Economic Cost-Benefit Analysis of Sulphate Geoengineering

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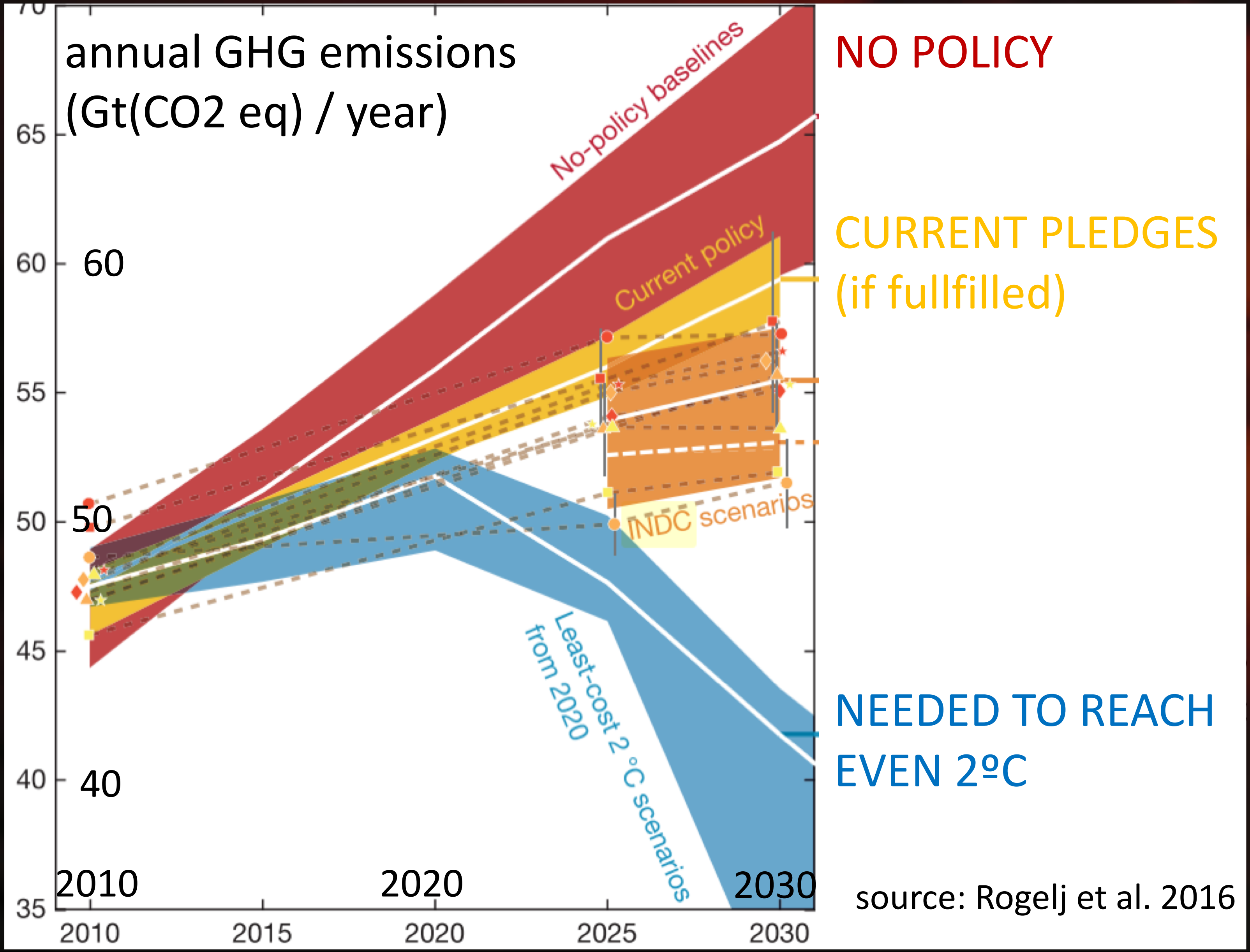
Photography encouraged

IMAU
Institute for Marine and Atmospheric research Utrecht

Current climate policy



Even if all states keep their current pledges, we are NOT on the right path to reach the Paris agreement!

we are not on our way to reach the Paris agreement...

WANTED: A cool plan to cool the Earth

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Pinatubo explosive eruption, 1991:
10Mt Sulphur (20Mt SO_2) into stratosphere
-> SO_2 reacts with water to sulphuric acid
-> reflective sulphate aerosol veil
-> global cooling ca 0.5K (1year)

e.g. Robock et al., 2000

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why can't **We**?

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why can't **We**?

Solar Radiation Management using Sulphate aerosol

Sulphate Geoengineering: Cool plan or Megalomania?

Potential benefits

-- Cool down Earth:
Stay below 2K warming
(avoid dangerous
"tipping points")

-- cheap to implement (?)

McClellan et al., 2010
Moriyama et al., 2017

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Caveats

-- Will not solve all problems:
--- precipitation changes
global decrease
pattern shift?

MacMartin and Kravitz, 2016

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-- Will not solve all problems:
--- precipitation changes
--- ocean acidification

-- effectiveness?

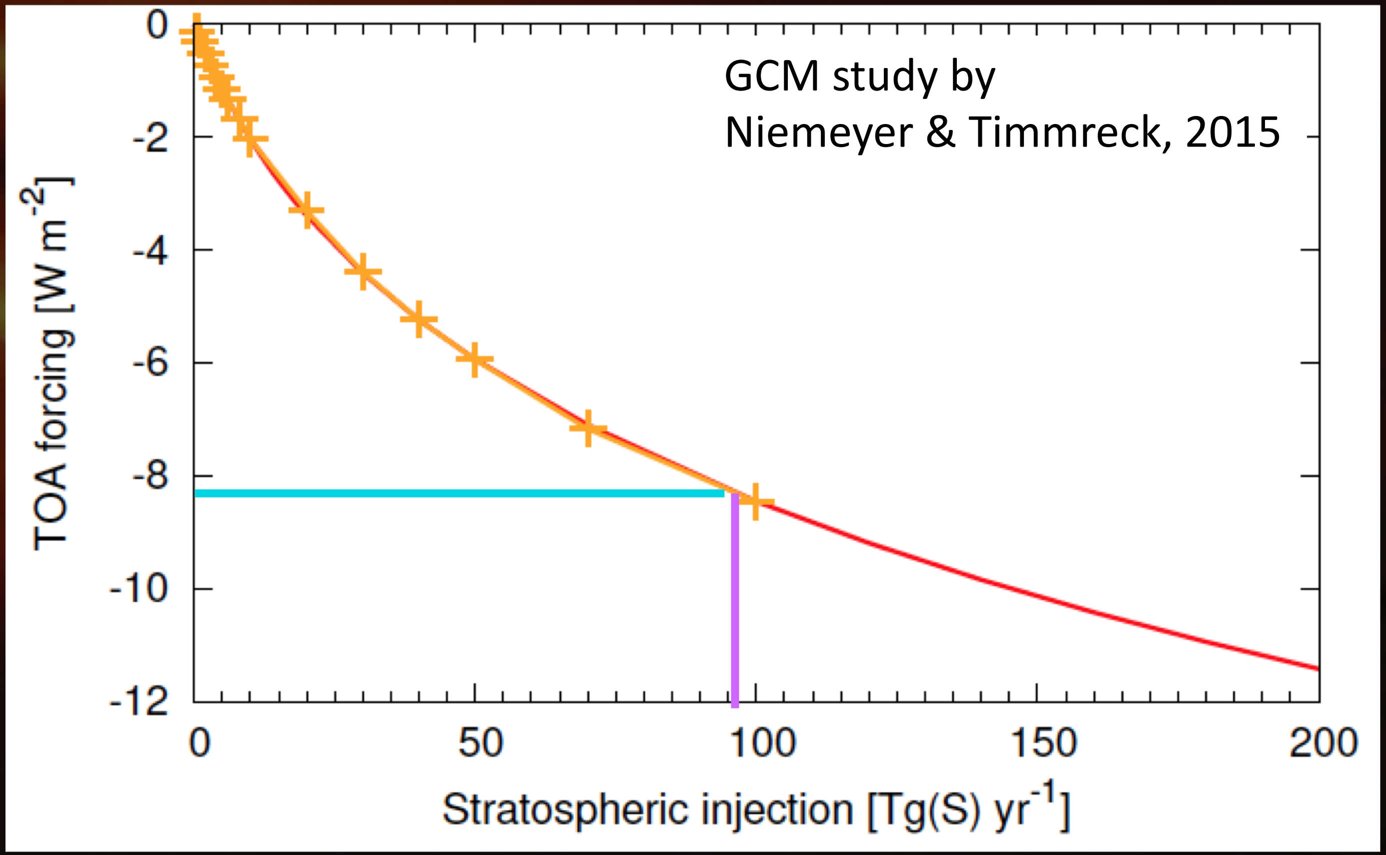
Sulphate Geoengineering: Effectiveness

High injection rate
-> coagulation
-> fewer, bigger droplets
-> less sunlight reflection

Radiative forcing increases only sublinearly with injection rate!

Counterbalancing RCP8.5 in 2100 requires 10 Pinatubos / year !

Still uncertainty about effectiveness!
Tilmes et al., 2018, Kleinschmidt et al., 2018



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Dangers

-- environmental damages:
--- ozone hole
--- tropospheric chemistry
--- acid rain
-- unknown unknowns?
-- political conflict?

e.g. Robock et al., 2009

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Is Sulphate Geoengineering an economically sound option?

(Exploratory) Cost-Benefit Analysis using
*Dynamic Integrated model of **C**limate and **E**conomy* (DICE)

DICE: Model Structure

The **D**ynamic **I**ntegrated model of **C**limate and the **E**conomy

(W. Nordhaus)

Economic production /GDP

spent for

Consumption + Capital

Utility $\int U e^{-Rt} dt$ Welfare

Decision makers' problem:
maximise Welfare
(time-integrated, discounted utility)

DICE: Model Structure

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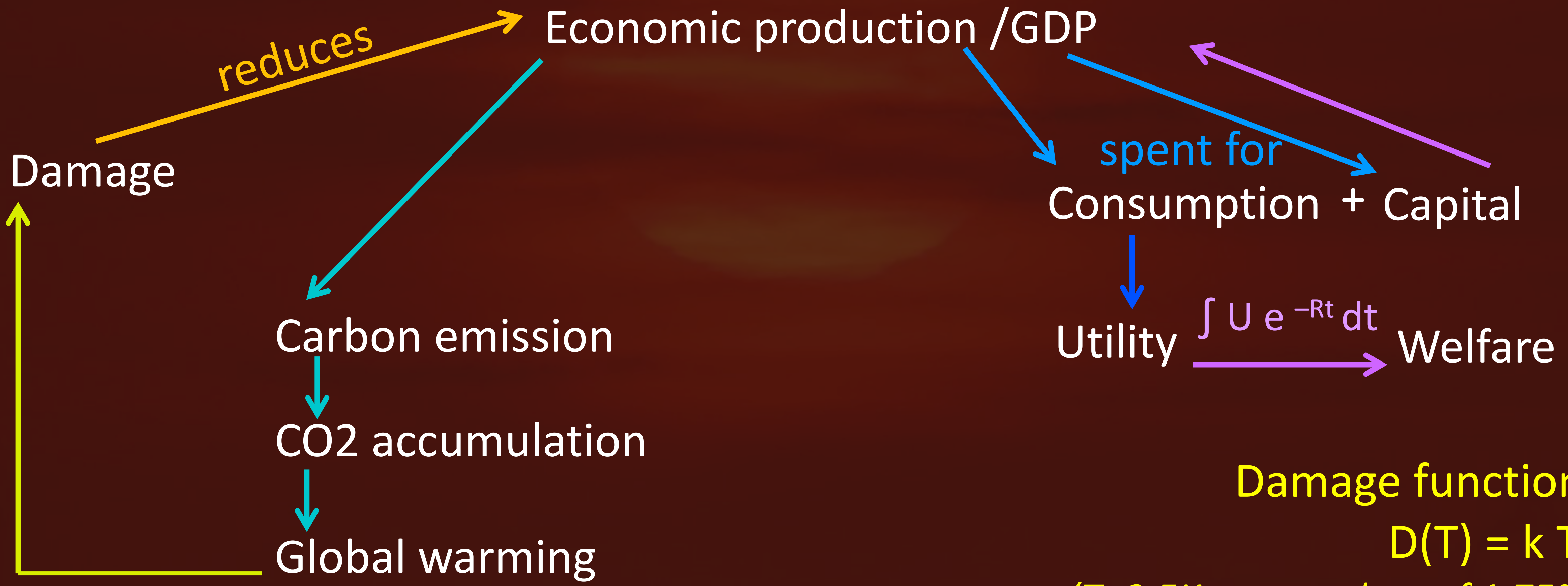

Damage function:

$D(T) = k\,T^2$

(T=2.5K -> econ. loss of 1.75%)

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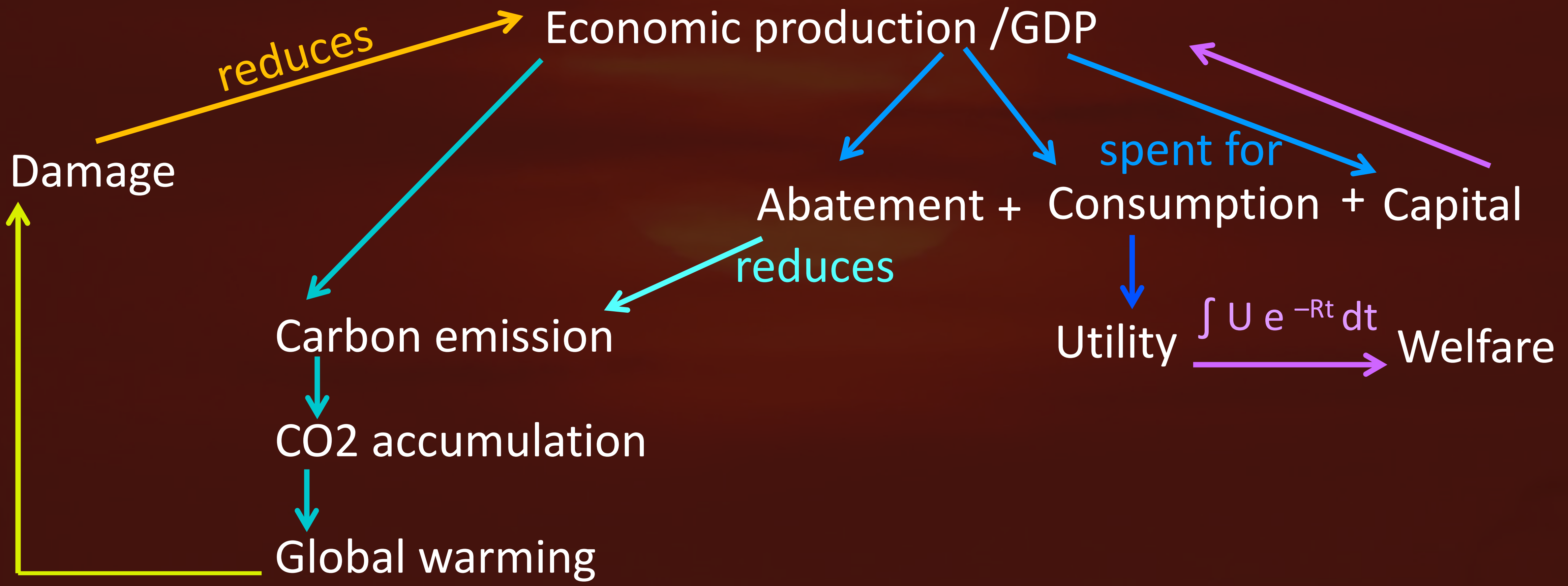

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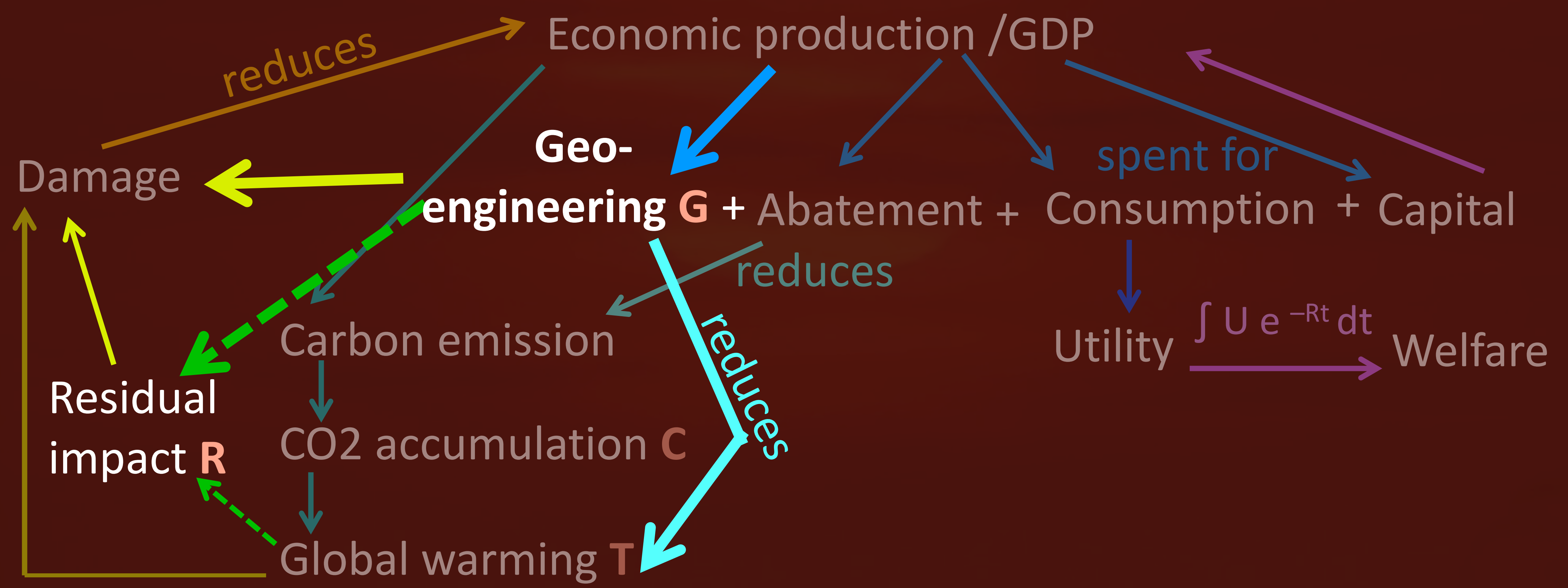

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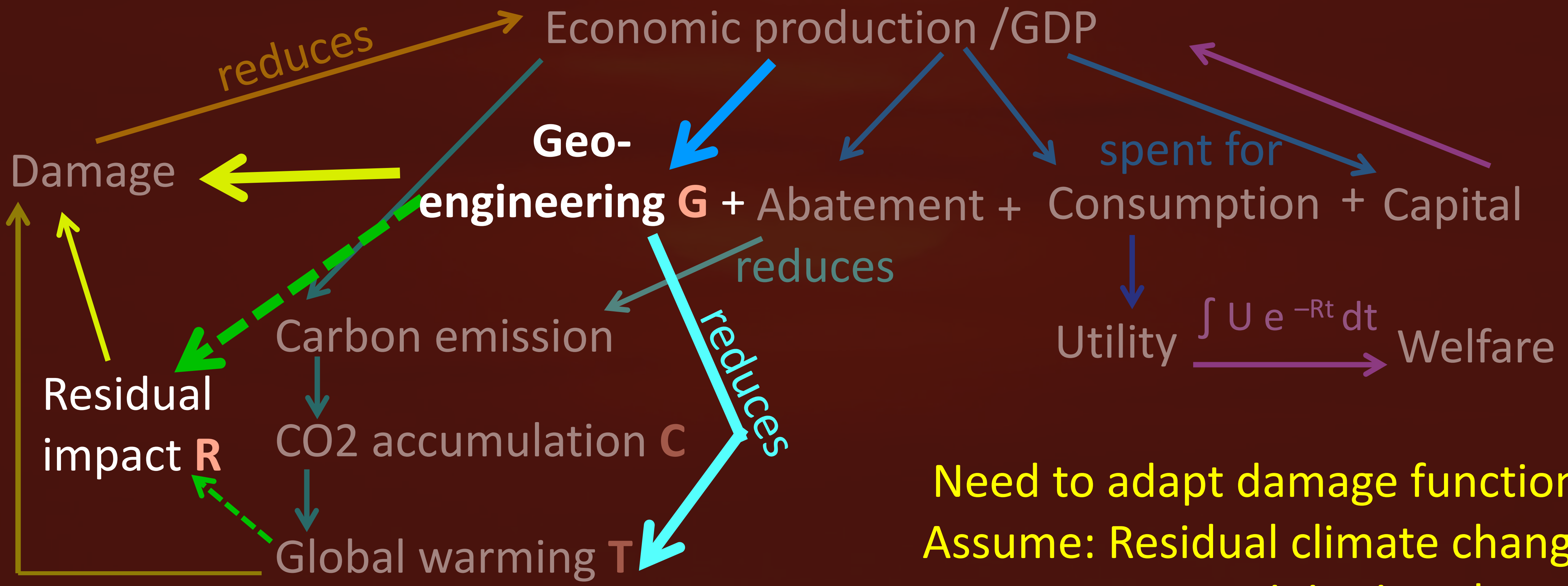

Need to adapt damage function!
Assume: Residual climate change
= precipitation change

DICE: Model Structure

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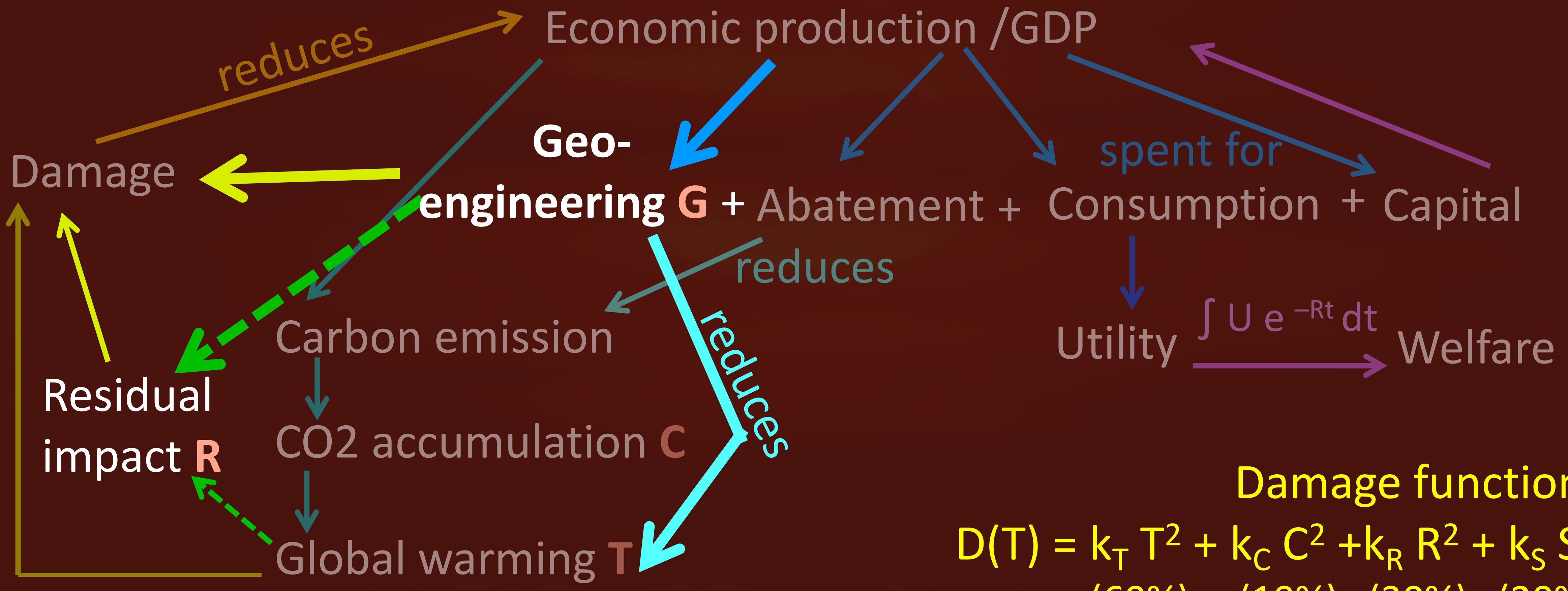


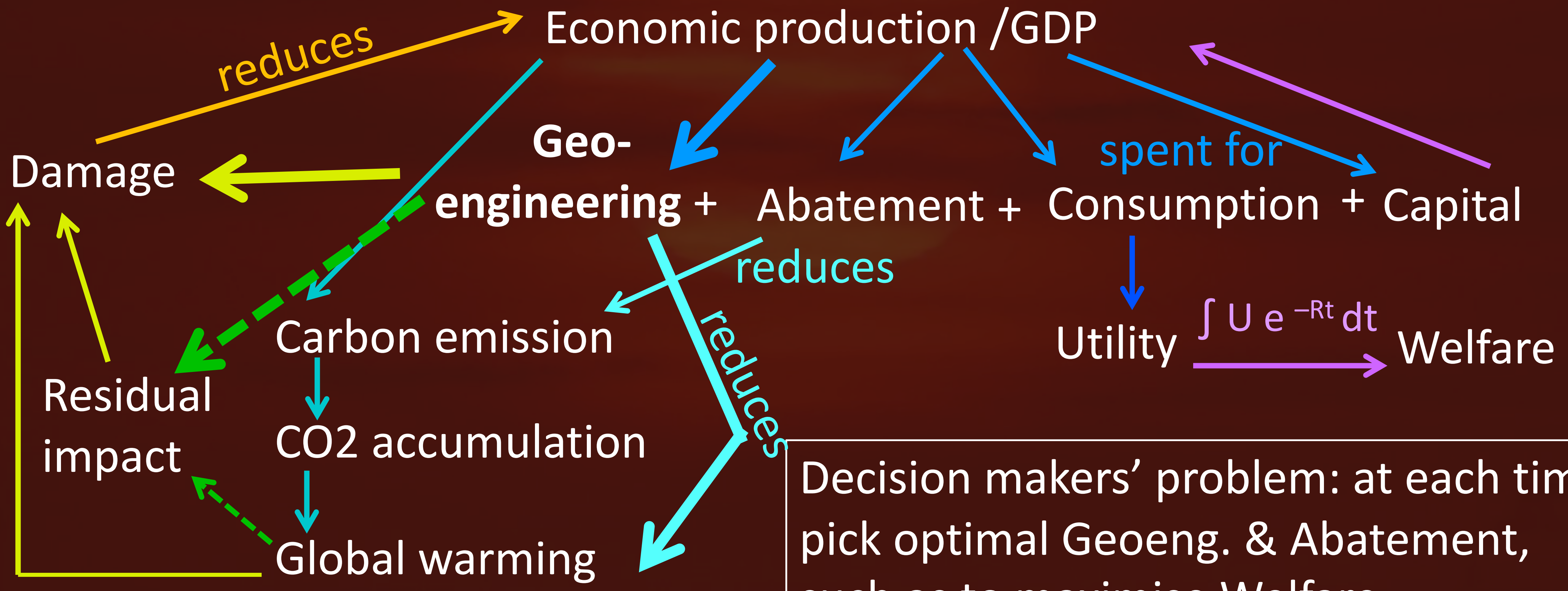
Damage function:

$$D(T) = k_T\, T^2 + k_C\, C^2 + k_R\, R^2 + k_S\, S^2$$

(60%) (10%) (30%) (20%)

DICE: Model Structure

The **D**ynamic **I**ntegrated model of **C**limate and the **E**conomy



Decision makers' problem: at each time, pick optimal Geoeng. & Abatement, such as to maximise Welfare

Planning under uncertainty

The social planner does not know…

1. Whether damaging “climate tipping” will occur

   -- If T>2K, irreversible “tipping” can occur (stochastic process)
   Once climate is tipped, 10% of GDP will be lost in *each* future year

2. Whether Geoengineering will work well

   -- At each time step, X % probability that Geoengineering is banned forever
   (total probability: 20% in 400 years)

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2. Whether Geoengineering will work well

   -- At each time step, X % probability that Geoengineering is banned forever
   (total probability: 20% in 400 years)

-> find optimal policy under uncertainty (dynamic programming)
-> run Monte-Carlo Ensemble with this policy to assess outcome

Optimal Policy: Scenarios

First, 3 simple scenarios:

1. Abate+Geo

   -- Social planner may use abatement and geoengineering
   -- in case of geoengineering ban: only abatement

2. Abate-Only

   -- Social planner may only use abatement

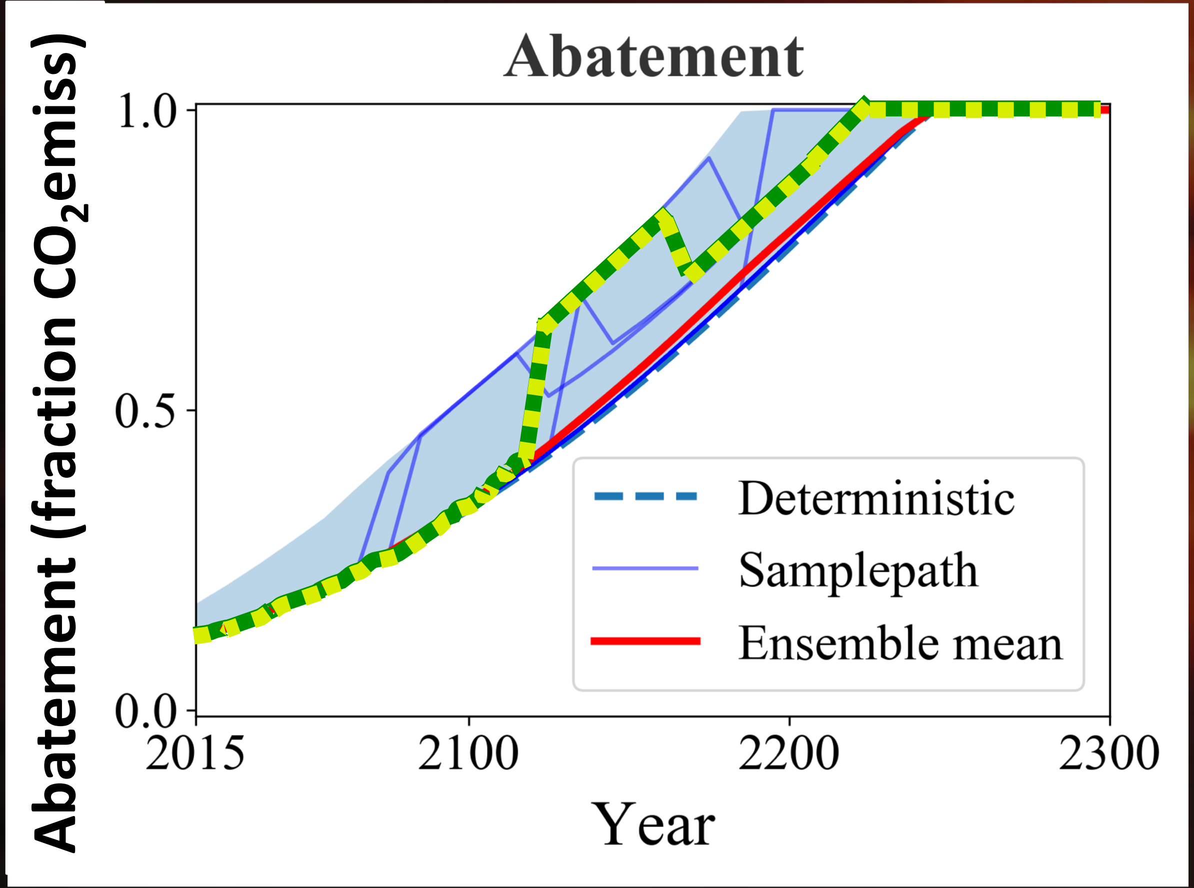
3. Geo-Only

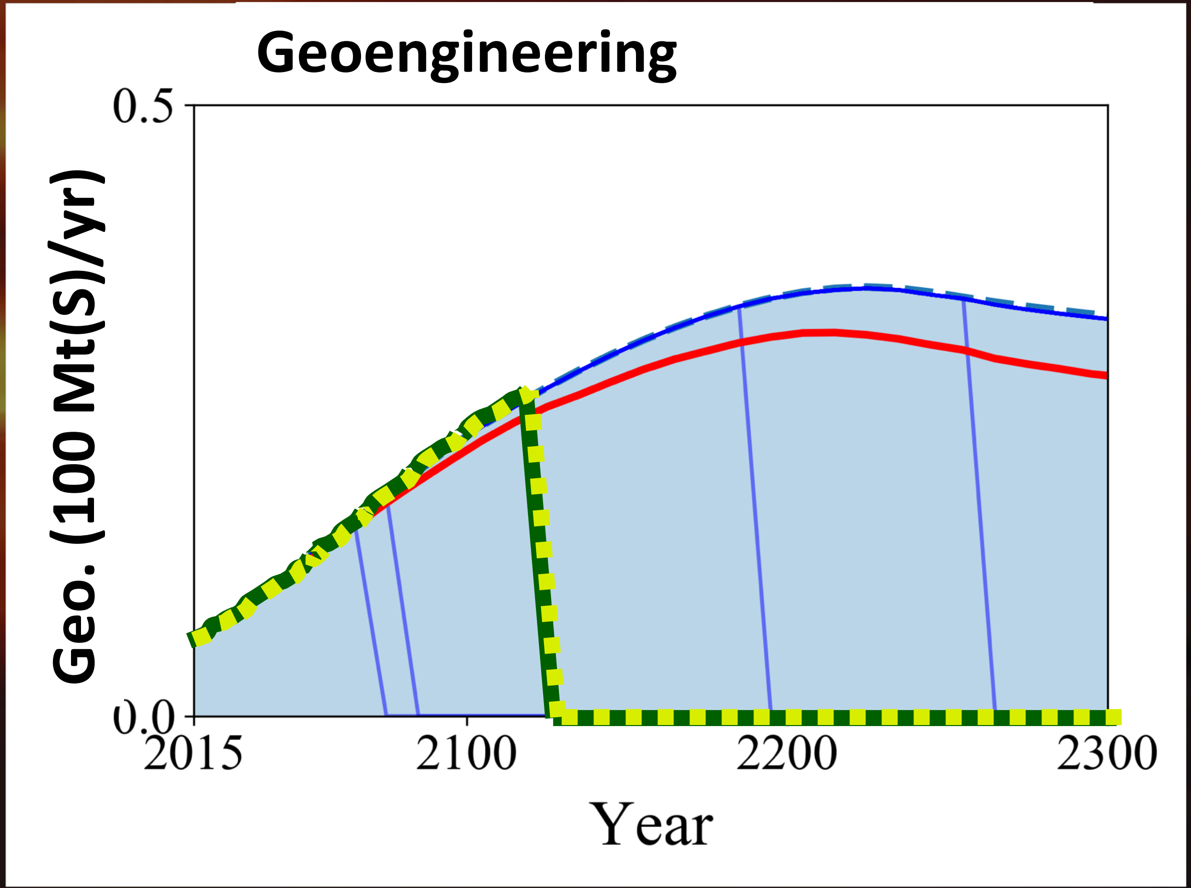
   -- Social planner may use only geoengineering
   -- in case of geoengineering ban: may use only abatement

Realistic Storyline (later)

Optimal Policy: Abate+Geo

A particular Monte-Carlo ensemble member (following optimal policy)

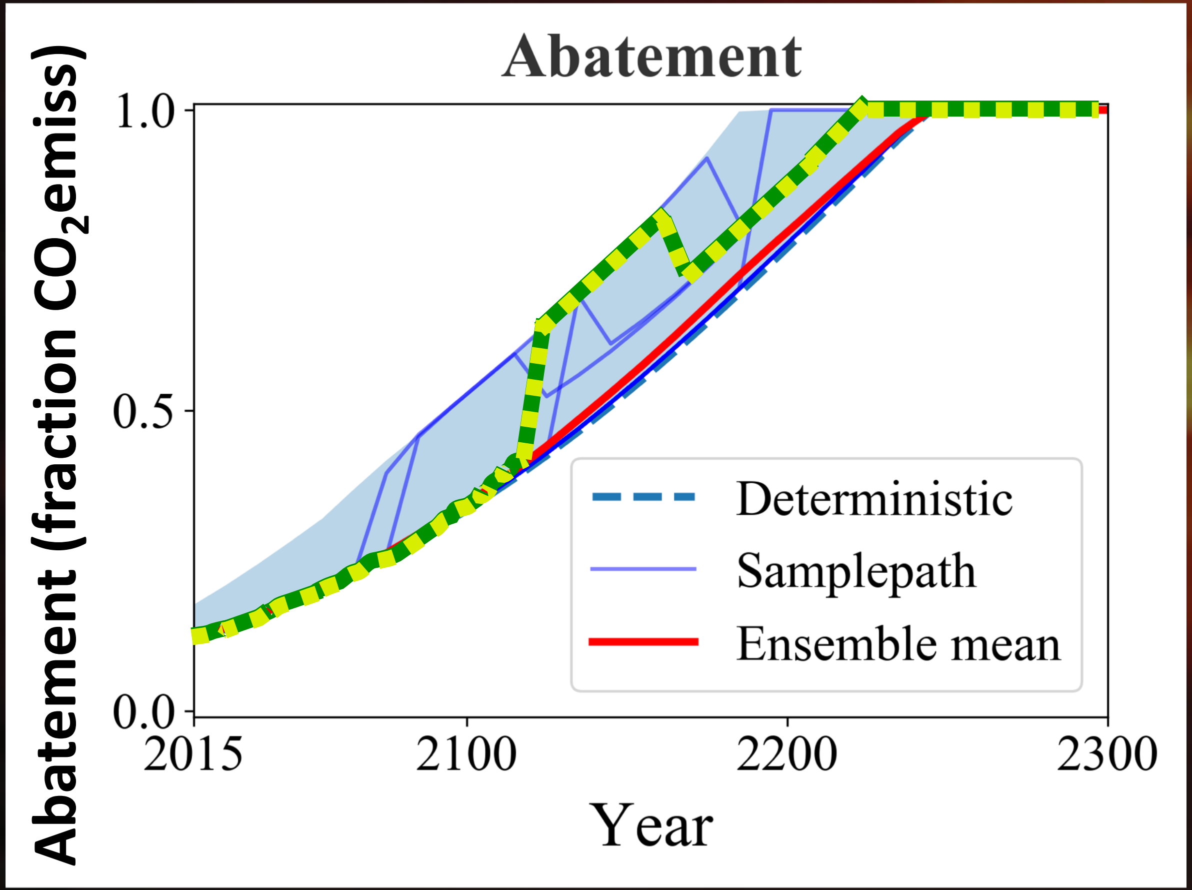


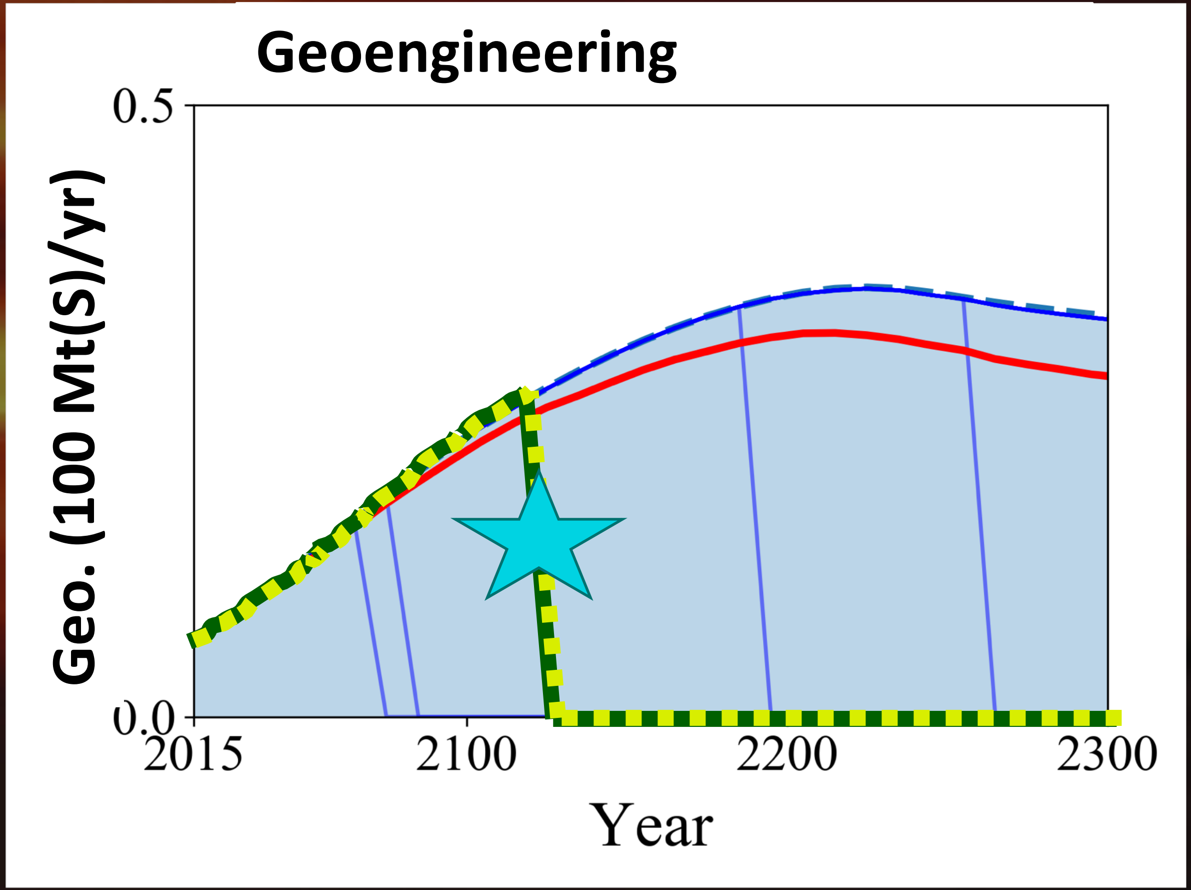


Optimal Policy: Abate+Geo

A particular ensemble member (following optimal policy)

★ 2130: Geoengineering failure

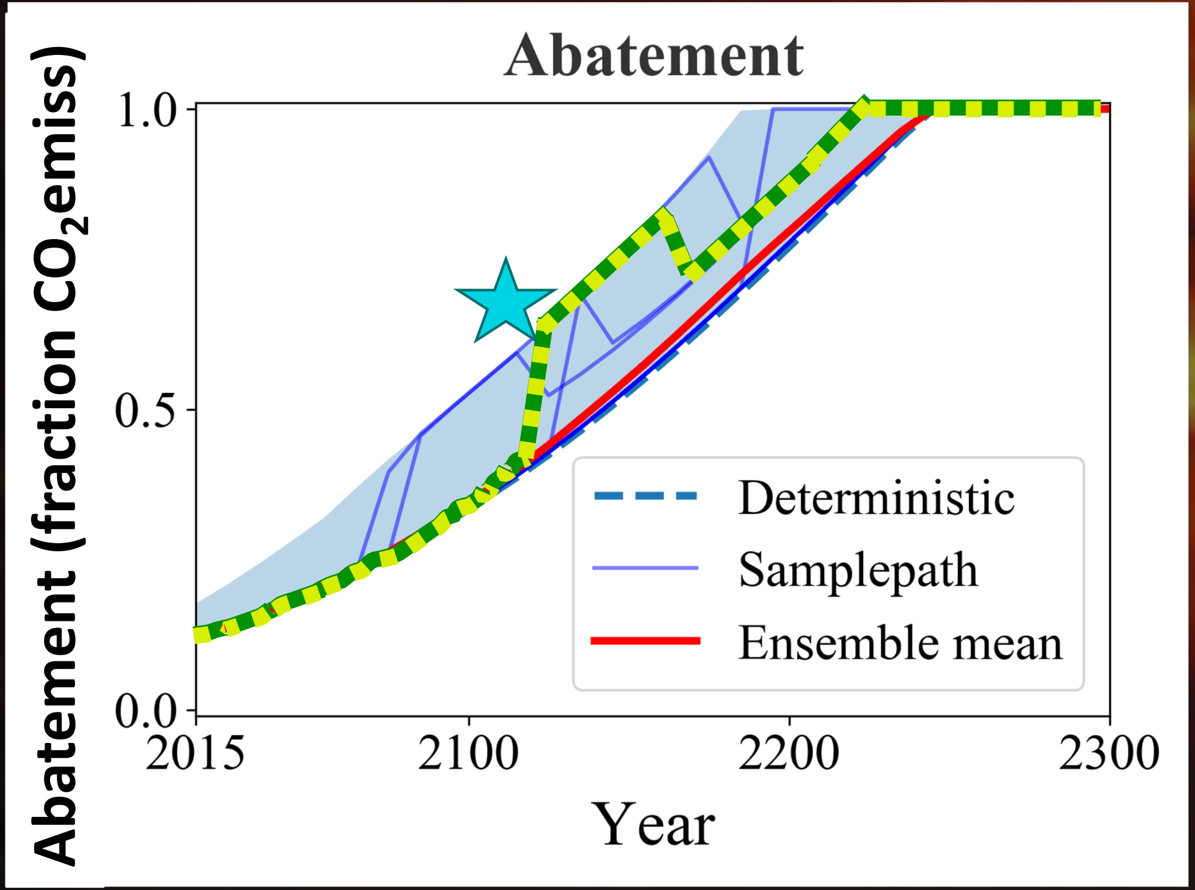


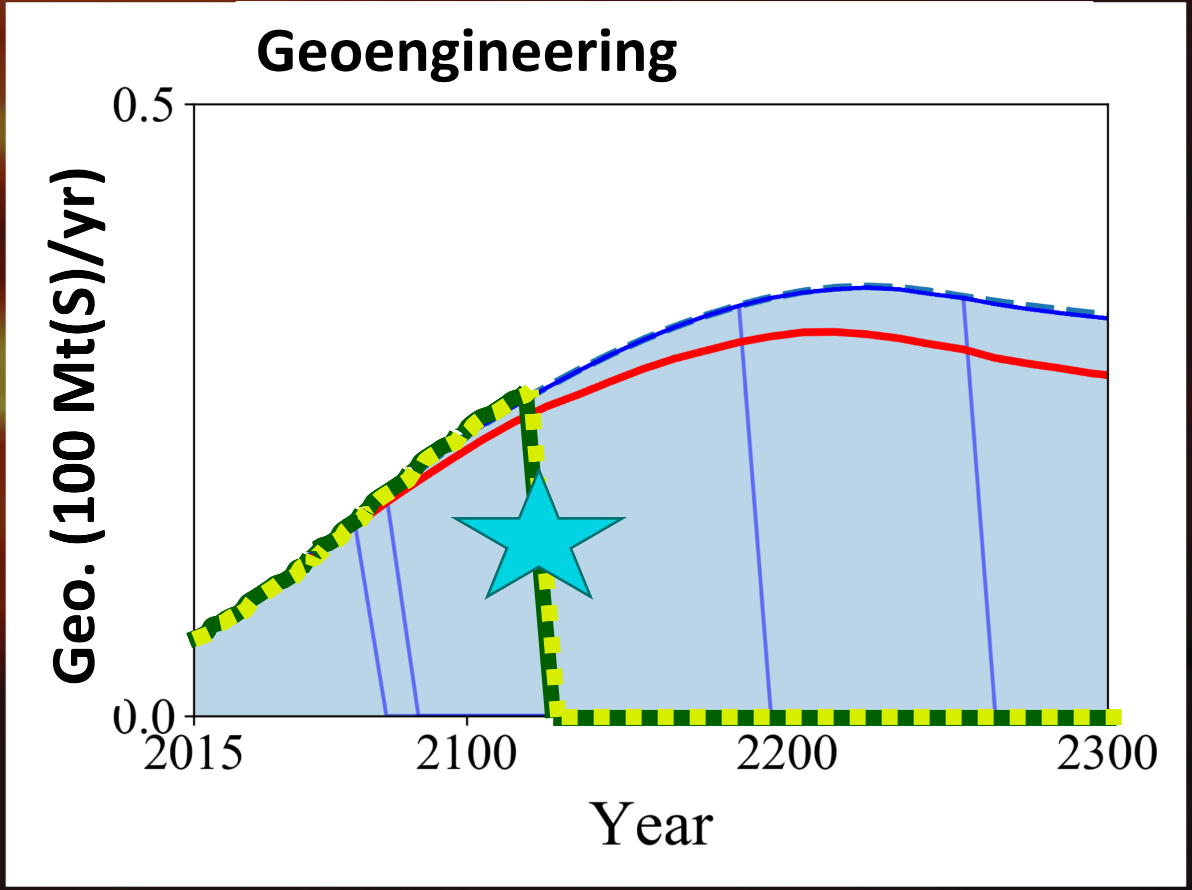


Optimal Policy: Abate+Geo

A particular ensemble member (following optimal policy)

★ 2130: Geoengineering failure -> increased abatement



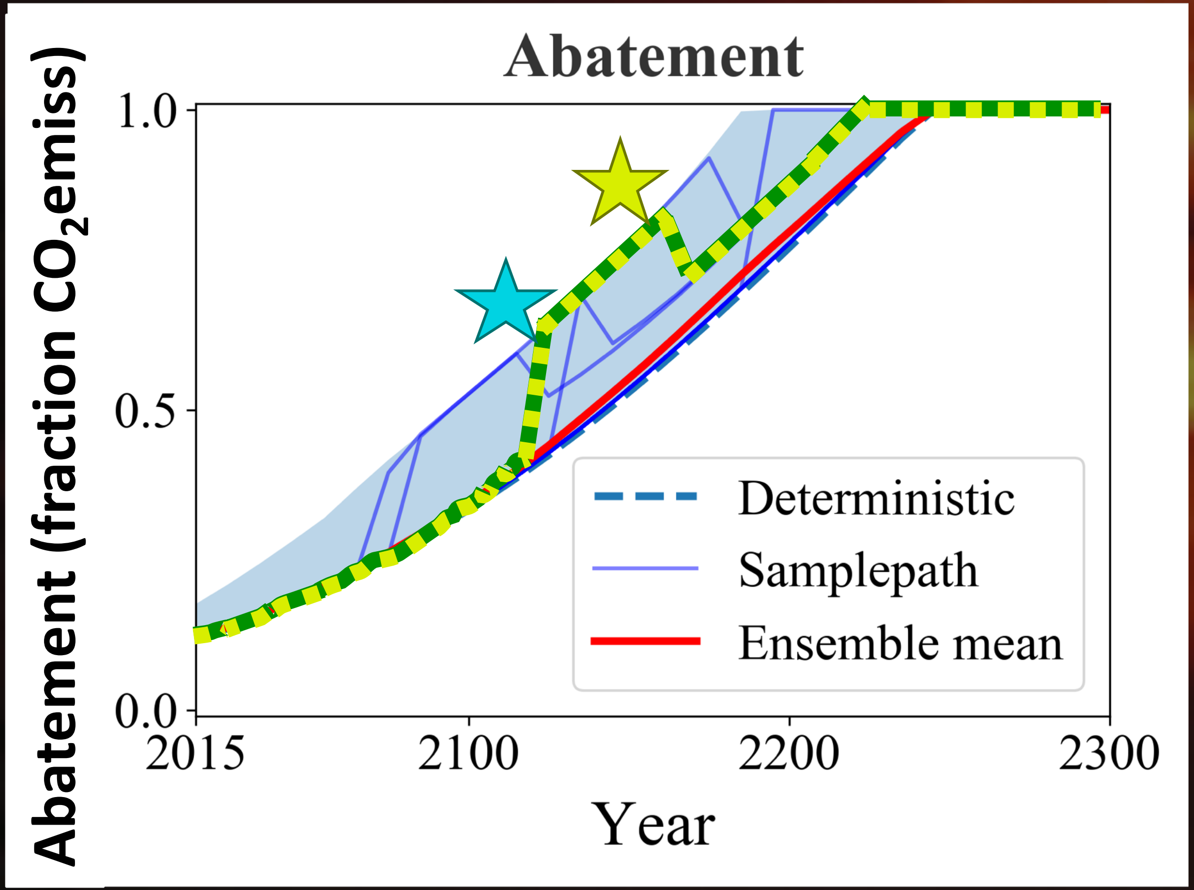


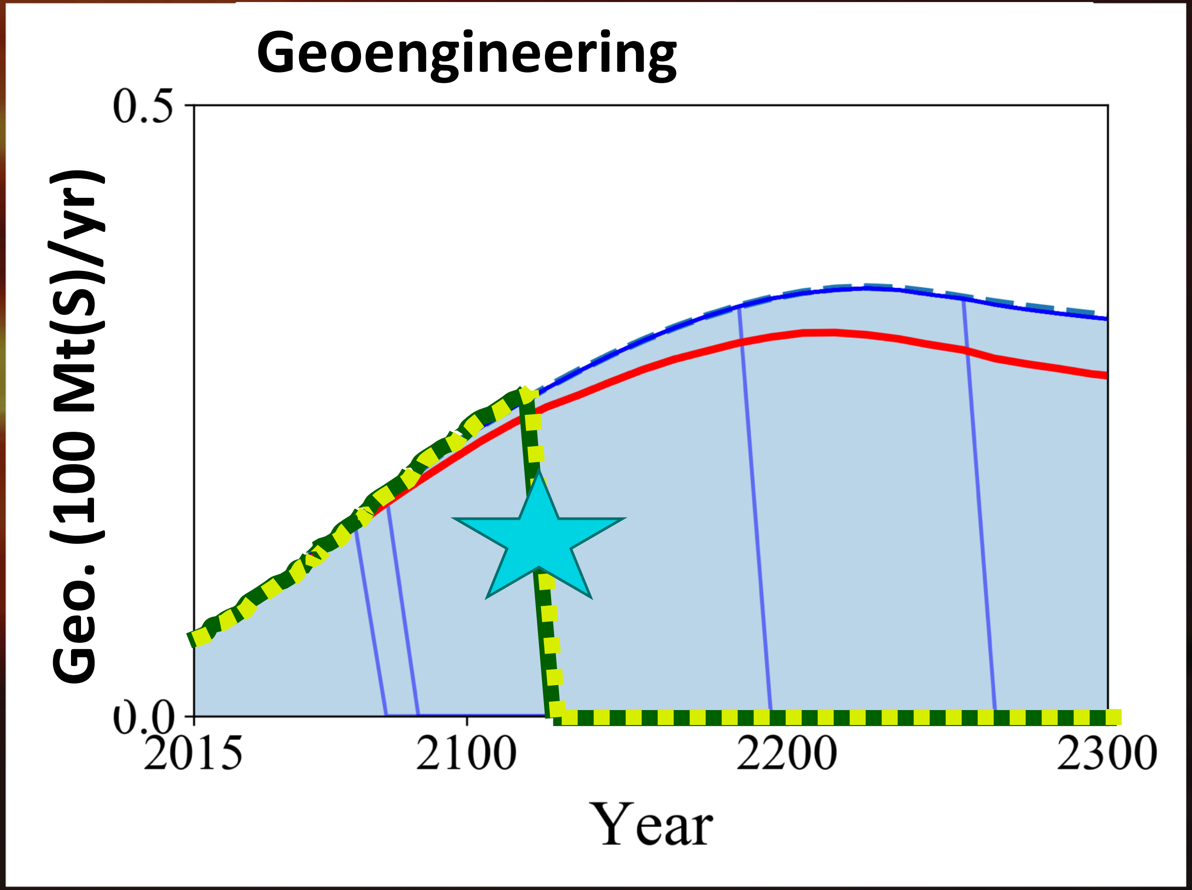
Optimal Policy: Abate+Geo

A particular ensemble member (following optimal policy)

★ 2130: Geoengineering failure -> increased abatement

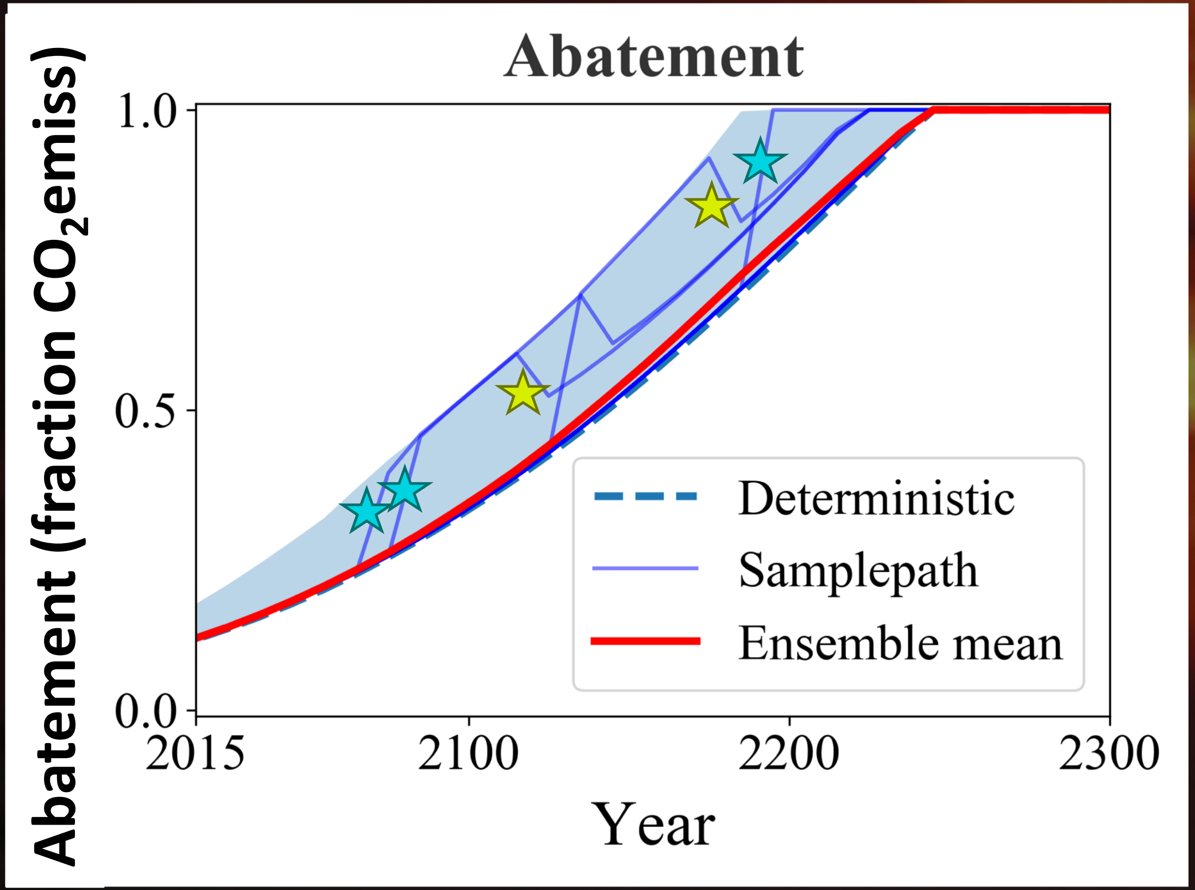
★ 2190: climate tipping -> reduced abatement

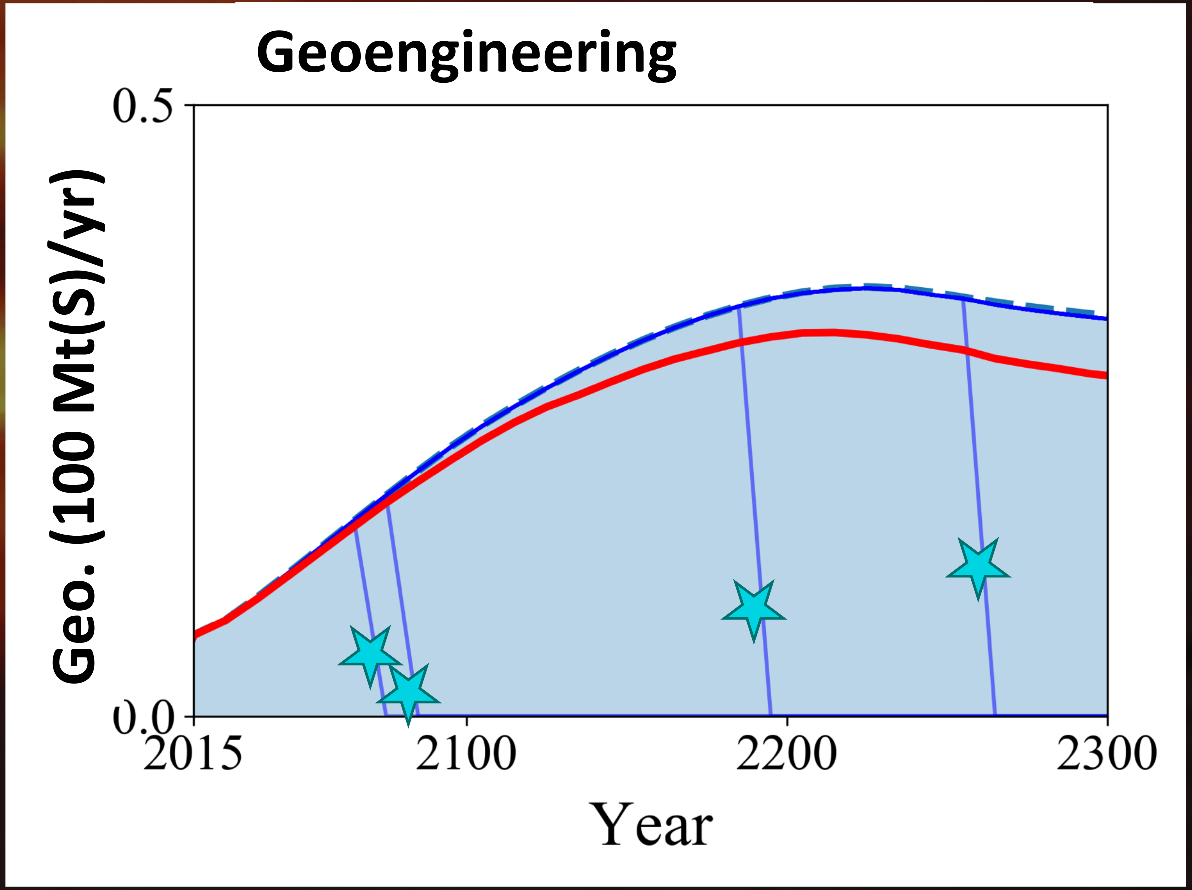




Optimal Policy: Abate+Geo

Ensemble members (few) — Deterministic results
Ensemble mean — Range of whole ensemble

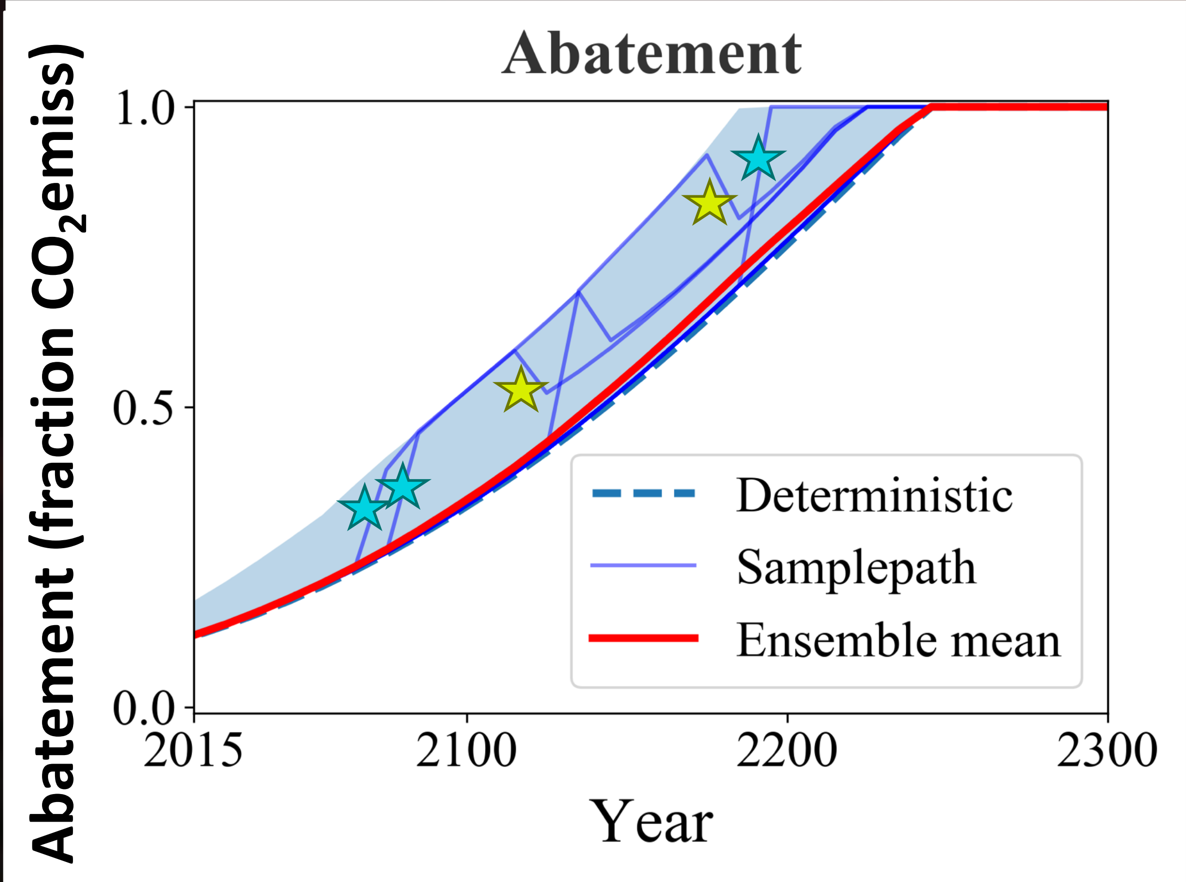


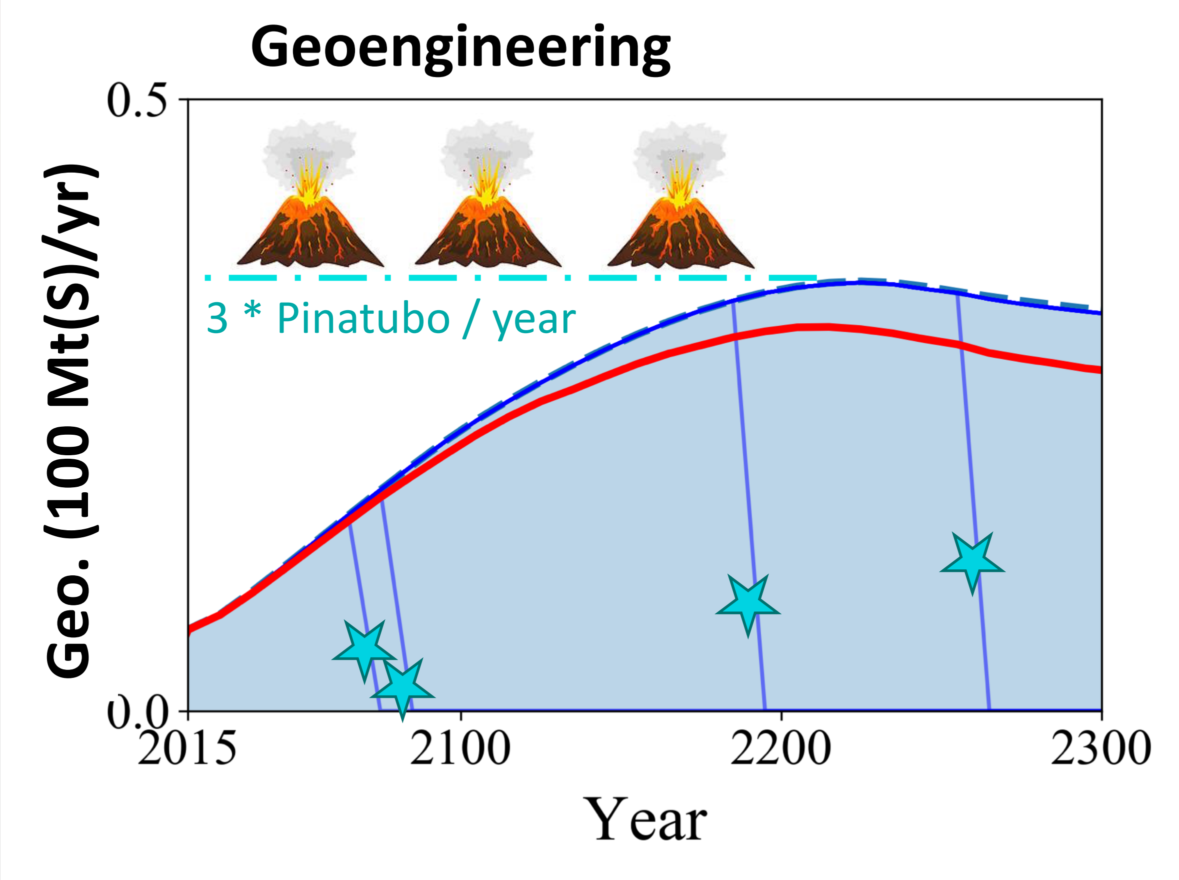


Geoengineering failure — Climate tipping

Optimal Policy: Abate+Geo

Optimal climate policy: Use abatement + (modest) Geoengineering

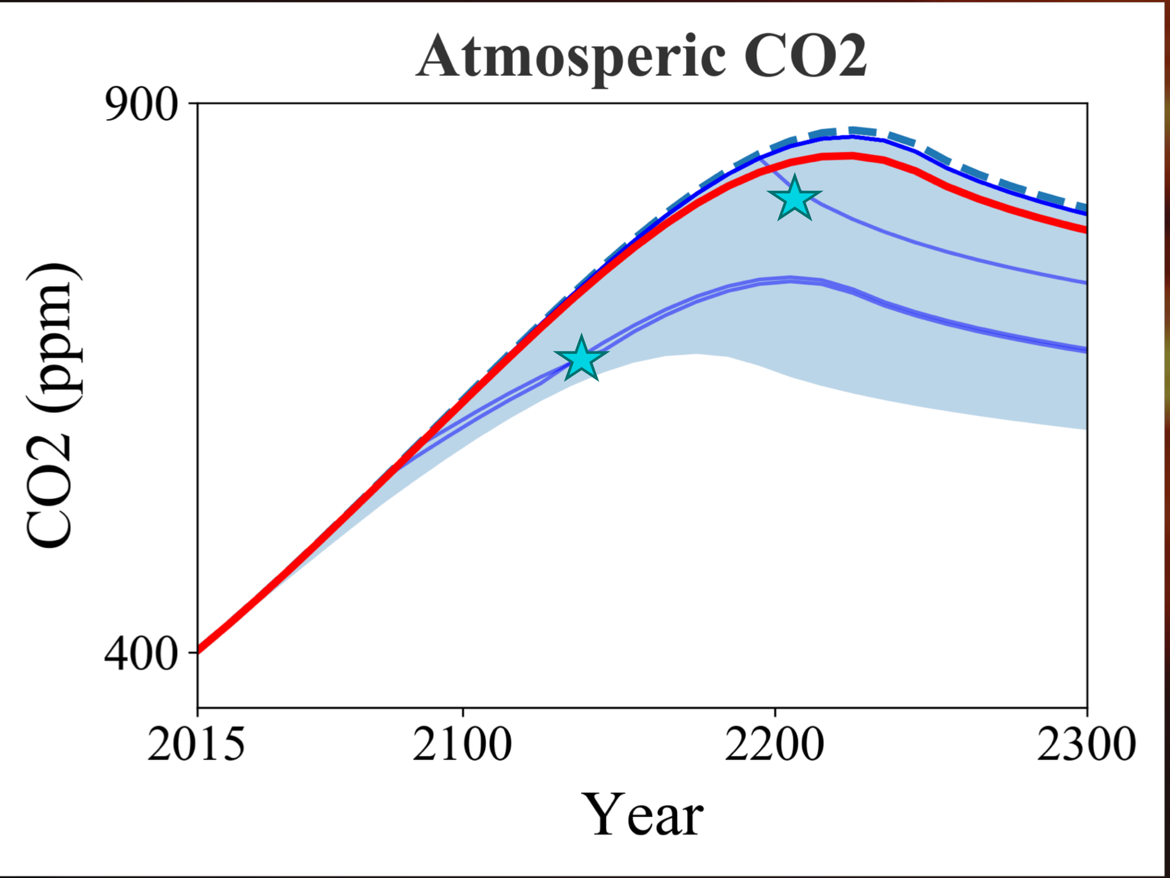


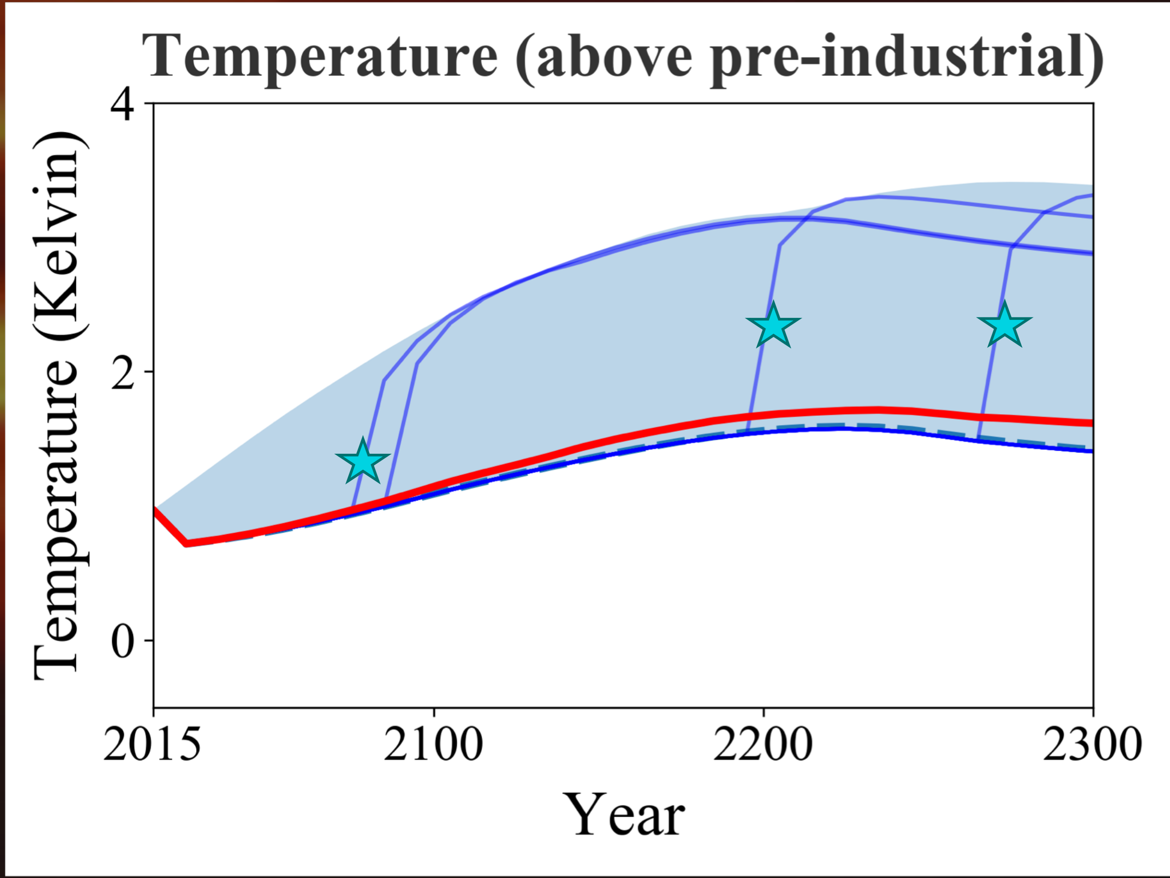


★ Geoengineering failure ★ Climate tipping

Optimal Policy: Abate+Geo

Optimal climate policy: Use abatement + (modest) Geoengineering stabilises T below 2K (unless Geoeng. fails)





★ Geoengineering failure ★ Climate tipping

Optimal Policy: Comparison with Geo-Only and Abate-Only

-- Abate+Geo keeps T<2K (unless failure occurs)

-- Abate+Geo reaches 50% abatement by 2139

-- Abate+Geo limits SO2 injections to 30Mt(S)/yr

Optimal Policy: Comparison with Geo-Only and Abate-Only

-- Abate+Geo keeps T<2K (unless failure occurs)
Neither Abate-Only nor Geo-Only achieve this (cost-efficiently)

-- Abate+Geo reaches 50% abatement by 2139
Abate-Only is faster by 45 years
-> Geoengineering delays abatement, but does not replace it!

-- Abate+Geo limits SO_2 injections to 30Mt(S)/yr
Geo-Only goes beyond 80Mt(S)/yr (without stabilising T!)
-> Abatement needed to limit warming in long-term.

Optimal Policy: Discount rate

R = “rate of pure time preference”

-- people prefer to be paid 100€ now over 100€ next year by factor e^{-Rt}

-- High R -> “We care less about the future”

Utility $\xrightarrow{\int U e^{-Rt} dt}$ Welfare

Previous result with (high) standard value R = 1.5%

Now use R=0.5%

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$$\text{Utility} \xrightarrow{\int U e^{-Rt} dt} \text{Welfare}$$

Previous result with (high) standard value R = 1.5%

Now use R=0.5%

→ Policy shift (Abate+Geo scenario):

More abatement (23 years earlier),

Less Geoengineering (peak 11% lower)

If you care about future, abate now! Don't rely on future Geoengineering!

Optimal Policy: Delayed Availability

Previous Scenarios:

-- Geoengineering available immediately
-- failure probability not time dependent

More realistic:

-- Geoengineering available from 2055 with only 30% likelihood
-- failure probability decreases in time

-> How does chance of later Geoengineering affect policy now?

-- If Geoengineering becomes available, it is used (and increases welfare)
-> don’t dismiss Geoengineering a priori!
-- Abatement in 2015 hardly differs from “Abate-Only”
-> keep abating - don’t rely on possible future geoengineering!

Summary: To cool or not to cool…?

Optimal climate policy combines CO_2 abatement and Geoengineering

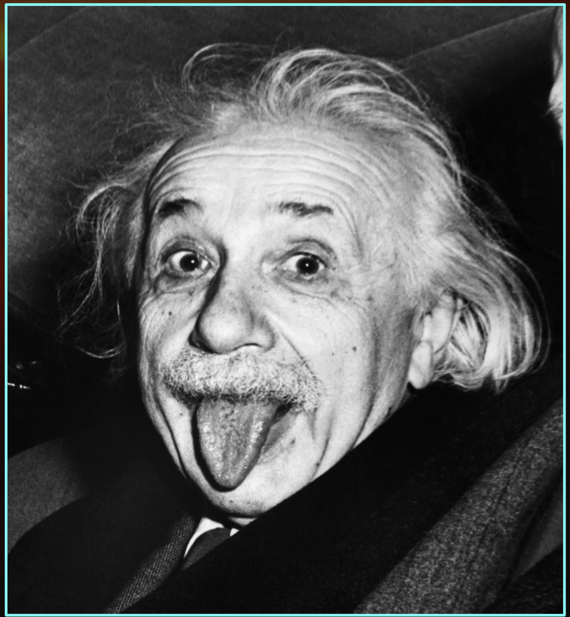
POLICY RECOMMENDATIONS

1. **Take Geoengineering seriously as policy option!**
2. **Do not abandon CO_2 abatement efforts!**

BUT

"God does not play DICE!"

(A. Einstein)



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BUT DICE model highly simplified -> Many open challenges:

-- benefits of Geoengineering: Effectiveness? How bad is climate change without?
-- ecological and climate hazards from Geoengineering?
-- better alternatives? (CCS, BECCS, … not represented in DICE!)
-- societal consequences: justice? coordination?

Interdisciplinary research needed to assess geoengineering!

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Contact: Claudia Wieners, c.e.wieners@uu.nl

Paper: Helwegen, K. G., Wieners, C. E., Frank, J. E., and Dijkstra, H. A.: Complementing CO_2 emission reduction by Geoengineering might strongly enhance future welfare, Earth Syst. Dynam. Discuss.

BACK-UP MATERIAL

-- Policy Metrics

-- SRM efficiency: GLENS + Kleinschmitt 2017

-- Solar dimming and global mean precipitation
-- Linear Response

-- deterministic results

-- plots comparing Abate+Geo to Abate-only and Geo-only

-- upcoming work (climate modelling)

Policy Metrics (Determistic)

Policy	ζ	peak SRM	Ab. 50%	Ab.90%	SCC
Abatement-only	100%	/	2114	2212	35
SRM-only	186%	*	/	/	21
Abatement+SRM	238%	35.1	2134	2243	20

* SRM does not peak, but keeps increasing until the upper limit of $100Mt(S)/yr$.

/ = Not applicable

Table 2. Comparison of policies in the deterministic setting (no tipping, no SRM failure). Abatement-only means that no SRM is used, SRM-only means that no abatement is used (unless SRM fails; see text), and in Abatement+SRM both are used. The performance ζ (see eq. (11)) is a measure of the increase in expected cumulated discounted utility w.r.t. the no-action scenario, and is normalised such as to yield 100% for Abatement-only. The column 'peak SRM' contains the highest SRM values (in Mt(S)/yr) over all time steps. 'Ab 50%' and 'Ab 99%' show the year in which the abatement reaches 50% and 99%, respectively. SCC is the social cost of carbon in (\$(2005)/t(C)).

Policy Metrics (Stochastic)

Policy	ζ	ζ_{10}	ζ_{90}	SRM fail	Tipping	peak SRM	Ab. 50%	Ab.90%	SCC
No action	0%			/	96.2%	/	/	/	45
Abatement-only (det. policy**)	100%			/	49.5%	/	2114	2212	42
Abatement-only	105%	77%	121%	/	37.8%	/	2095	2215	41
SRM-only	181%	179%	185%	19.8%	60.96%	*	/	/	23
Abatement + SRM	219%	220%	223%	20.2%	6.2%	35.0	2139	2242	20
Realistic Storyline	125%	78%	190%	79.9%	30.1%	31.4	2106	2234	37

* SRM does not peak, but keeps increasing until the upper limit of $100Mt(S)/yr$.

** Tipping can occur, but the policy maker ignores this and chooses the policy which would be optimal in the deterministic case.

/ = Not applicable

Table 3. Comparison of policies in the stochastic setting, i.e. including climate tipping and SRM failure. No action means that neither abatement nor SRM are used; other scenarios are explained in Sect. 2.3. The perfomance measures ζ, ζ_{10} and ζ_{90} are given in eq. (11) and eq. (12). The columns 'SRM fail' and 'Tipping' show the probability that SRM failure or climate tipping occurs before 2415. The column 'peak SRM' contains the highest SRM value (in Mt(S)/yr) over all time steps and over all ensemble members. This corresponds to members in which no SRM failure or climate tipping occurred, at least before the time of the SRM peak. 'Ab 50%' and 'Ab 99%' show the year in which the abatement reaches 50% and 99%, respectively. SCC is the social cost of carbon in ($(2005)/t(C)).

Policy Metrics (Sensitivity Runs)

Scenario	Abate 50%	peak SRM	SCC
Abatement-only, standard	2095	/	41
Ab.+SRM, standard	2139	35.0	20
Abatement-only, low rate of pure time preference ($\rho = 0.5\%$)	2068	/	70
Ab.+SRM, low rate of pure time preference ($\rho = 0.5\%$)	2116	31.1	30
Ab.+SRM, less temp. damage, more precip.damage ($\psi_T \rightarrow \psi_T/2, \psi_P \rightarrow \psi_P \times 2$)	2143	32.6	17
Ab.+SRM, double damage from tipping ($\Omega = 0.8$)	2136	34.8	20
Ab.+SRM, double climate tipping probability ($\kappa_{tipp} \rightarrow \kappa_{tipp} \times 2$)	2137	34.9	20
Ab.+SRM, quadrupled SRM failure probability ($\kappa_{fail} \rightarrow \kappa_{fail} \times 4$)	2121	34.3	23
Ab.+SRM, double damage from SRM ($\psi_S \rightarrow \psi_S \times 2$)	2133	26.8	22

Table 4. Policy metrics of the sensitivity runs. 'Abate 50%' is the year in which Abatement reaches 50% ($\mu = 0.5$). 'peak SRM' (in $Mt(S)/yr$) is the highest SRM value of the ensemble (over all times and all members) and corresponds to those ensemble members without early SRM failure or climate tipping. 'SCC' is the social cost of carbon in $\$(2005)/t(C)$. All simulations were preformed in the stochastic settings and are either Abatement-only or Abatement+SRM (abbreviated here as Ab.+SRM). The first two cases, labelled 'standard', are repeated from Table 3 for convenience. The sensitivity runs correspond to those discussed in Sect. 3.4.

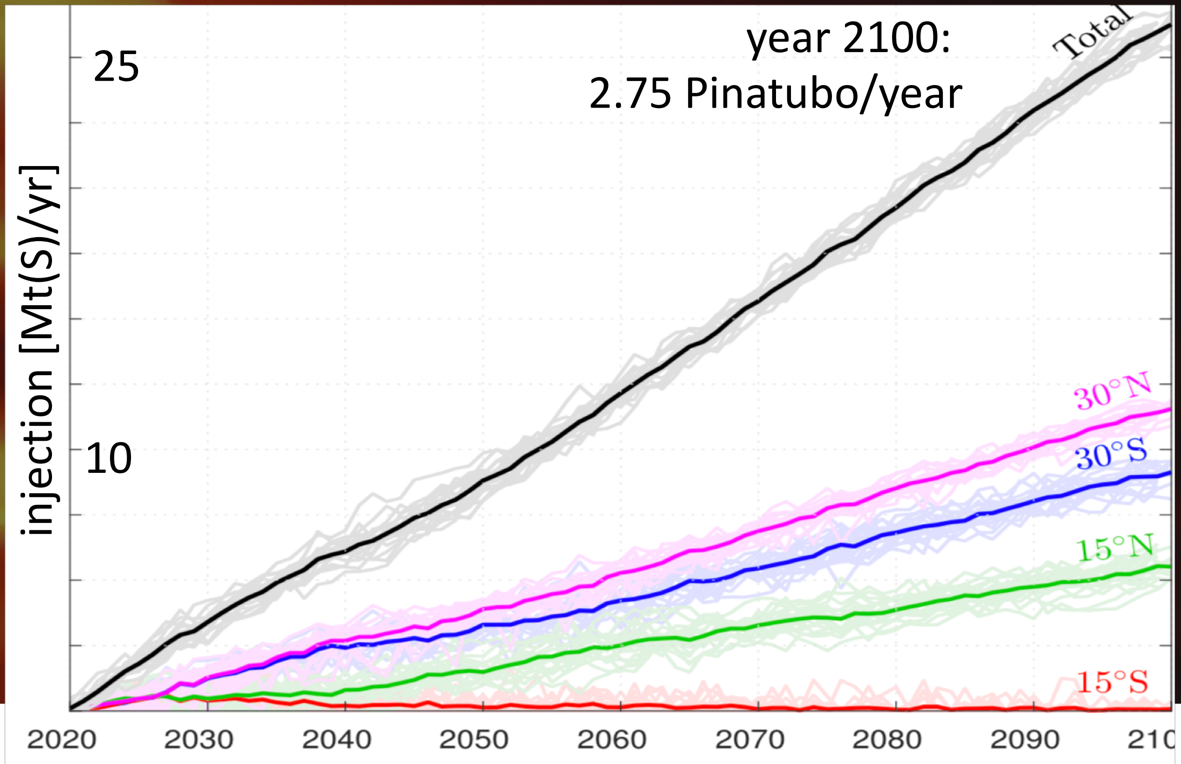
SRM- Rad. FORCING: GLENS

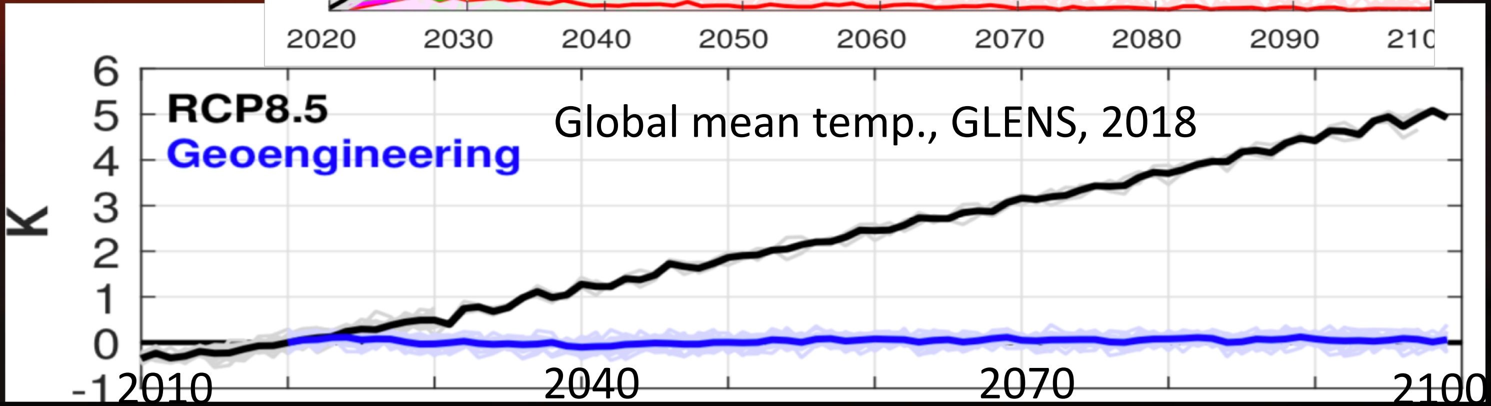
Niemeyer and Timmreck, 2015
Counterbalancing RCP8.5 in 2100
requires 10 Pinatubos / year !

Tilmes et al, 2018 (GLENS):
linear.
Stabilising T at 2020 values under
RCP8.5 : 2.75 Pinatubos/year in 2100

Kleinschmitt et al, 2017:
Max. cooling = 2K

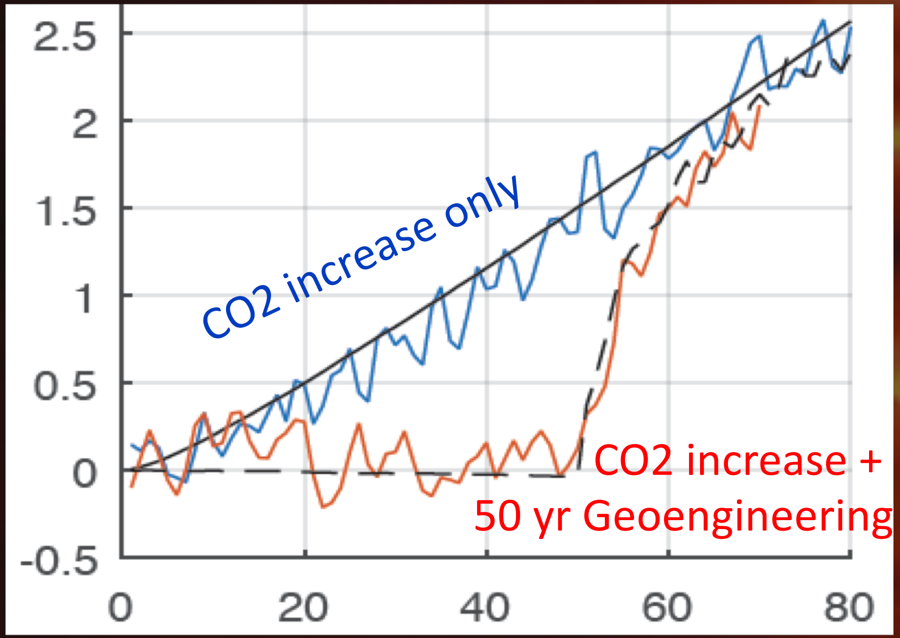
We used Niemeyer and Timmreck.





Sulphate Geoengineering: Influence on Precipitation

Global Temp. change T [K]



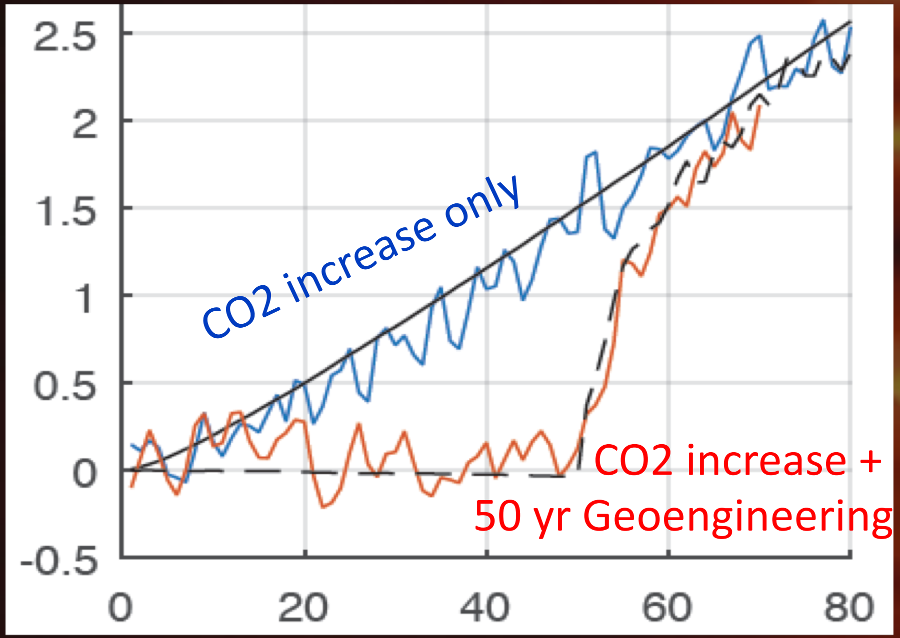
time [model year]

McMartin et al (2016); CESM-CAM5

Simulation with CO_2 increase 1%/year and NO Geoengineering / GE compensation temp change

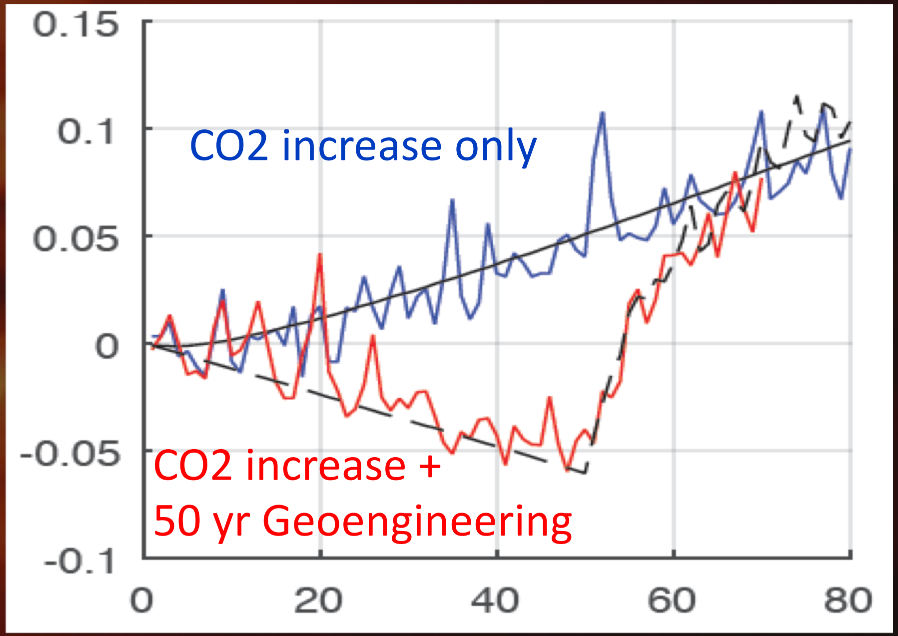
Sulphate Geoengineering: Influence on Precipitation

Global Temp. change T [K]



time [model year]

Global precip. change R [mm/day]



time [model year]

McMartin et al (2016); CESM-CAM5

Simulation with CO_2 increase 1%/year and NO Geoengineering / GE compensation temp change

-- Even if T is kept zero by GE, R will decrease (drying)

-- Reason: CO2 warms atmosphere first, sea surface later -> more stable stratification

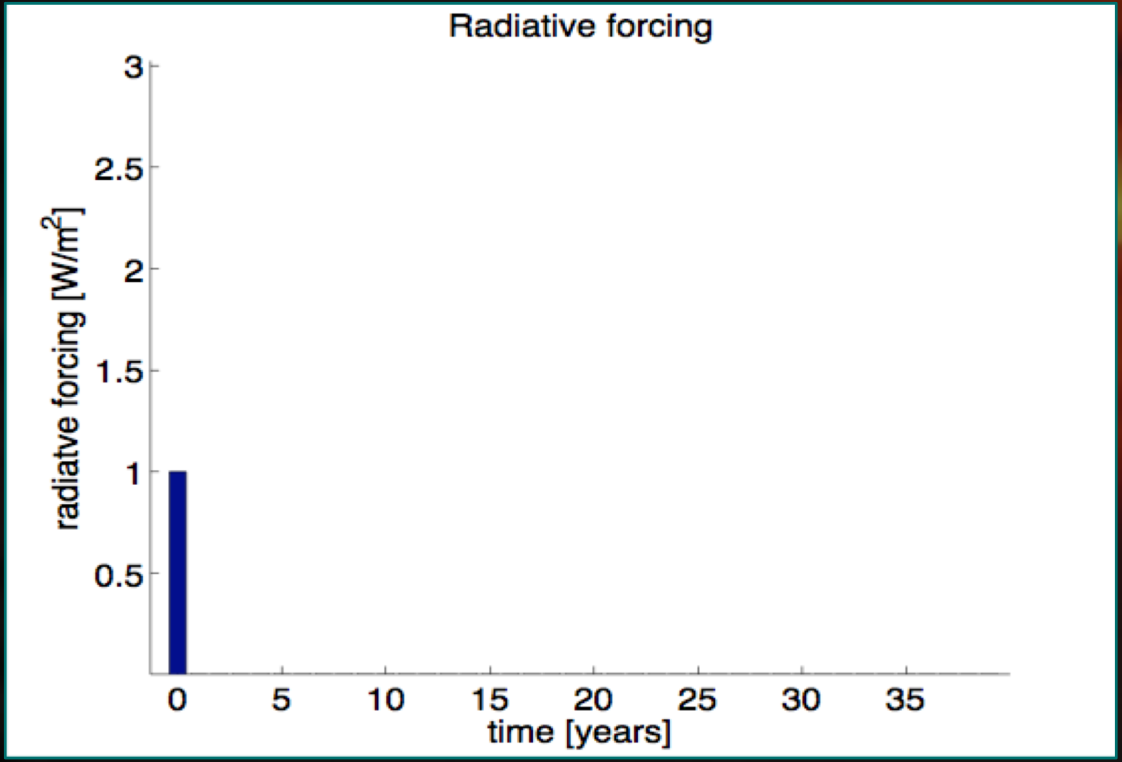
Climate model: Linear Response Theory

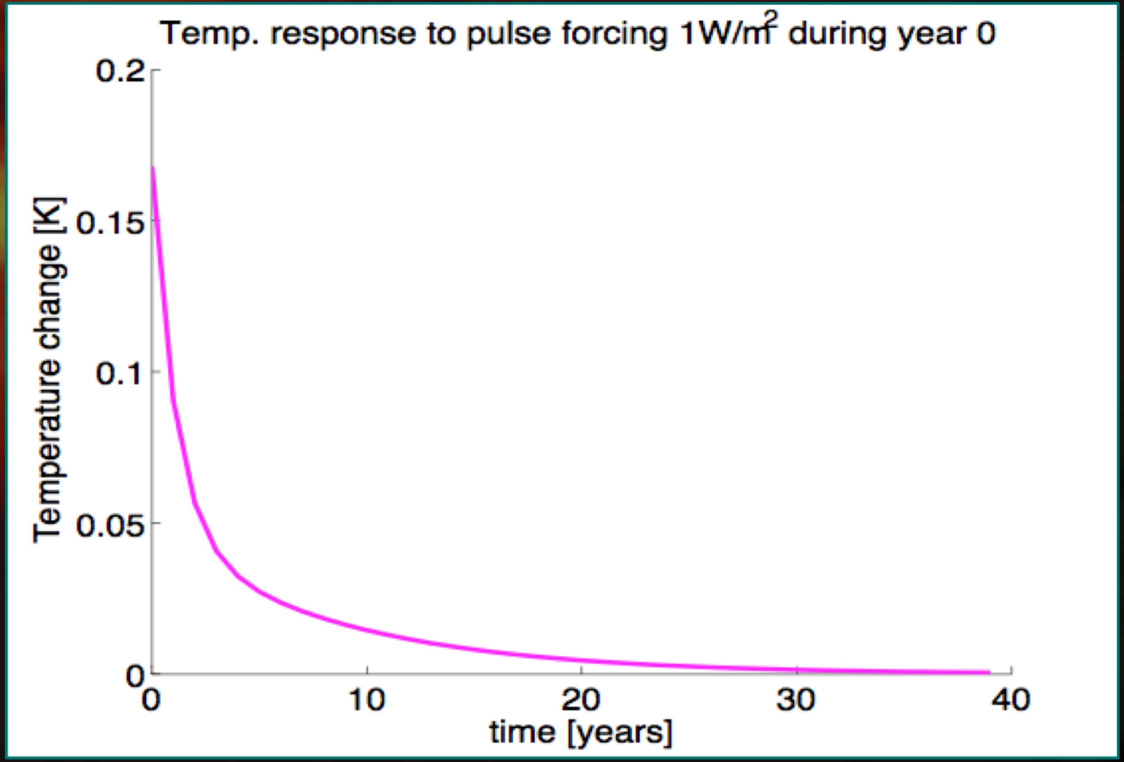
Use global Precipitation R as Proxy for Residual Climate change.

-> need response of temperature T and precip. T to CO_2 and Geoengineering

-> Use Linear Response Model tuned on big climate models (GCMs).

Pulse response from GCM

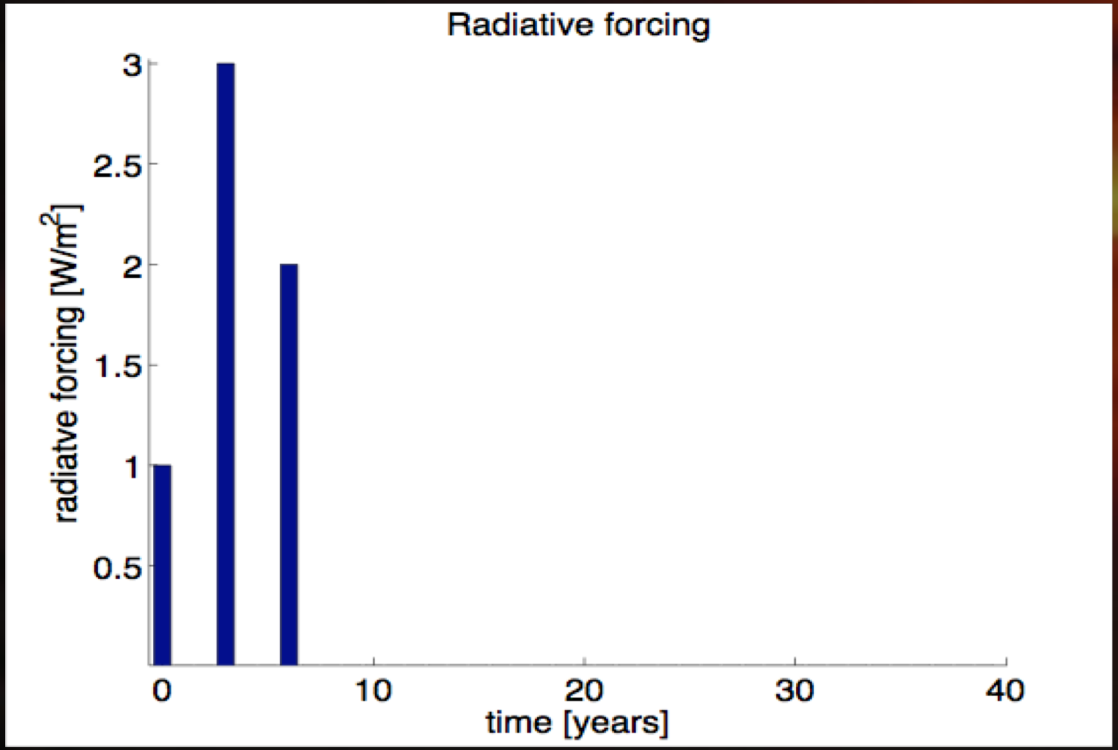


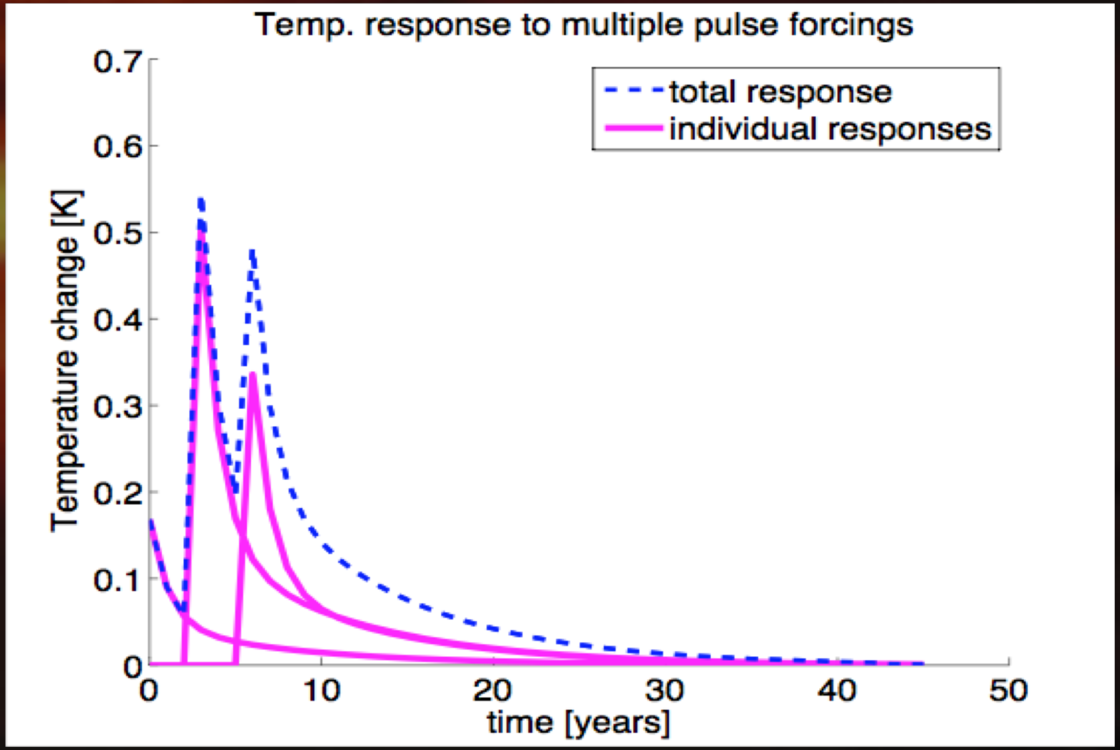


Climate model: Linear Response Theory

Use global Precipitation R as Proxy for Residual Climate change.
-> need response of temperature T and precip. T to CO2 and Geoengineering
-> Use Linear Response Model tuned on big climate models (GCMs).

Constructed response to arbitrary forcing





Climate model: Linear Response Theory

Use global Precipitation R as Proxy for Residual Climate change.
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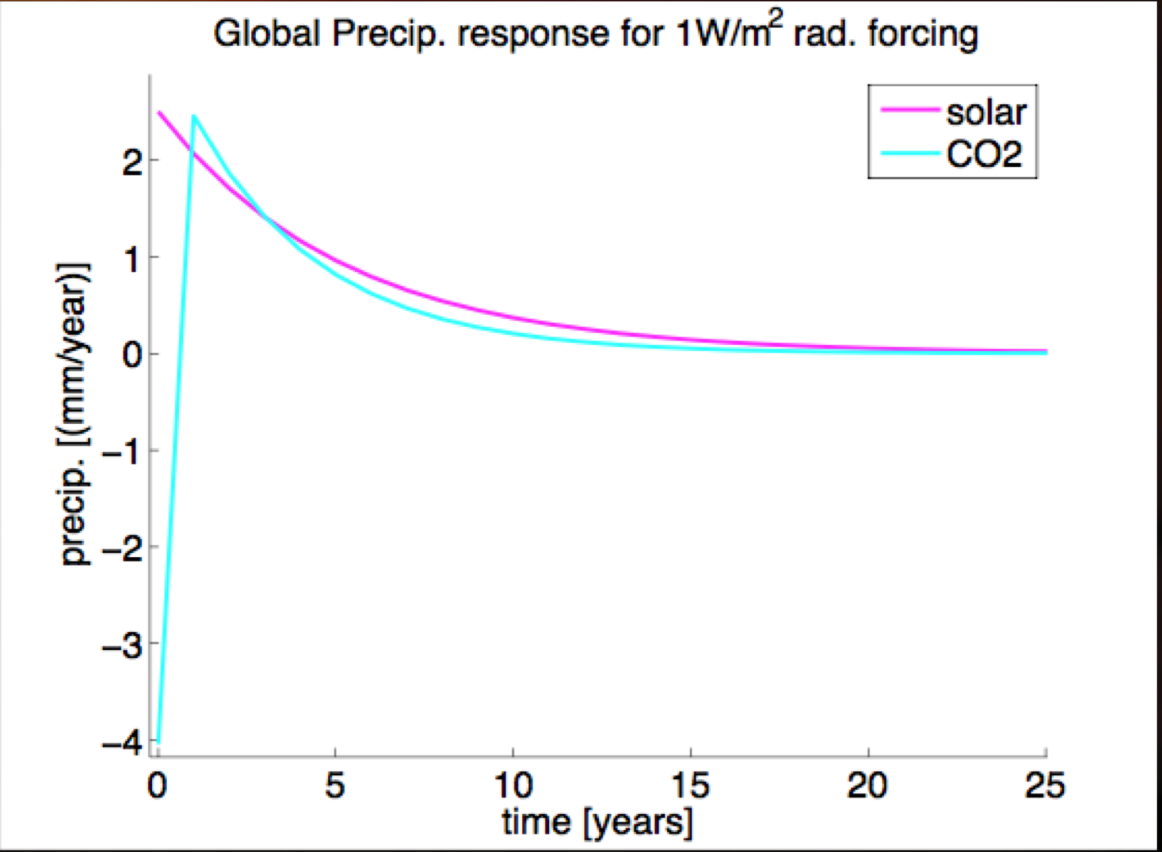
Pulse responses can be constructed from GCM simulations (McMartin and Kravitz 2016)

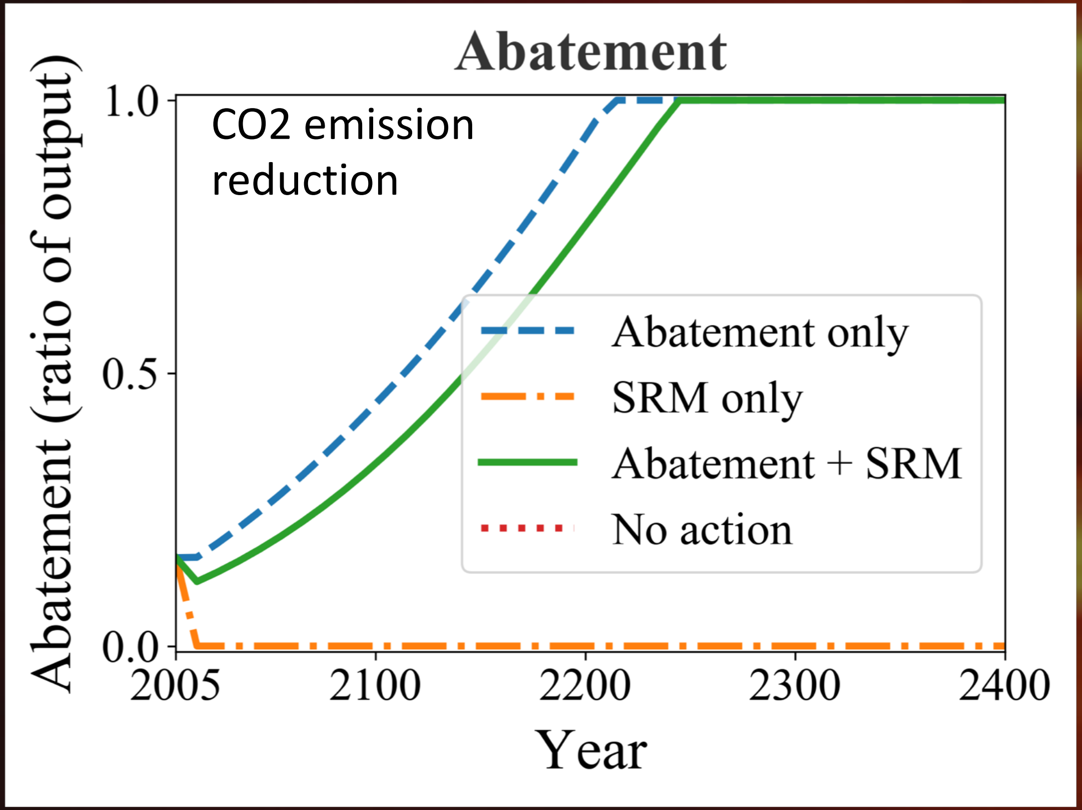


CO2 pulse decreases precipitation in first year (stabilising), then increases it due to warming (more evaporation)

Geoengineering decreases precipitation immediately due to cooling (less evaporation)

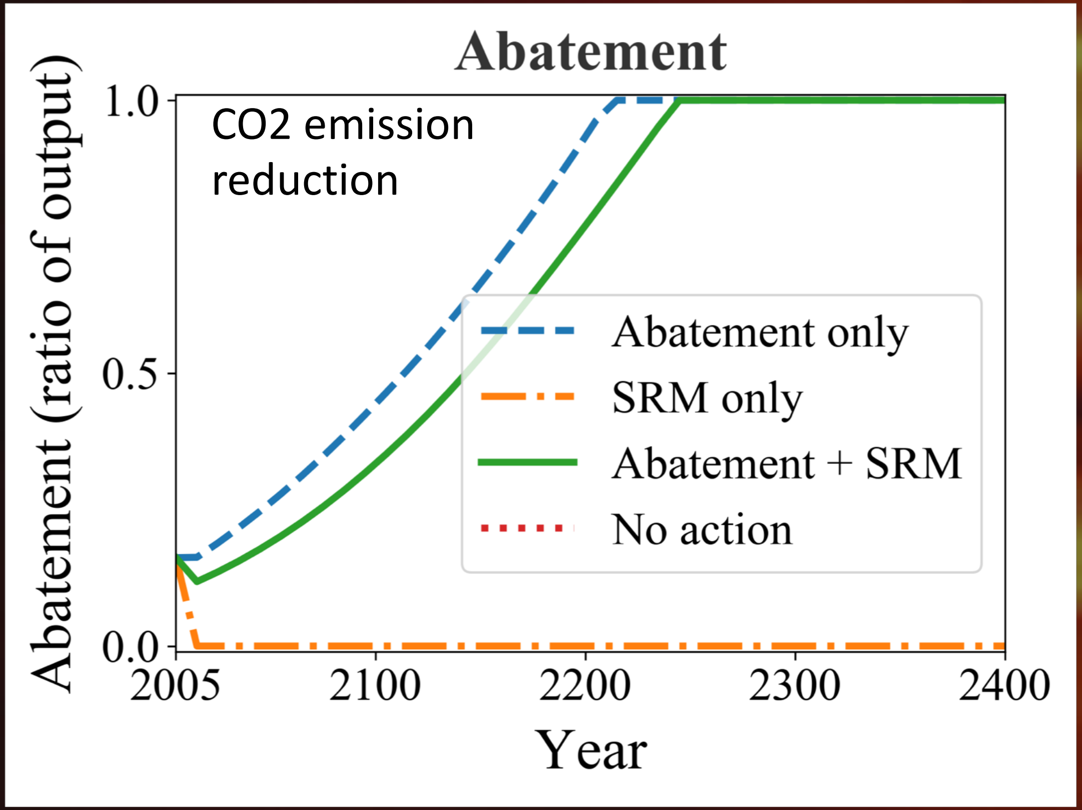
Responses do NOT cancel!

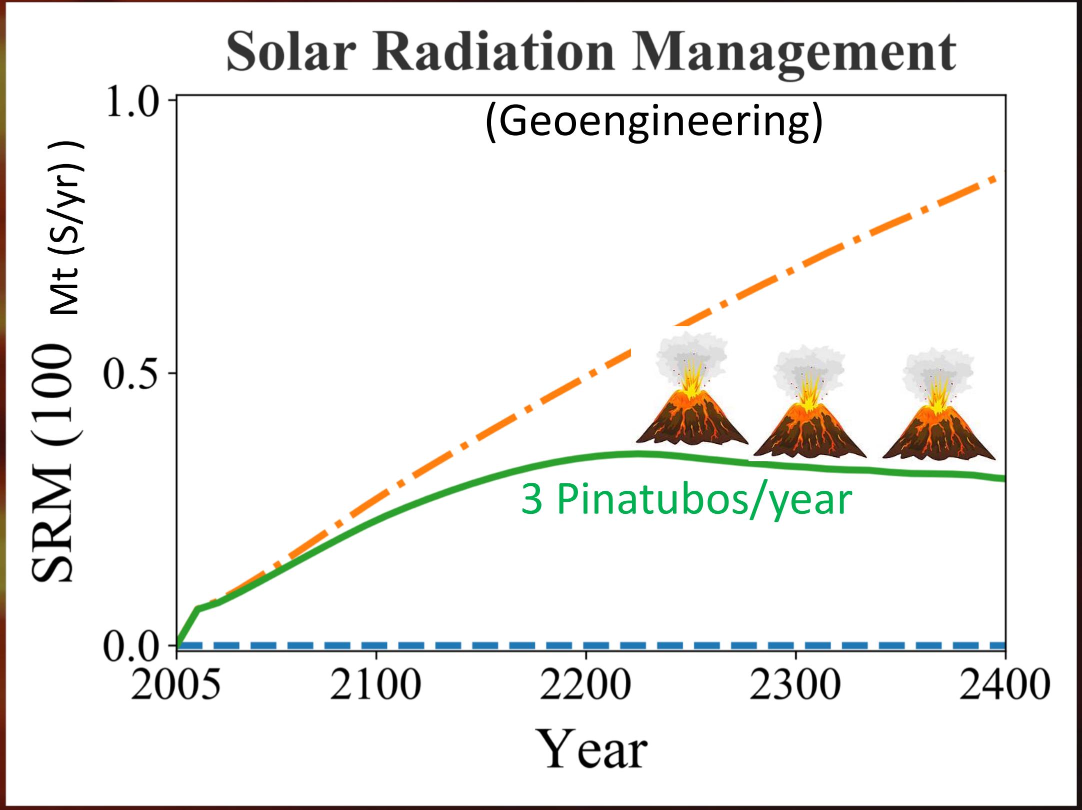
Optimal Policy: Deterministic Results



-- Geoengineering delays abatement by ca 30 years, but does not replace it

Optimal Policy: Deterministic Results





-- Geoengineering delays abatement by ca 30 years, but does not replace it

-- With abatement, Geoengineering remains limited to ≈3 Pinatubos / year (30Mt(S)/yr)

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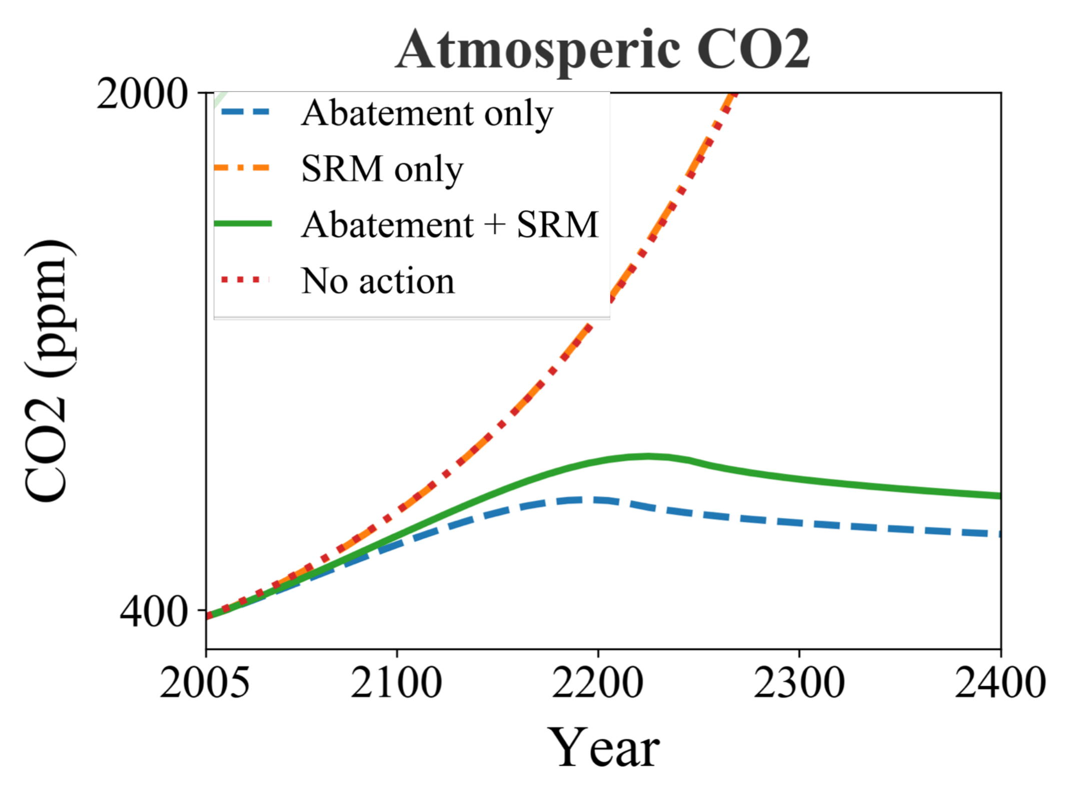
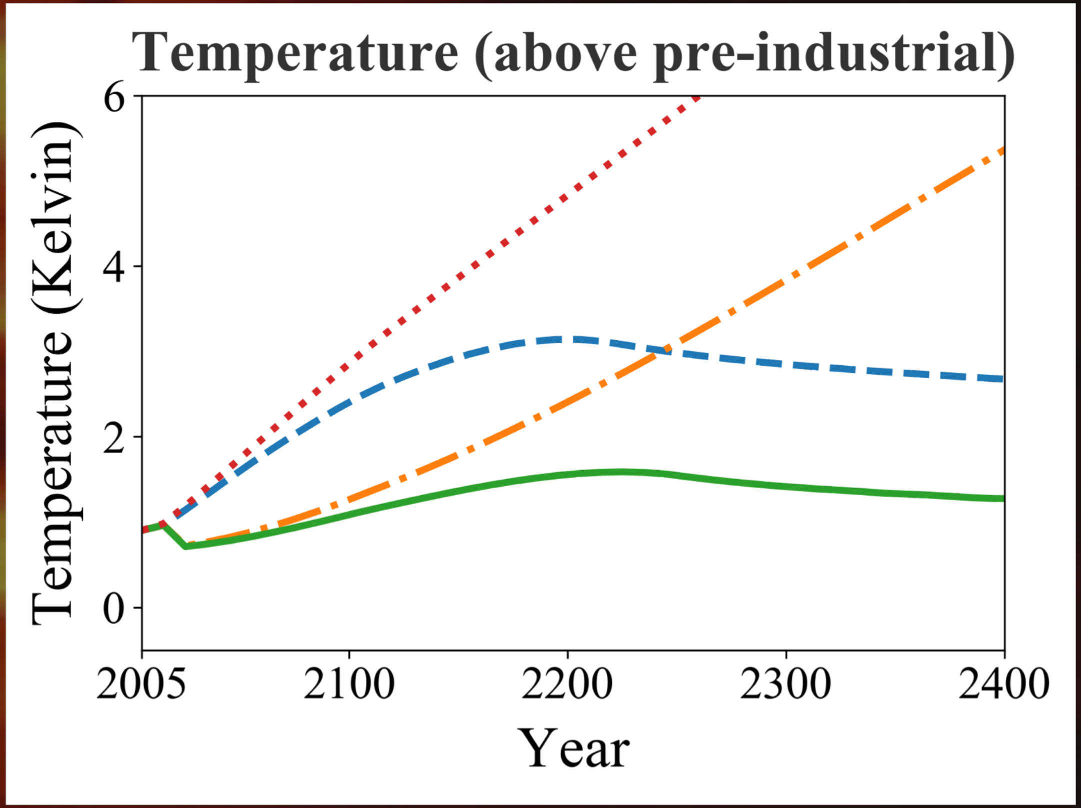




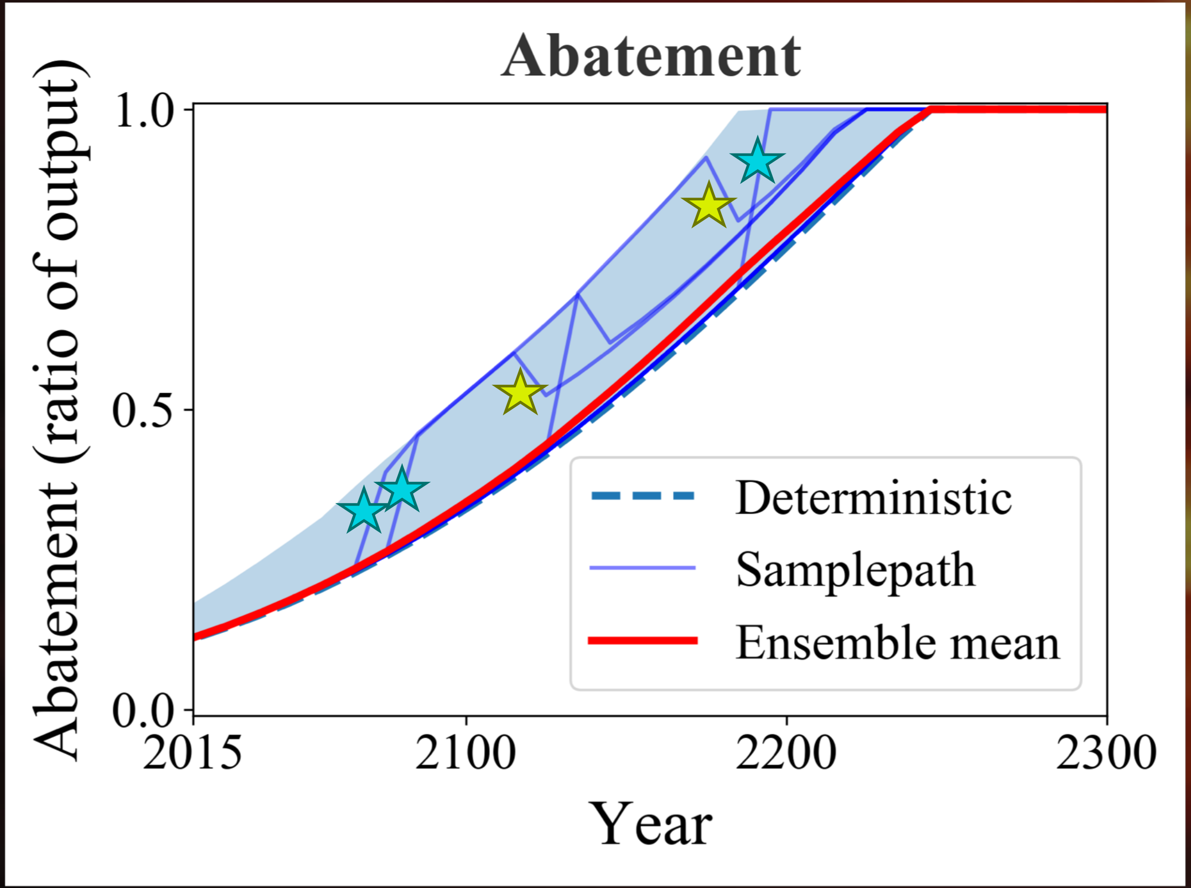
-- Geoengineering delays abatement by ca 30 years, but does not replace it

-- With abatement, Geoengineering remains limited to ≈3 Pinatubos / year (30Mt(S)/yr)

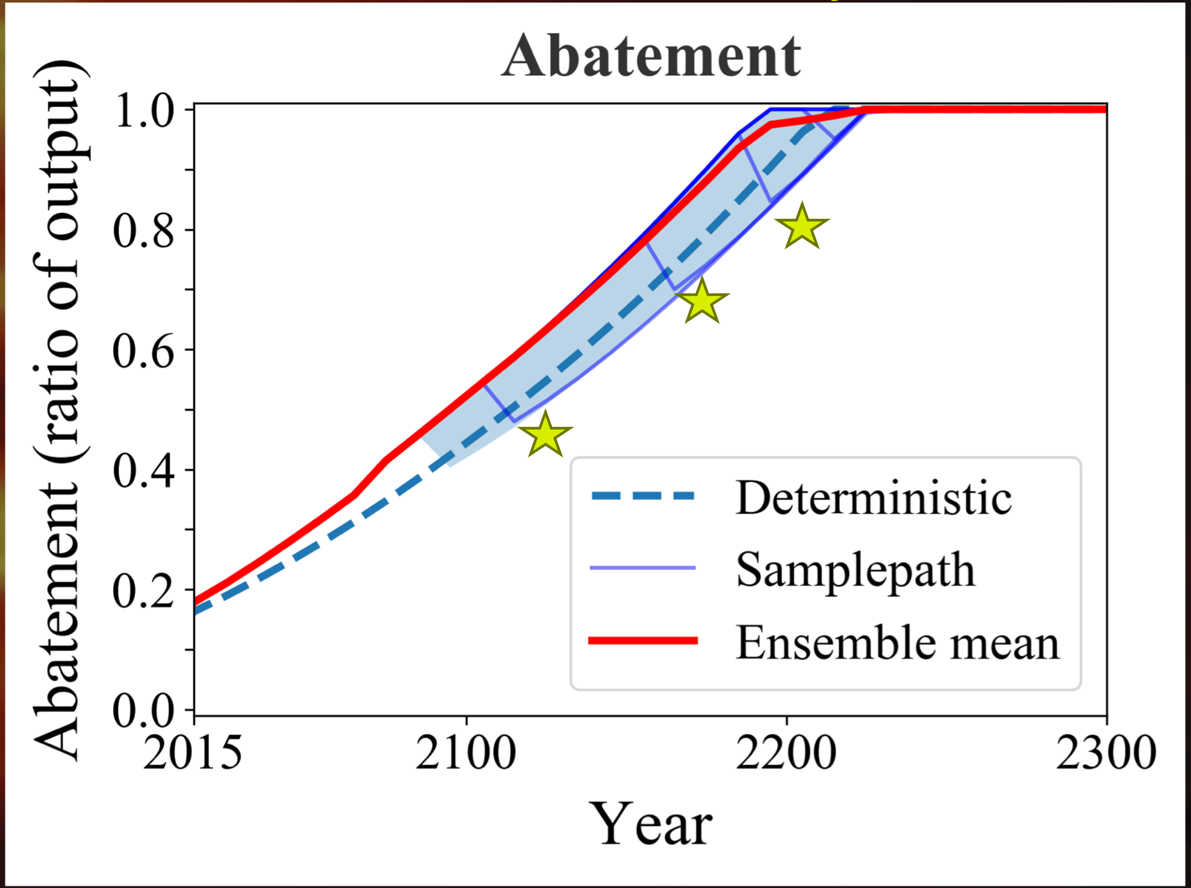
-- Only combination of Geo.+Abate keeps T<2K

Optimal Policy: Abate+Geo vs Abate-only

Abate+Geo



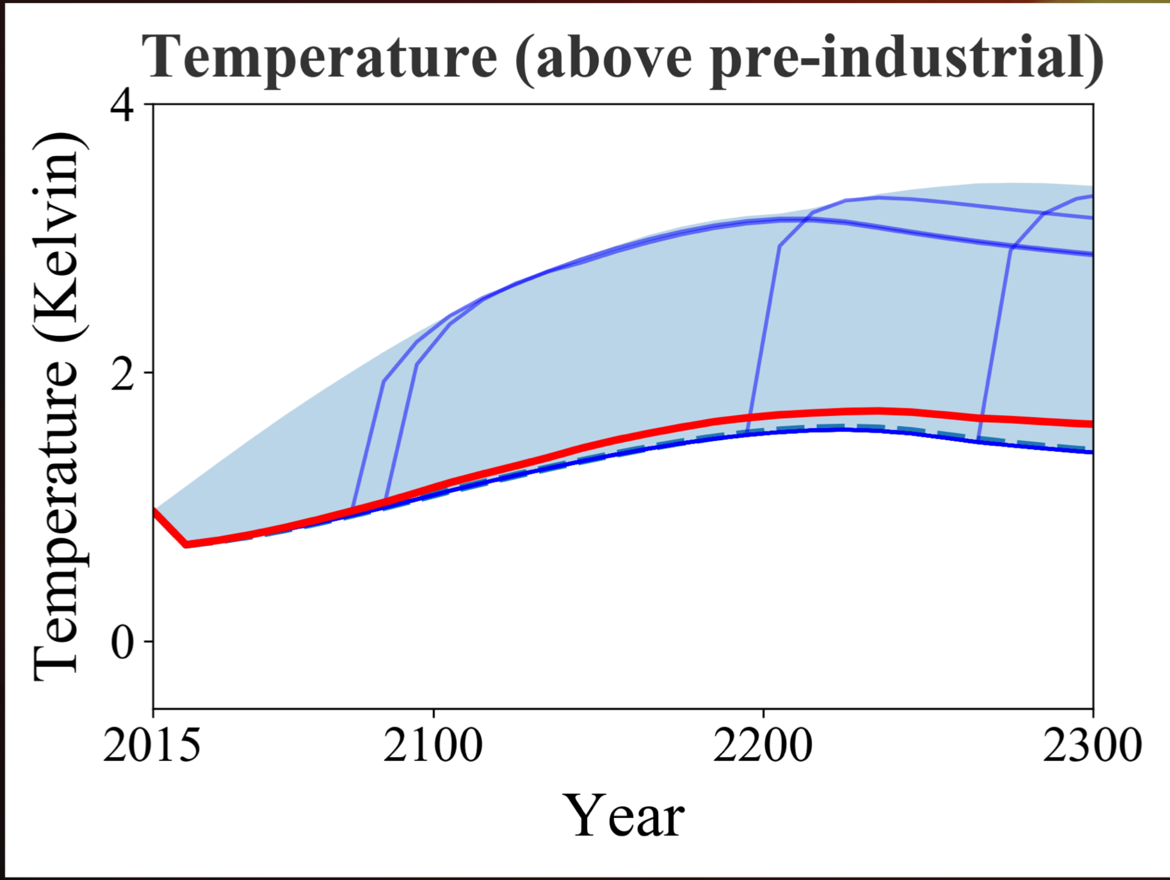
Abate-Only



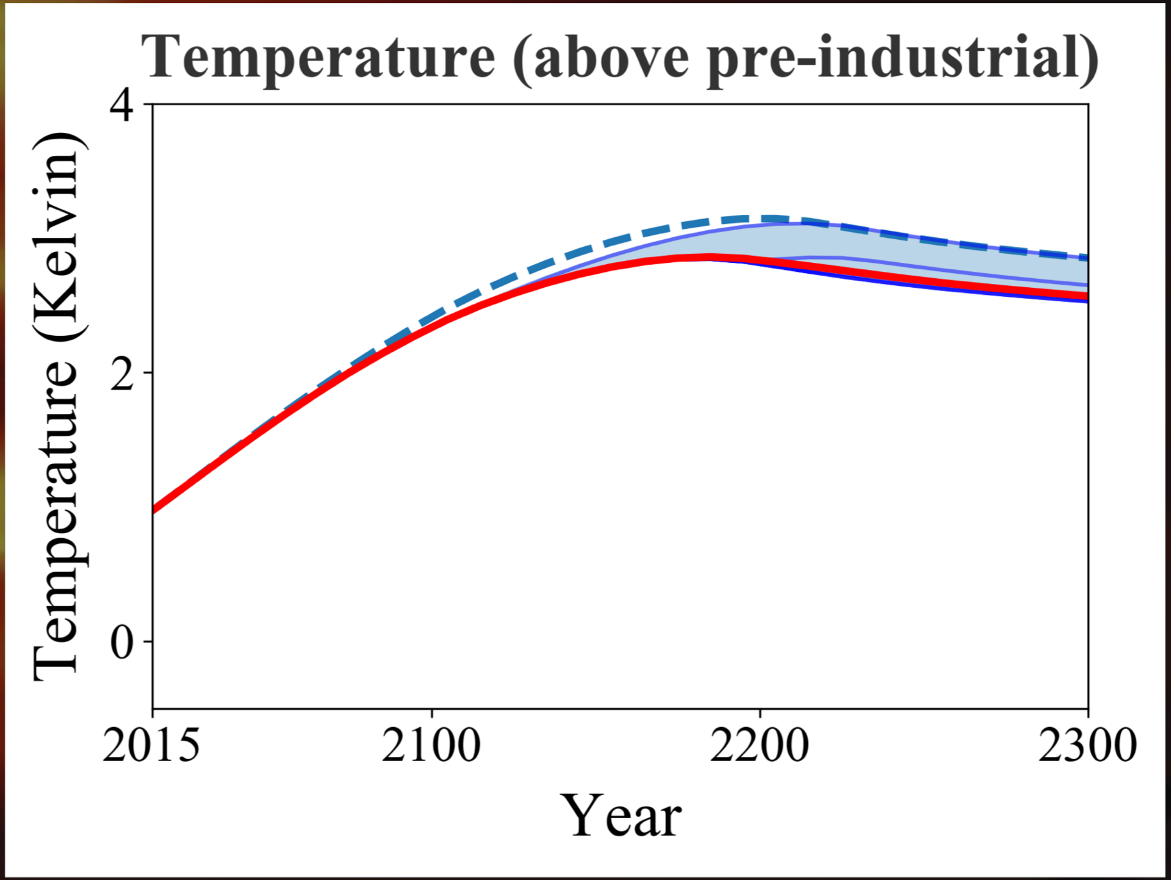
Allowing Geoengineering does *not replace* abatement, but delays by 30-40 years

Optimal Policy: Abate+Geo vs Abate-only

Abate+Geo



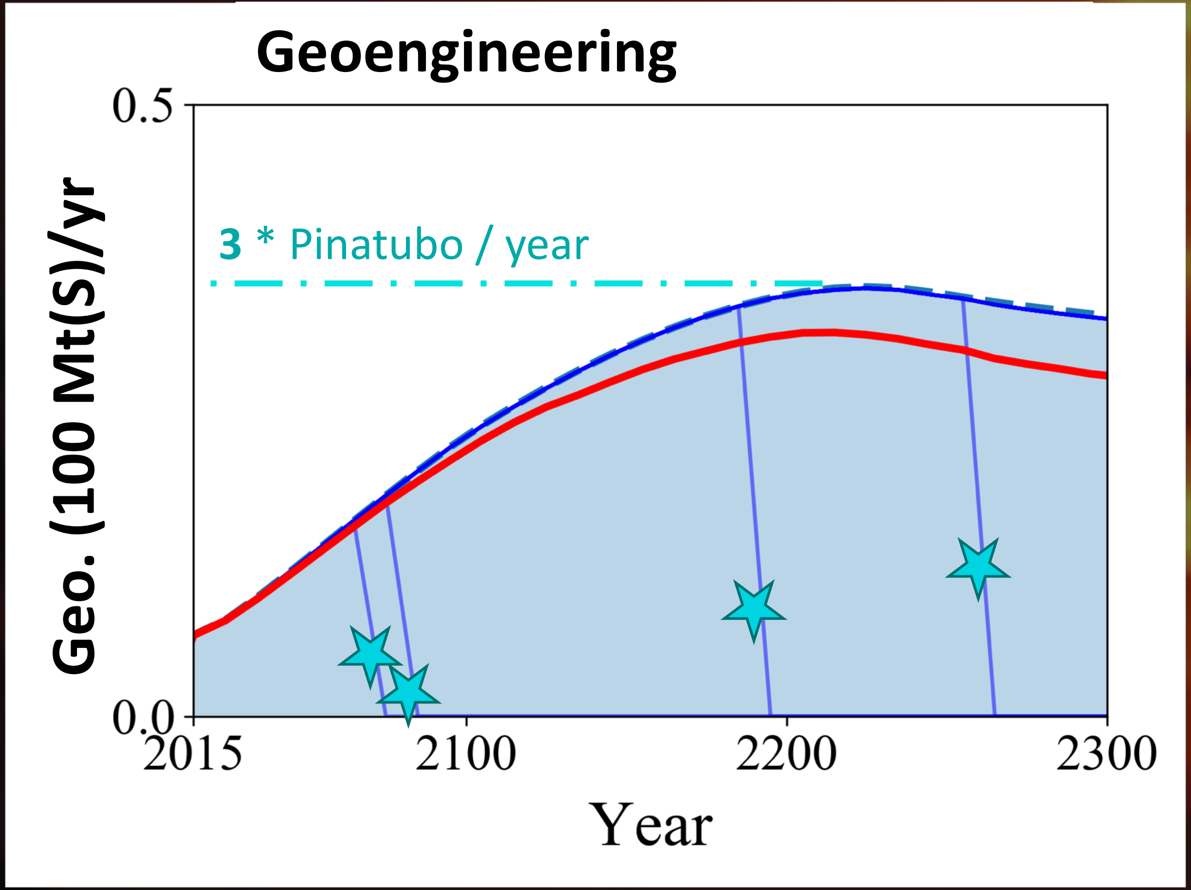
Abate-Only



Abatement-only does not stabilise T below 2K.

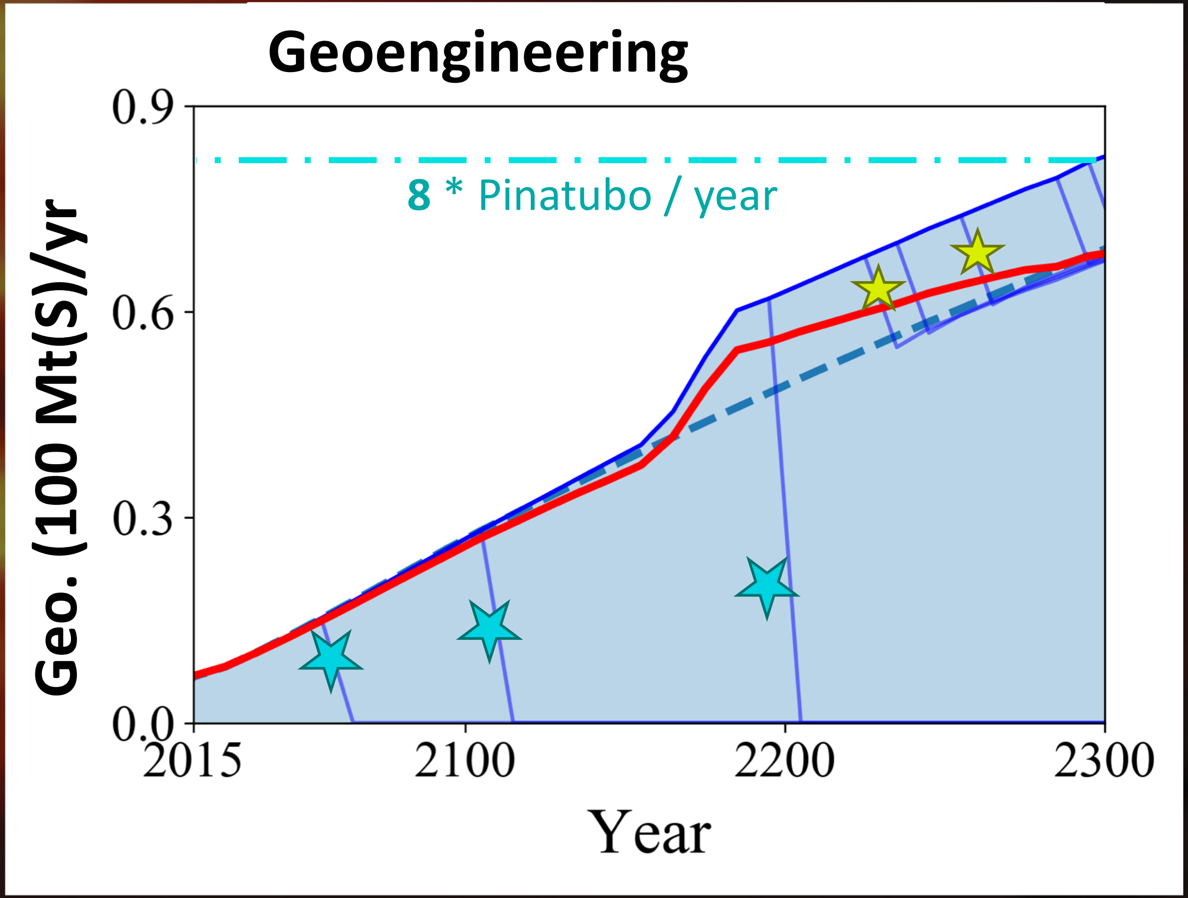
Optimal Policy: Abate+Geo vs Geo-only

Abate+Geo



Note different y-axis scales

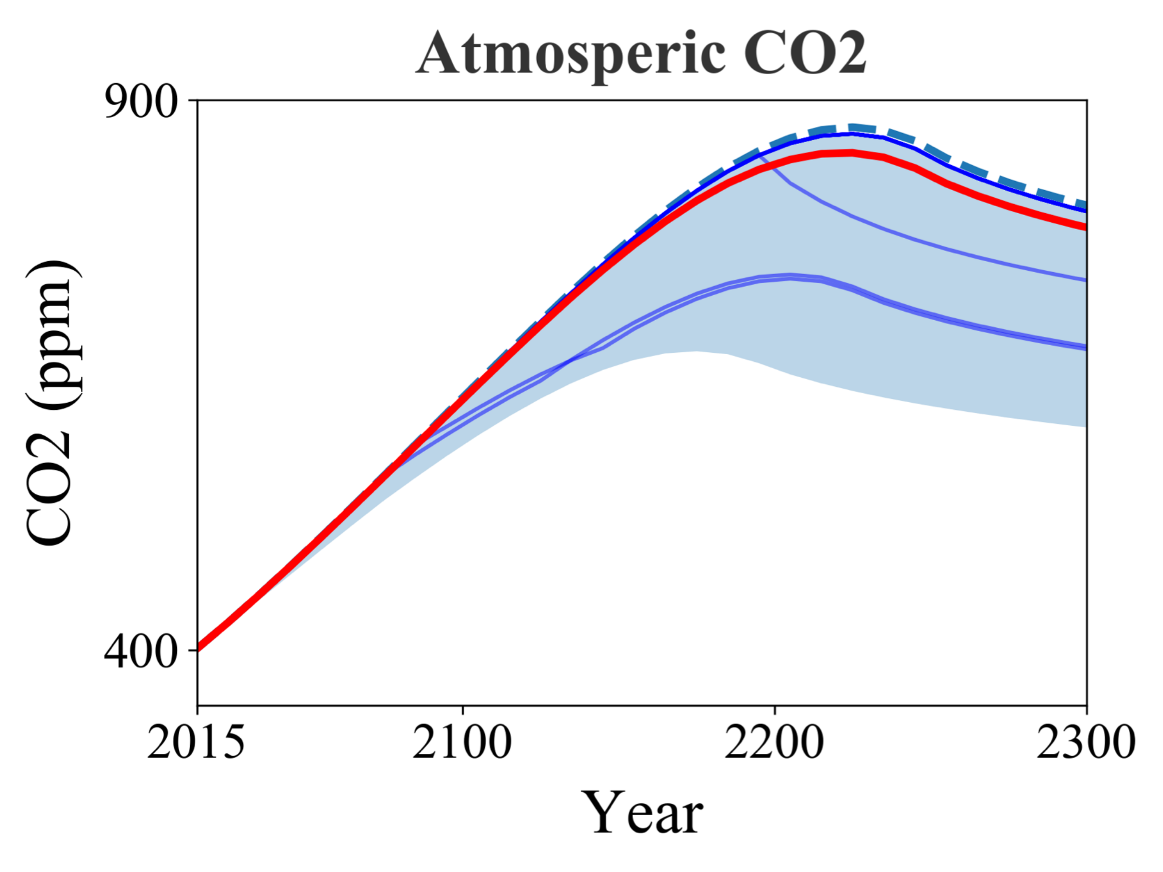
Geo-Only



For Geo-only, very high injection rates are needed; keep increasing…

Optimal Policy: Abate+Geo vs Geo-only

Abate+Geo



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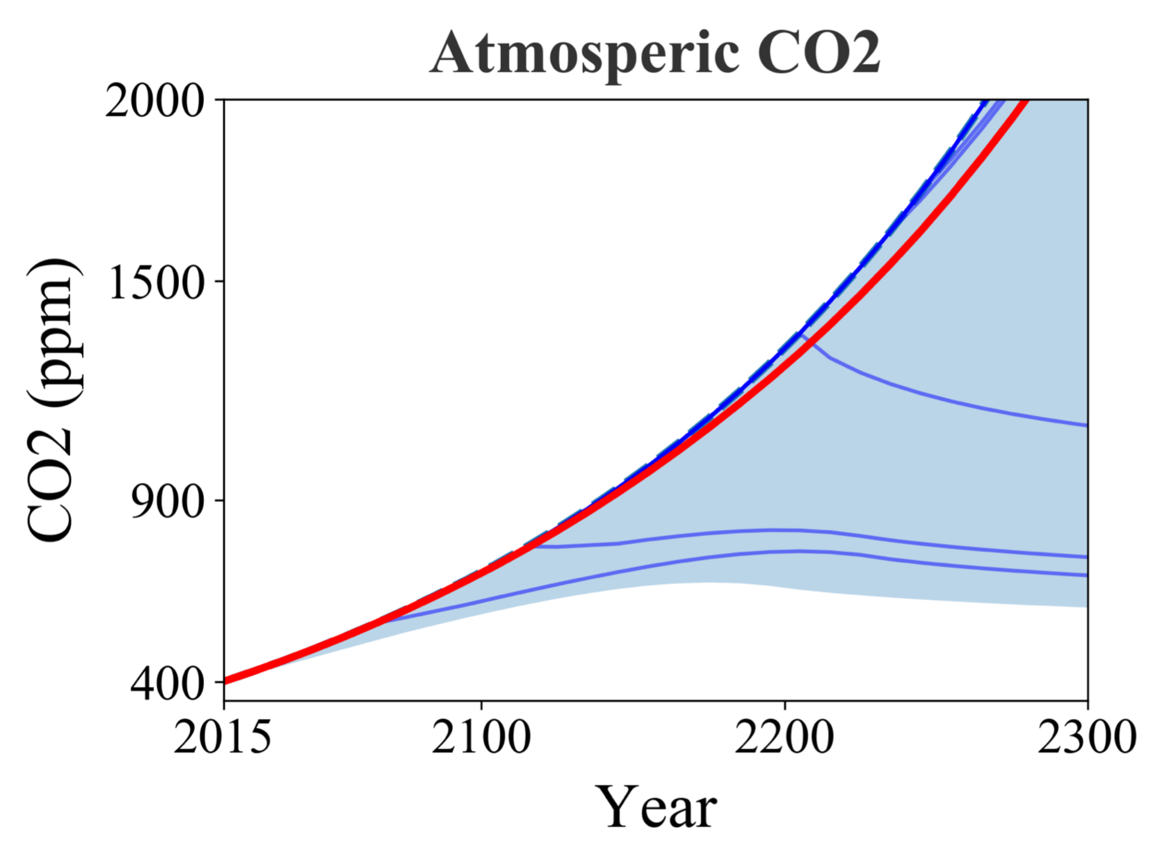
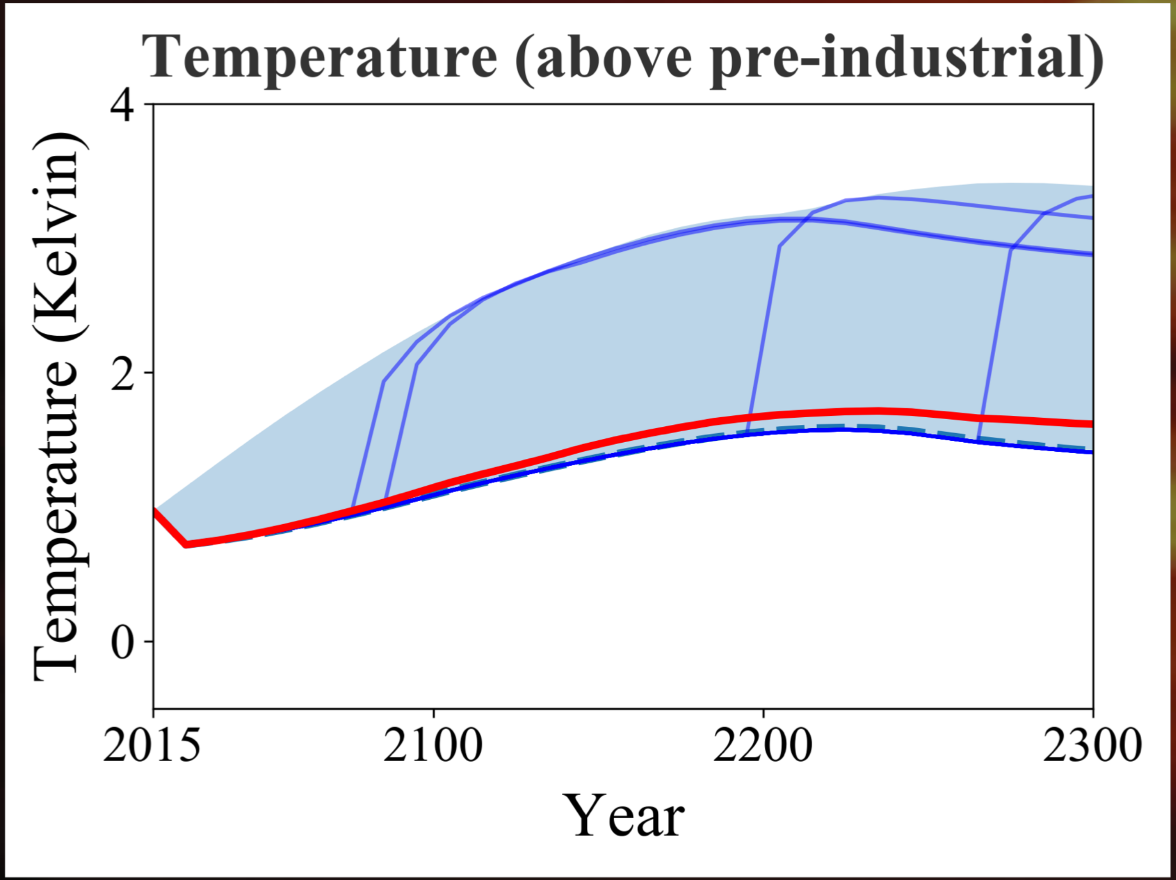


For Geo-only, CO_2 concentrations keeps increasing beyond 2000ppmv

Optimal Policy: Abate+Geo vs Geo-only

Abate+Geo



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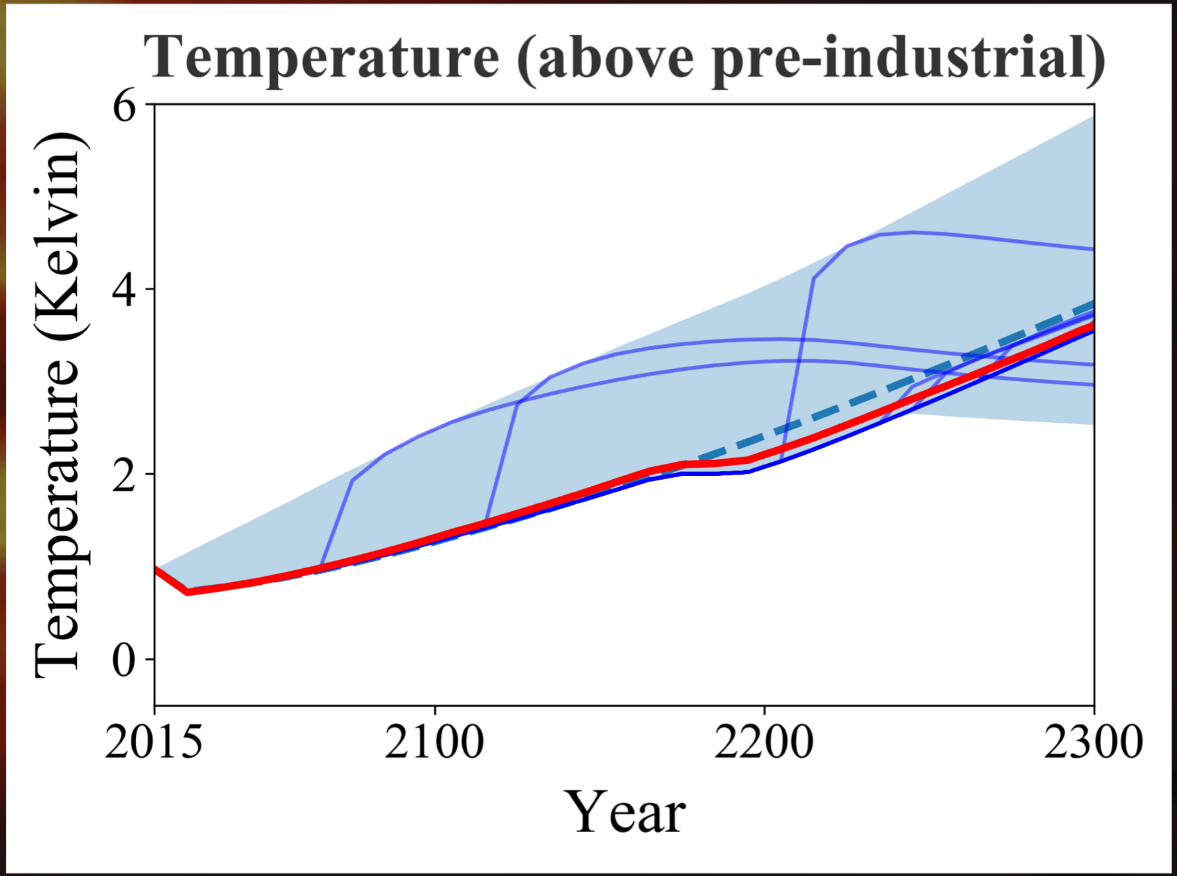

For Geo-only, CO_2 concentrations keeps increasing beyond 2000ppmv, and temperature exceeds 2K and is never stabilised!

Sulphate Geoengineering: Outlook

Upcoming work (with Henk Dijkstra, Bárbara Delgado, Niek Collot d'Escury)

Investigate climate impact of sulphate geoengineering in high-resolution CESM run
-- use aerosol distribution from GLENS project to force CESM (physics only)
-- 3 simulations:
  -- pre-industrial
  -- 4*CO_2
  -- 4*CO_2 compensated by Geoengineering

} Run to equilibrium

-- ¼ degree atmosphere -> resolves hurricanes
-- long simulation, equilibrated -> can look at long-term oceanic effects ("Gulfstream")