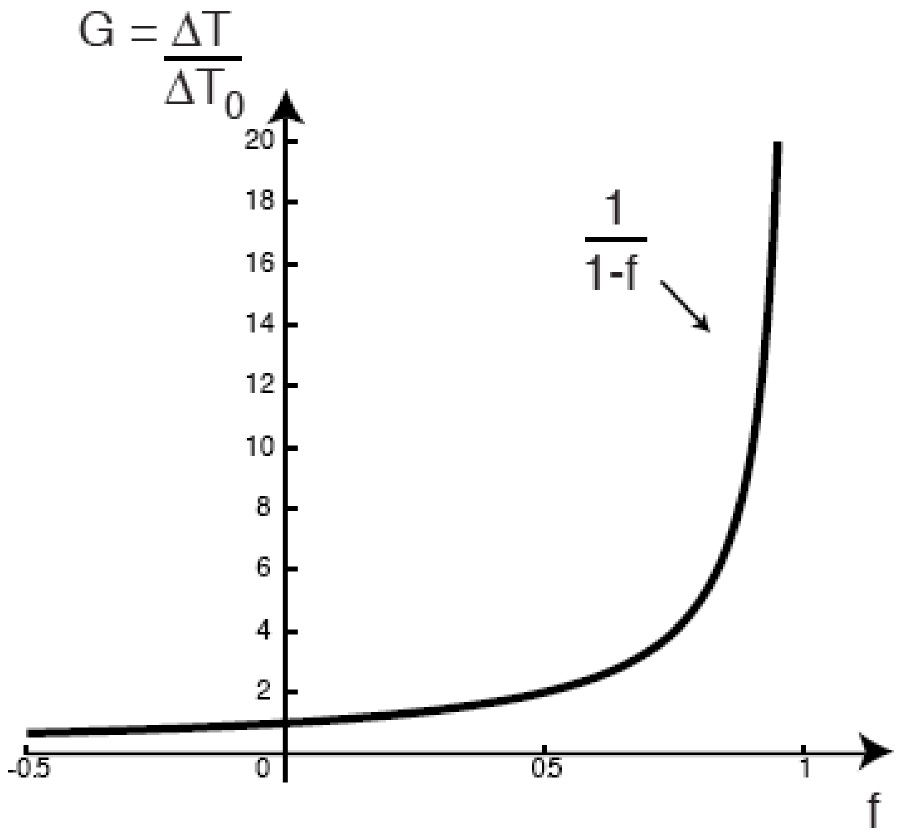
From before

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

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

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

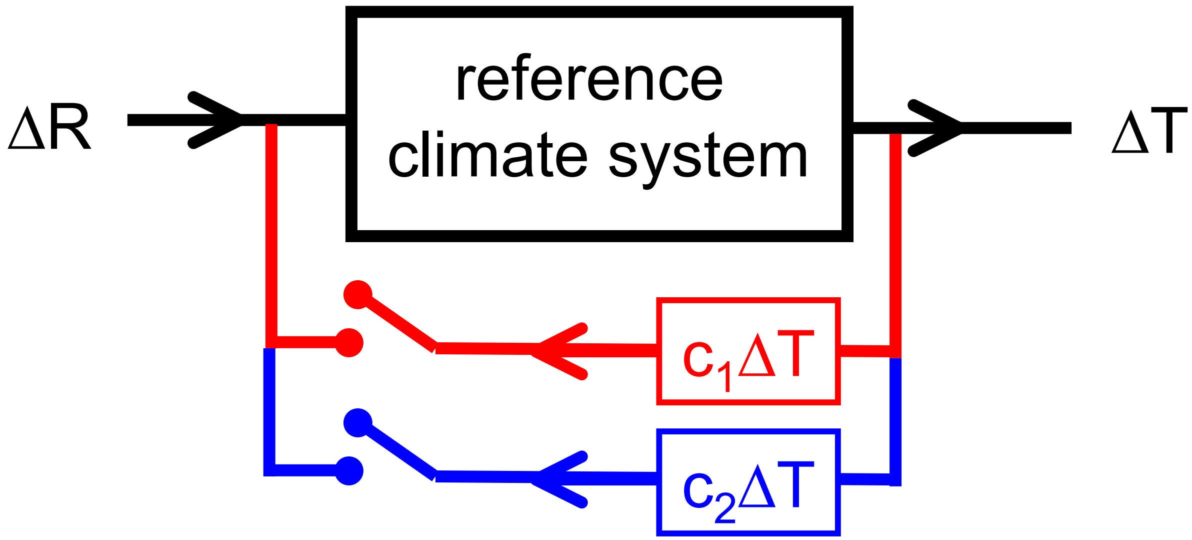
Feedbacks: gain curve



Range of possibilities:

$-\infty < f < 0$: $G < 1$ ⇒ response damped ⇒ NEGATIVE fdbk.
$0 < f < 1$: $G > 1$ ⇒ response amplified ⇒ POSITIVE fdbk.
$f > 1$: G undef. ⇒ Planet explodes…

Feedback analysis: more than one feedback

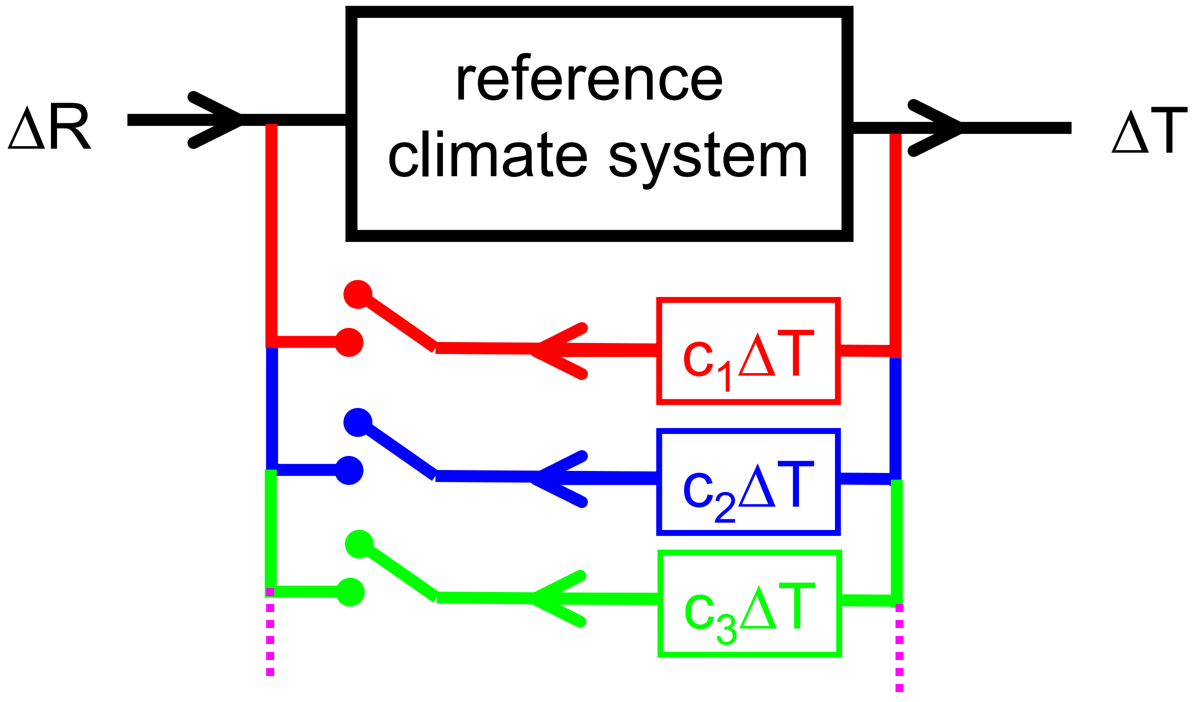


Now have $\Delta T = \lambda_0(\Delta R + c_1\Delta T + c_2\Delta T)$ (two nudges)

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..

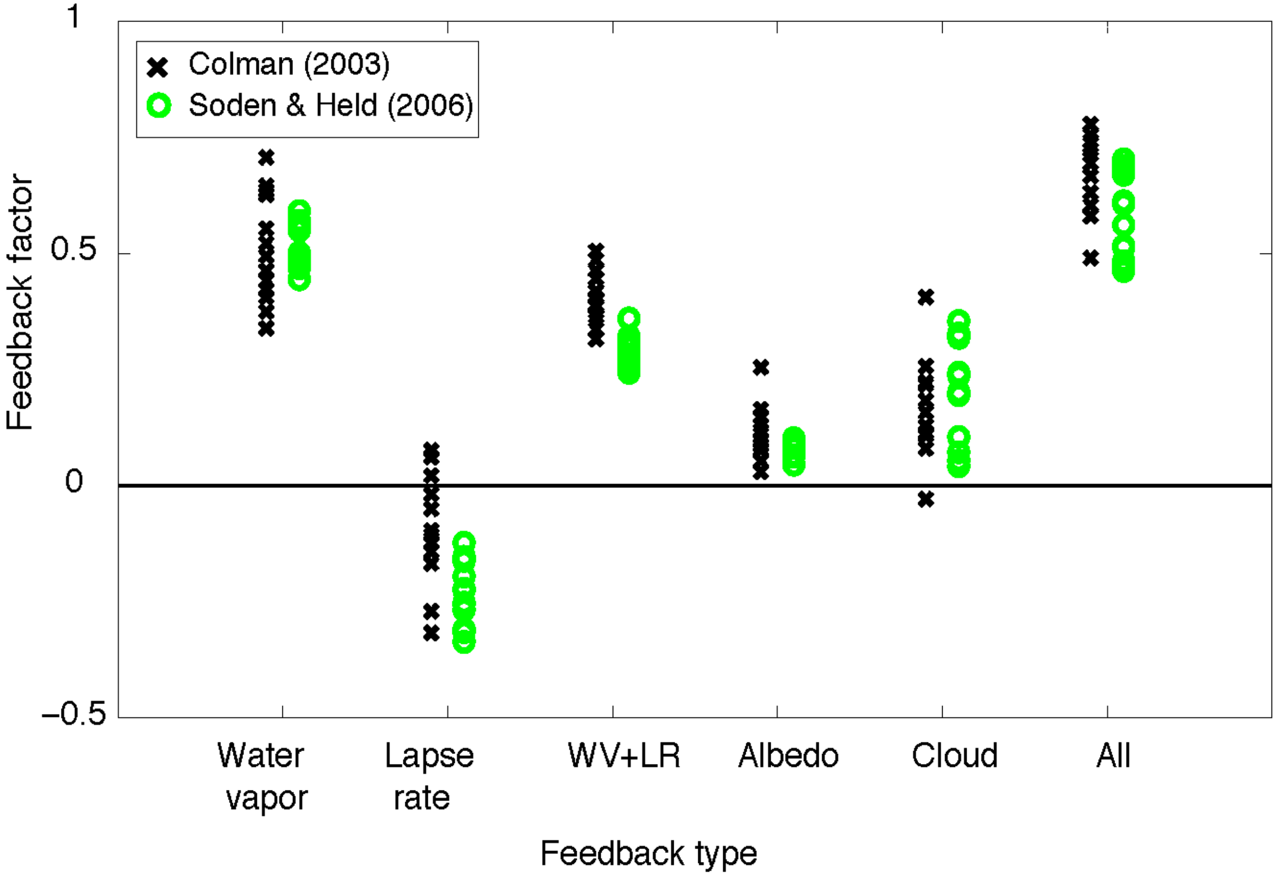
For i^{th} climate variable: $$c_i \Delta T = \delta R\Big)_{j,\, j \neq i} = \frac{\partial R}{\partial \alpha_i}\bigg)_{j,\, j \neq i} \frac{d\alpha_i}{dT} \Delta T$$

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):

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

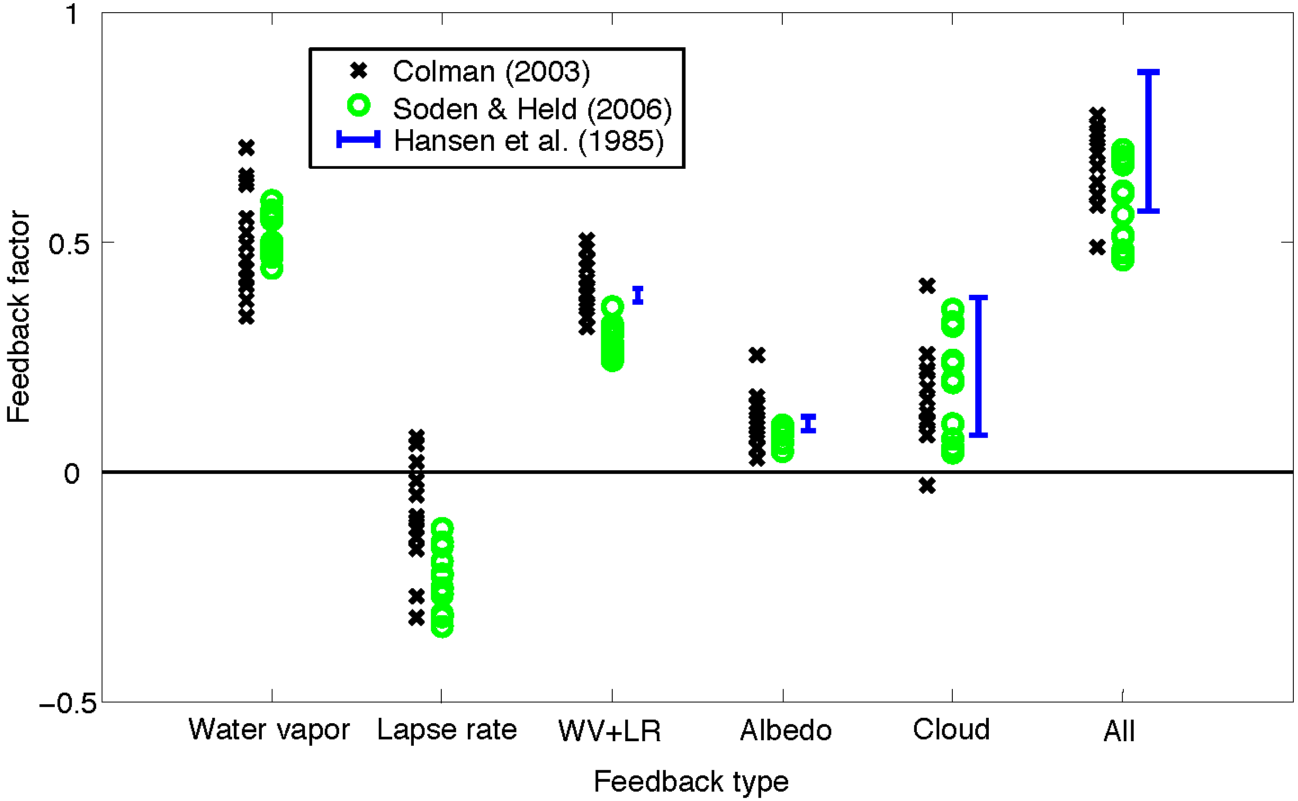
Colman (2003):

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

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

Climate feedbacks: estimating from models

From suites of GCMS:



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

Soden & Held (2006):

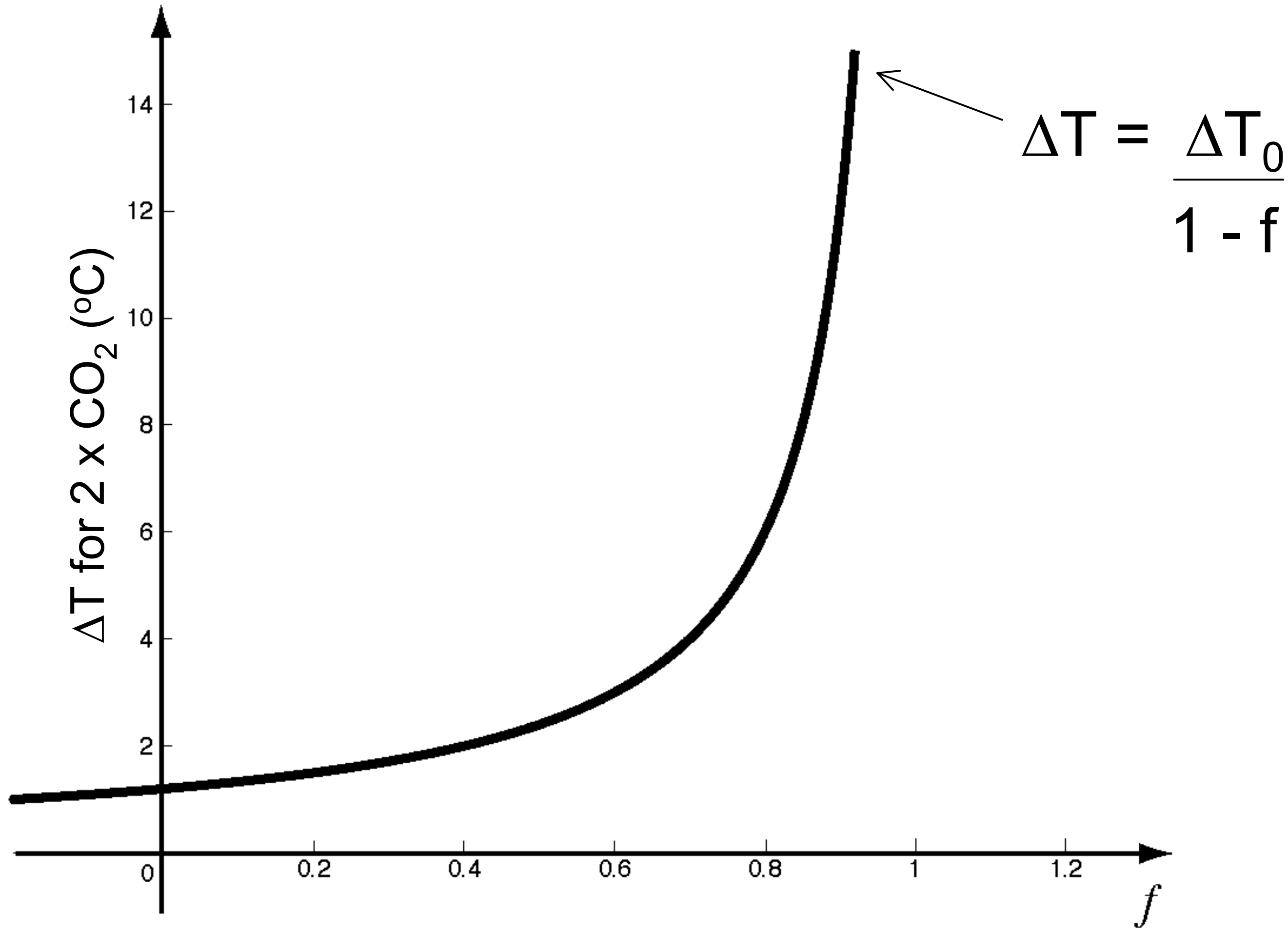
$$\bar{f} = 0.62; \sigma_f = 0.13$$

Colman (2003):

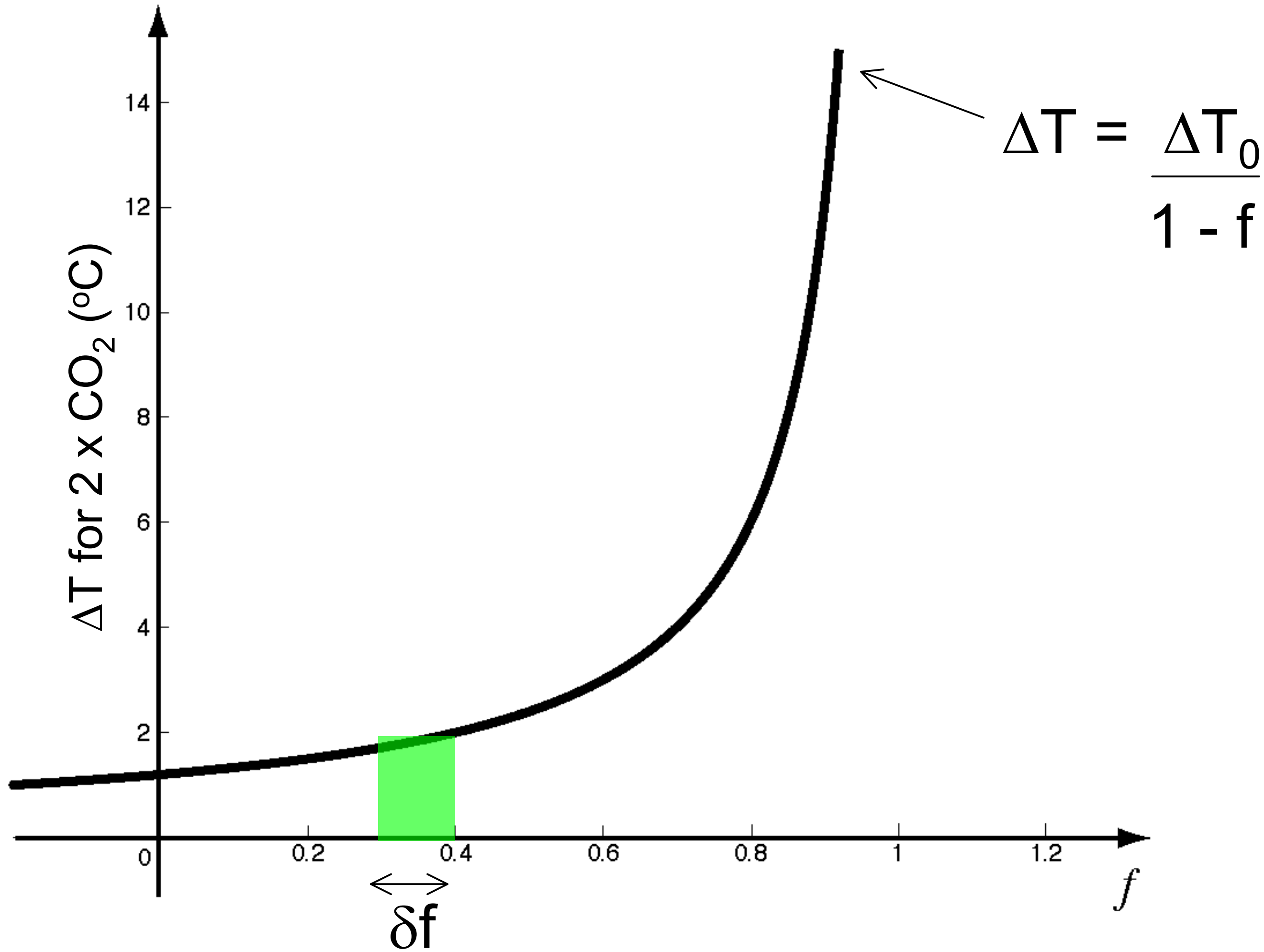
$$\bar{f} = 0.70; \sigma_f = 0.14$$

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

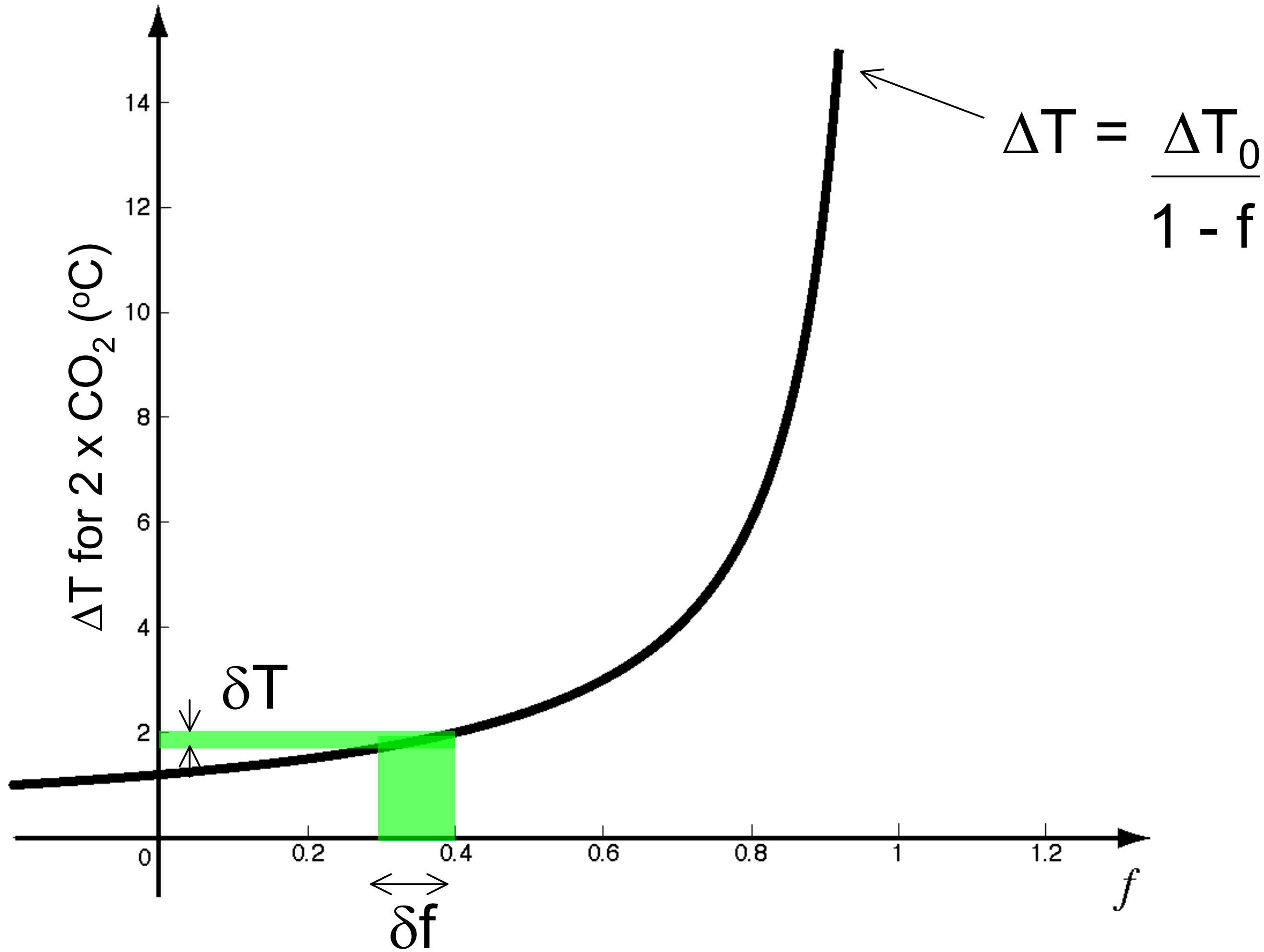
Uncertainty: it all depends on where you are.



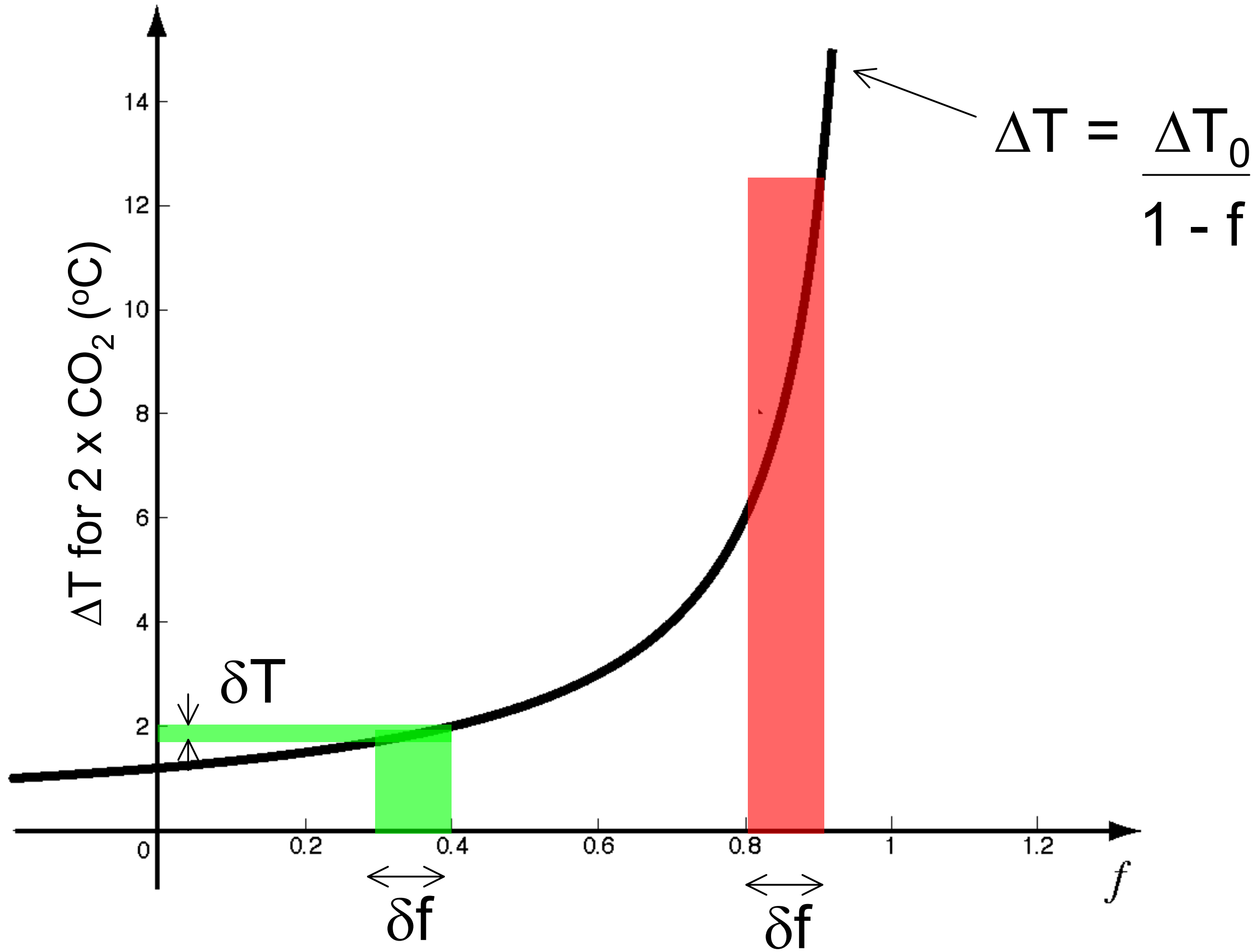
Uncertainty: it all depends on where you are.



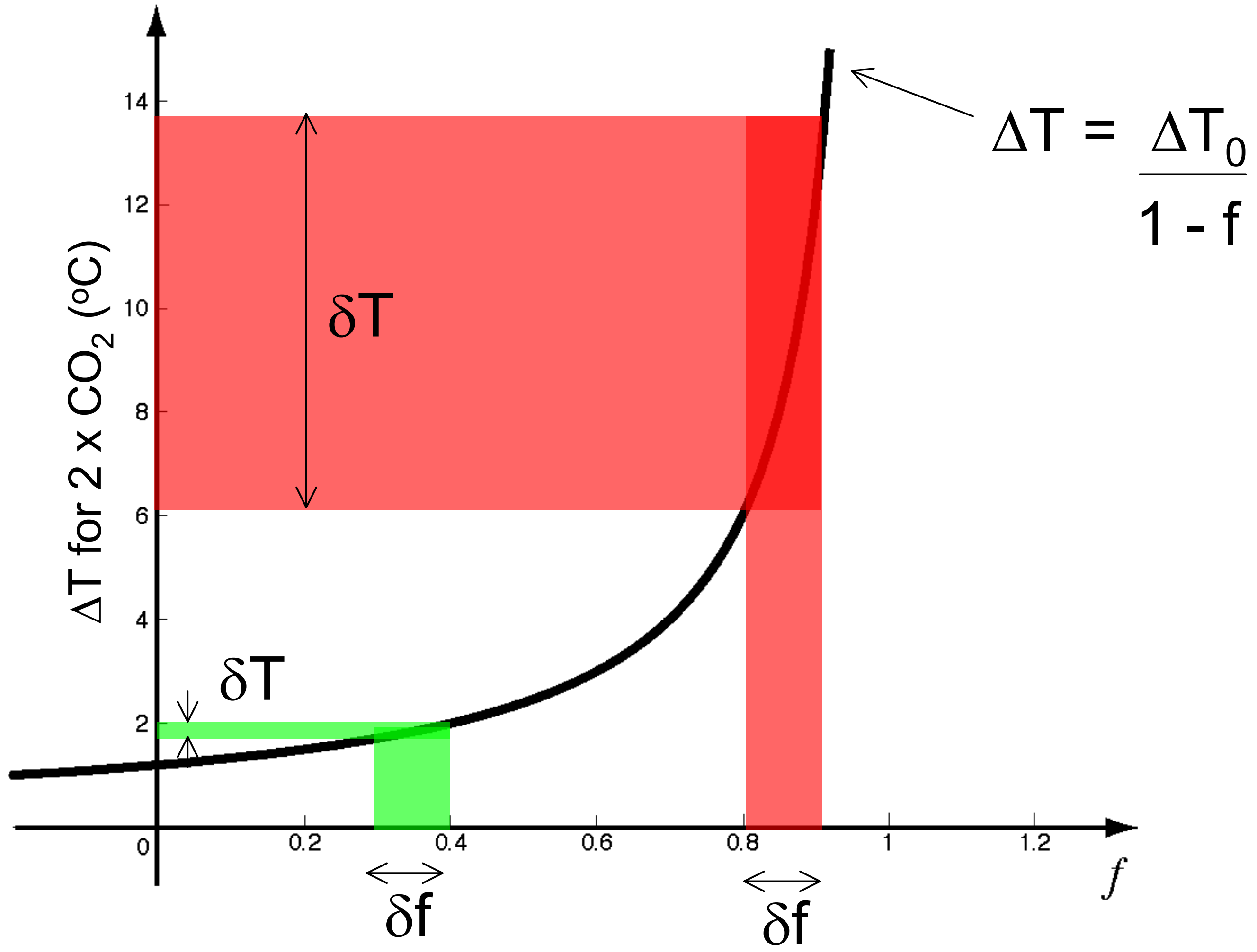
Uncertainty: it all depends on where you are.



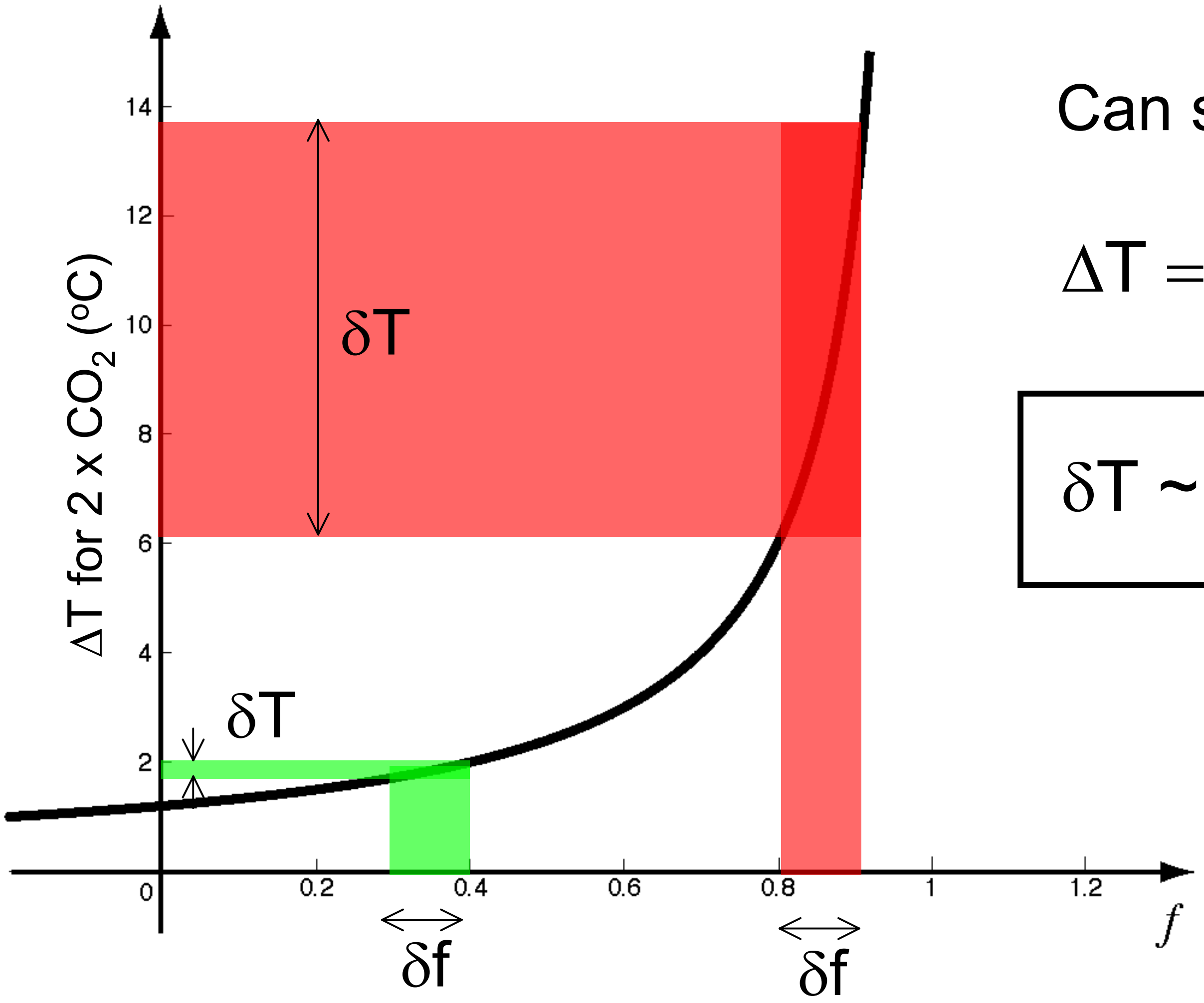
Uncertainty: it all depends on where you are.



Uncertainty: it all depends on where you are.



Uncertainty: it all depends on where you are.



Can show:

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

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

• Uncertainty in climate sensitivity strongly dependent on the gain.

Climate sensitivity: the math

Let pdf of uncertainty in feedbacks $h_f(f)$: $$h_f(\mathbf{f})$$

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

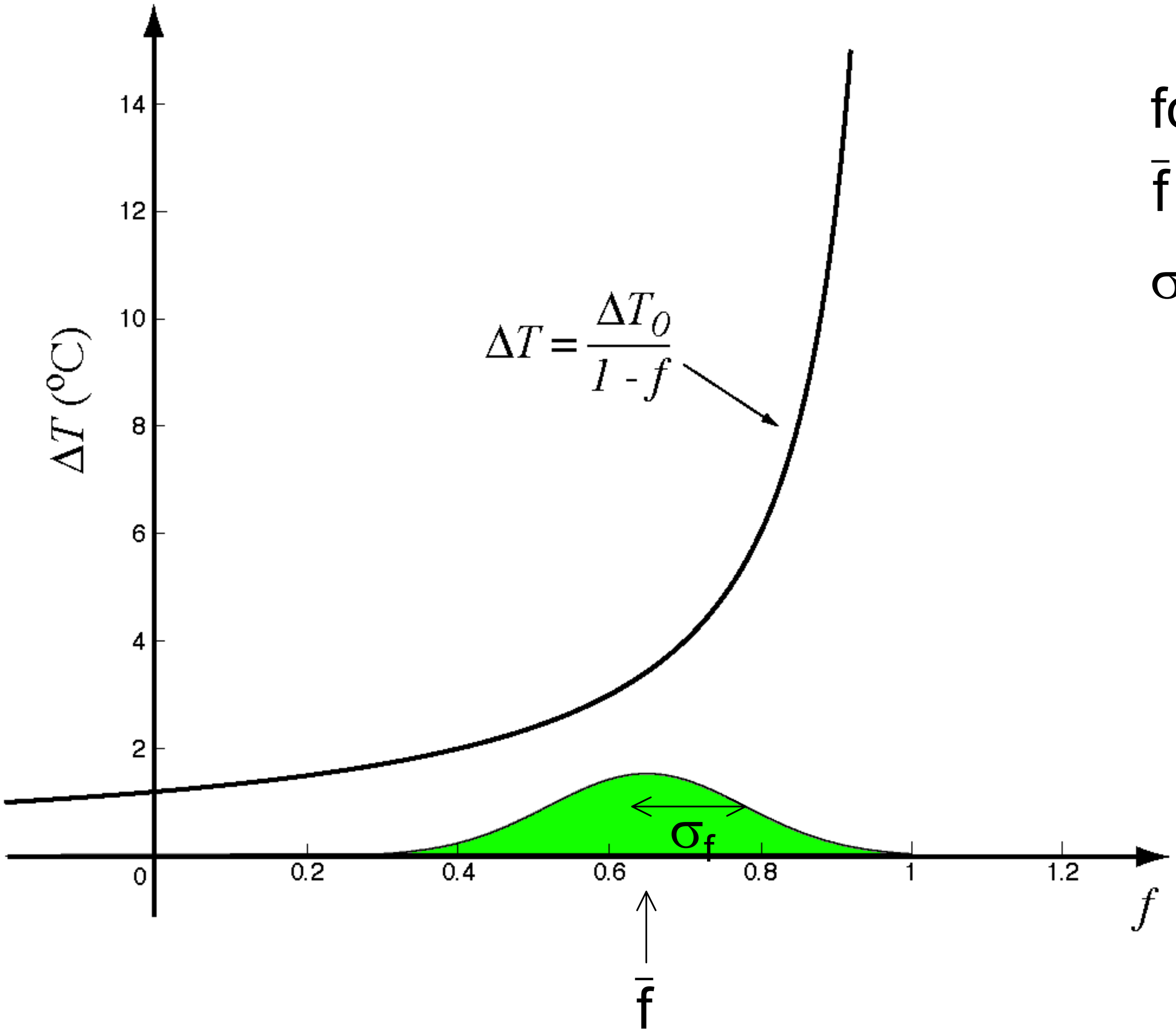
So can write: $$h_{\Delta T}(\Delta T) = h_f(\mathbf{f}) \cdot \frac{df}{d(\Delta T)} = \frac{\Delta T_0}{\Delta T^2} \cdot h_f\left(1 - \frac{\Delta T_0}{\Delta T}\right)$$

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

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

Climate sensitivity: the picture

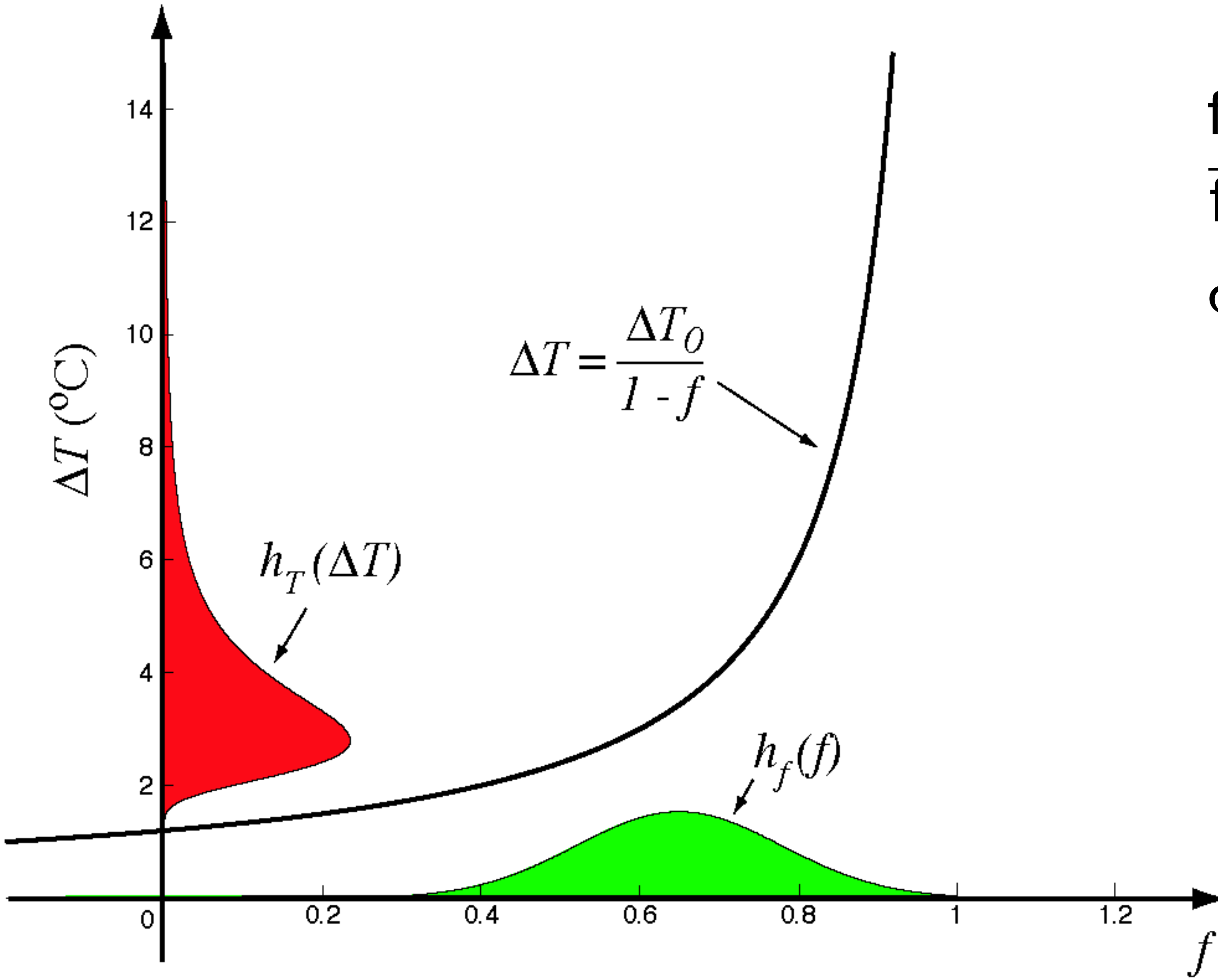


for:

$\bar{f} = 0.65$

$\sigma_f = 0.14$

Climate sensitivity: the picture

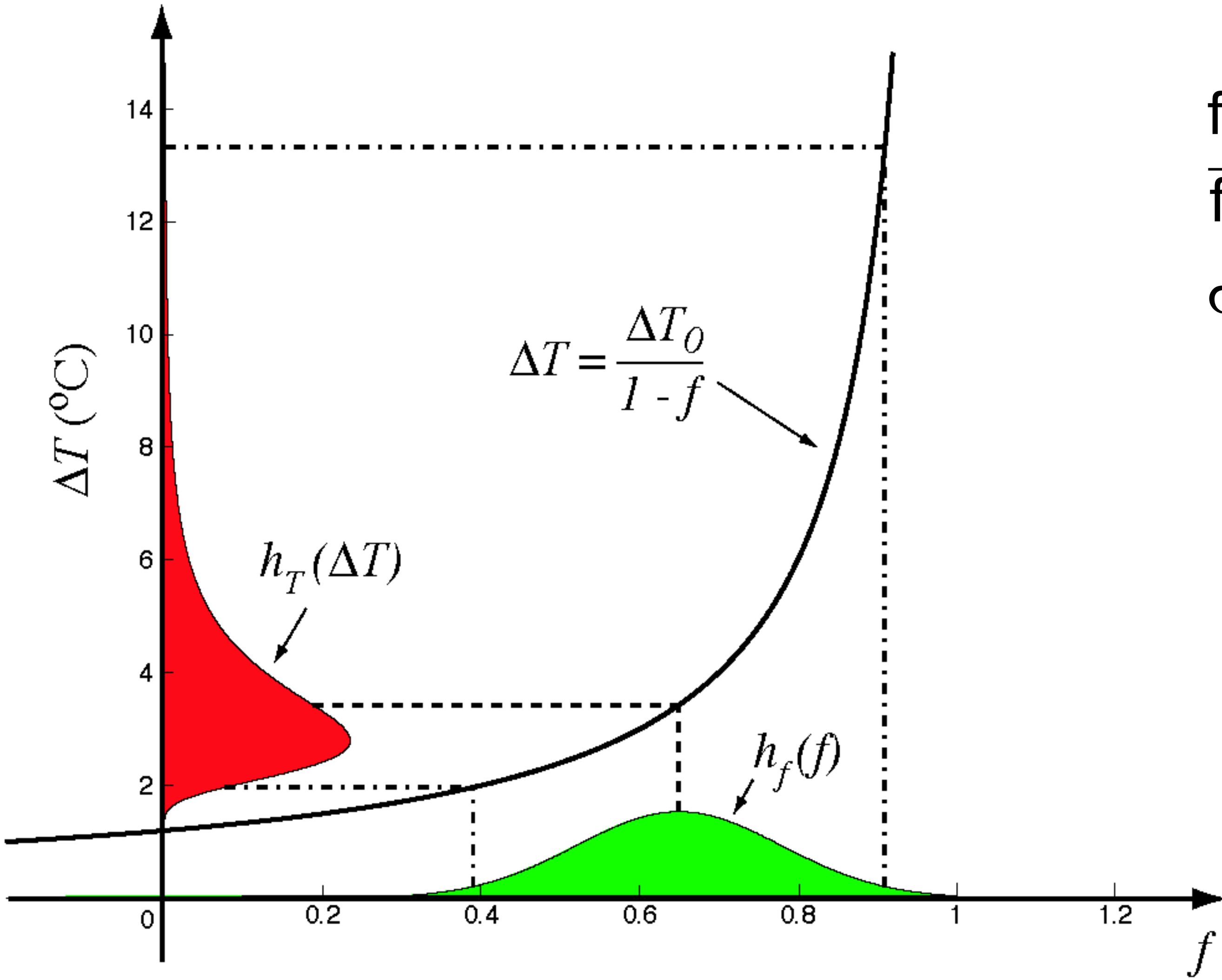


for:

$\bar{f} = 0.65$

$\sigma_f = 0.14$

Climate sensitivity: the picture



for:

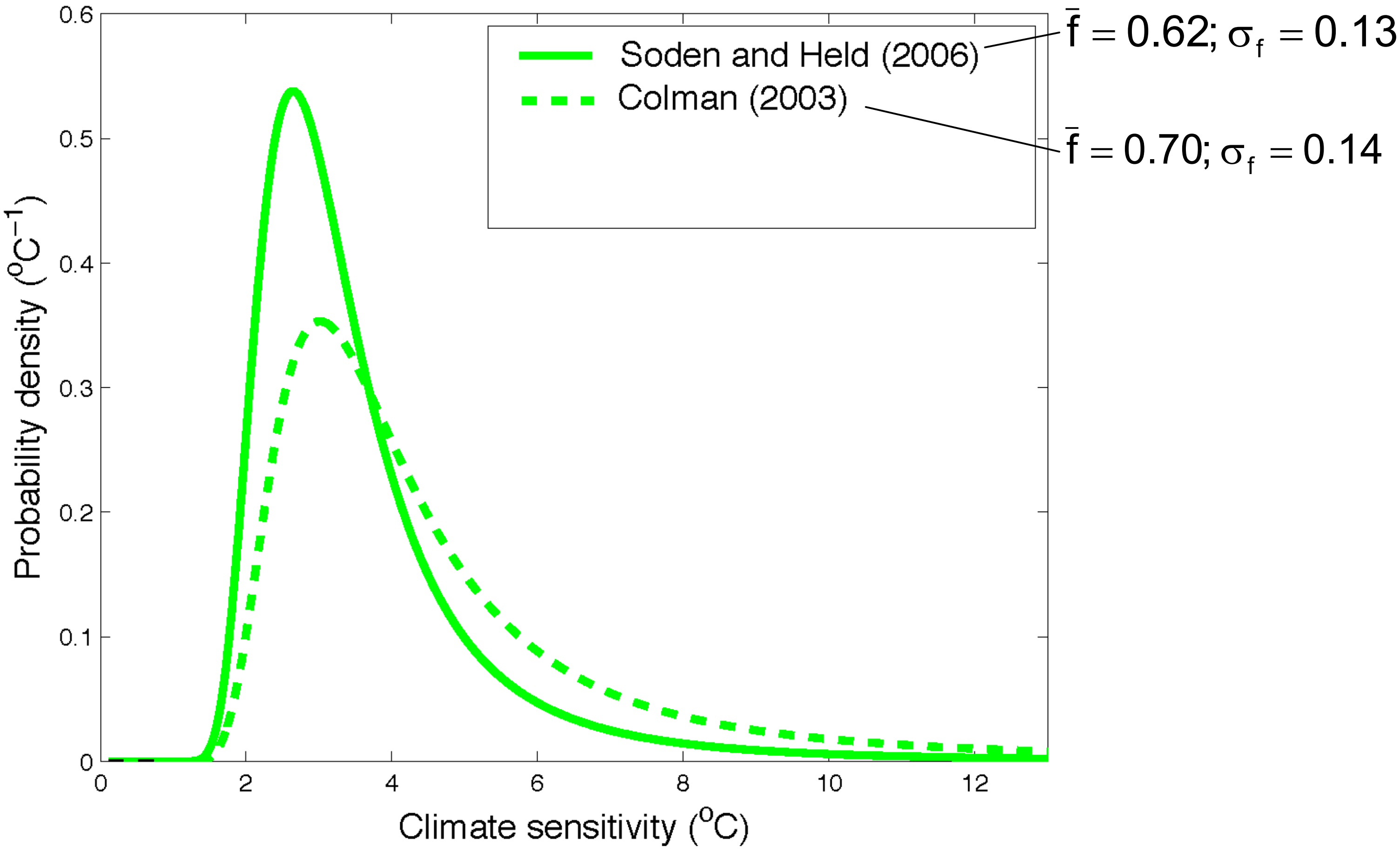
$\bar{f} = 0.65$

$\sigma_f = 0.14$

- Skewed tail of high climate sensitivity is inevitable!

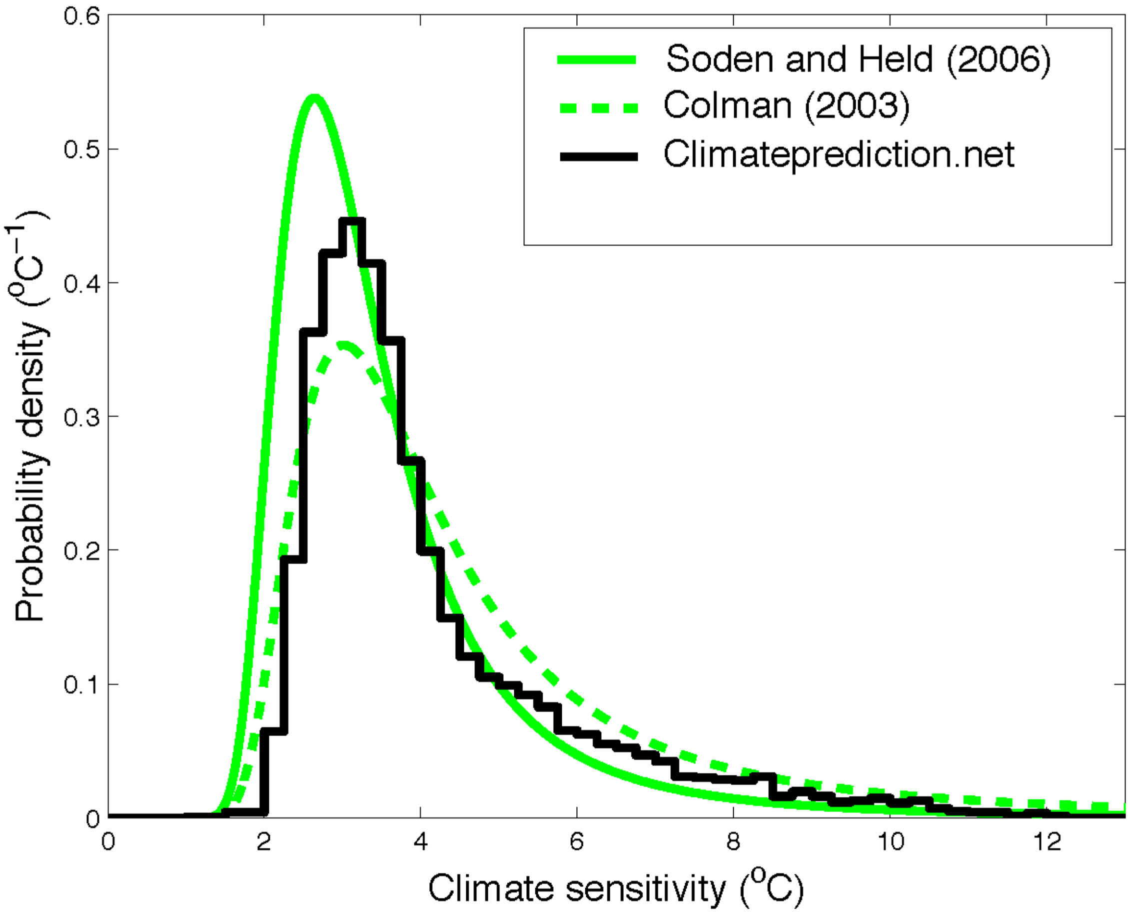
Climate sensitivity:

GCM from linear sum of feedback factors

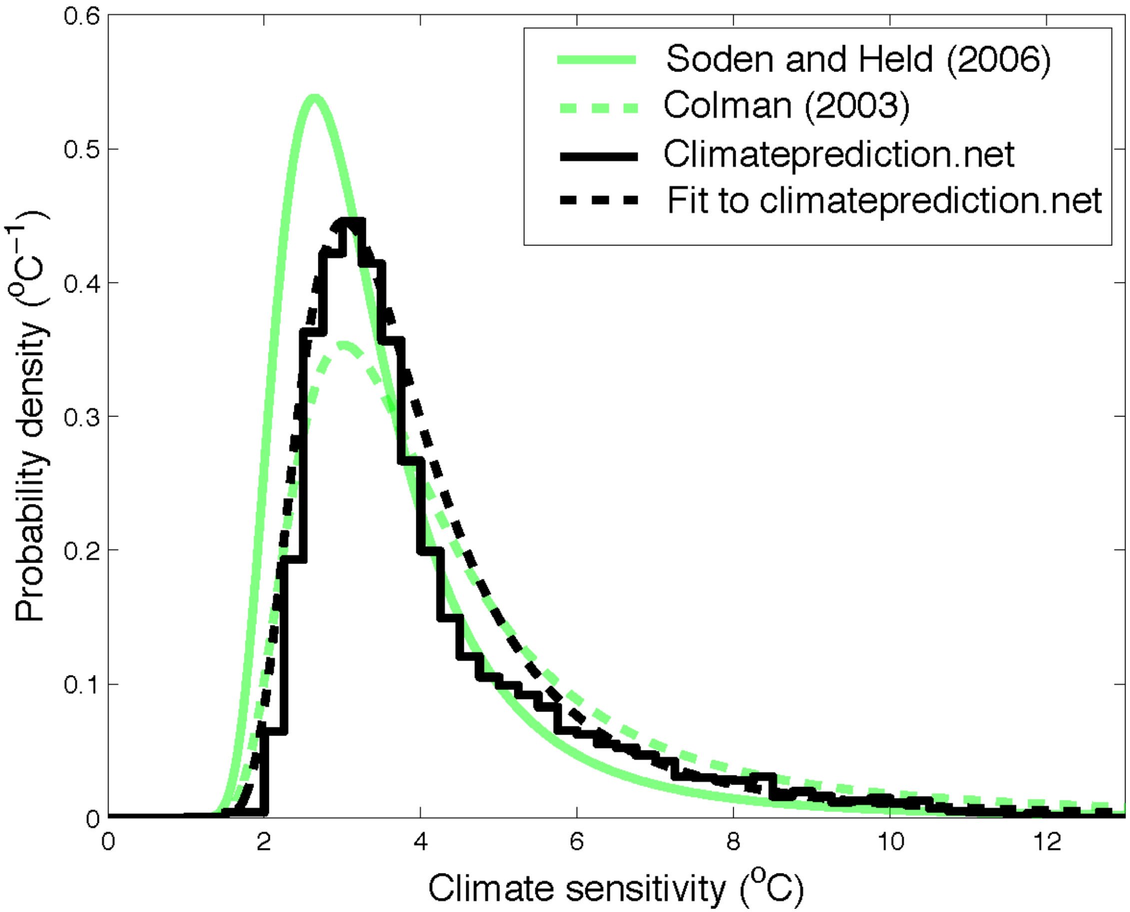


Climate sensitivity:

comparison with climateprediction.net

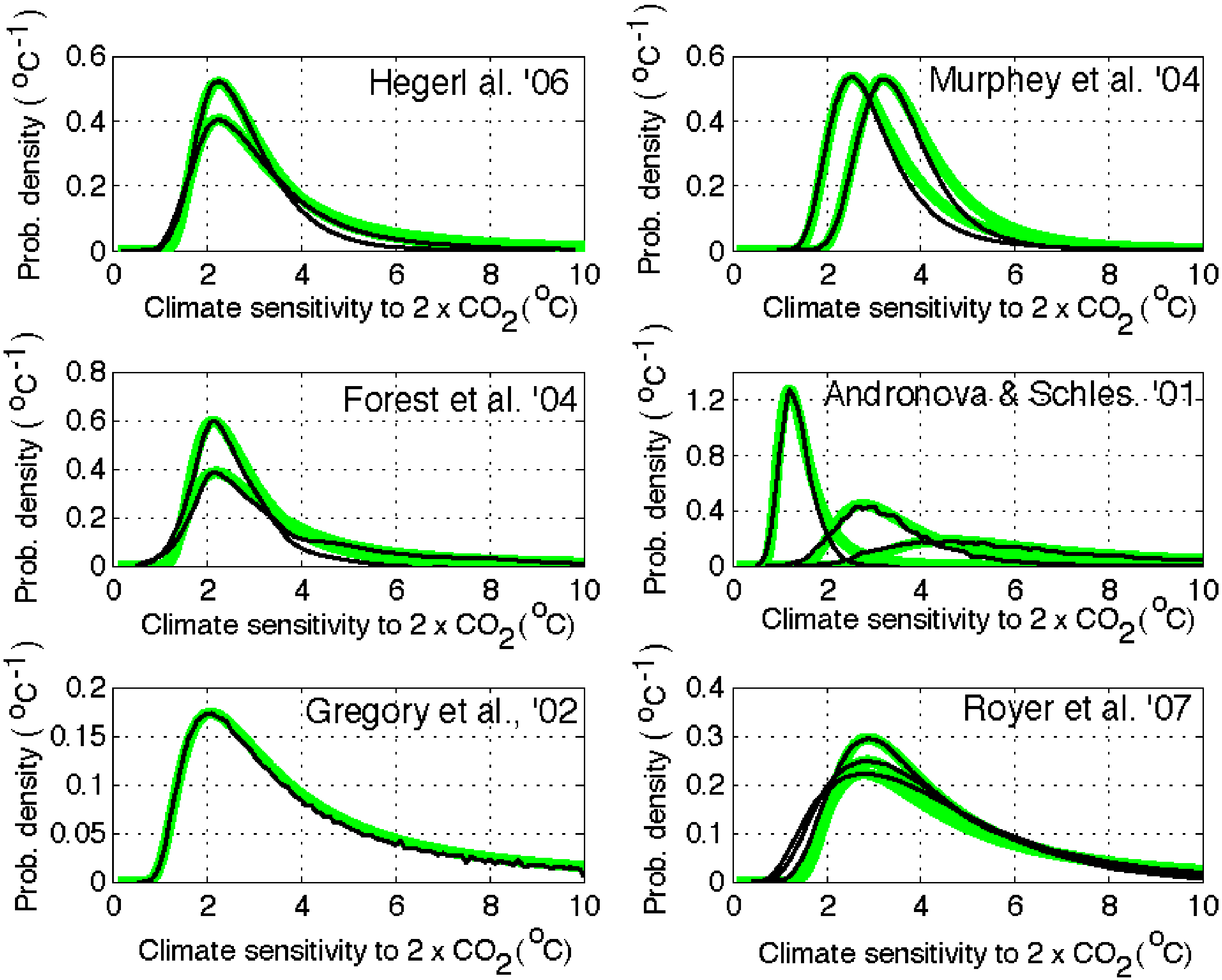


Climate sensitivity:
comparison with climateprediction.net



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

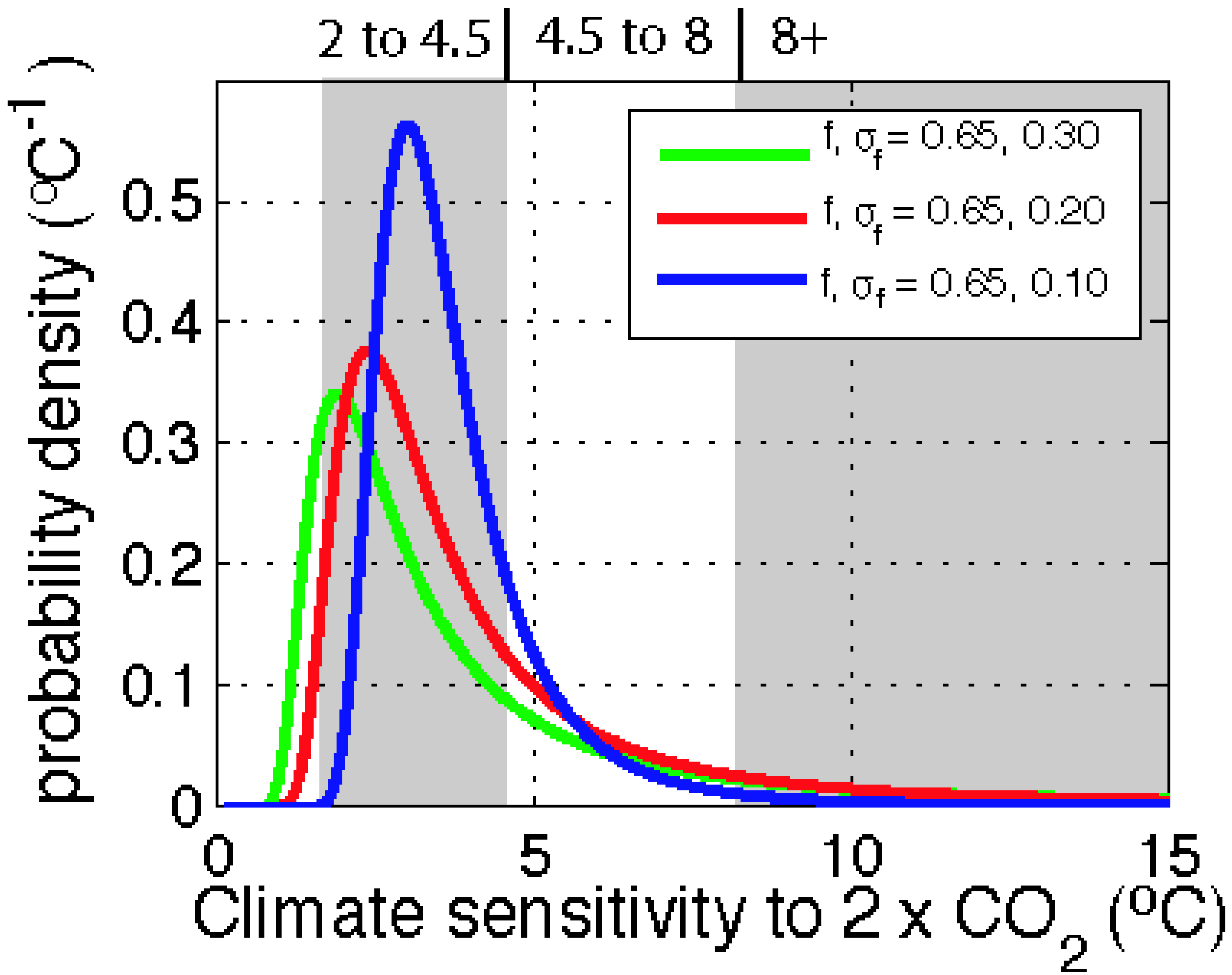
Climate sensitivity: comparison with studies



- $h_{\Delta T}(\Delta T)$ 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?

$\bar{f}, \sigma_f$ \ ΔT	2 to 4.5 °C	4.5 to 8 °C	> 8 °C
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%

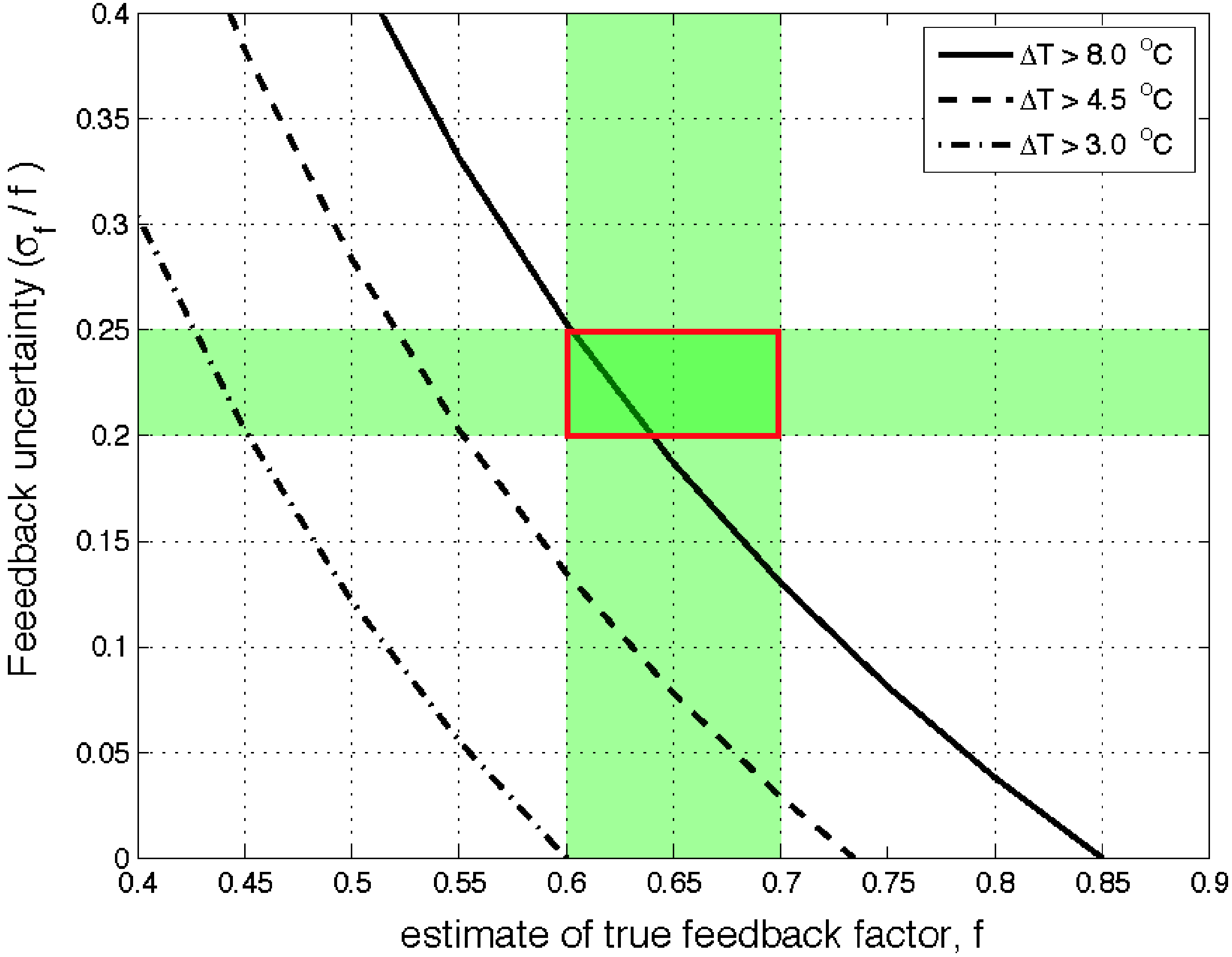
science is here

need to get here!

- Not much change as a function of σ_f

Climate sensitivity: can we do better?

- 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.*

-*Fat tail of the possibility of extreme climate sensitivity is inevitable, and has severe policy & planning consequences (e.g., Weitzman, 2008)*

• The unpredictability of climate is predictable.

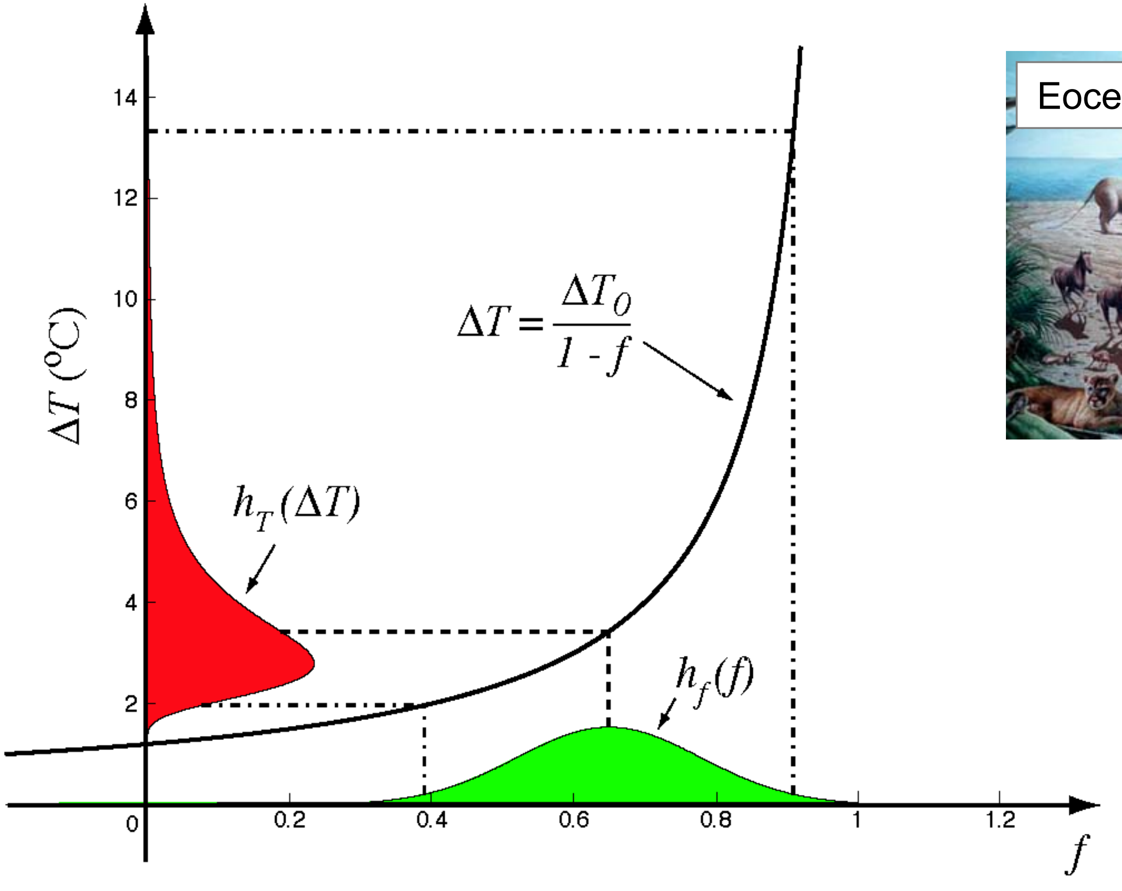
-*Compounding effect of essentially linear feedbacks dominates system sensitivity.*

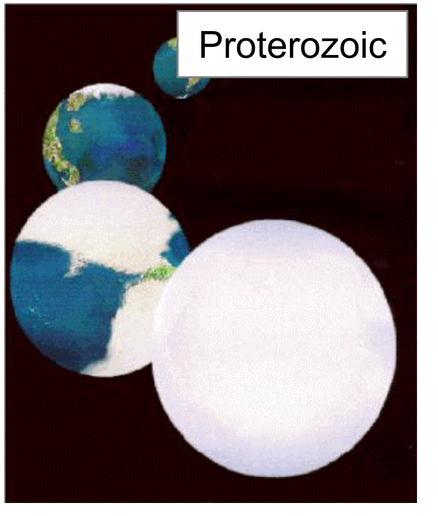
• If you know the feedback factors, and their uncertainties don't need10^4 GCMs (or 10^7 model years!).

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

Paleoclimate speculations?

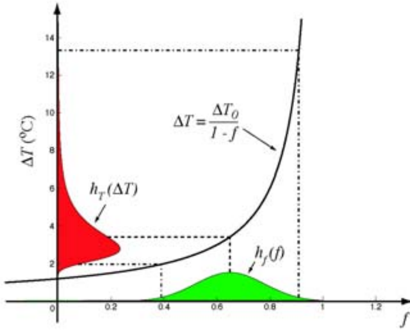
- What if feedback strengths change as a function of mean state?





- Dramatic changes in physics are not necessary for dramatic changes in climate sensitivity!

Can it be this simple?



- What is right about these ideas?

  - *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.*

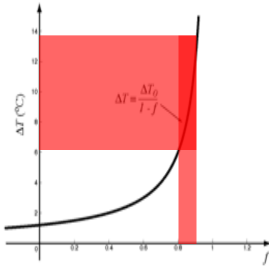
- What is wrong about these ideas?

  - *h(f) cannot strictly be Gaussian.*

  - *feedback framework is a linear analysis in a very nonlinear world.*

  - *conclusions come from a modeling perspective. Observations of what actually happens have not been used!*

Climate sensitivity: other approaches.



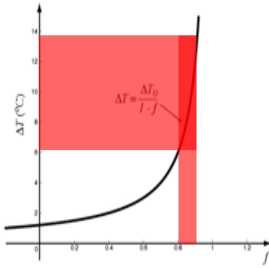
Using observations (Allen et al., 2006)

Estimate λ from global energy budget:

$$\lambda(\Delta R - \Delta Q) \sim \Delta T$$

ΔR = climate forcing;
ΔQ = energy imbalance;
ΔT = temperature change

Climate sensitivity: other approaches.



Using observations (Allen et al., 2006)

Estimate λ from global energy budget:

$$\lambda \sim \frac{\Delta T}{\Delta R - \Delta Q}$$

ΔR = climate forcing;
ΔQ = energy imbalance;
ΔT = temperature change

Example: for present day.

$\Delta T = 0.65 \pm 0.025\ ^oC$;

$\Delta Q = 0.85 \pm 0.08$ W m^{-2};

$\Delta R = 1.8 \pm 0.42$ W m^{-2}

™ and a
decompressor
is picture.

Lessons:

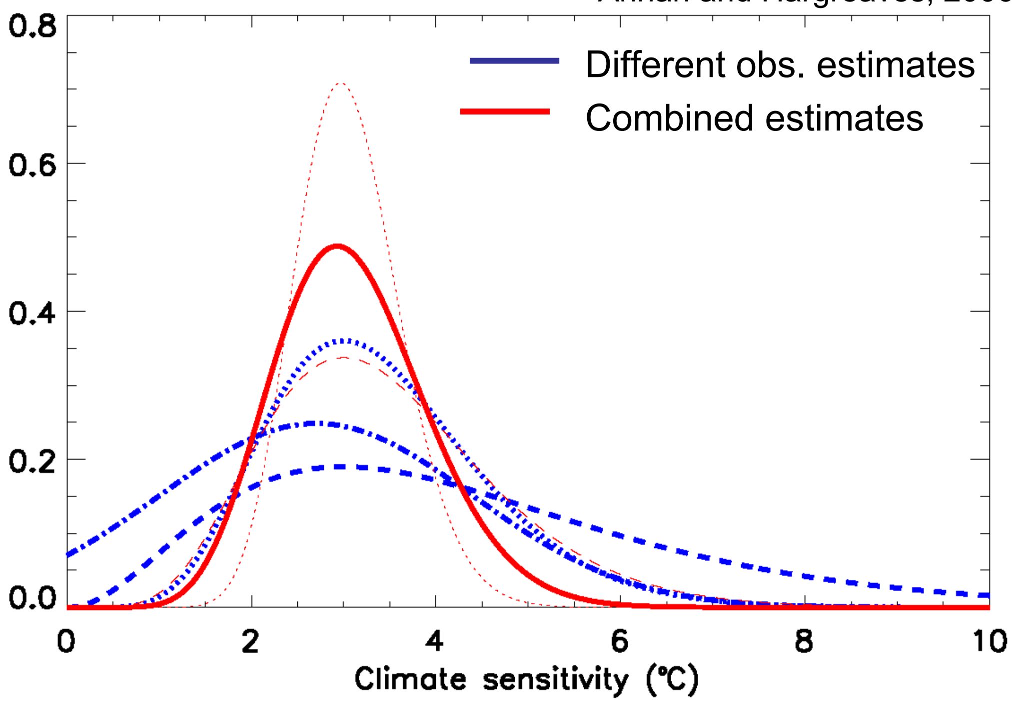
- Uncertainties in forcing dominate and still produce skewed tails.
- Forcing uncertainty comes from solar variability, volcanoes, aerosols, etc.
- True for any past climate reconstruction & also for modern…

Climate sensitivity: other approaches.

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

• In principle, climate sensitivity can be derived from multiple time intervals (little ice age, last ice age, modern, etc)

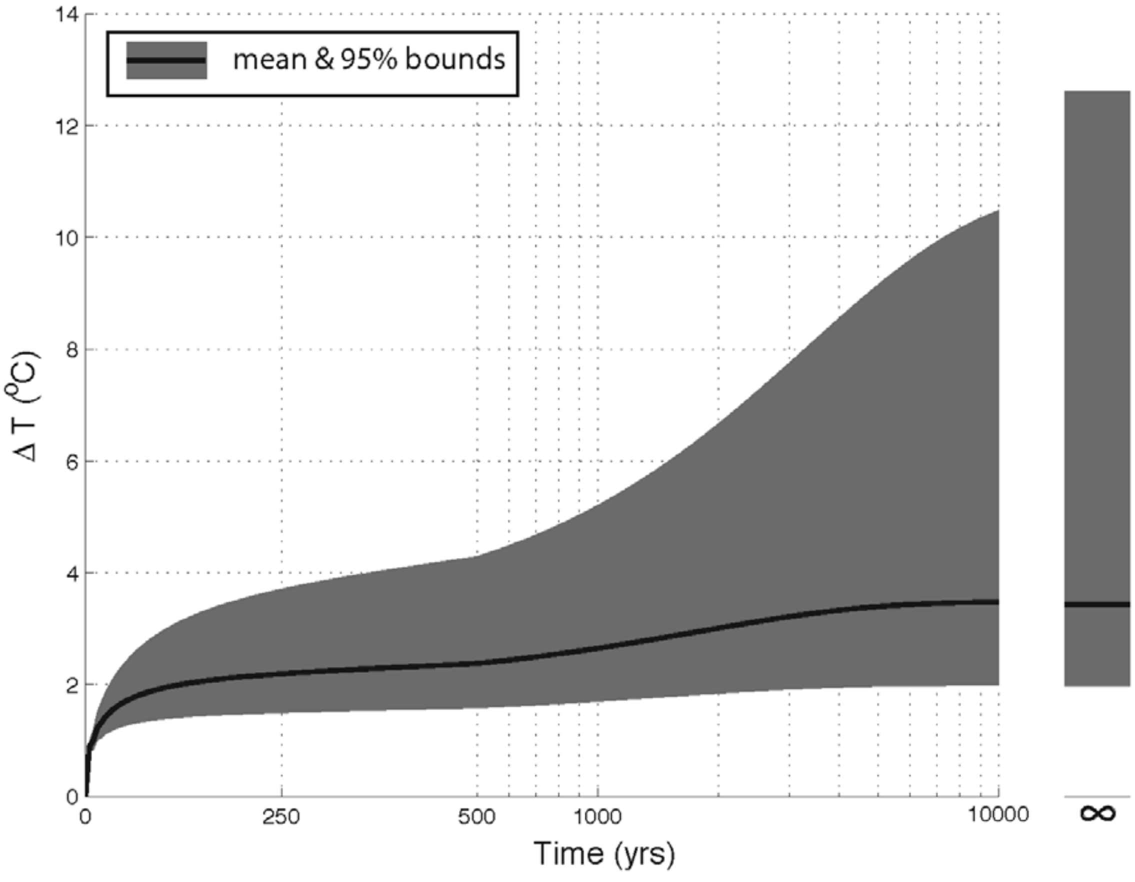
Annan and Hargreaves, 2006



Bayesian estimates depend very sensitively on prior assumptions and the independence of different information.

Time dependent climate change:

However, climate sensitivity is an equilibrium measure of climate, and climate change is a time dependent problem…



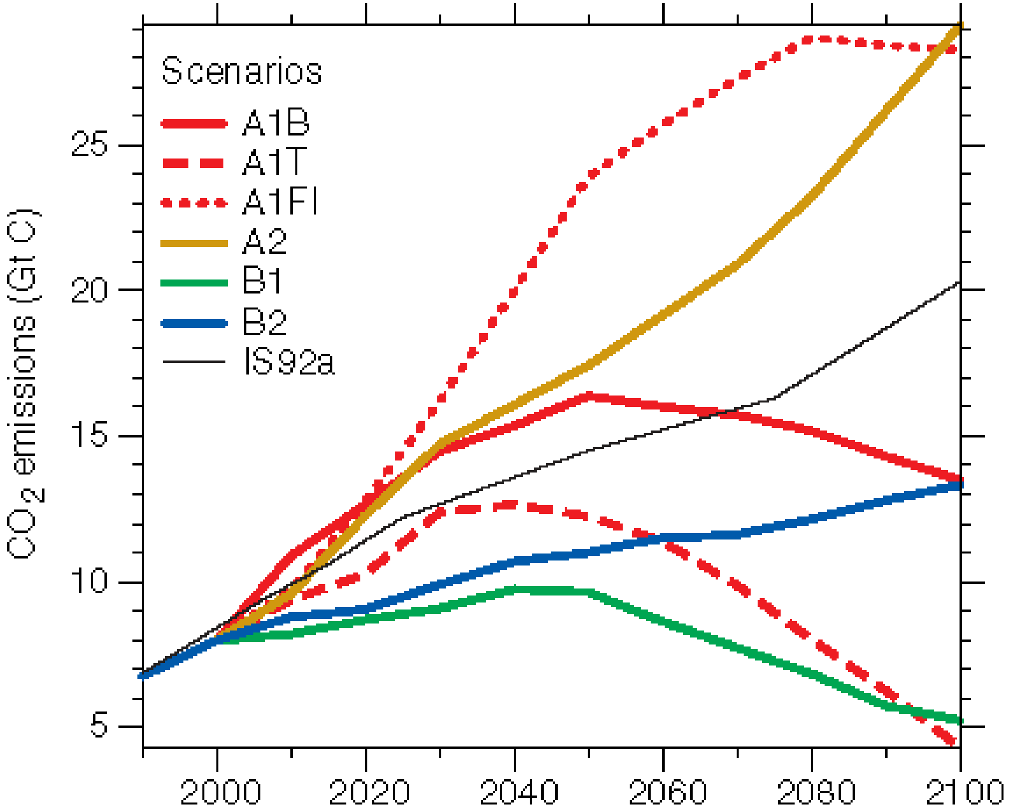
climate model response (mean & 95% bounds) to step function in forcing

- It takes a very long time for the full pdf of climate response to be realized

Time dependent climate change:

However, climate sensitivity is an equilibrium measure of climate, and climate change is a time dependent problem…

IPCC CO_2 emissions scenarios,



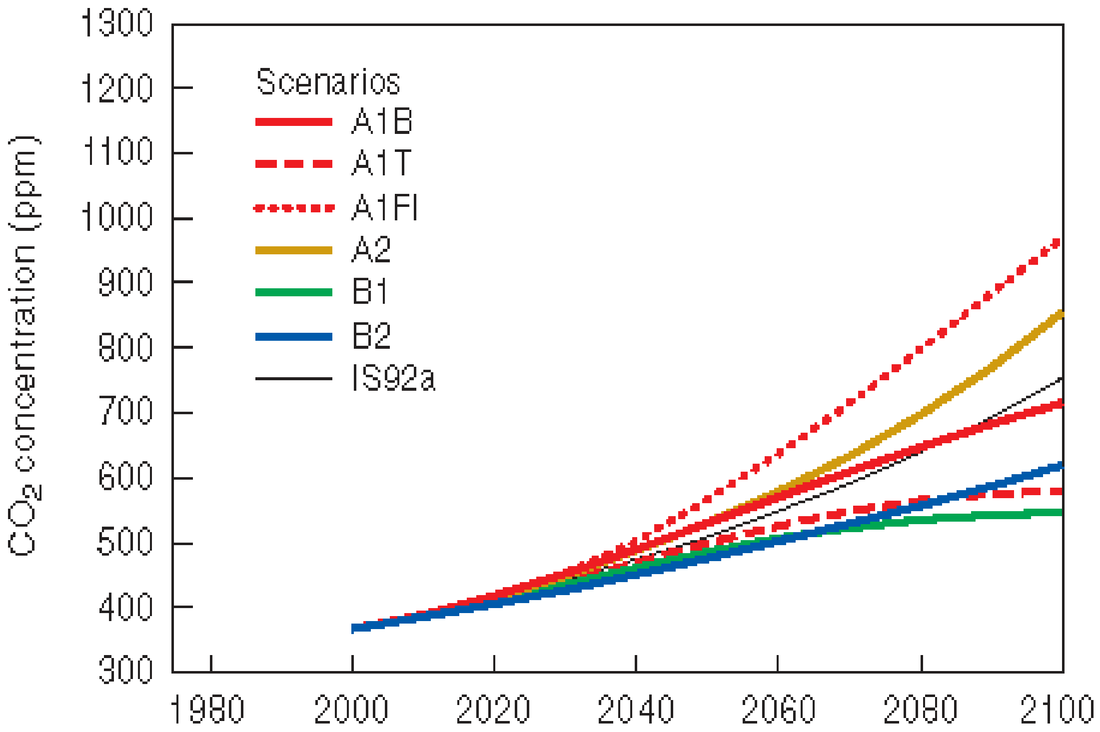
IPCC, 2001

Time dependent climate change:

However, climate sensitivity is an equilibrium measure of climate, and climate change is a time dependent problem…

IPCC CO_2 concentration scenarios:

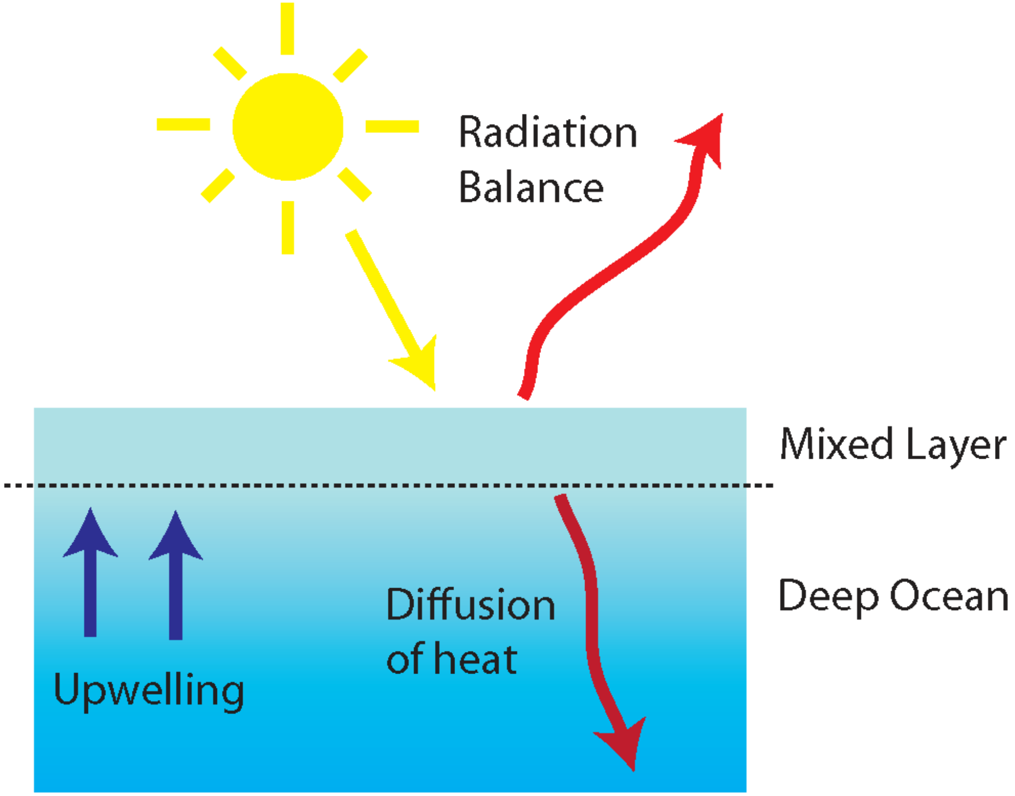
IPCC, 2001



How does the envelope of response evolve in time?

Time dependent climate change:

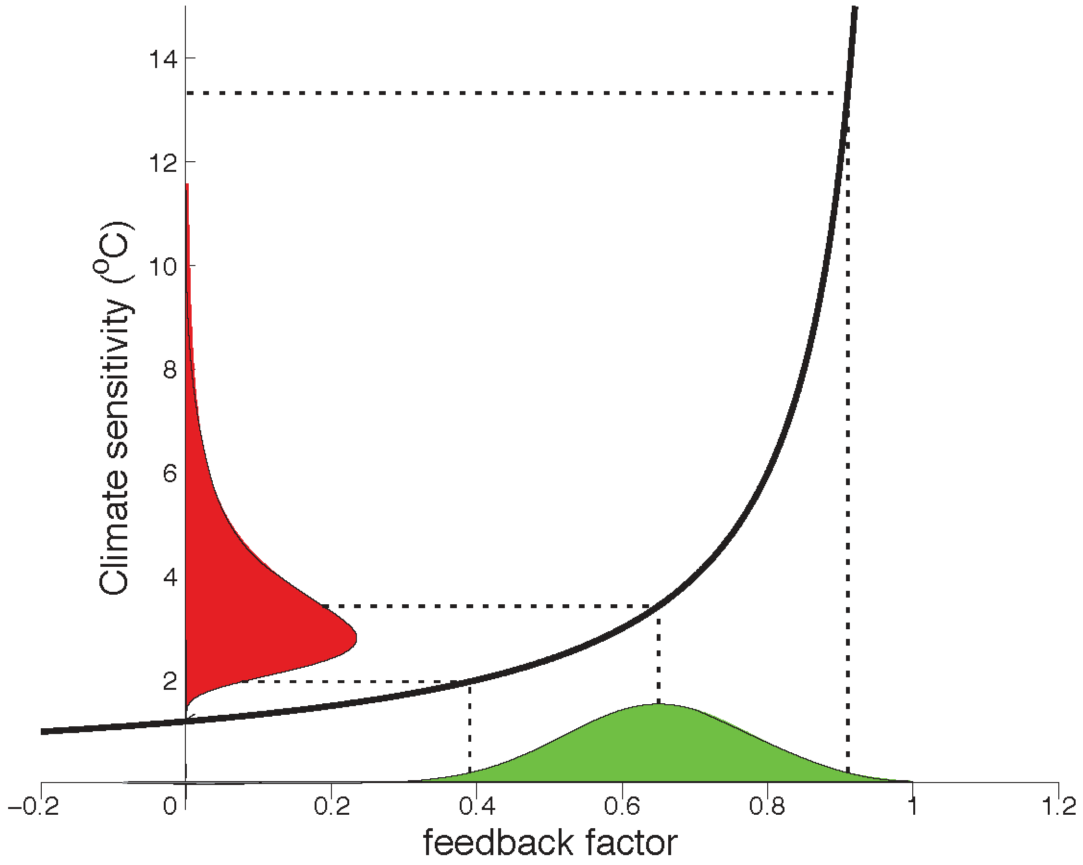
The role of the ocean



• The ocean heat uptake acts as a (transient) negative feedback.

Time dependent climate change:

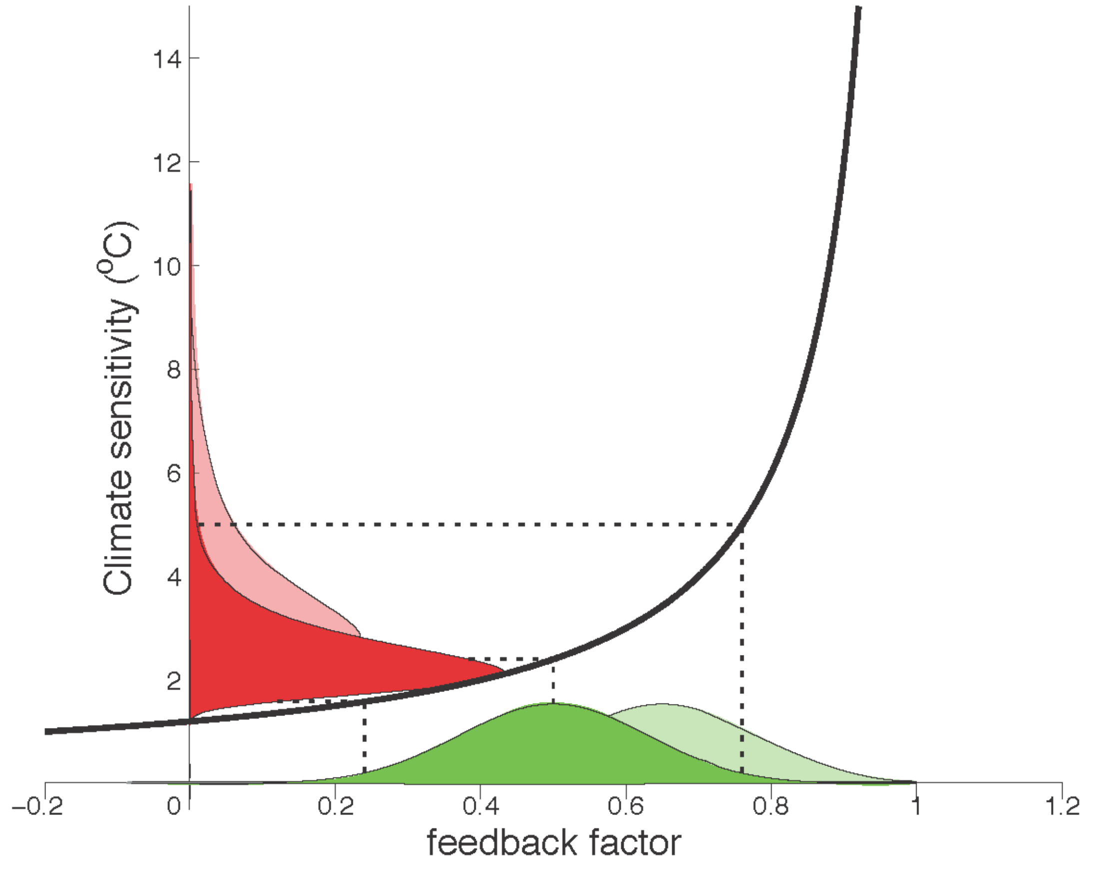
The role of the ocean



Time dependent climate change:

The role of the ocean

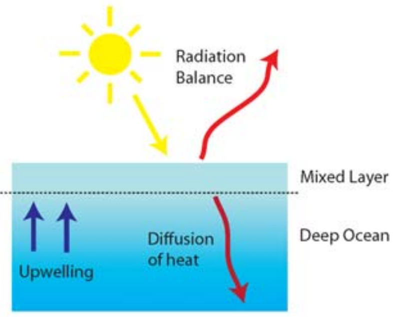
Addition of (transient) ocean feedback



• Ocean -ve feedback strongly reduces the width of the envelope

<u>Time dependent climate change:</u>

The role of the ocean



- Equations for a climate model…..

Mixed layer: $$\rho C h_{ml} \frac{\partial T'_{ml}}{\partial t} + \frac{T'_{ml}}{\lambda} - \kappa \frac{\partial T'}{\partial z}\bigg|_{z=0} = \Delta R_f(t)$$

Deep ocean: $$\frac{\partial T'}{\partial t} = \chi \frac{\partial^2 T'}{\partial z^2} - w \frac{\partial T'}{\partial z}$$

- Forget the equations, the point is…

  - Climate feedbacks combine simply, so…

  - Can integrate a simple climate model to propagate the full range of uncertainty in feedbacks, ocean heat uptake, forcing etc…

Time dependent climate change:

The role of the ocean

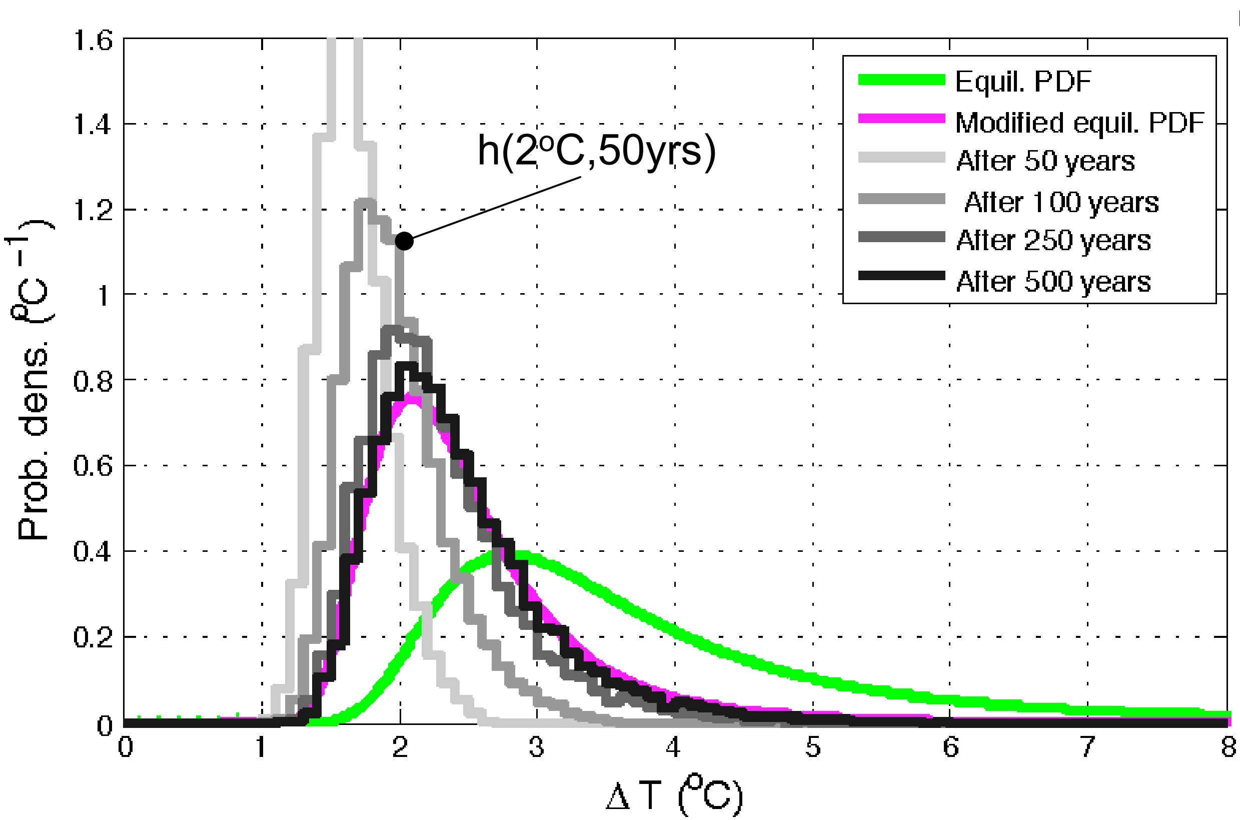
Response of temperature to a doubling of CO_2

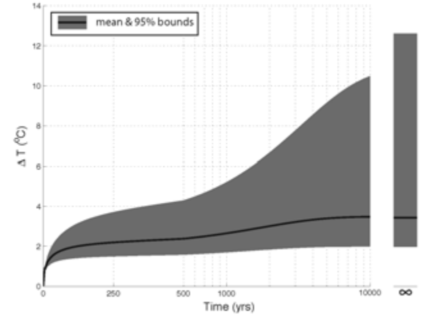
Eq^{m}. prob. distr.

Eq^{m}. prob. distr. modified by -ve ocean feedback

Time dependent climate change:

Why does the tail grow so slowly?



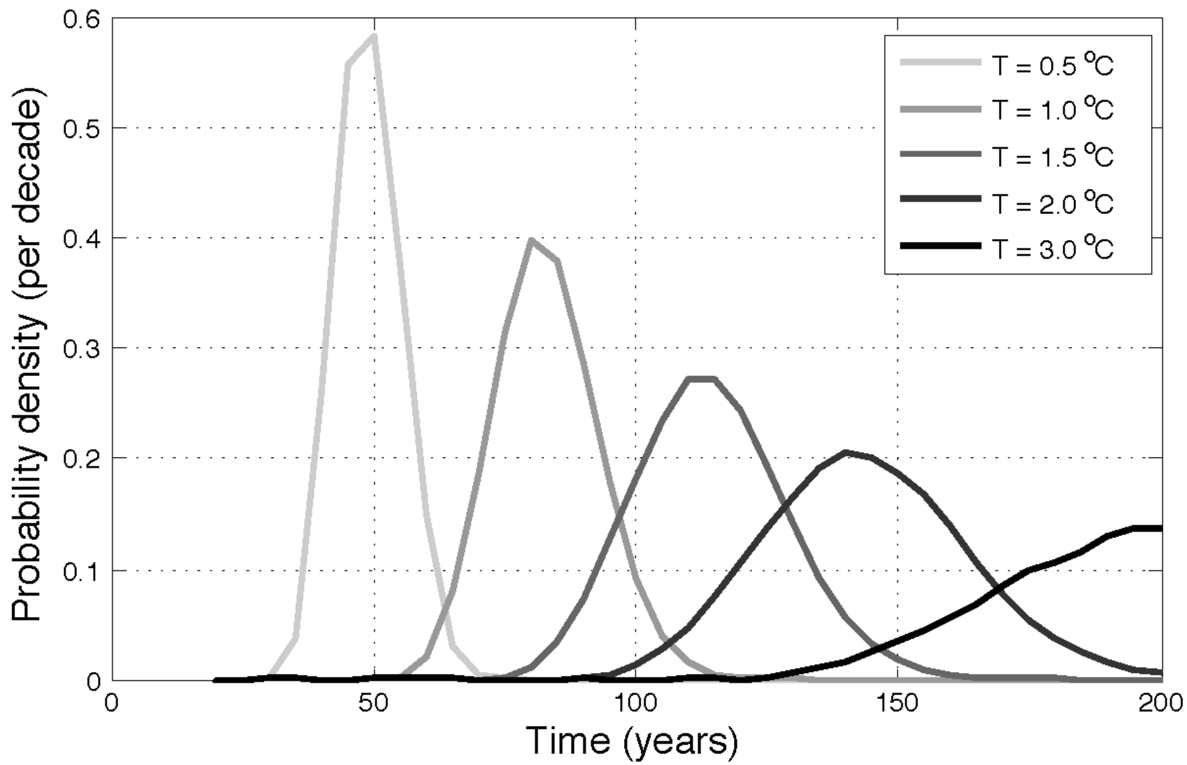


Let h(T,t) = probability density at some (T,t).

What governs how h(T,t) varies with time? (can talk about later…)

Time dependent climate change: 3 questions

1. What is the likelihood of reaching a given temperature at a given time?

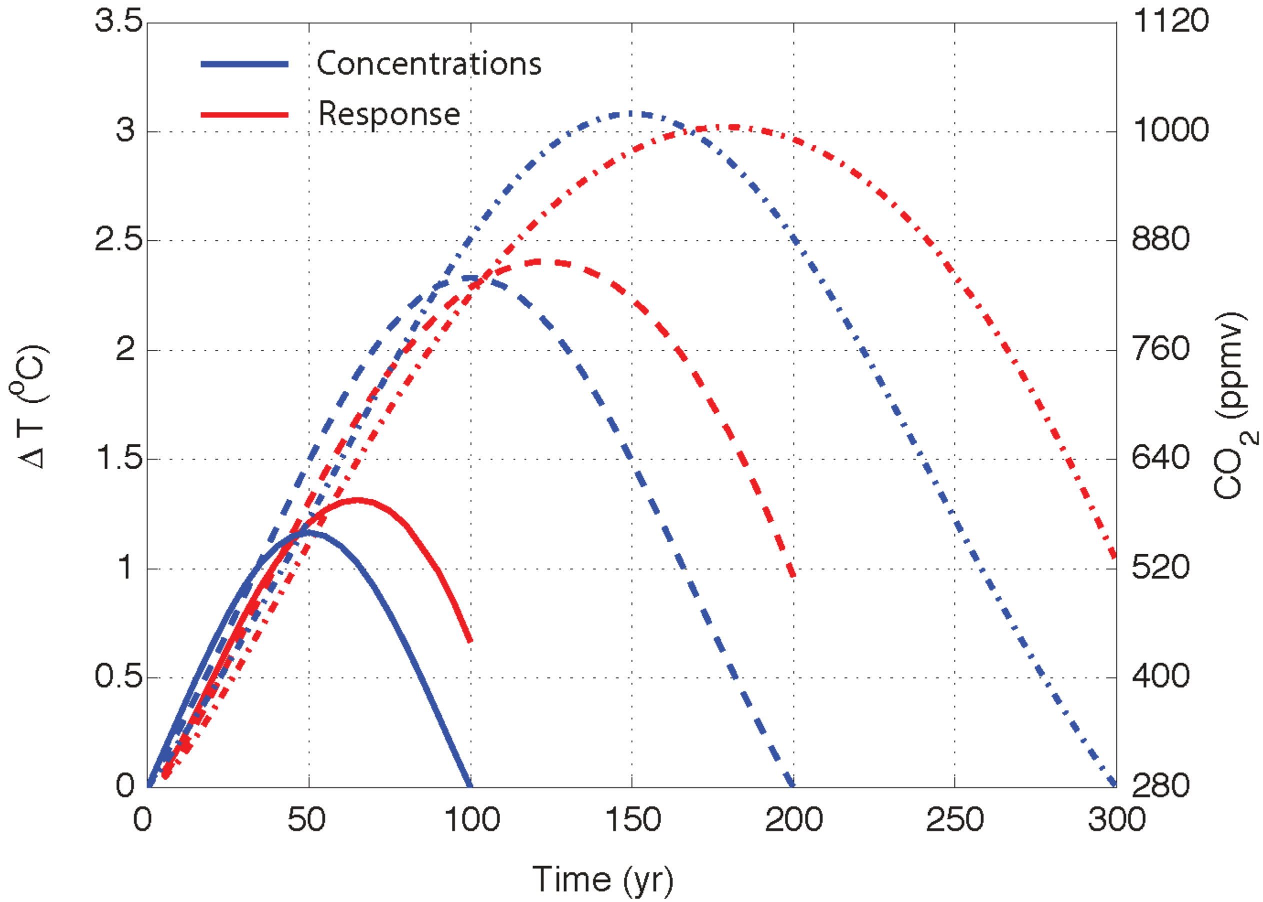


Doubling of CO_2 every 100 years

- The larger the temperature contemplated, the more uncertain it is when that temperature will be reached *(policy implications?).*

Time dependent climate change: 3 questions

2. Which uncertainties matter most?

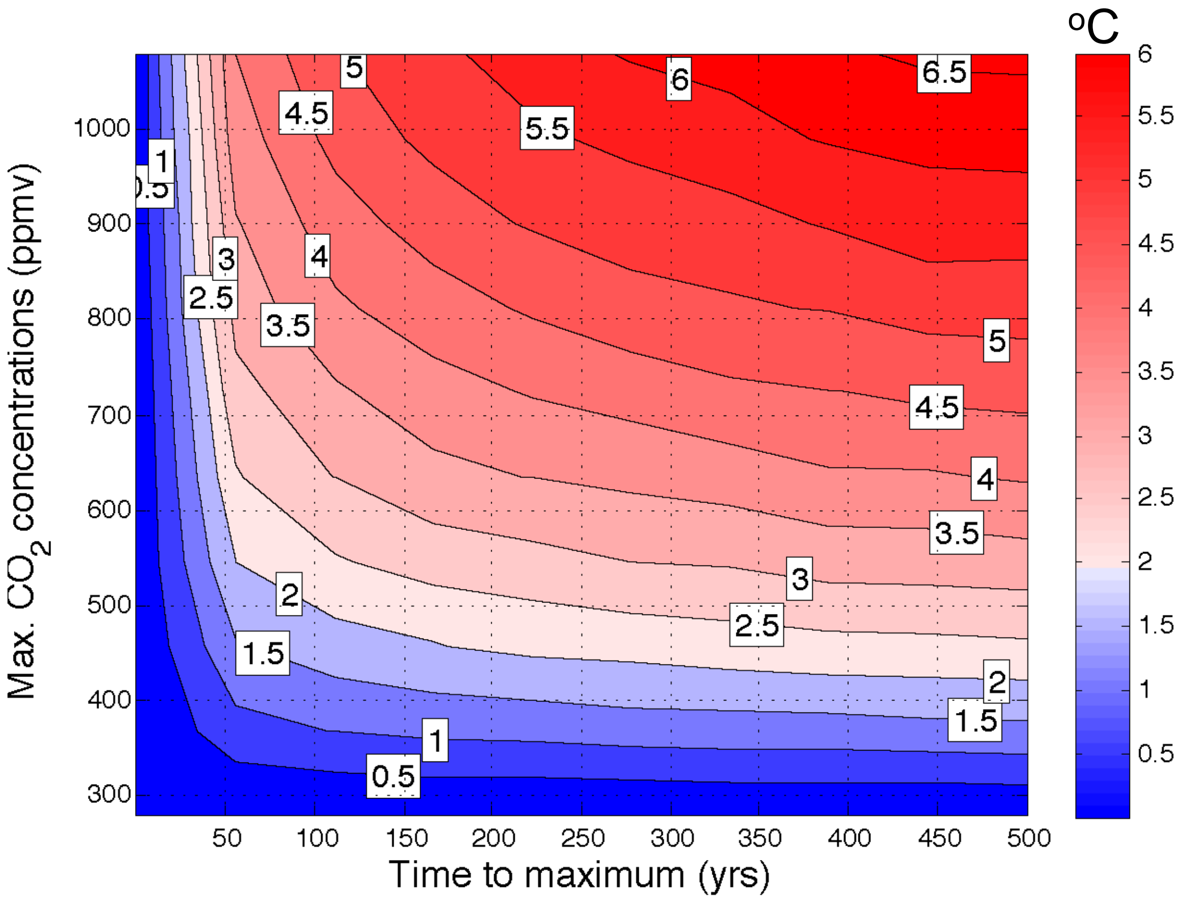


Concentration scenarios controlled by:

- maximum concentration.
- time to maximum.

Time dependent climate change: 3 questions

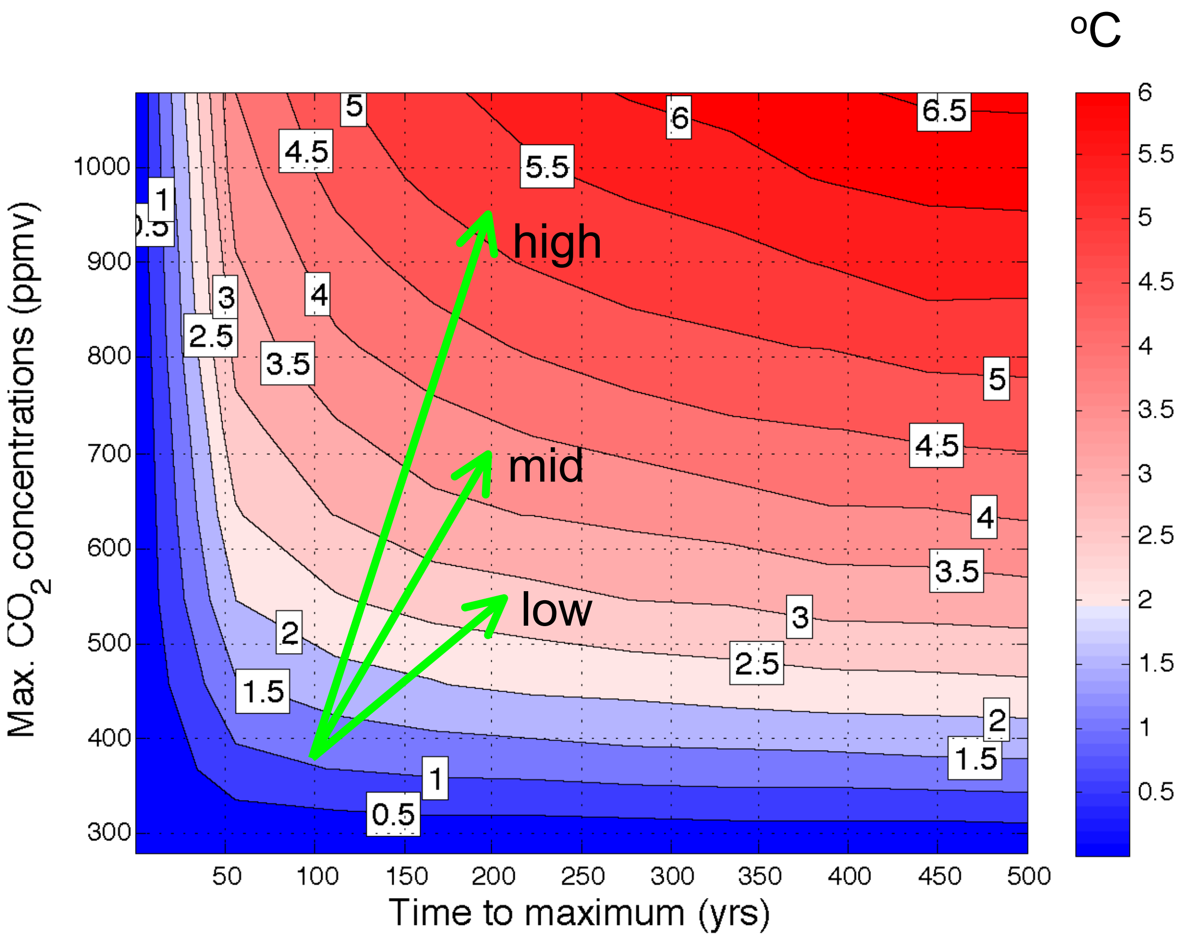
2. Which uncertainties matter most?



• If you are above the line, there is a 1 in 20 chance of seeing that climate change.

Time dependent climate change: 3 questions

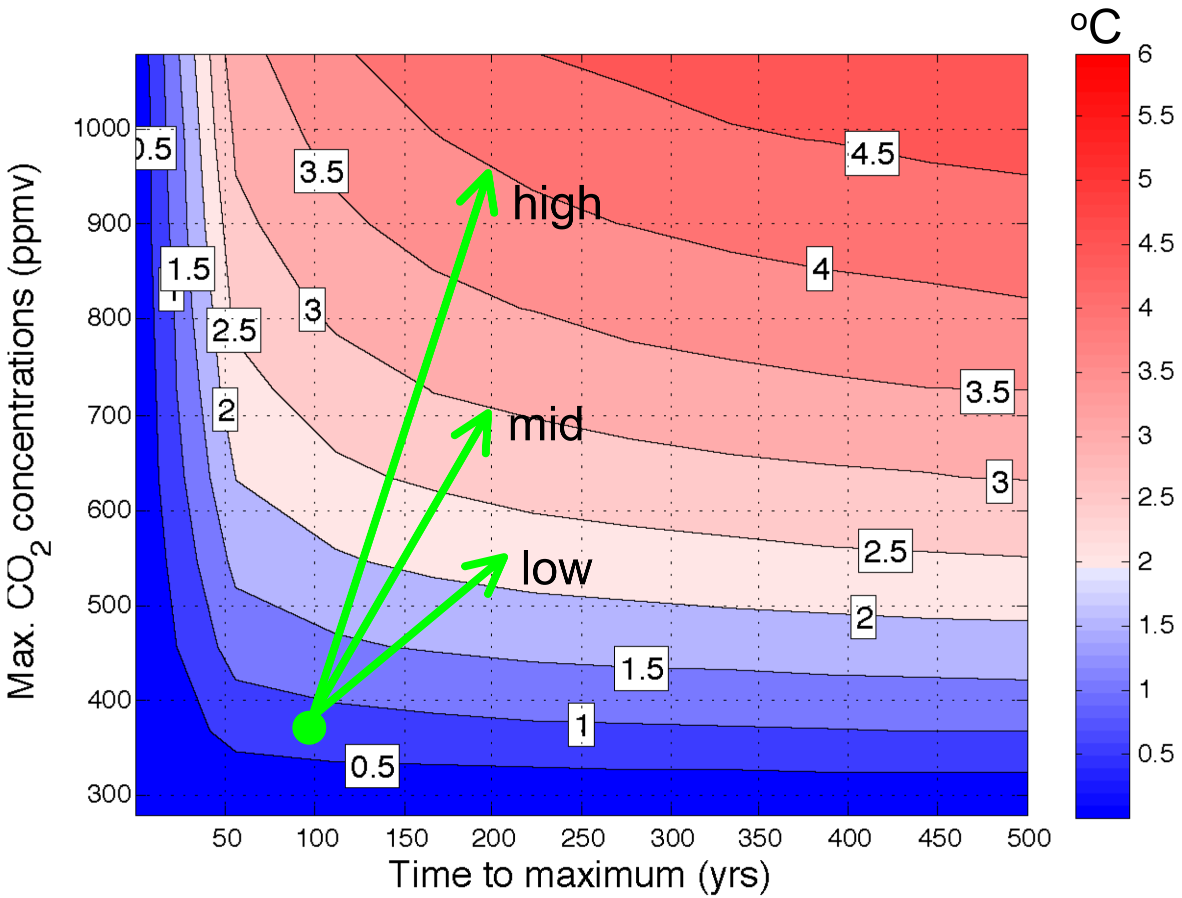
2. Which uncertainties matter most?



- All IPCC emissions scenarios yield a significant risk of dangerous climate change…

Time dependent climate change: 3 questions

2. Which uncertainties matter most?



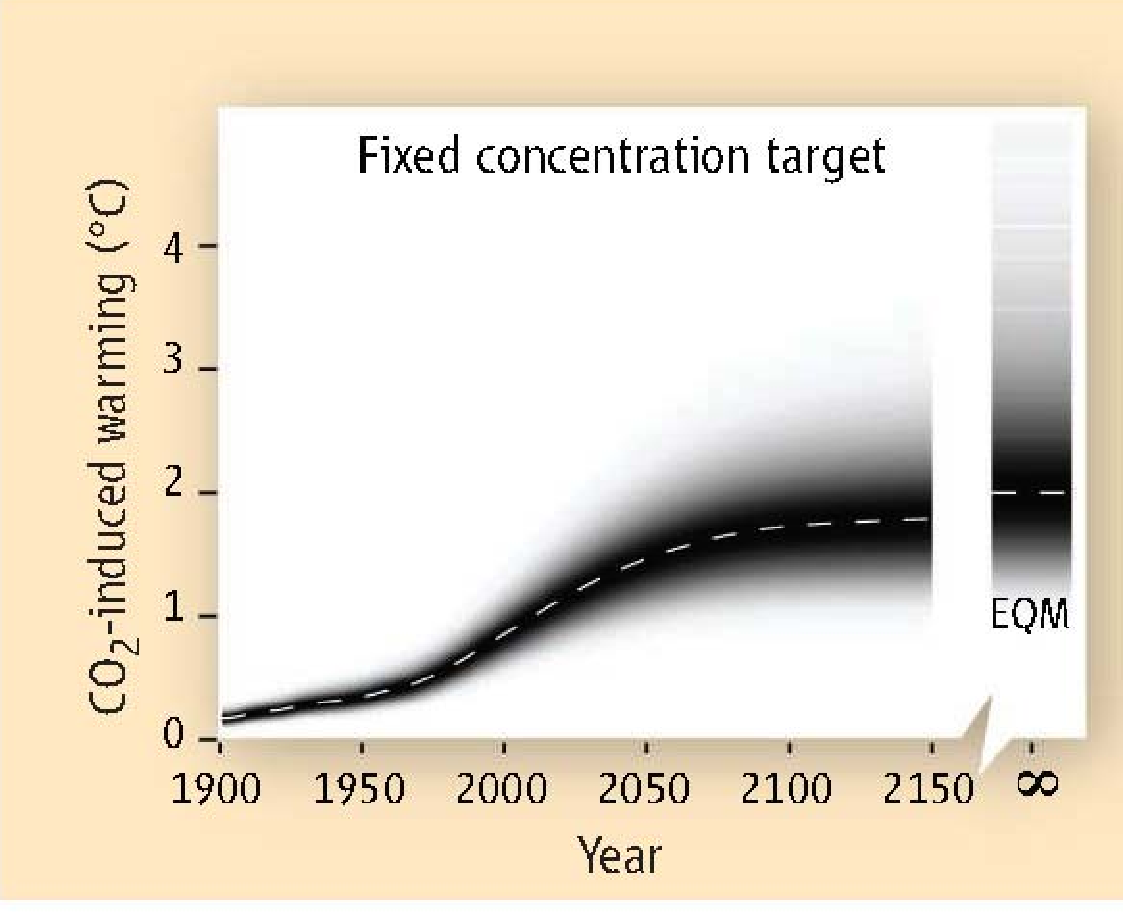
What happens
In you halve the
uncertainty
in all climate
model parameters?

- Getting smarter about climate, and reducing uncertainty, does not help that much.
- Uncertainty in emissions (and eventual concentrations) dominates.

Time dependent climate change: 3 questions

2. Why even care about climate sensitivity? *(sense and sensitivity…)*

• Constraining climate sensitivity not terribly relevant for predicting climate change…



(Allen and Frame, 2007)

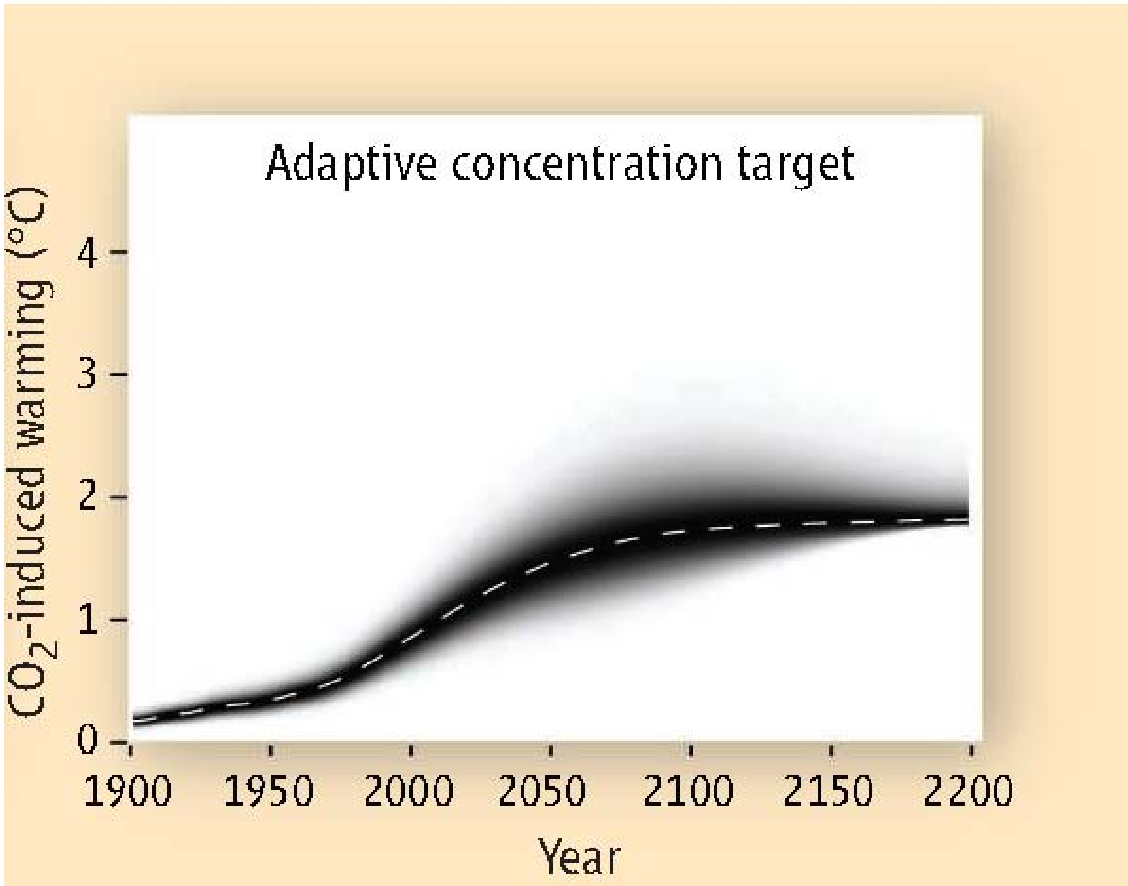
Stabilization target of 450 ppm at 2100

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

Time dependent climate change: 3 questions

2. Why even care about climate sensitivity? (sense and sensitivity…)

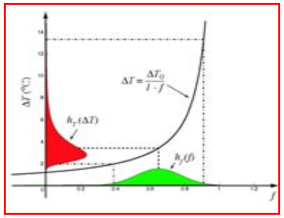
Constraining climate sensitivity not terribly relevant for predicting climate change… (Allen and Frame, 2007)



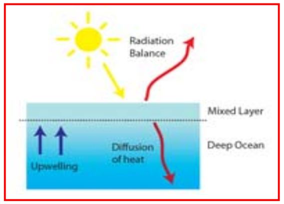
Concentration target adjusted at 2050.

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

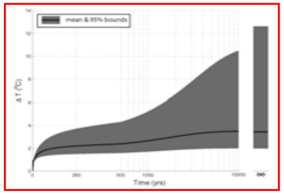
Conclusions II:



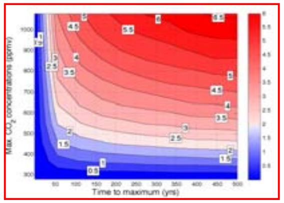
• We face a practical limit to the predictability of climate sensitivity - the fat tail is inevitable…



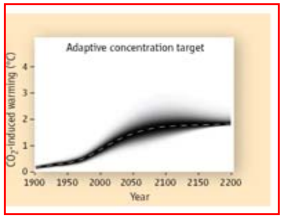
• Ocean heat uptake acts as a strong buffer.



• Growth of the fat tail is very slow.



• Uncertainty in emissions swamps uncertainty in climate feedbacks.

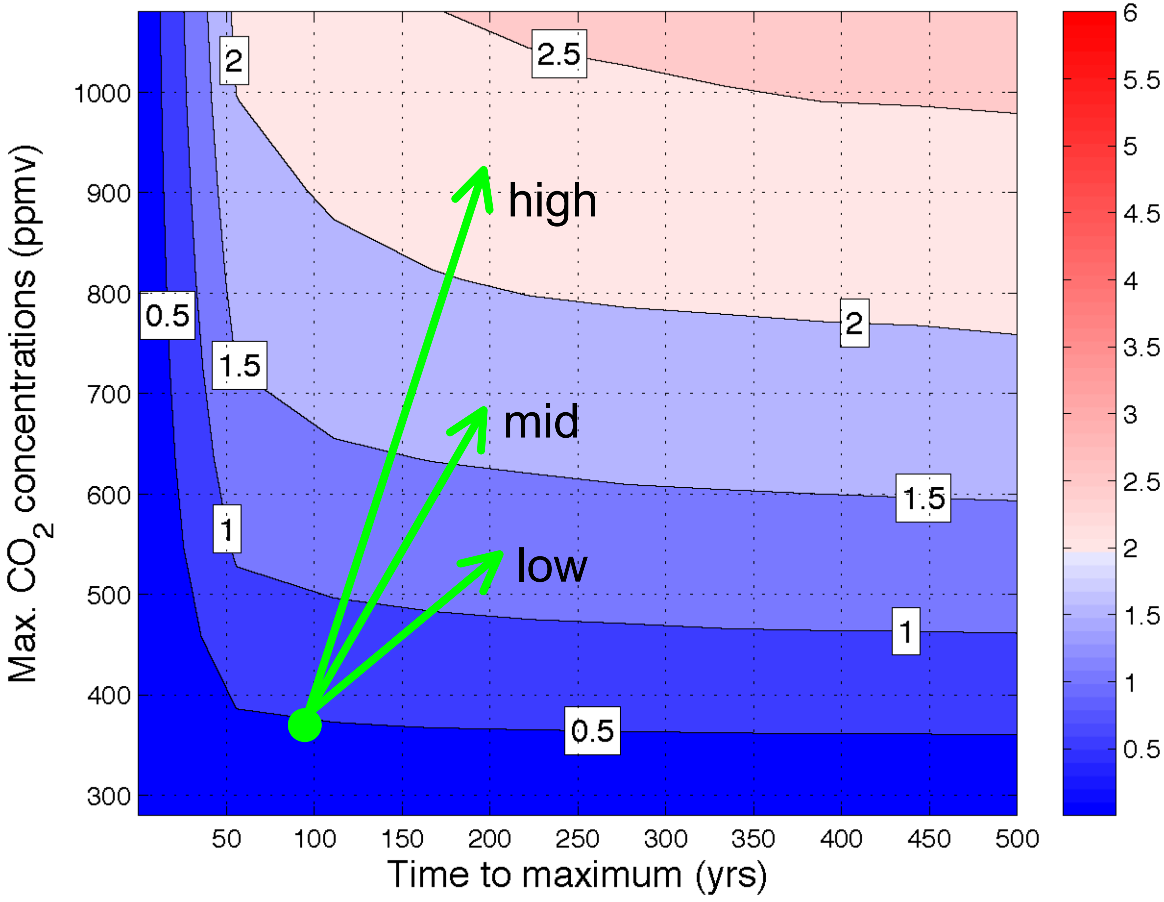


• Flexibility is key!

Time dependent climate change:

The role of the ocean

95% likelihood climate change

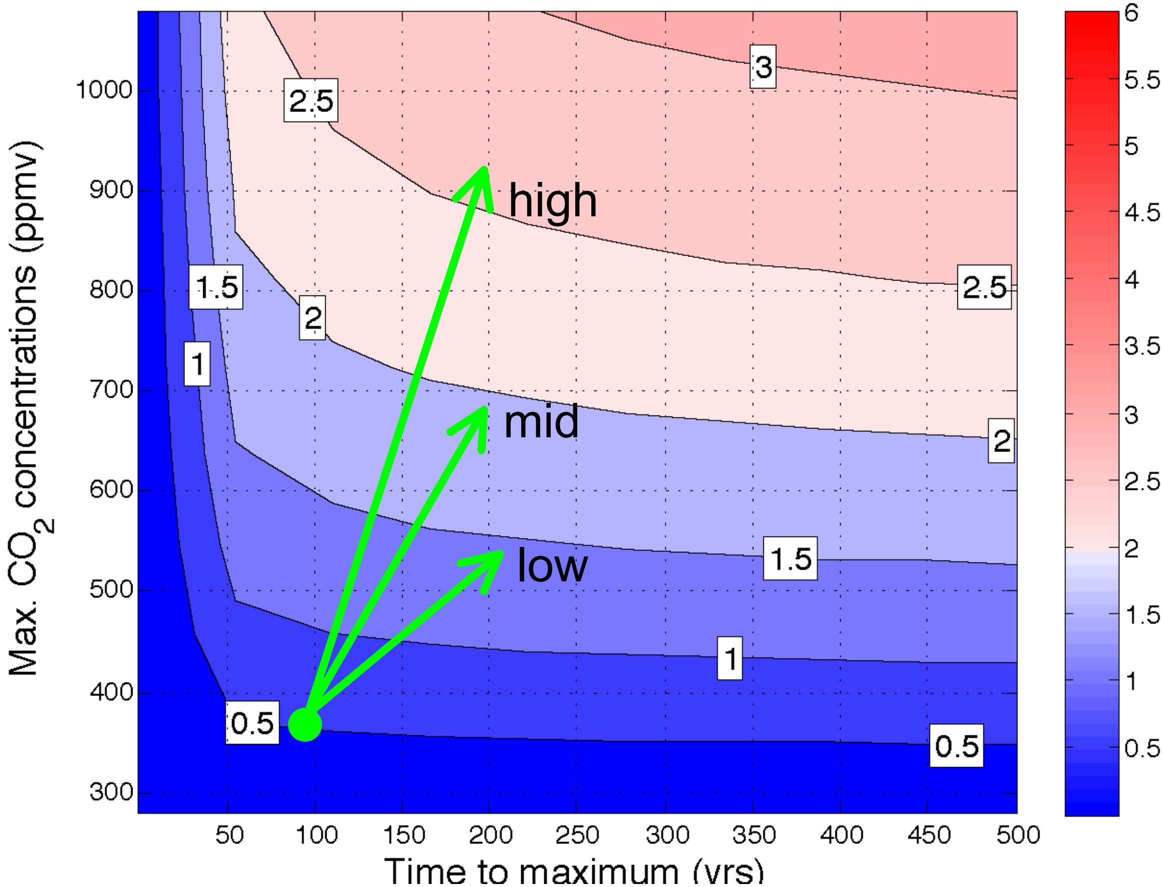


if you are above the line you have at least a 19 in 20 chance of that climate change

Time dependent climate change:

The role of the ocean

95% likelihood of climate change

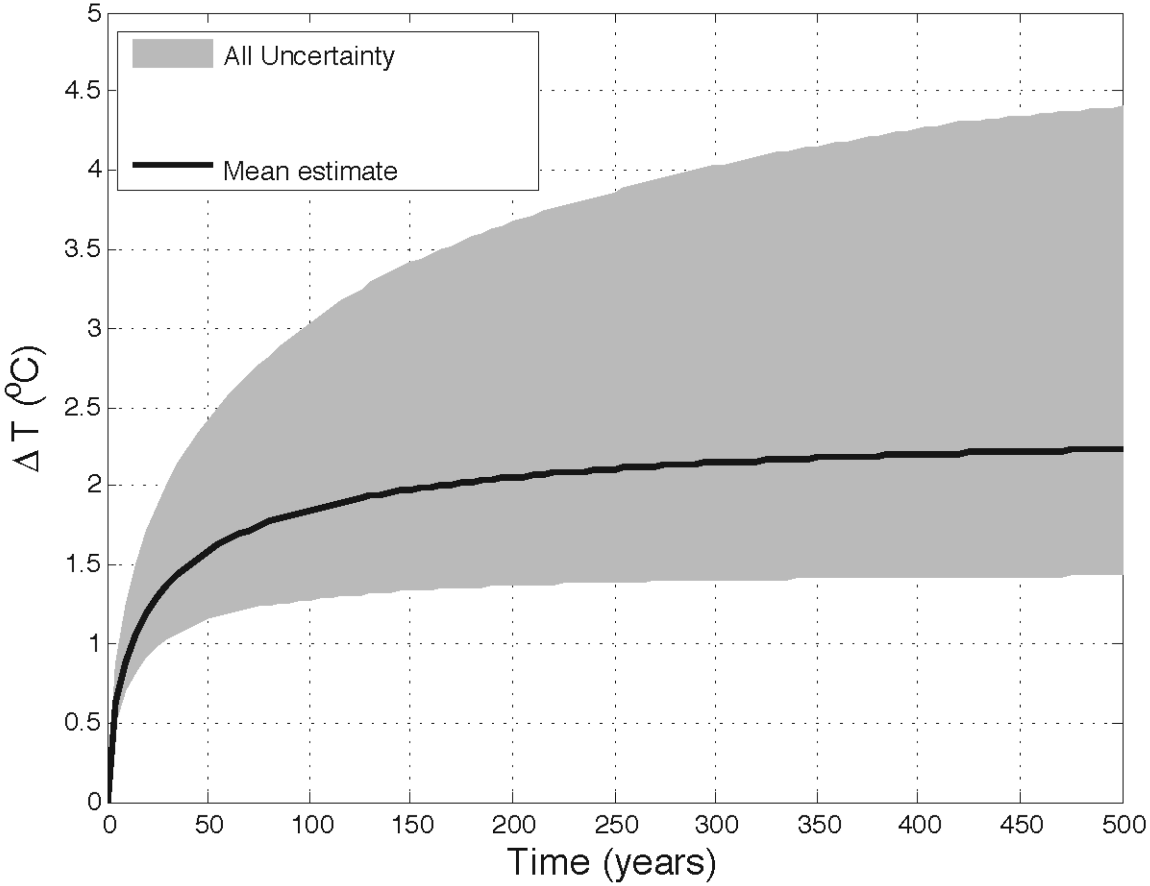


And if you halve the uncertainty…

if you are above the line you have at least a 19 in 20 chance of that climate change

What kind of uncertainties matter for projections?

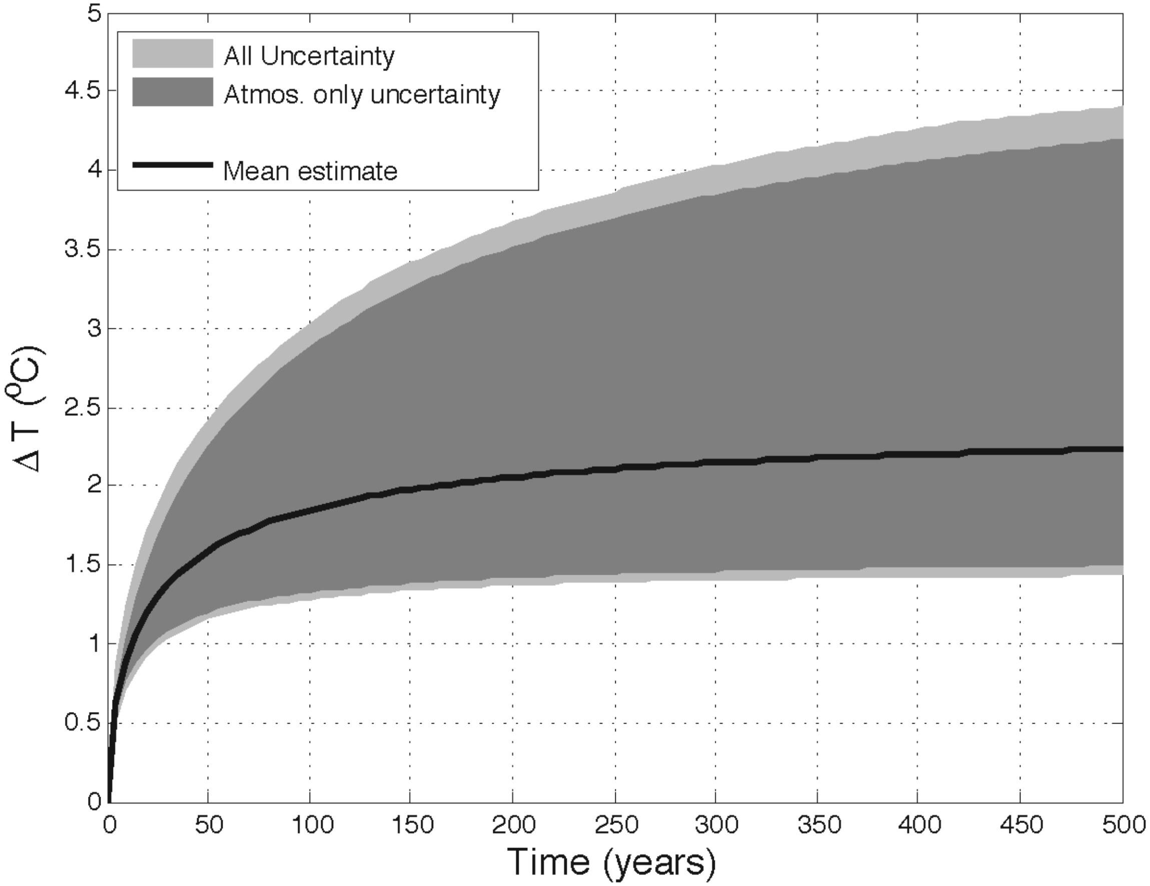
Response to a step-function doubling of CO_2



95% range

What kind of uncertainties matter for projections?

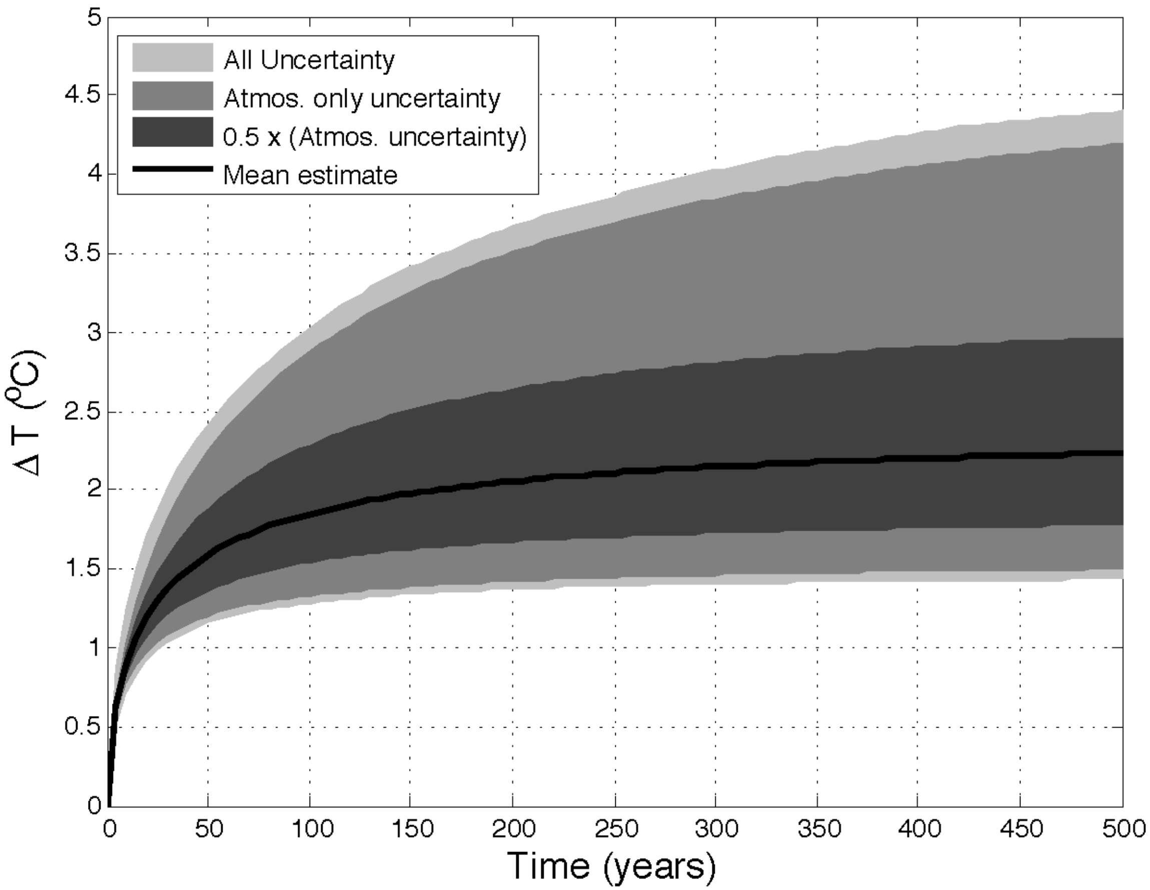
Response to a step-function doubling of CO_2



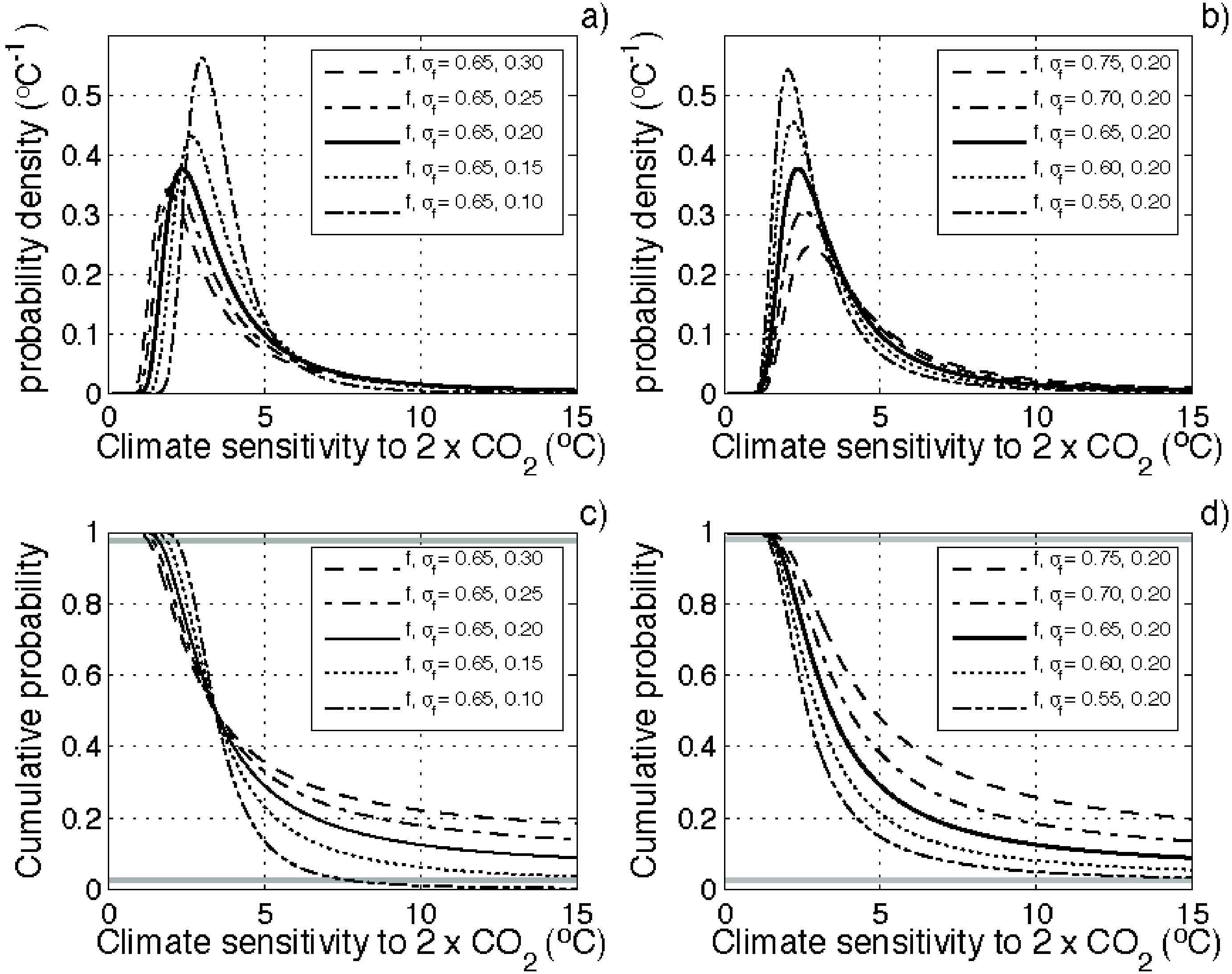
95% range

What kind of uncertainties matter for projections?

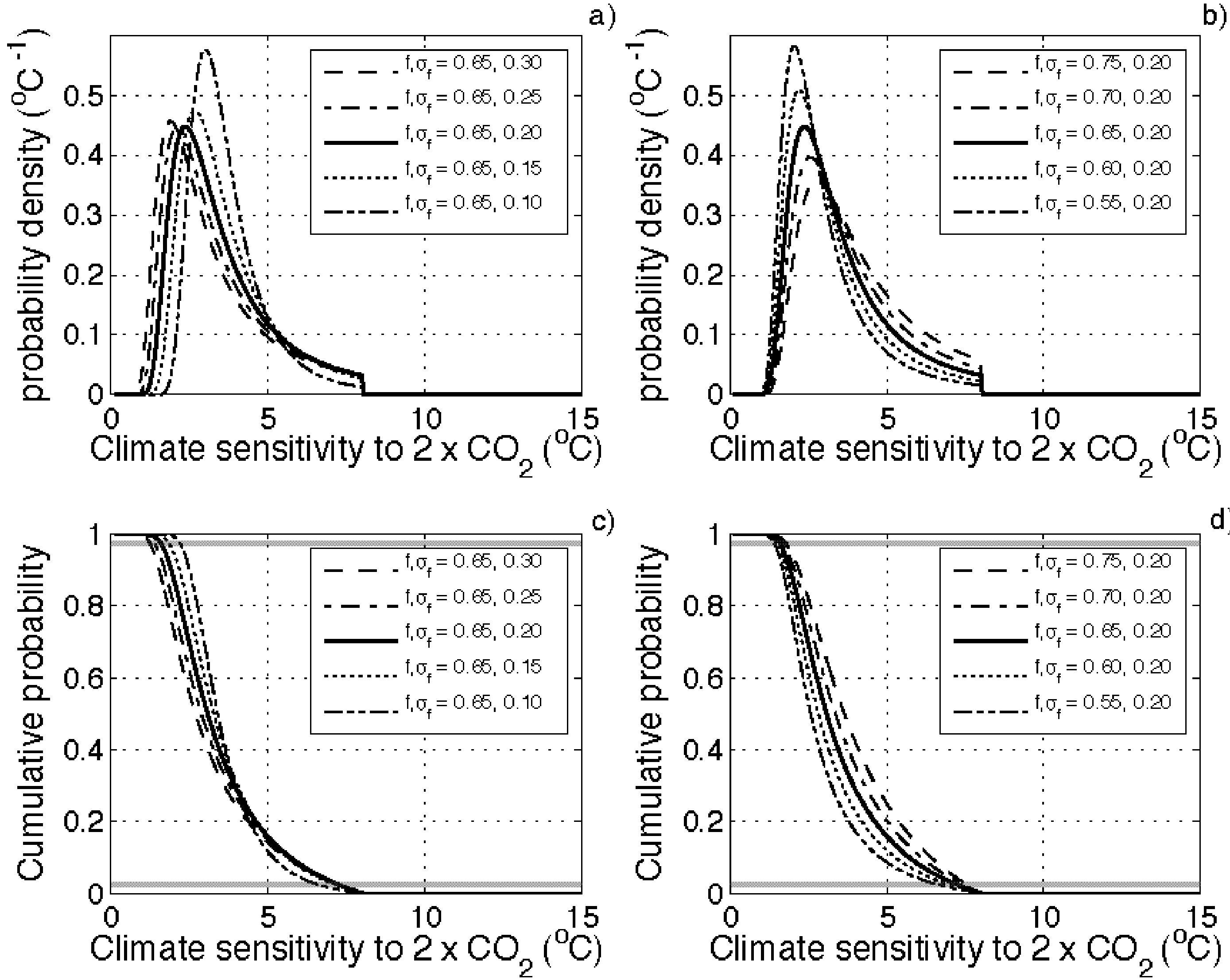
Response to a step-function doubling of CO_2



95% range



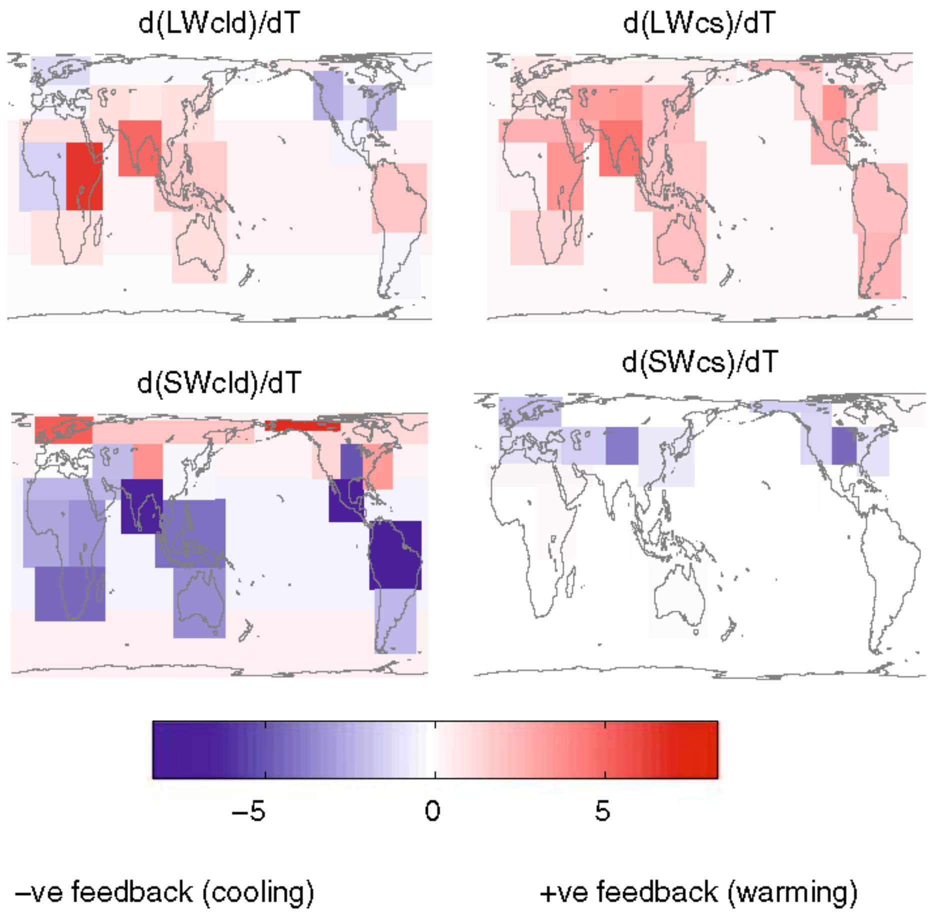
a)
b)
c)
d)
probability density (°C⁻¹)
Cumulative probability
Climate sensitivity to 2 x CO2 (°C)
f, σf = 0.65, 0.30
f, σf = 0.65, 0.25
f, σf = 0.65, 0.20
f, σf = 0.65, 0.15
f, σf = 0.65, 0.10
f, σf = 0.75, 0.20
f, σf = 0.70, 0.20
f, σf = 0.65, 0.20
f, σf = 0.60, 0.20
f, σf = 0.55, 0.20


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

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 ↑



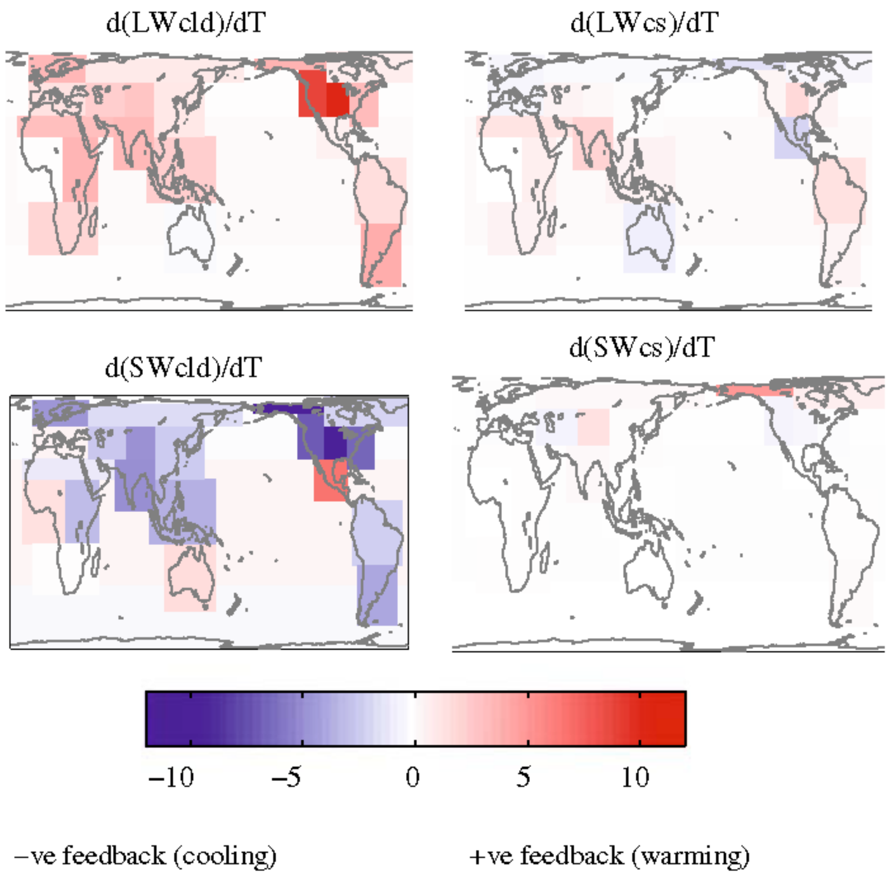
Surface rad^{n} tendencies assoc. with entrainment

Spatial patterns of feedbacks

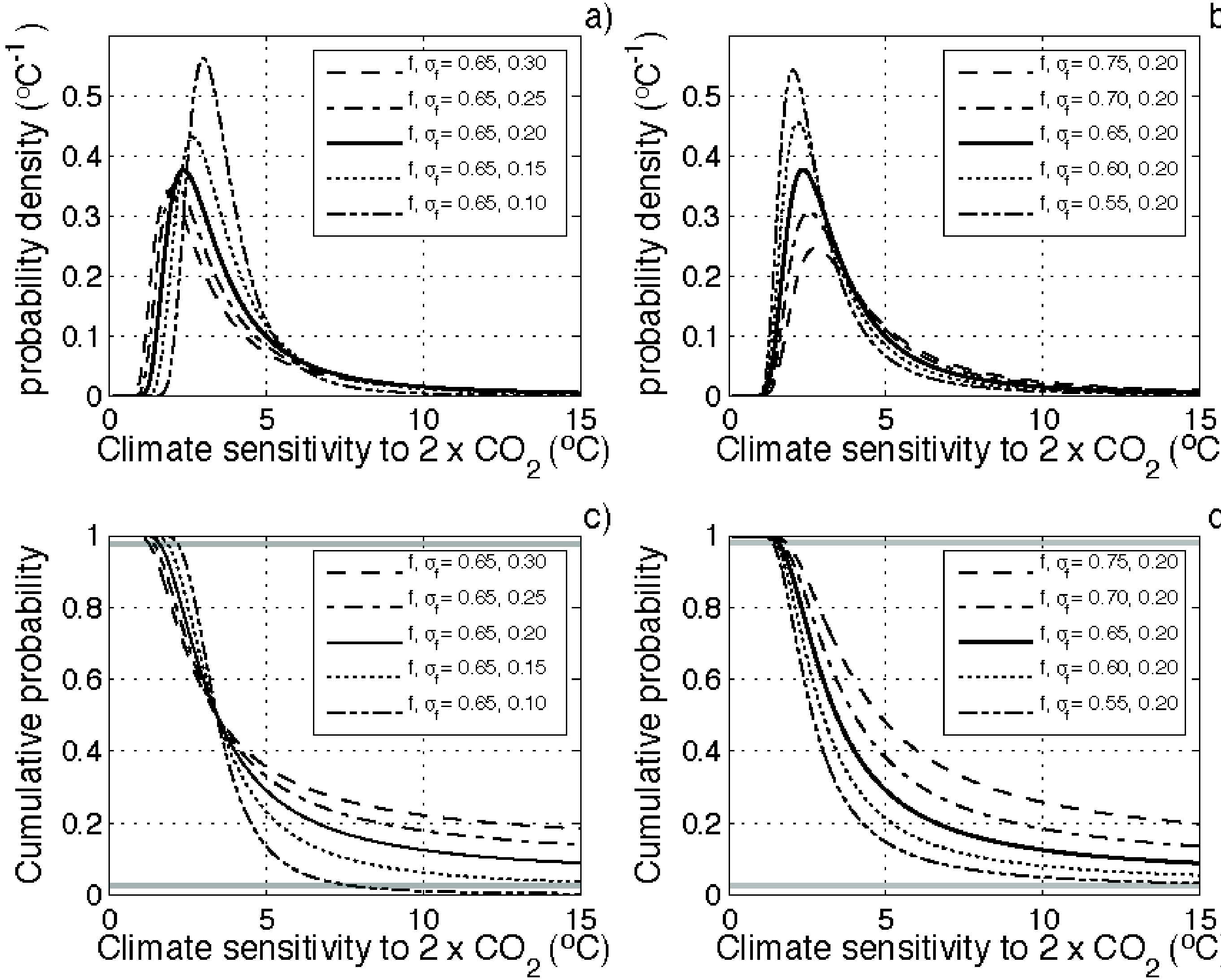
Sanderson et al., 2007

• **ice fall speed** has 2nd biggest impact on climate sensitivity in *climateprediction.net* ensemble.

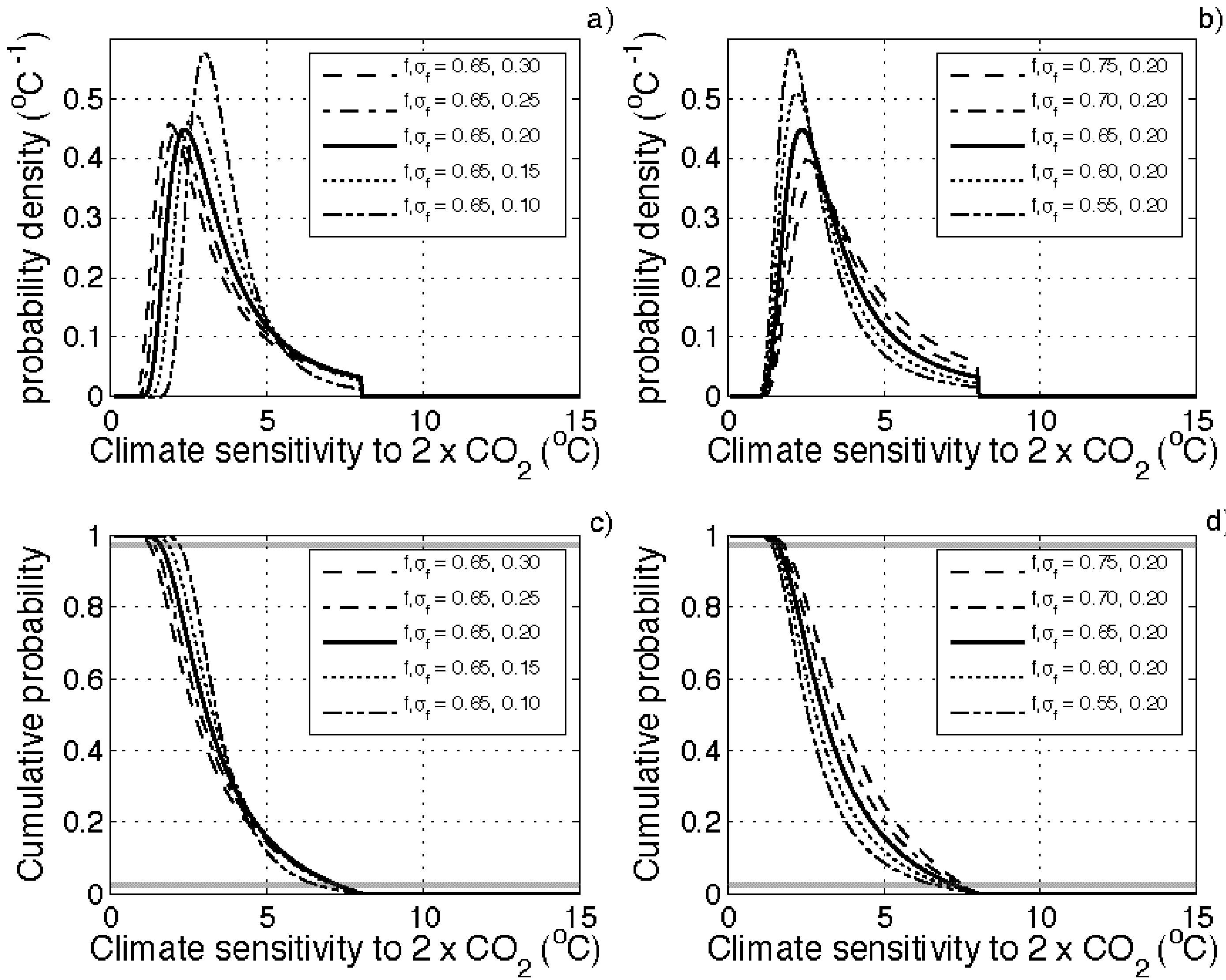
• fall speed ↓, clouds/humidity ↑, greenhouse effect↑



Surface rad^n Tendencies assoc. with fall speed

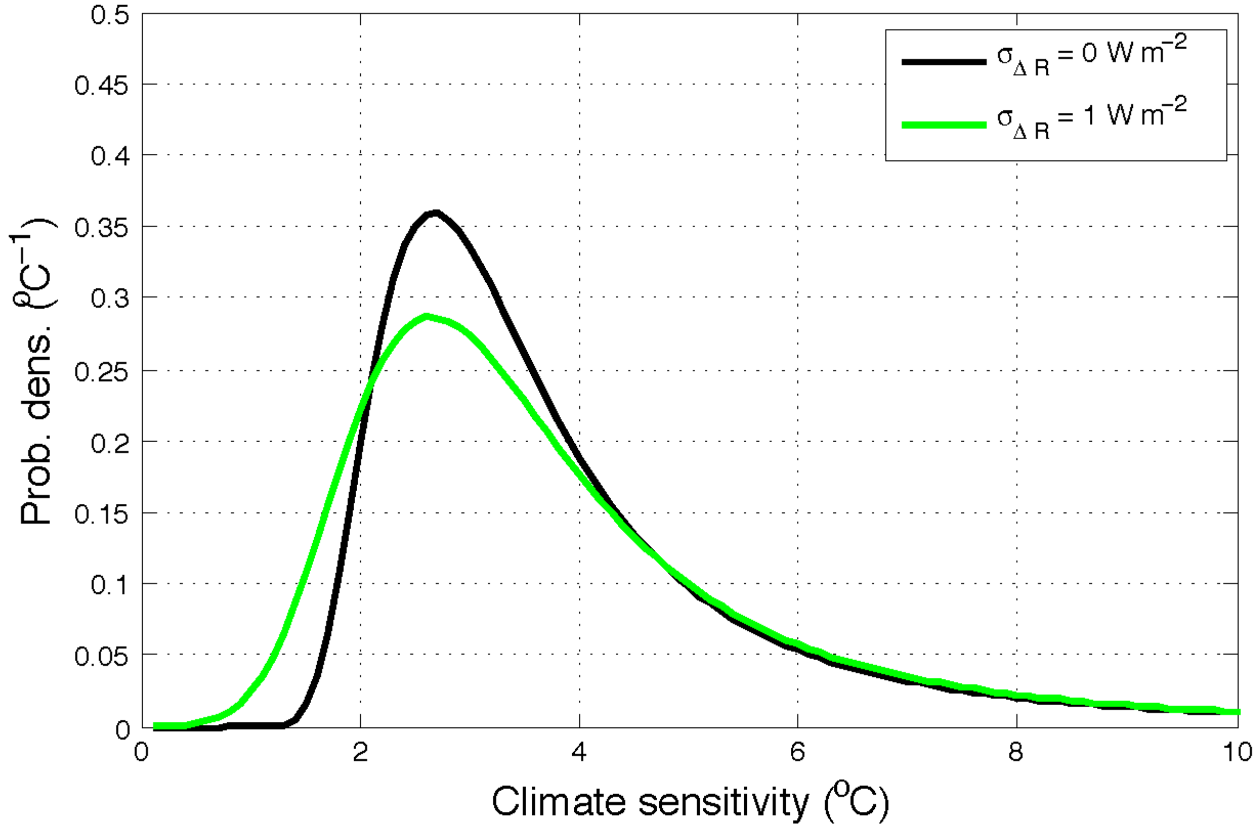


a)
probability density (°C⁻¹)
f, σf = 0.65, 0.30
f, σf = 0.65, 0.25
f, σf = 0.65, 0.20
f, σf = 0.65, 0.15
f, σf = 0.65, 0.10
Climate sensitivity to 2 x CO2 (°C)
b)
probability density (°C⁻¹)
f, σf = 0.75, 0.20
f, σf = 0.70, 0.20
f, σf = 0.65, 0.20
f, σf = 0.60, 0.20
f, σf = 0.55, 0.20
Climate sensitivity to 2 x CO2 (°C)
c)
Cumulative probability
f, σf = 0.65, 0.30
f, σf = 0.65, 0.25
f, σf = 0.65, 0.20
f, σf = 0.65, 0.15
f, σf = 0.65, 0.10
Climate sensitivity to 2 x CO2 (°C)
d)
Cumulative probability
f, σf = 0.75, 0.20
f, σf = 0.70, 0.20
f, σf = 0.65, 0.20
f, σf = 0.60, 0.20
f, σf = 0.55, 0.20
Climate sensitivity to 2 x CO2 (°C)



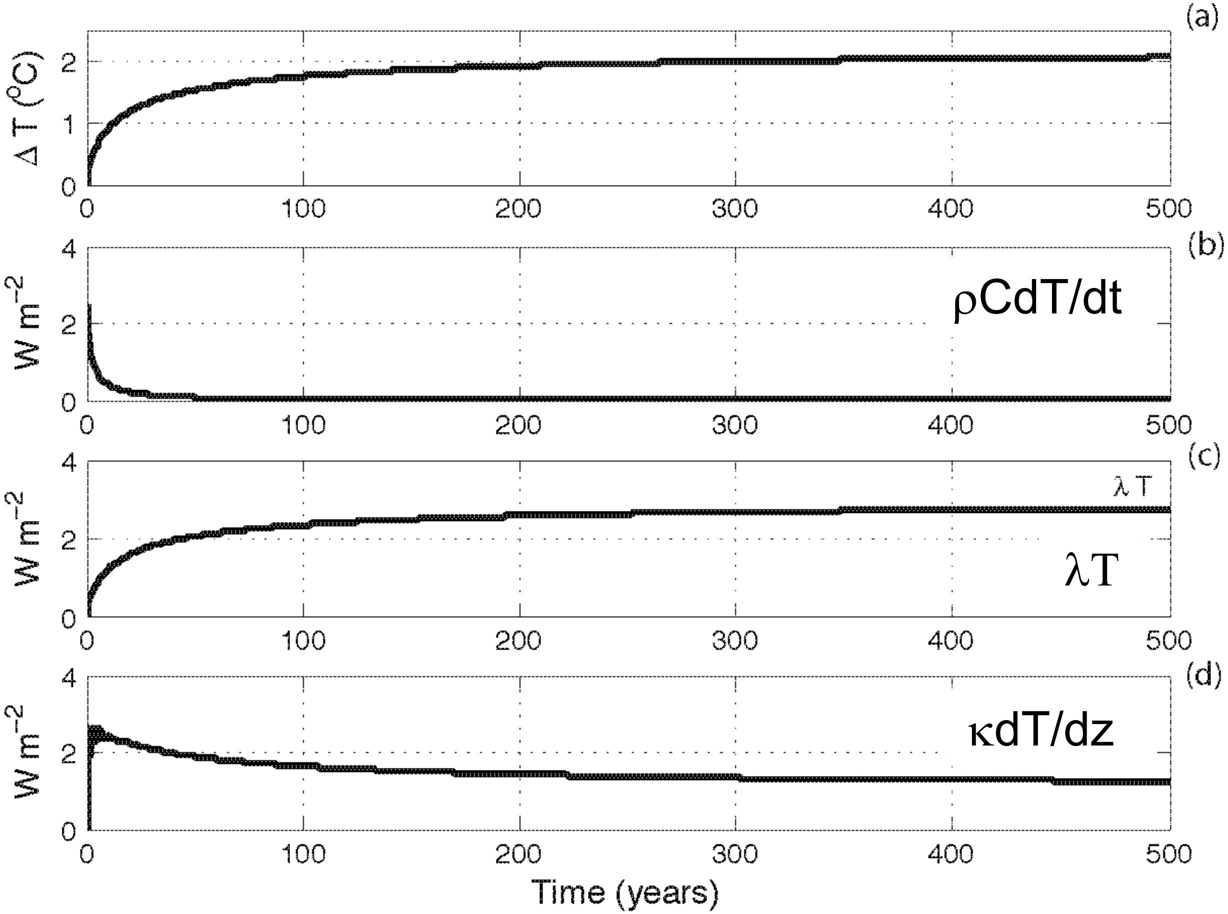
a)
b)
c)
d)
probability density (°C⁻¹)
Cumulative probability
Climate sensitivity to 2 x CO2 (°C)
f,σf = 0.65, 0.30
f,σf = 0.65, 0.25
f,σf = 0.65, 0.20
f,σf = 0.65, 0.15
f,σf = 0.65, 0.10
f,σf = 0.75, 0.20
f,σf = 0.70, 0.20
f,σf = 0.65, 0.20
f,σf = 0.60, 0.20
f,σf = 0.55, 0.20

Effect of introducing uncertainty in the forcing on equilibrium climate response



Makes lower climate response more likely

Evolution of the three terms in the energy balance in response to a step function in forcing



Mixed layer

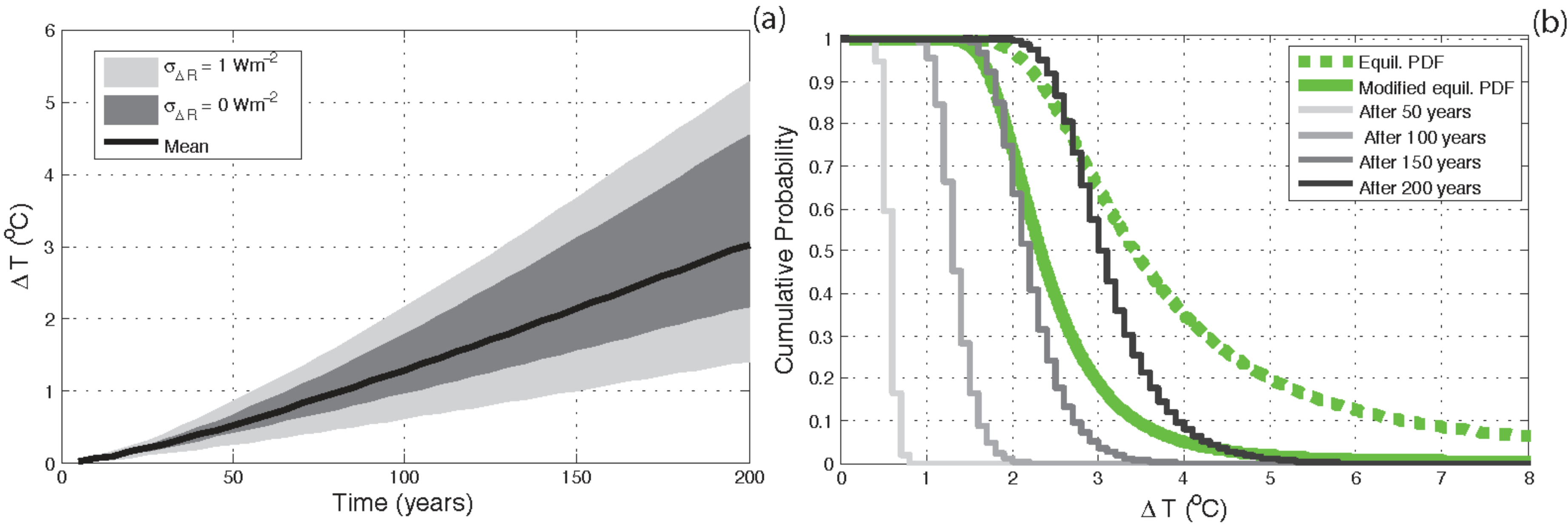
To space

Into deep ocean

- Warming term rapidly diminshes to near zero…

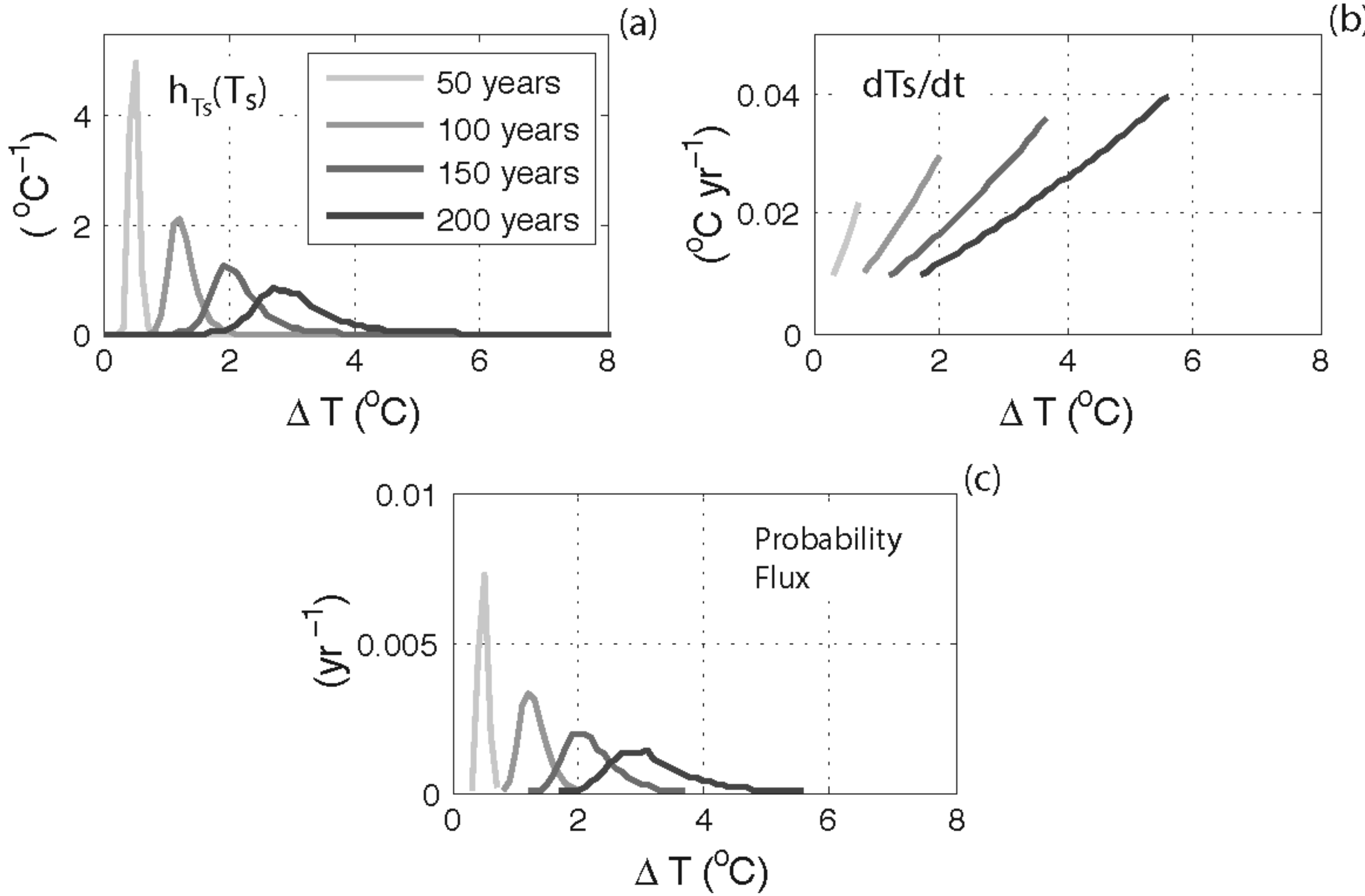
Response to ramp forcing

CO2 doubling every 100 years

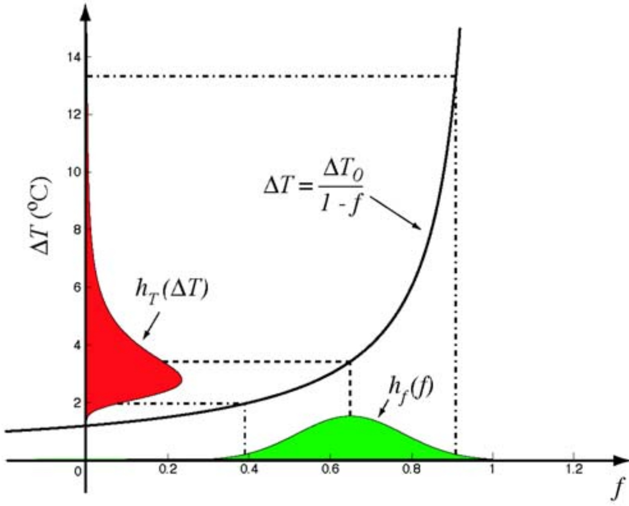


Response to ramp forcing

CO2 doubling every 100 years



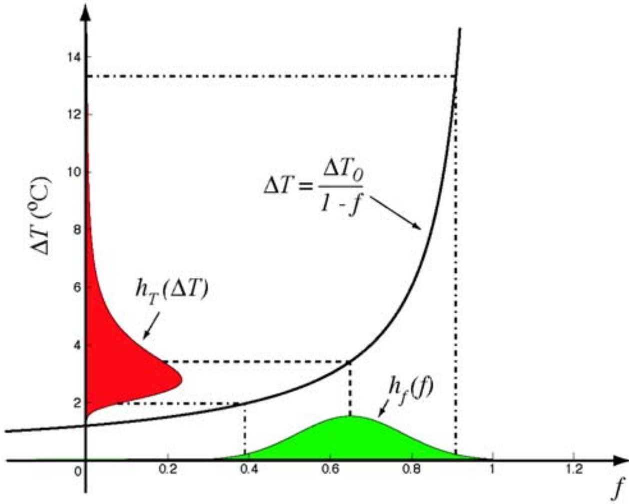
What's right about this?



- 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.

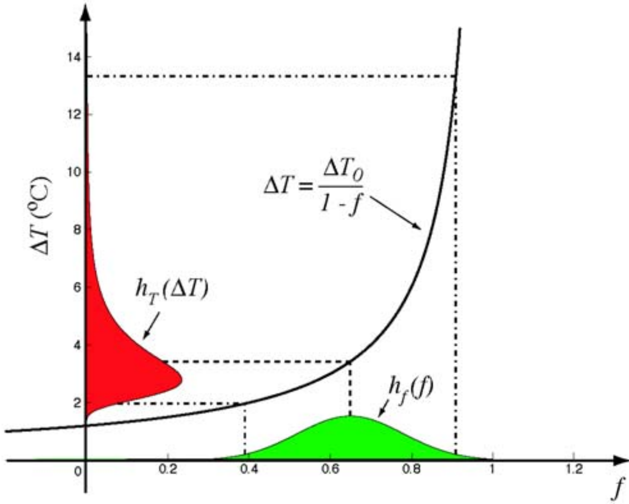
• feedback framework is a linear analysis

in a very nonlinear world.

• conclusions come from a modeling perspective.

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

Where does our uncertainty in f come from?



1. Ignorance?!

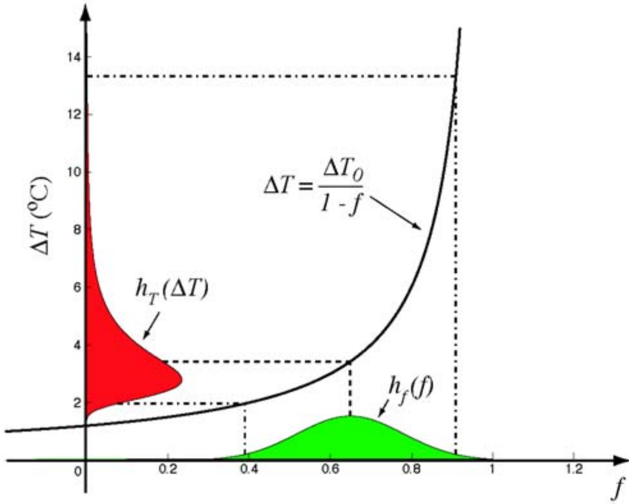
2. Nonlinearities in climate feedbacks

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

Where does our uncertainty in f come from?

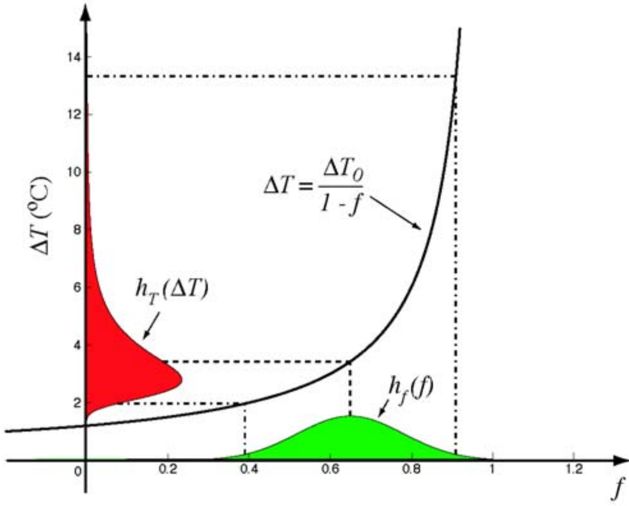


2. Nonlinearities in climate feedbacks.

- *Stefan-Boltzmann, Clausius-Clapeyron nonlinearities give δf ~0.02 for ΔT~ 4^{o}C.*

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

Where does our uncertainty in f come from?



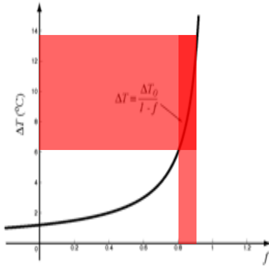
3. Climate sensitivity varies with mean state.

- *Senior and Mitchell (2000) climate sensitivity increases 40% under a global warming scenario.*
- *Boer and Yu (2003) climate sensitivity decreases 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., 2006)

Estimate λ from global energy budget:

$$\lambda \sim \frac{\Delta T}{\Delta R - \Delta Q}$$

ΔR = climate forcing;
ΔQ = energy imbalance;
ΔT = temperature change

Example: for present day.

- $\Delta T = 0.65 \pm 0.025$ ^{o}C; $\Delta Q = 0.85 \pm 0.08$ W m^{-2}; $\Delta R = 1.8 \pm 0.42$ W m^{-2}
- Uncertainties in forcing dominate and still produce skewed tails.

Combining different estimates

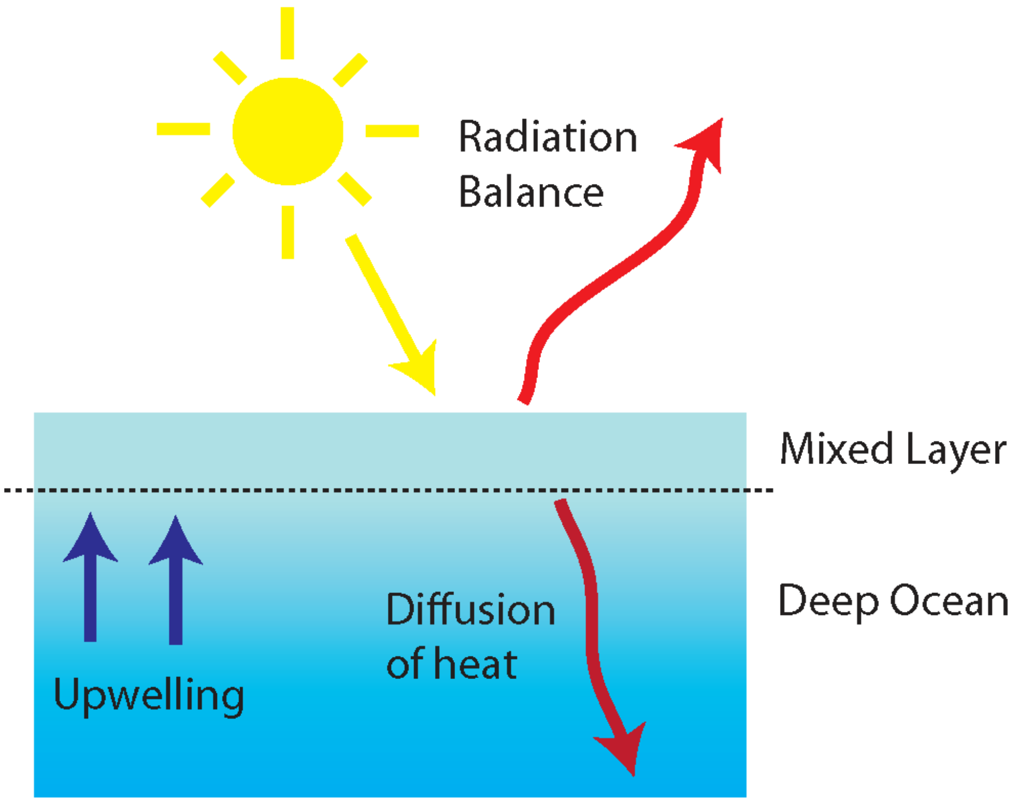
(e.g. Annan & Hargreaves, 2006; Crucifix, 2006; Sherwood & Forest, 2007)

Bayesian estimates:-

depends very sensitively on prior assumptions,
and the independence of different information.

Time dependent climate change:

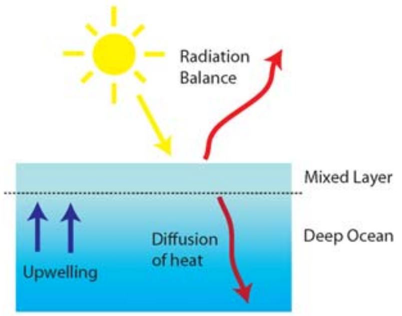
The role of the ocean



- The ocean heat uptake acts as a (transient) negative feedback.

Time dependent climate change:

The role of the ocean

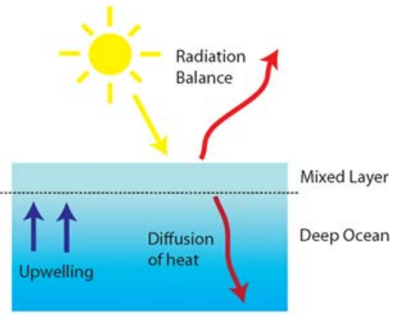


Mixed layer: $$\rho C h_{ml} \frac{\partial T'_{ml}}{\partial t} + \frac{T'_{ml}}{\lambda} - \kappa \left. \frac{\partial T'}{\partial z} \right|_{z=0} = \Delta R_f(t)$$

Deep ocean: $$\frac{\partial T'}{\partial t} = \chi \frac{\partial^2 T'}{\partial z^2} - w \frac{\partial T'}{\partial z}$$

Time dependent climate change:

The role of the ocean



Nondimensionalized:

Mixed layer: $$X\frac{\partial T}{\partial t}+(1-f_a)T-f_o\frac{\partial T}{\partial z}\bigg|_{z=0}=1$$

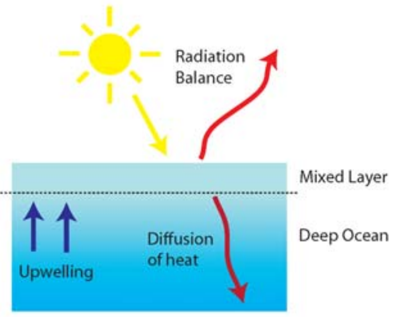
Deep ocean: $$\frac{\partial T'}{\partial t}=\frac{\partial^2 T'}{\partial z^2}-\frac{\partial T'}{\partial z}$$

Solution depends three nondimensional parameters f_a, X, & f_o

$$X=\frac{\tau_{ml}}{\tau_o}=\frac{\text{mixed layer response time}}{\text{deep ocean mixing time}}\approx 10^{-2}$$

Time dependent climate change:

The role of the ocean



Mixed layer: $$X\frac{\partial T}{\partial t} + (1 - f_a)T - f_o\frac{\partial T}{\partial z}\bigg|_{z=0} = 1$$

Deep ocean: $$\frac{\partial T'}{\partial t} = \frac{\partial^2 T'}{\partial z^2} - \frac{\partial T'}{\partial z}$$

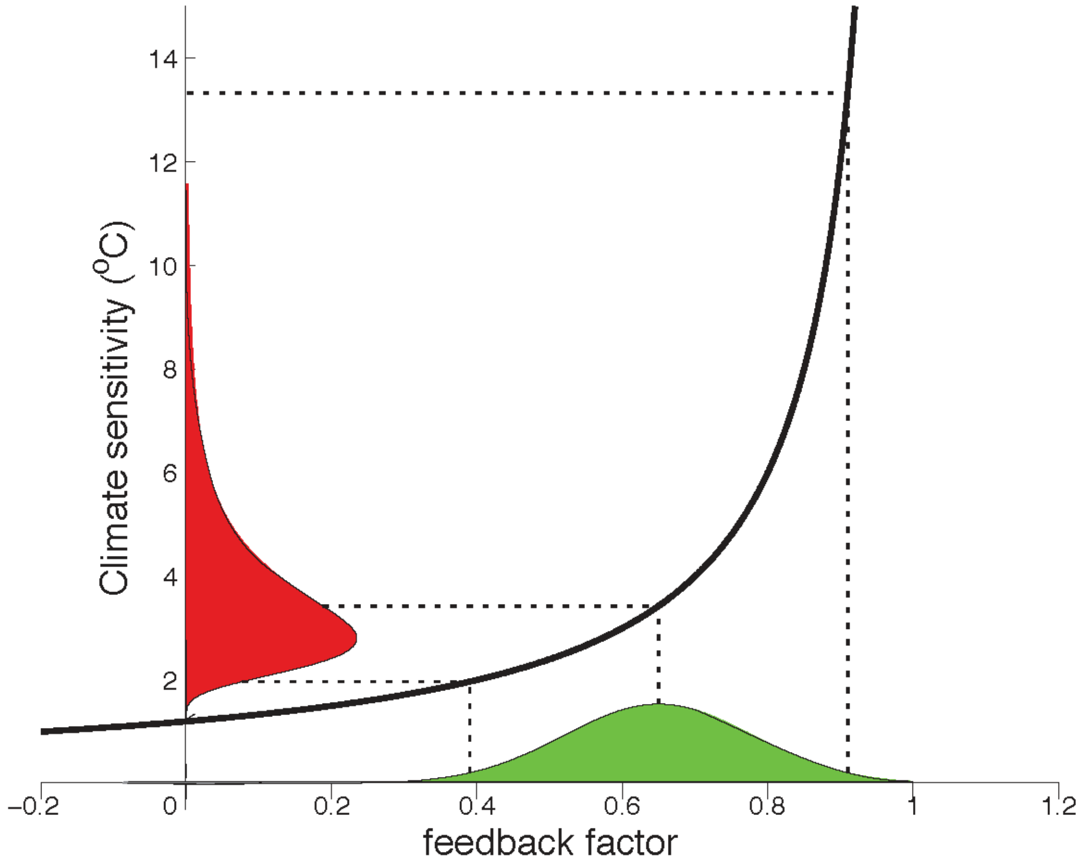
Solution depends three nondimensional parameters f_a, X, & f_o

$$f_o = \rho C \lambda_o w = \text{ocean feedback factor} \approx -0.15$$

w = upwelling rate

Time dependent climate change:

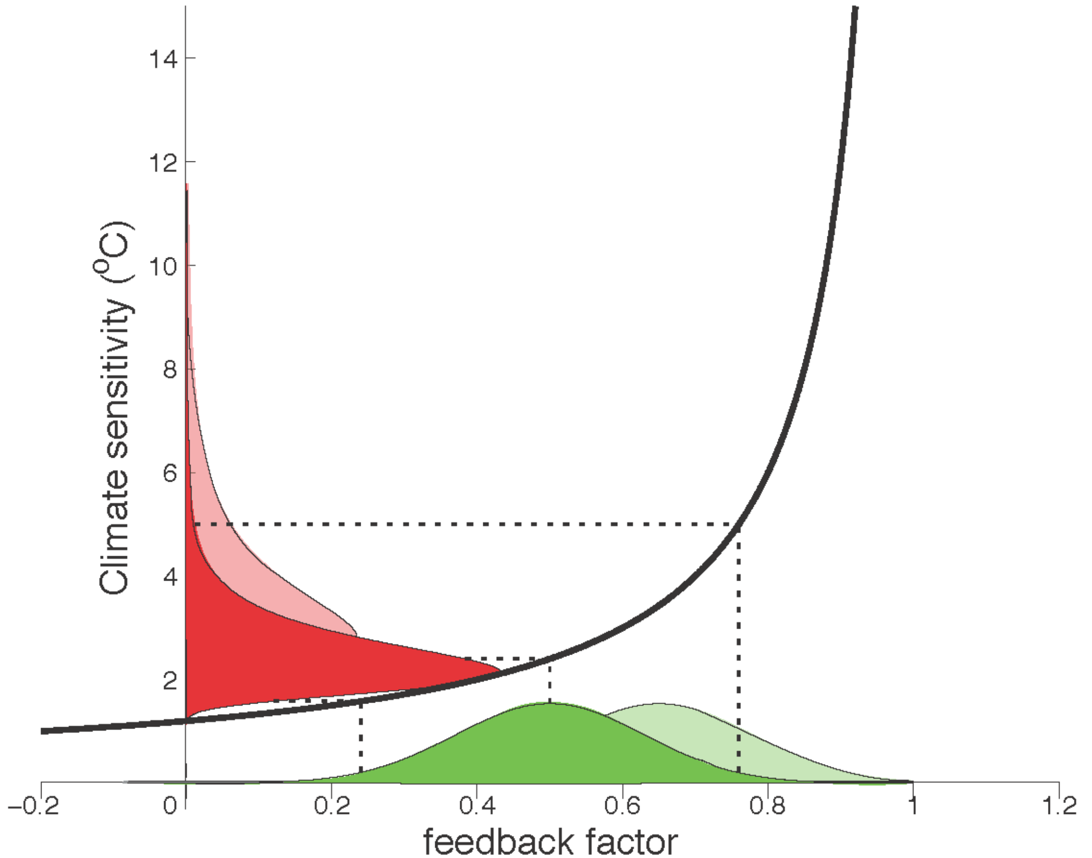
The role of the ocean



Time dependent climate change:

The role of the ocean

Addition of (transient) ocean feedback



- Ocean -ve feedback strongly reduces the width of the envelope

Time dependent climate change:

The role of the ocean

Analytical solution allows for extremely efficient Monte Carlo computation of the effect of parameter uncertainties

Parameter	Mean	1σ
Atmospheric feedback	0.65	0.15
Upwelling rate	4 m yr^{-1}	1.5 m yr^{-1}
Mixed layer depth	75 m	25 m
Ocean diffusivity	1.5 cm^2 s^{-1}	0.5 cm^2 s^{-1}

Time dependent climate change:

The role of the ocean

Response of temperature to a doubling of CO_2

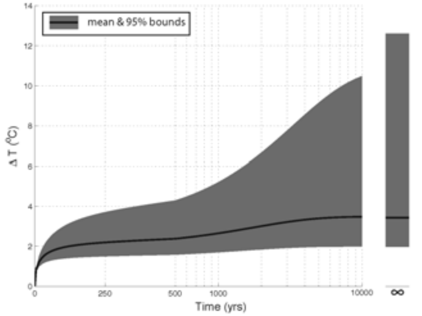
Eq^m. prob. distr.

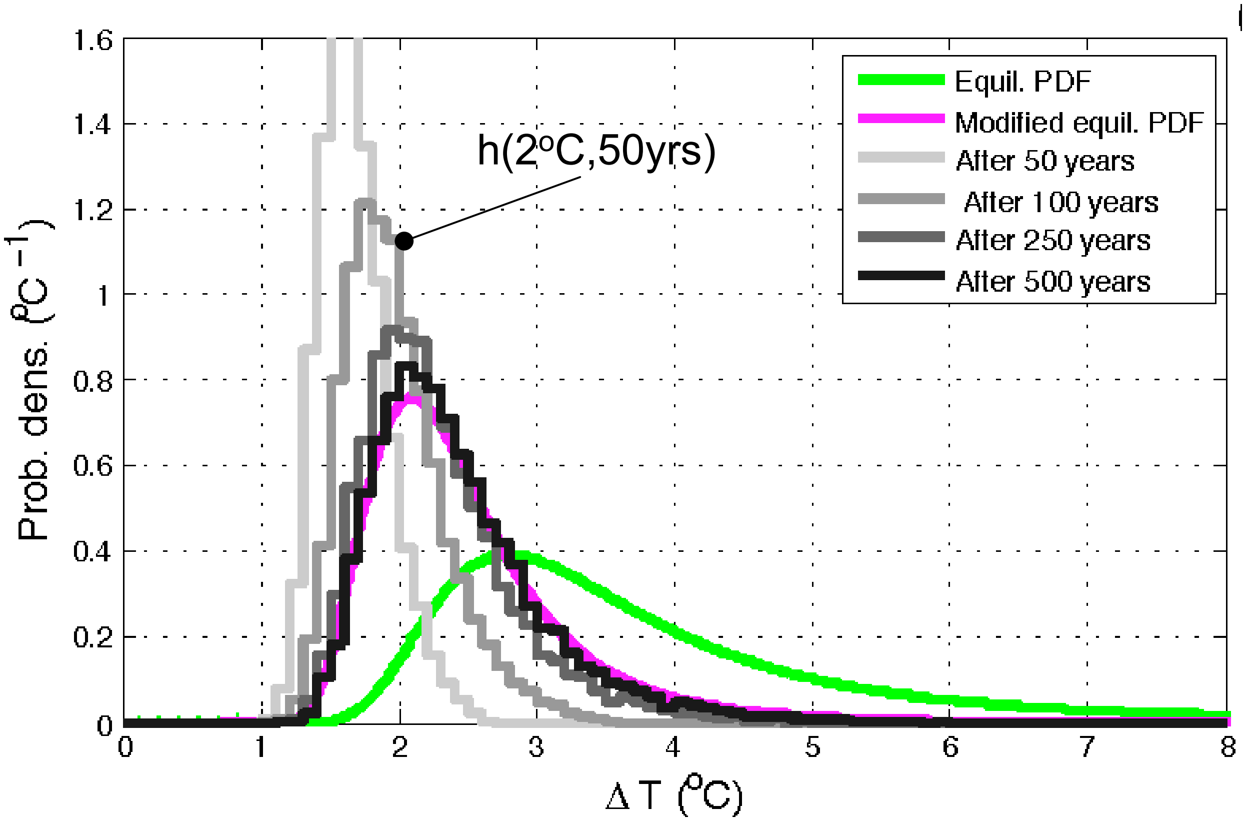
Eq^m. prob. distr. modified by -ve ocean feedback

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.

Time dependent climate change:

Why does the tail grow so slowly?



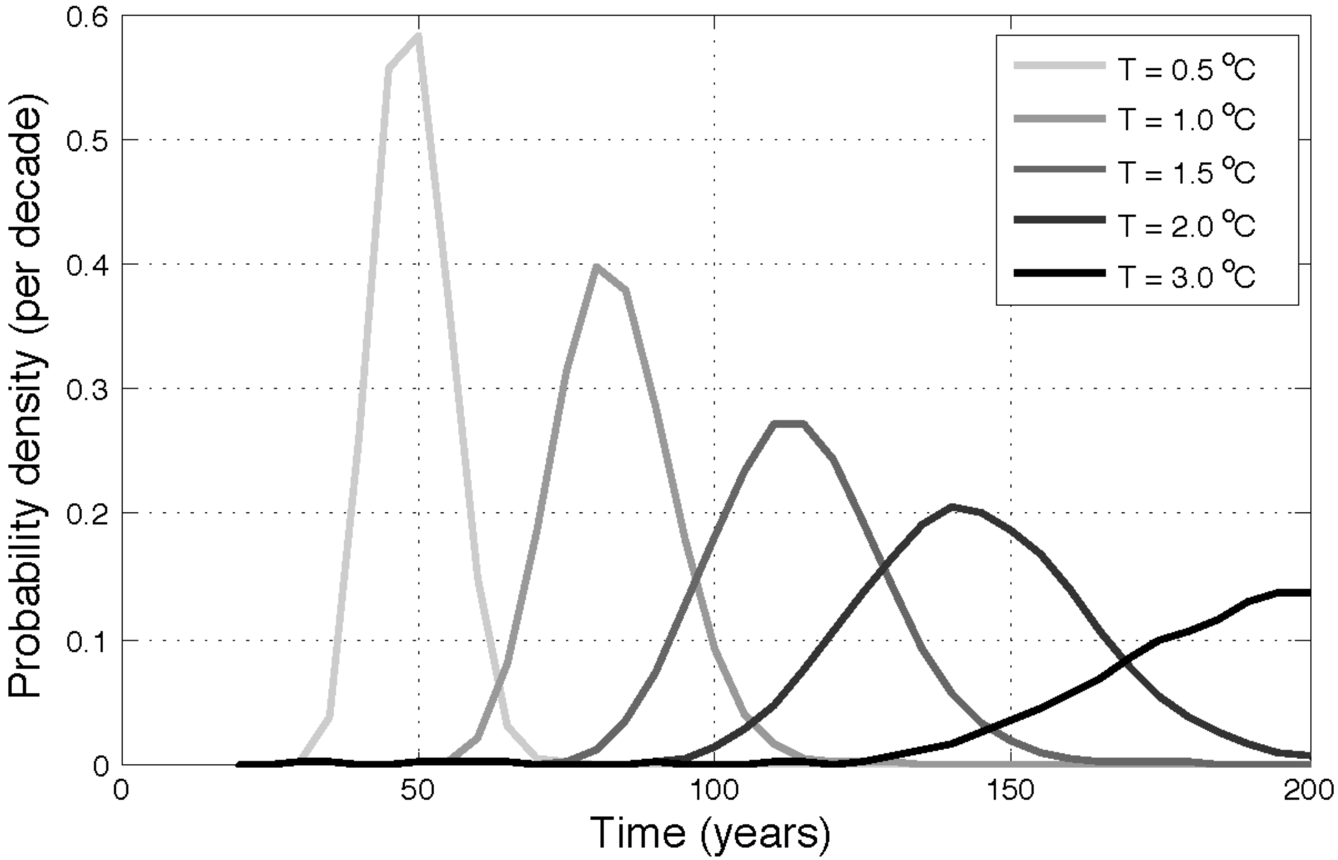


Let h(T,t) = probability density at some (T,t).

What governs how h(T,t) varies with time?

Response to a ramp forcing

□*What is the likelihood of reaching a given temperature at a given time?*

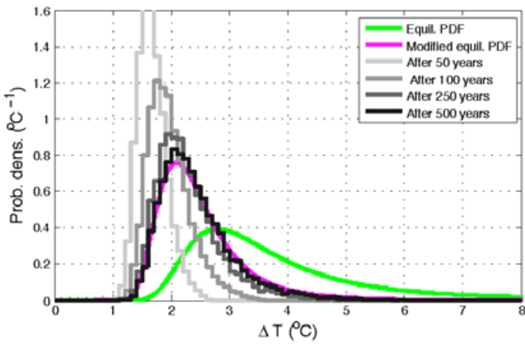


Doubling of CO_2 every 100 years

- The larger the temperature contemplated, the more uncertain it is when that temperature will be reached.

Time dependent climate change:

Why does the tail grow so slowly?



Probabilities are conserved so can write a conservation equation:-

$$\frac{\partial h}{\partial t} + \nabla . \left(h \frac{dT}{dt} \right) = 0$$

h: probability density

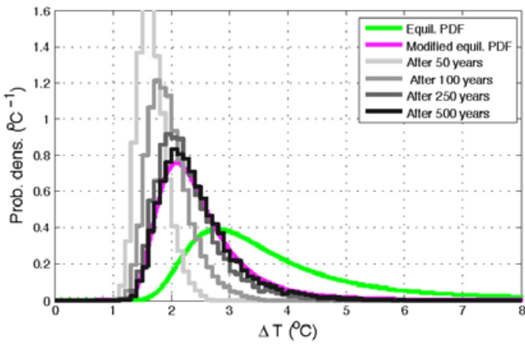
$\frac{dT}{dt}$: probability 'velocity'

Therefore:-

$$h(T,t) \times \frac{dT}{dt}$$ = flux of probabilities to higher T

Time dependent climate change:

Why does the tail grow so slowly?



Probabilities are conserved so can write a conservation equation:-

$$\frac{\partial h}{\partial t} + \nabla . \left(h \frac{dT}{dt} \right) = 0$$

probability density

probability 'velocity'

Can integrate from T_c to ∞:

$$\left. \frac{dp_{cum}}{dt} \right|_{T>T_c, t} = h(T_c, t) \times \left. \frac{dT}{dt} \right|_{T_c, t}$$

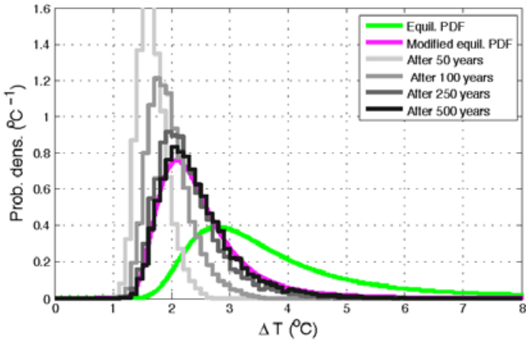
(since $h(\infty,t)=0$)

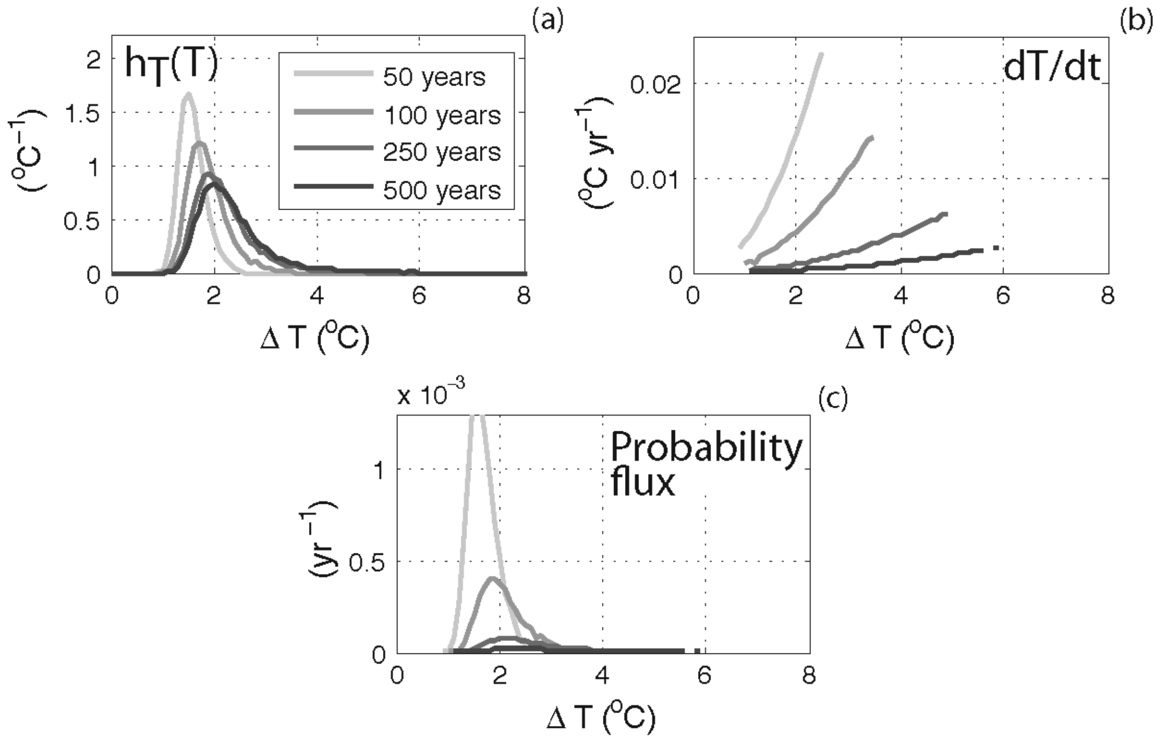
$\left. p_{cum} \right|_{T>T_c, t}$ = cumulative probability of $T > T_c$

Time dependent climate change:

Why does the tail grow so slowly?

$$h(T_c, t) \times \left.\frac{dT}{dt}\right|_{T_c, t} \quad = \text{flux of probabilities to higher T}$$





- Flux in the tail diminishes quickly to low (but non zero) values.