Complementing CO2 emission reduction by geoengineering might strongly enhance future welfare

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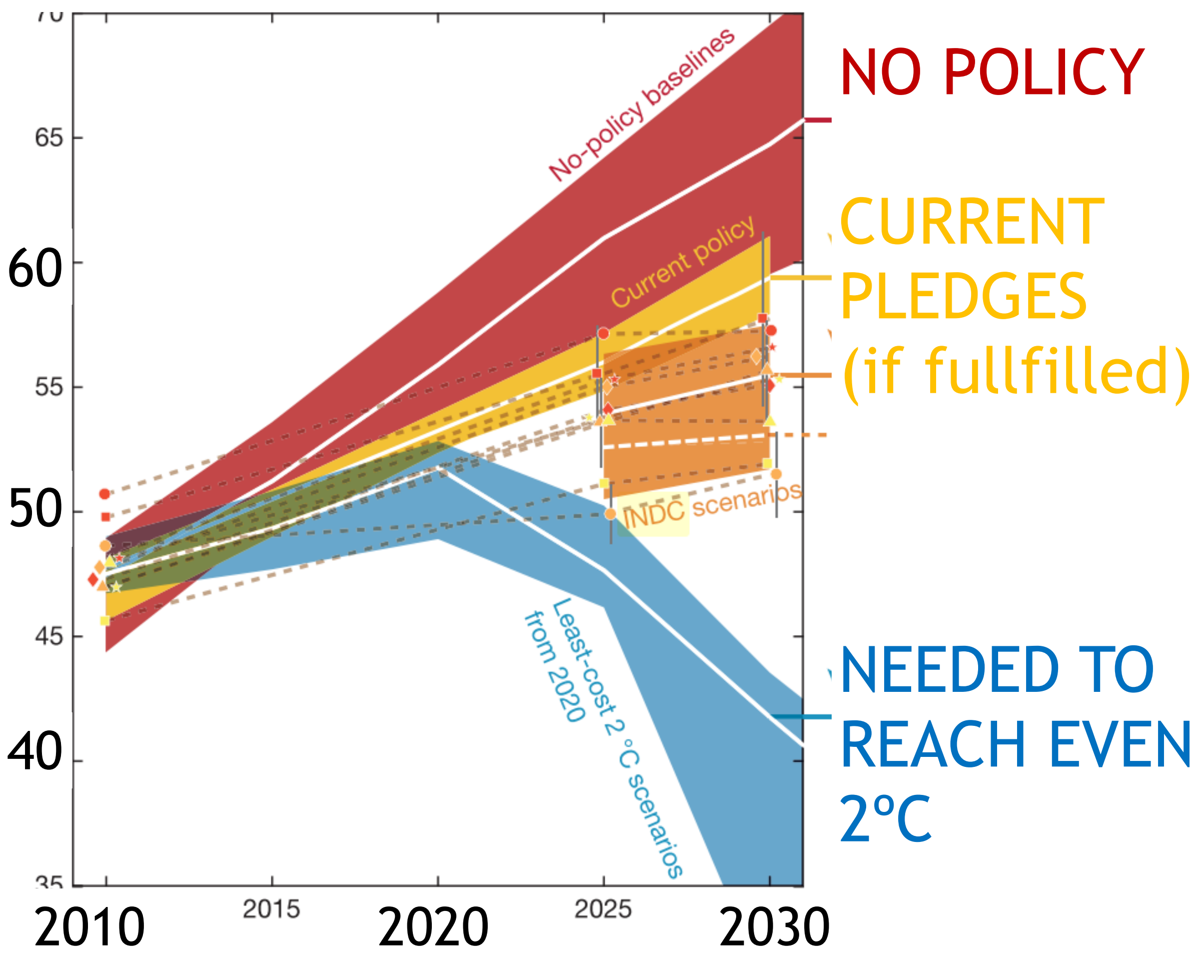
Current Climate Policy

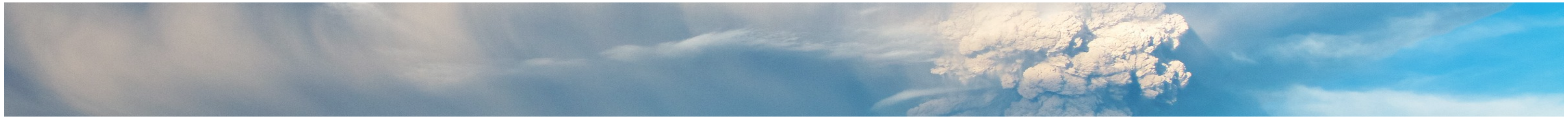
annual GHG emissions
(Gt(CO2 eq) / year)



Rogelj et al. 2016

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

Cooling the Planet?



Pinatubo explosive eruption, 1991:
8-10Mt S into stratosphere

-> global cooling ca 0.5K (1year)

e.g. Robock et al., 2000

Sulfur-aerosol
Solar Radiation Management (SRM)

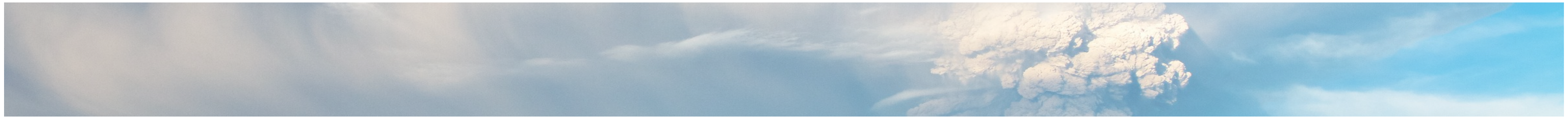
-- put SO_2 (or other precursor gas) into stratosphere
-- will react to H_2SO_4 and this leads to growth of aerosol droplets
-- these reflect sunlight

-- residence time: about 1-2 years (tropics)

-- cost estimate (very rough)
2-10 x 10^9 US$/Mt at injection height 20 km
(GDP 2017: 80 x 10^{12} US$)

e.g., Moriyama et al., 2017)

What is needed?



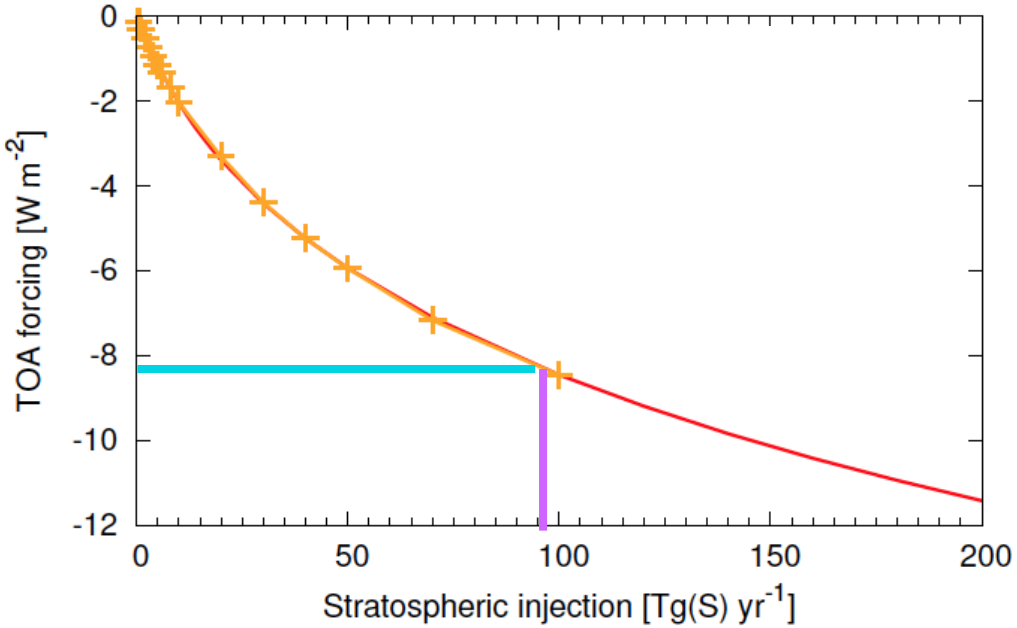
High injection rate
-> coagulation
-> fewer, bigger droplets
-> less sunlight reflection

Radiative forcing changes 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



1 Tg = 1 Mt

Niemeyer & Timmreck, 2015

Sulphate-aerosol SRM:
a cool plan or megalomania?

Potential benefits	Caveats	Dangers
-- Cool down Earth: Stay below 2K warming (avoid dangerous "tipping points")	-- Will not solve all problems: --- precipitation changes --- ocean acidification	-- environmental damages: --- ozone hole --- tropospheric chemistry --- acid rain
		-- unknown unknowns?
		-- political conflict?
-- cheap to implement (?)	-- effectiveness?	*e.g. Robock et al., 2009*

Is SRM an economically sound option?

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

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

DICE: Model Structure

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

Economic production /GDP

reduces

Damage

spent for

Consumption+ Capital

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

Carbon emission

CO2 accumulation

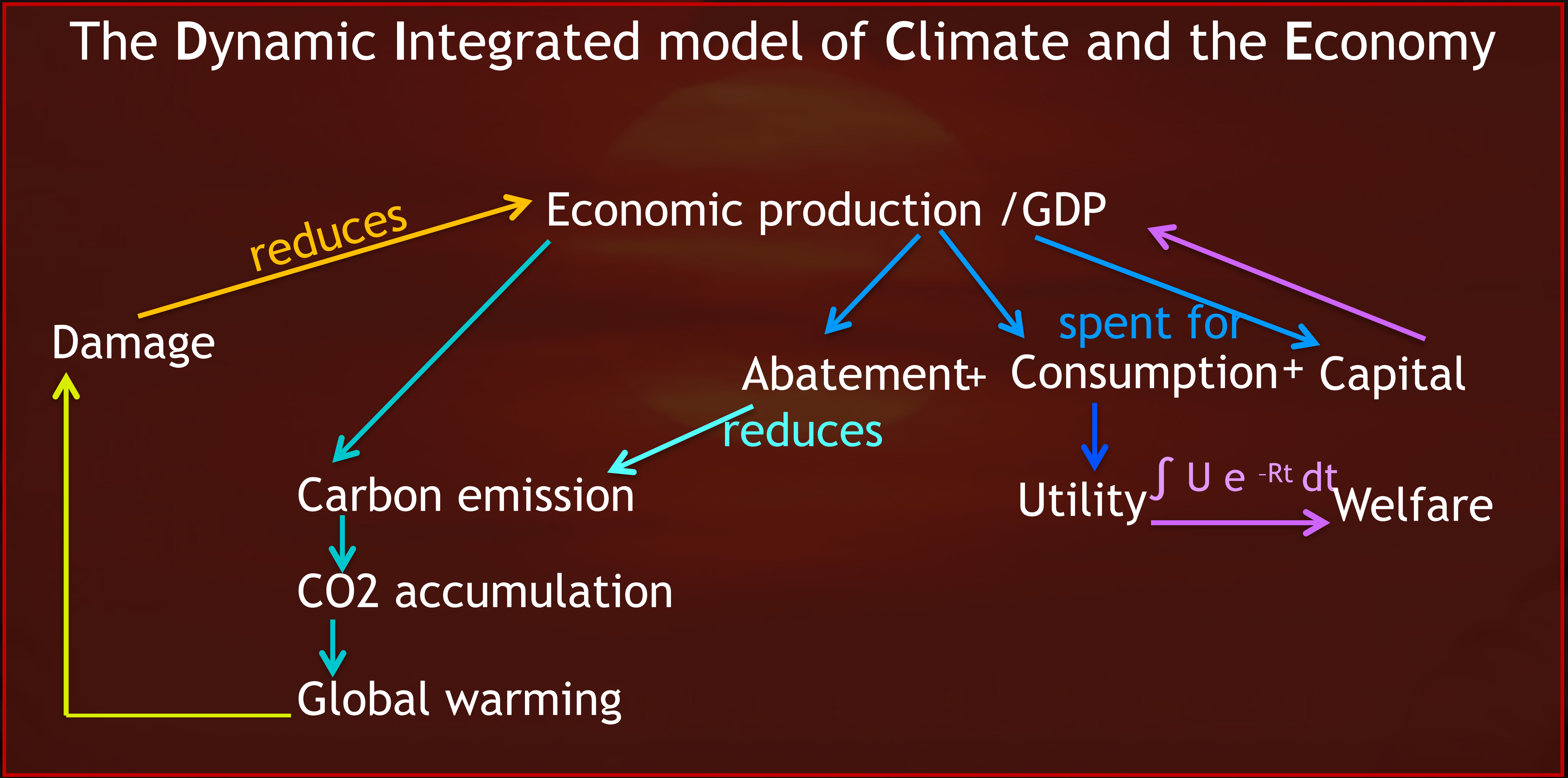
Global warming

Damage function:

$D = k T^2$

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

DICE: Model Structure



new Climate Model Component: LRT model

$$CO_2 \longrightarrow \Delta F \longrightarrow \boxed{\Delta T}$$

- Perturbation theory

$$\Delta T_{\Delta F}(t) = \Delta T_0 + \sum_{n=1}^{\infty} \Delta T_{\Delta F}^{(n)}(t) \tag{1}$$

- Linear Response Theory: stop series at $n = 1$

$$\Delta T_{\Delta F}^{(1)}(t) = \int_0^t G_T(t')\Delta F(t - t')\ dt' \tag{2}$$

- Take a forcing-response pair $\Delta F_{abrupt}(t) = A\theta(t), \Delta T_{abrupt}(t)$

$$G_T(t) = \frac{1}{A}\frac{d}{dt}\Delta T_{abrupt} \tag{3}$$

Using LRT one can determine the response to any forcing!

Aengenheyster et al. (2018)

Stochastic State Space Model

Carbon

$$dC_P = a_0 E dt$$

$$dC_1 = \left(a_1 E - \frac{1}{\tau_1} C_1 \right) dt$$

$$dC_2 = \left(a_2 E - \frac{1}{\tau_2} C_2 \right) dt$$

$$+ \sigma_{C2} \, dW_t$$

$$dC_3 = \left(a_3 E - \frac{1}{\tau_3} C_3 \right) dt$$

$$C_{CO2} = C_P + \sum_{i=1}^{3} C_i$$

Temperature

$$\Delta F = A \, \alpha \ln(C_{CO2}/C_0)$$

$$d\Delta T_0 = \left(b_0 \Delta F - \frac{1}{\tau_{b0}} \Delta T_0 \right) dt$$

$$+ \sigma_{T0} \, dW_t$$

$$d\Delta T_1 = \left(b_1 \Delta F - \frac{1}{\tau_{b1}} \Delta T_1 \right) dt$$

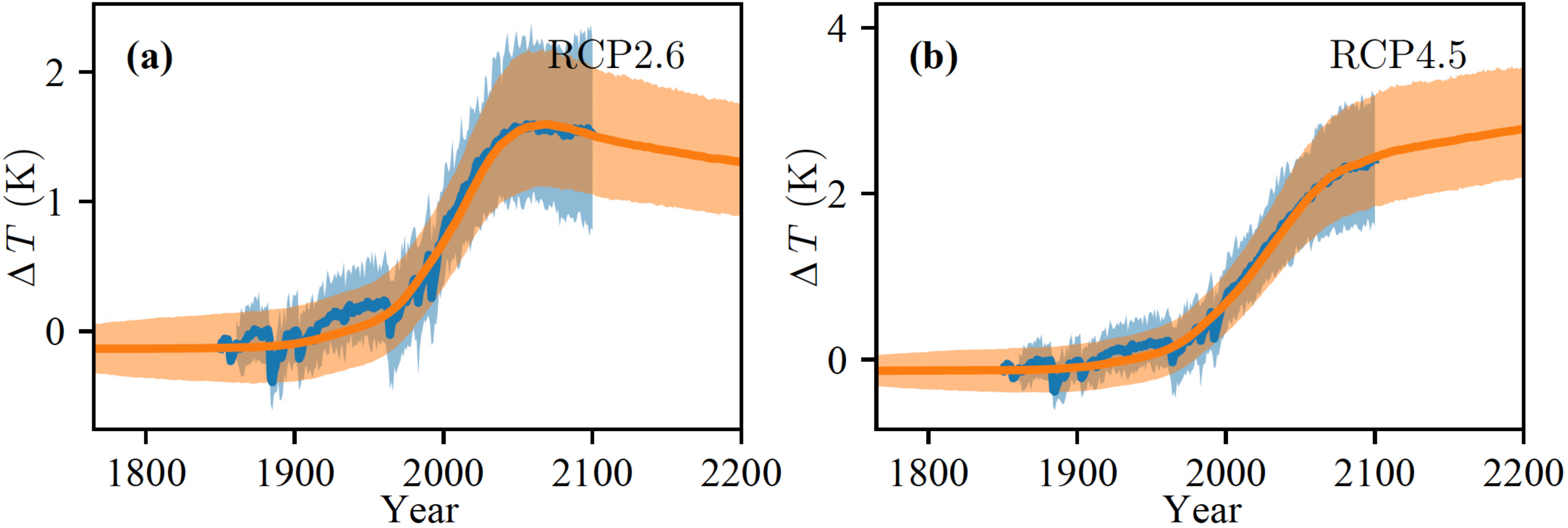
$$d\Delta T_2 = \left(b_2 \Delta F - \frac{1}{\tau_{b2}} \Delta T_2 \right) dt$$

$$+ \sigma_{T2} \Delta T_2 \, dW_t$$

$$\Delta T = \sum_{i=0}^{2} \Delta T_i$$

Aengenheyster et al. (2018)

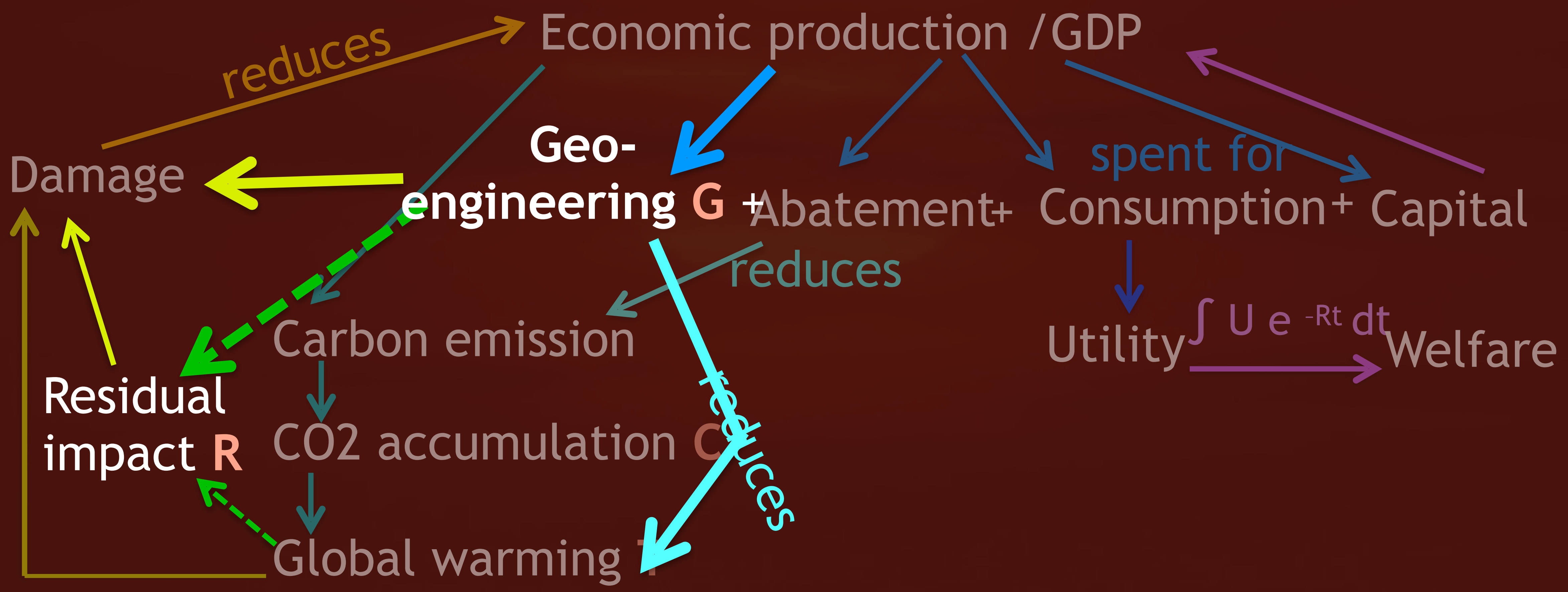
Results: RCP responses



Aengenheyster et al. (2018)

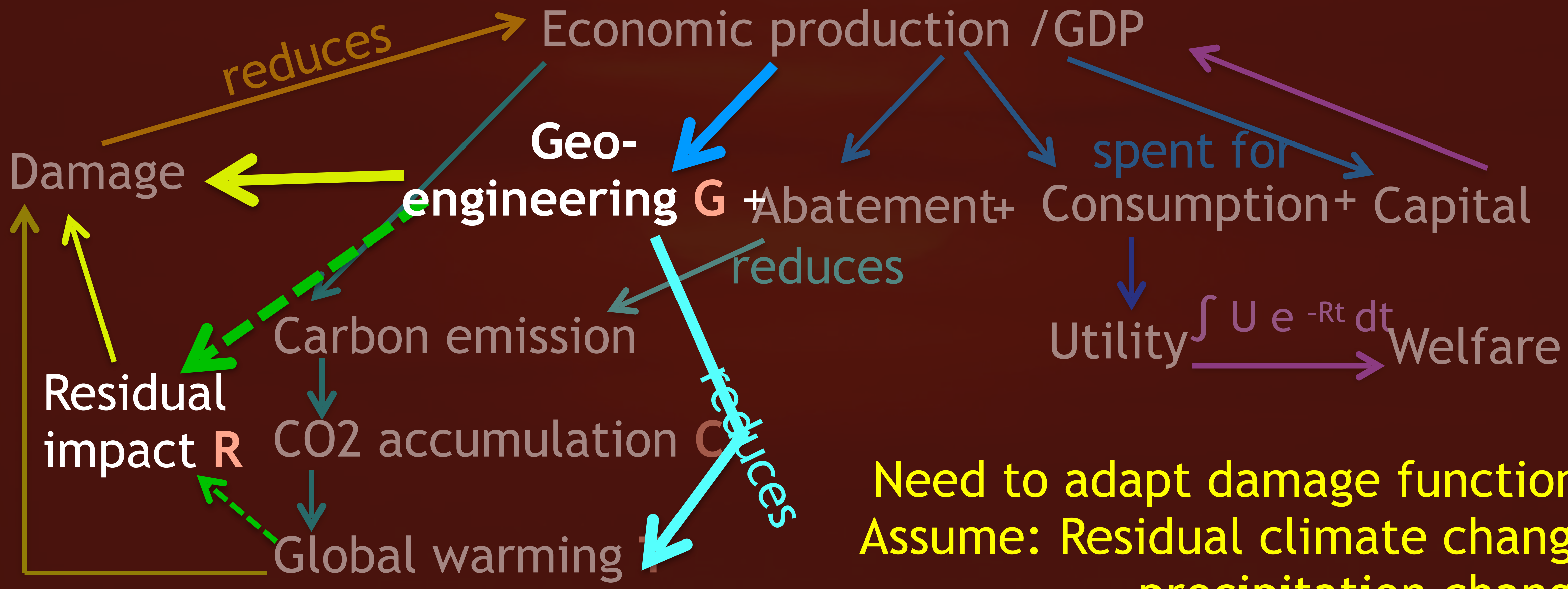
DICE - > GeoDICE

The Dynamic Integrated model of Climate and the Economy



Geo-DICE: Model Structure

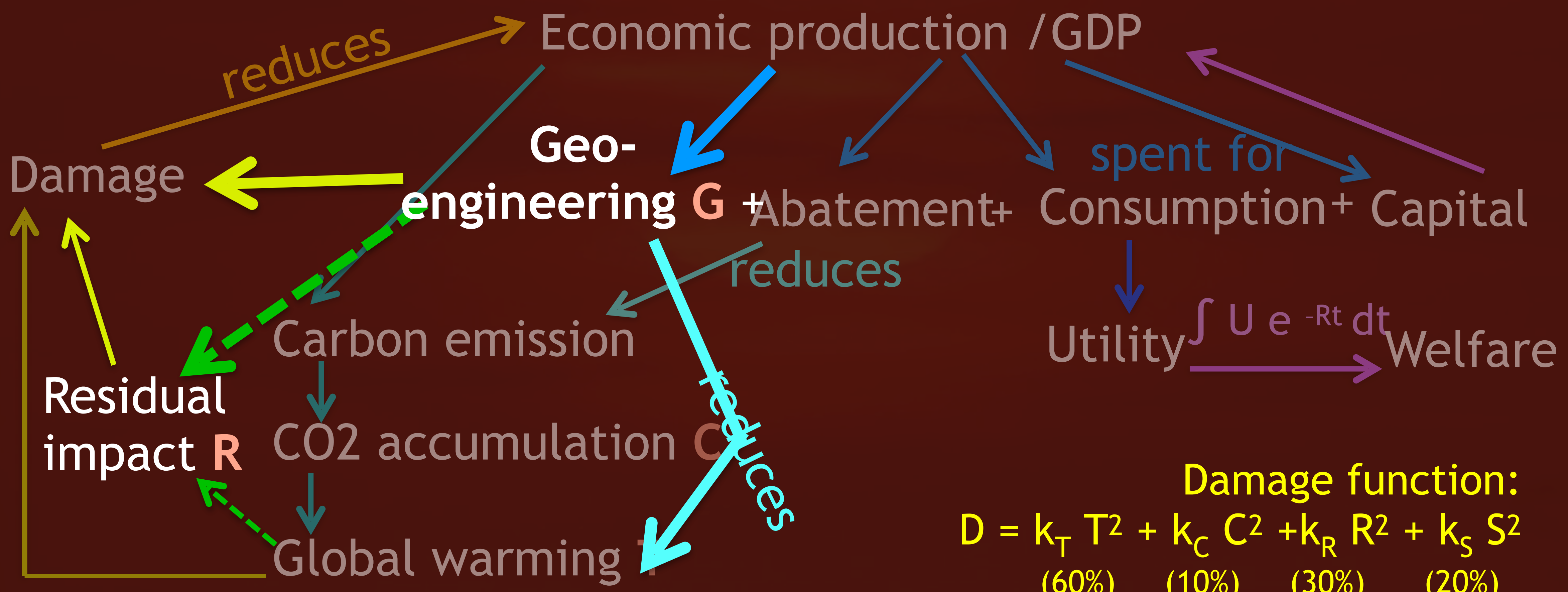
The Dynamic Integrated model of Climate and the Economy



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

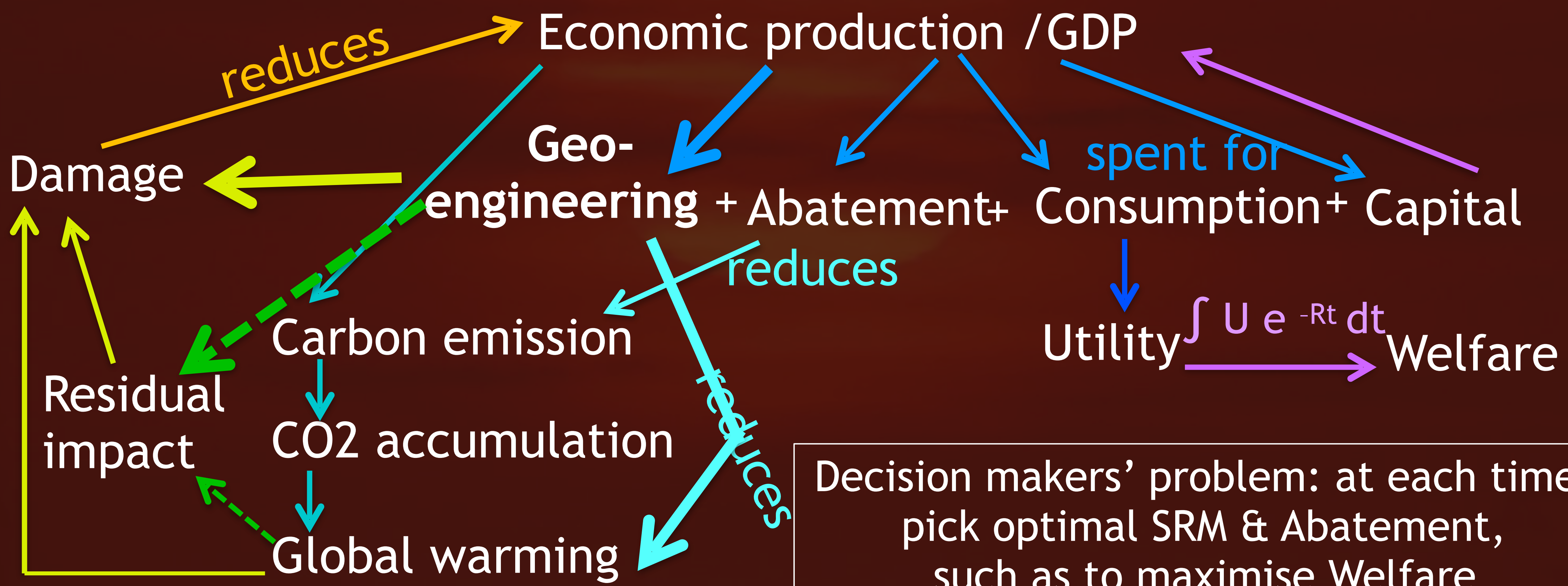
Geo-DICE: Model Structure

The Dynamic Integrated model of Climate and the Economy



Geo-DICE: Model Structure

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



Decision makers' problem: at each time, pick optimal SRM & 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 SRM will work well

   -- At each time step, probability that SRM is banned forever
   (cumulative probability: 20% in 400 years)

-> find optimal policy under uncertainty (dynamic programming)
-> run Monte-Carlo Ensemble (5000) with this policy to assess outcome

following: Cai et al. 2016

Optimal Policy: Scenarios

1. Abate + SRM

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

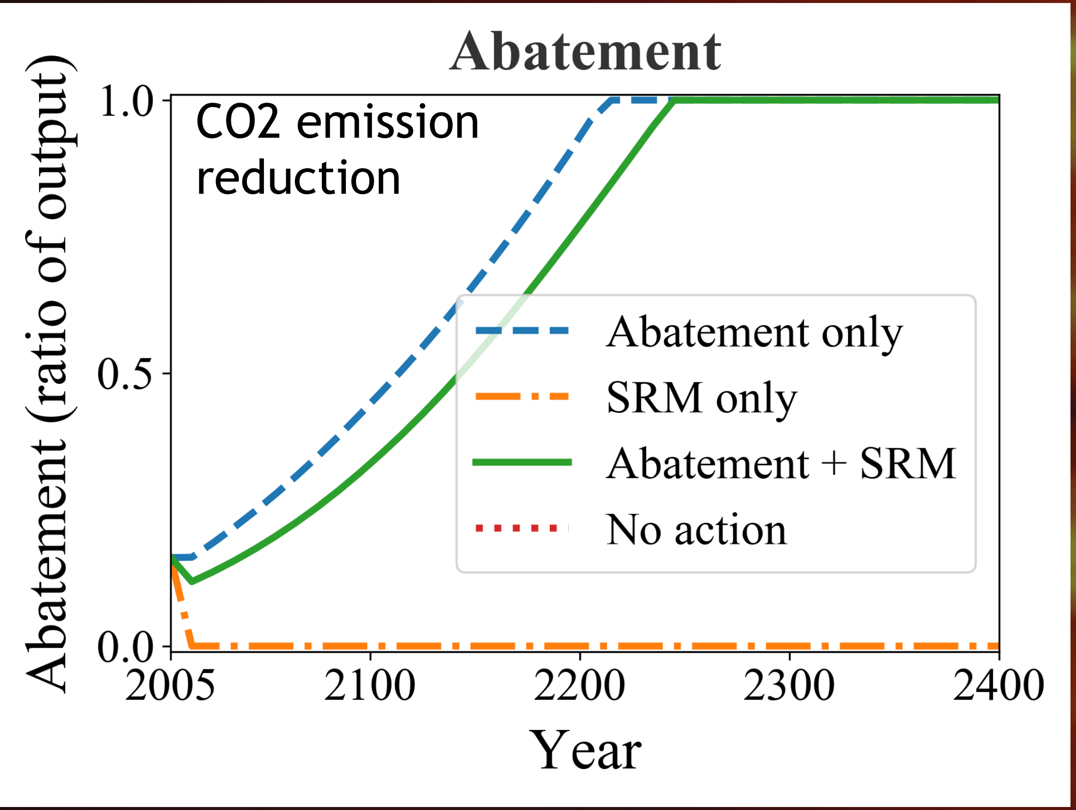
2. Abate - Only

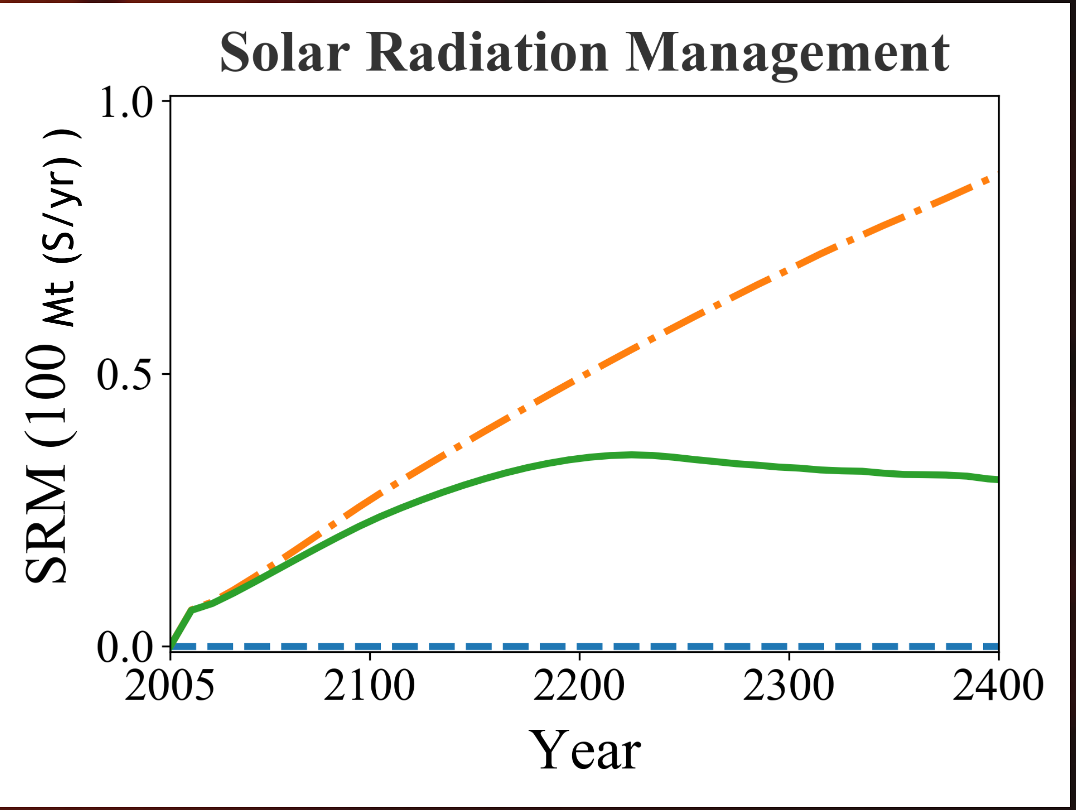
-- Social planner may only use abatement

3. SRM - Only

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

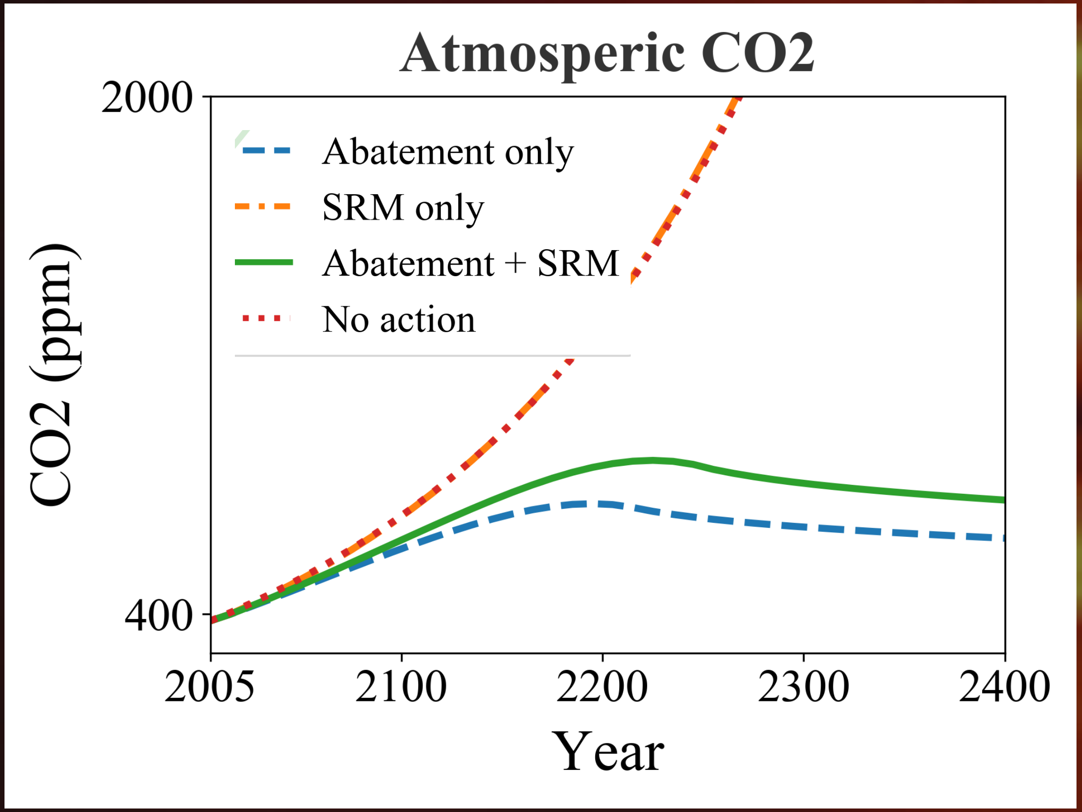
Optimal Policy: Deterministic results

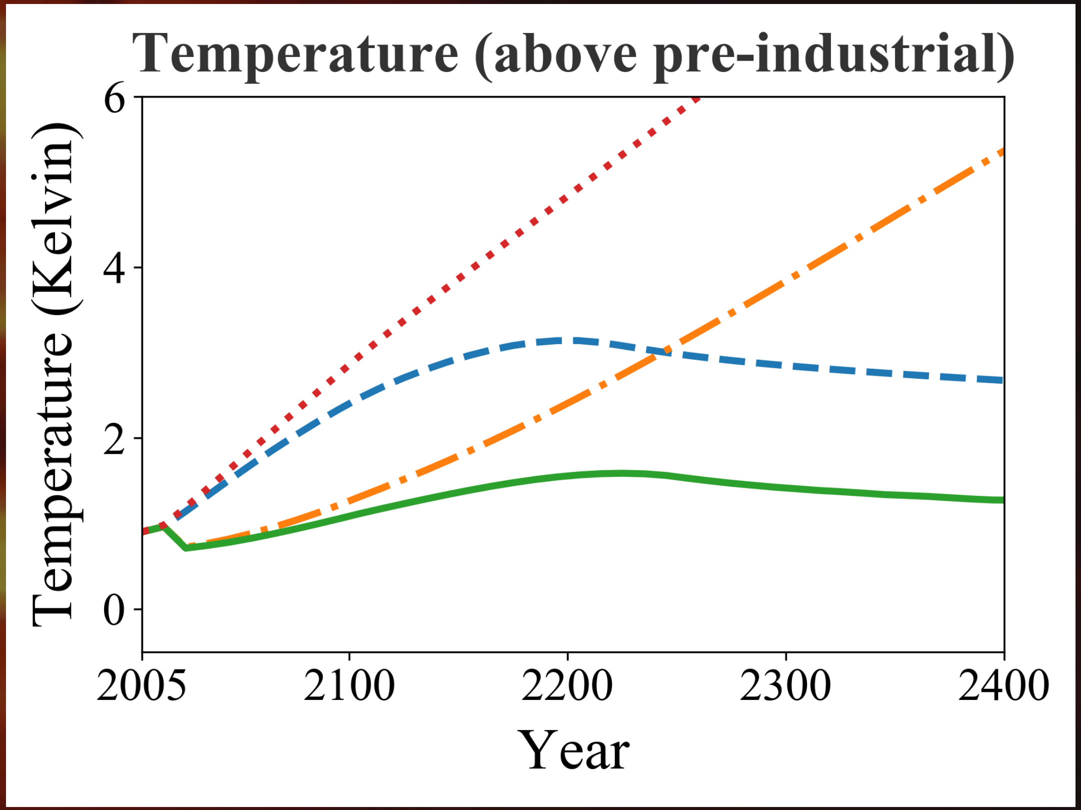




- -- SRM delays abatement by ca 30 years, but does not replace it
- -- With abatement, SRM remains limited to ≈3 Pinatubos / year (30Mt(S)/yr)

Optimal Policy: Deterministic results





-- SRM delays abatement by ca 30 years, but does not replace it
-- With abatement, SRM remains limited to ≈3 Pinatubos / year (30Mt(S)/yr)
-- Only combination of SRM+Abate keeps T<2K

Summary: deterministic case

$$\zeta(\pi) = 100\,\% \times \frac{W_\pi - W_0}{W_{\mathrm{AD}} - W_0},$$

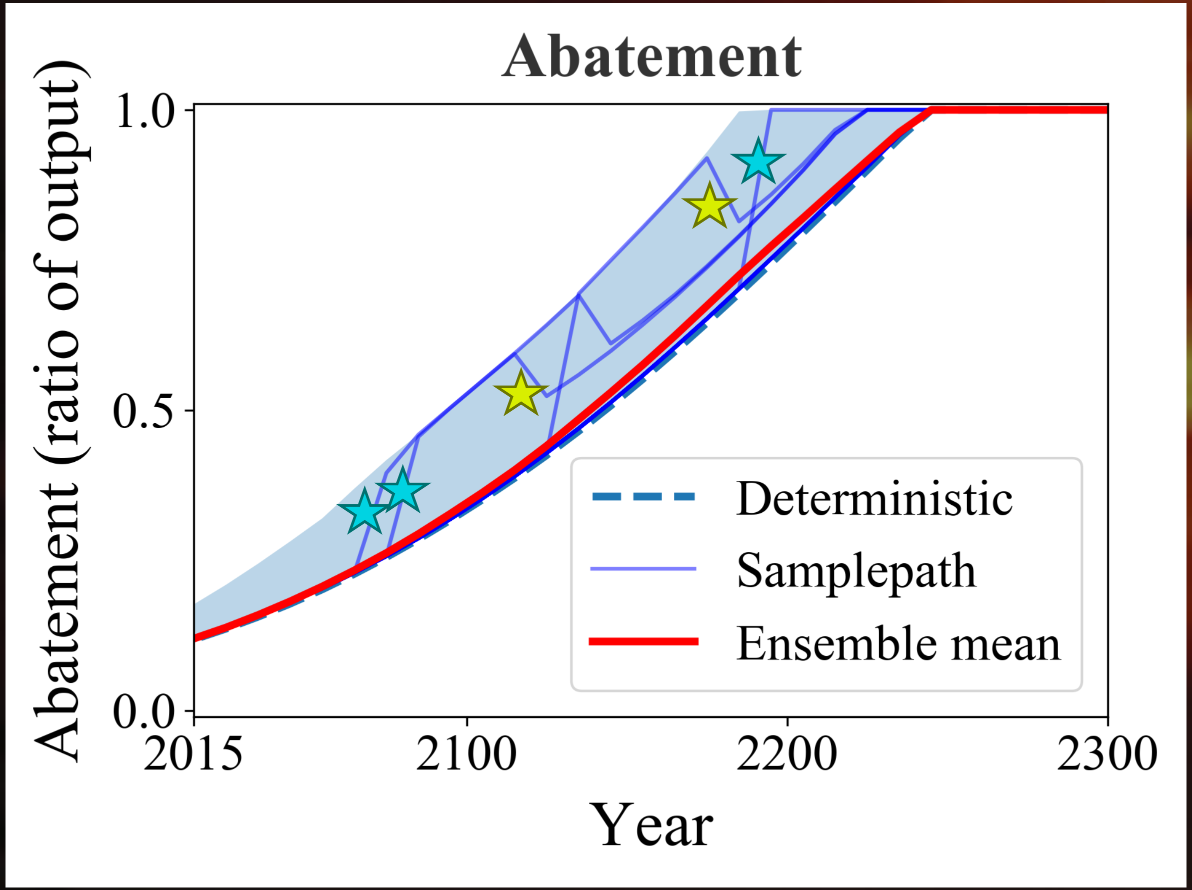
AD: Abatement-only, deterministic
0 : no-action policy

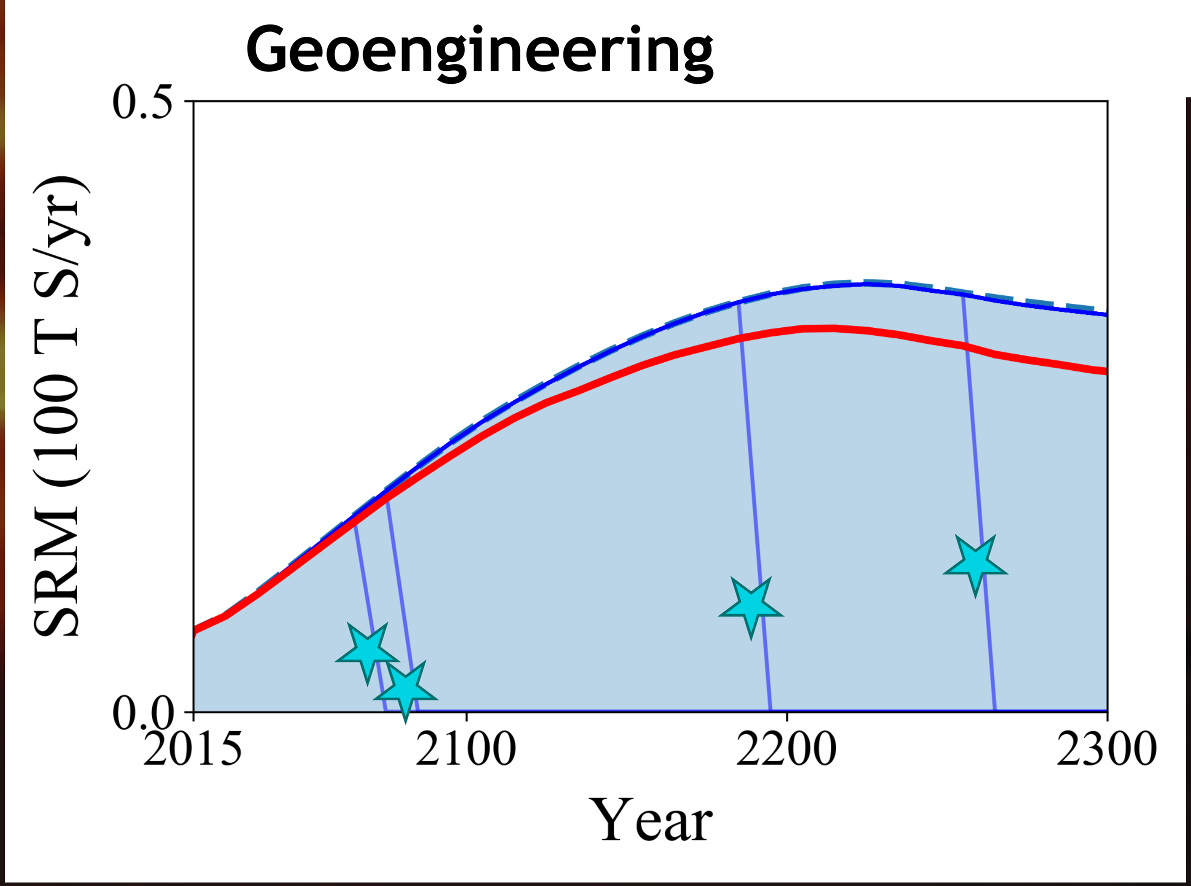
Policy	ζ	Peak SRM	Ab. 50 %	Ab. 99 %	SCC
Abatement-only scenario	100 %	n/a	2114	2212	35
SRM-only scenario	186 %	*	n/a	n/a	21
Abatement+SRM scenario	238 %	35.1	2134	2243	20

* SRM does not peak but keeps increasing until the upper limit of 100 Mt(S) yr^{-1}. n/a means not applicable.

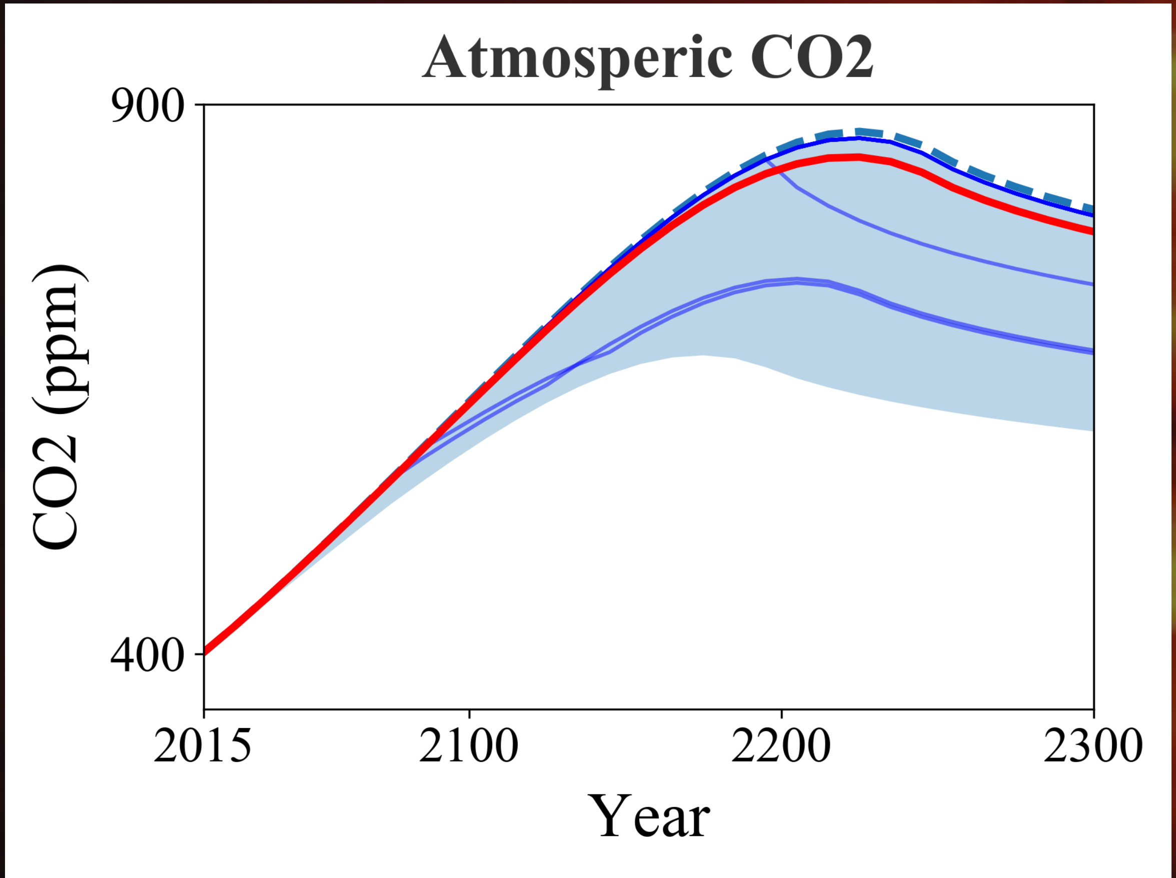
Optimal Policy: Abate + SRM

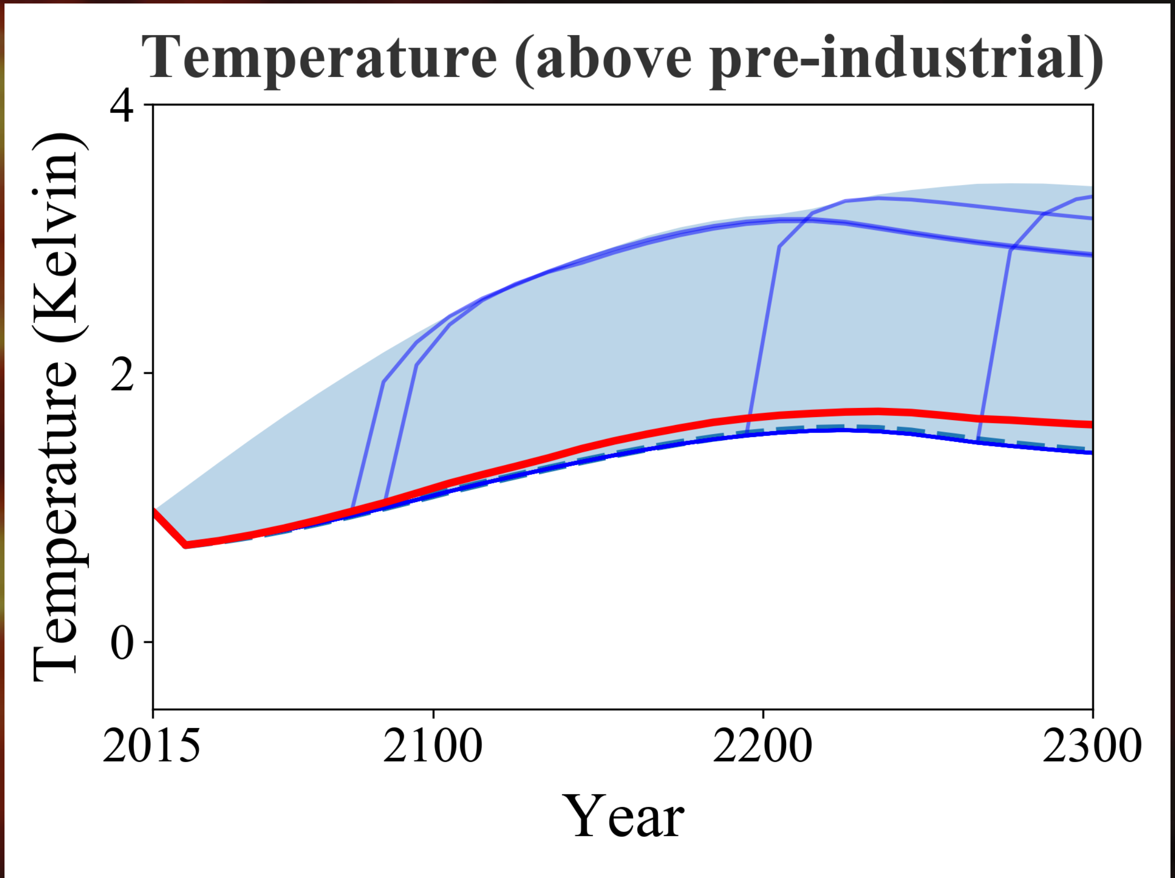
Ensemble members (few)
Ensemble mean
SRM failure
Deterministic results
Range of whole ensemble
Climate tipping





Optimal Policy: Abate + SRM

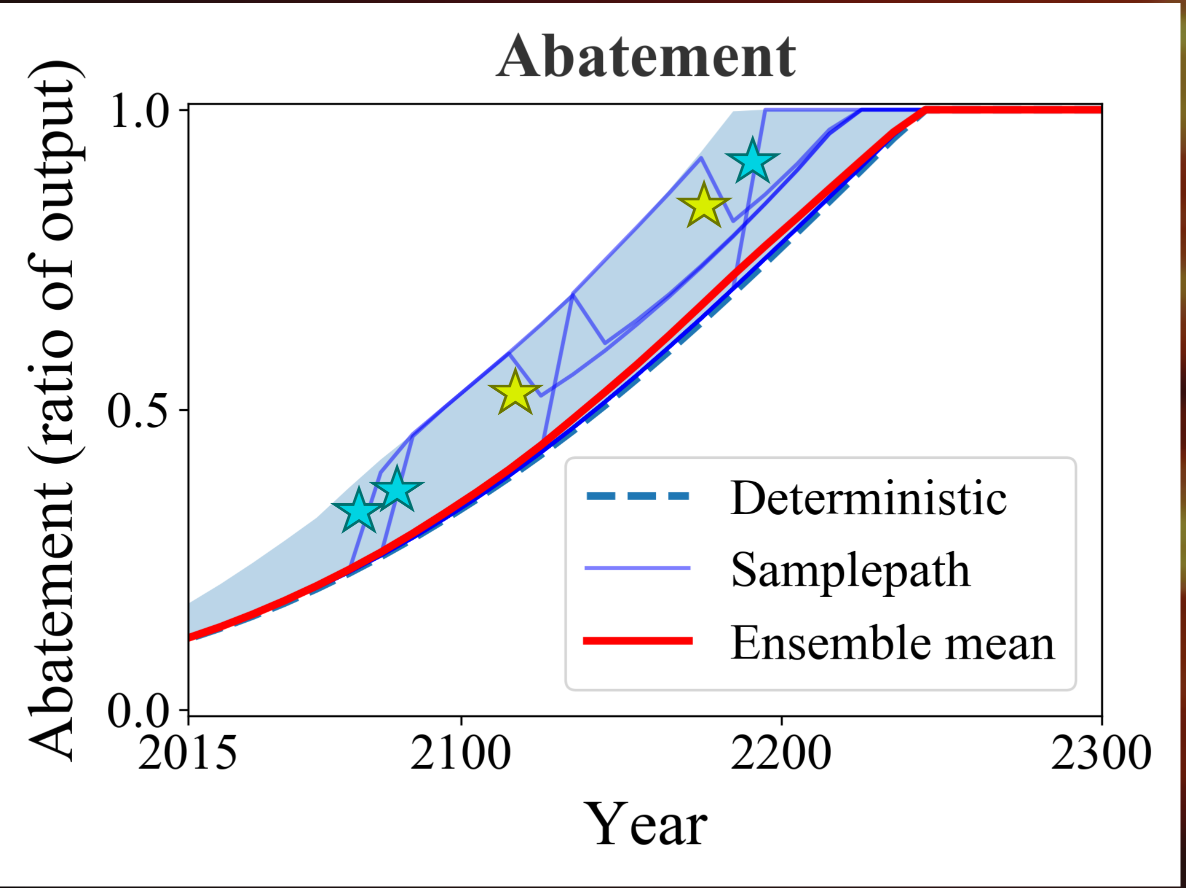




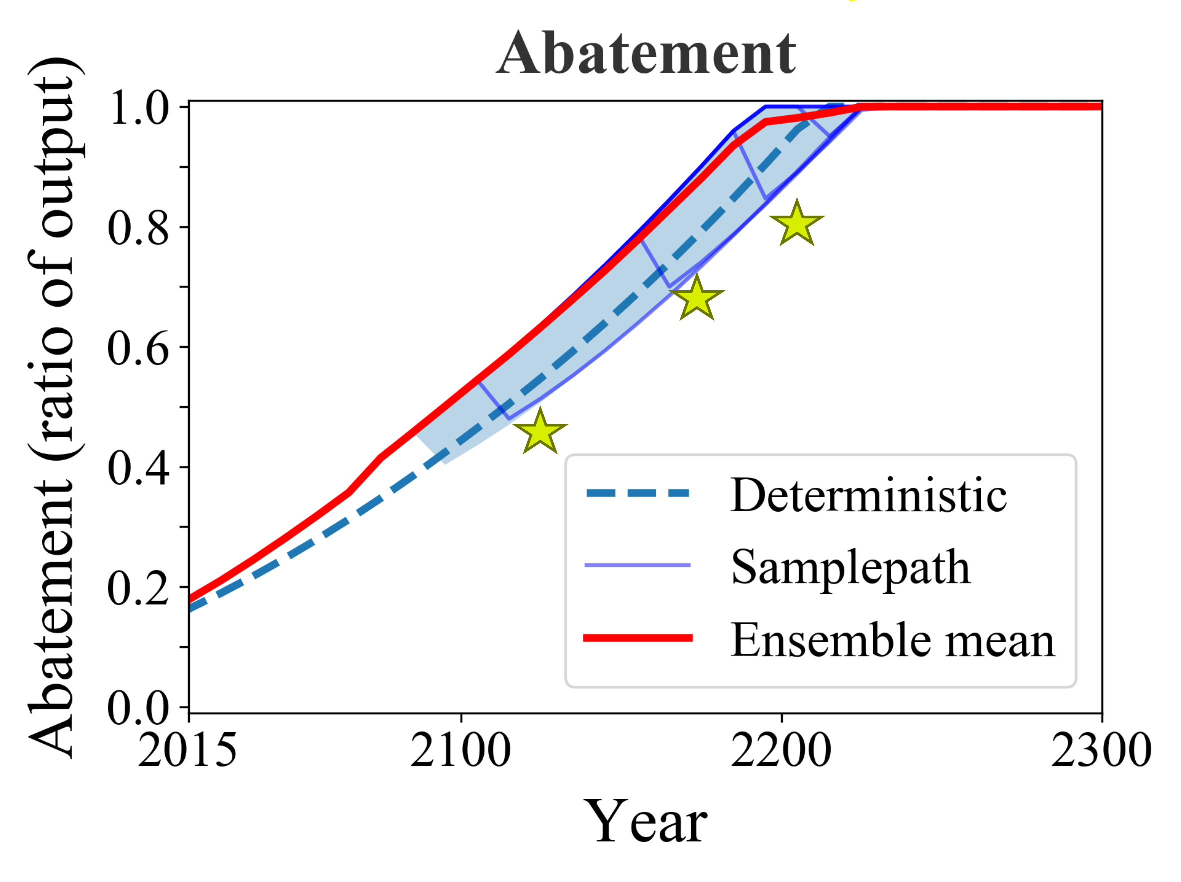
Use of abatement + (modest) SRM stabilises T below 2K (unless SRM fails)

Optimal Policy: Abate+SRM vs Abate-only

Abate+SRM



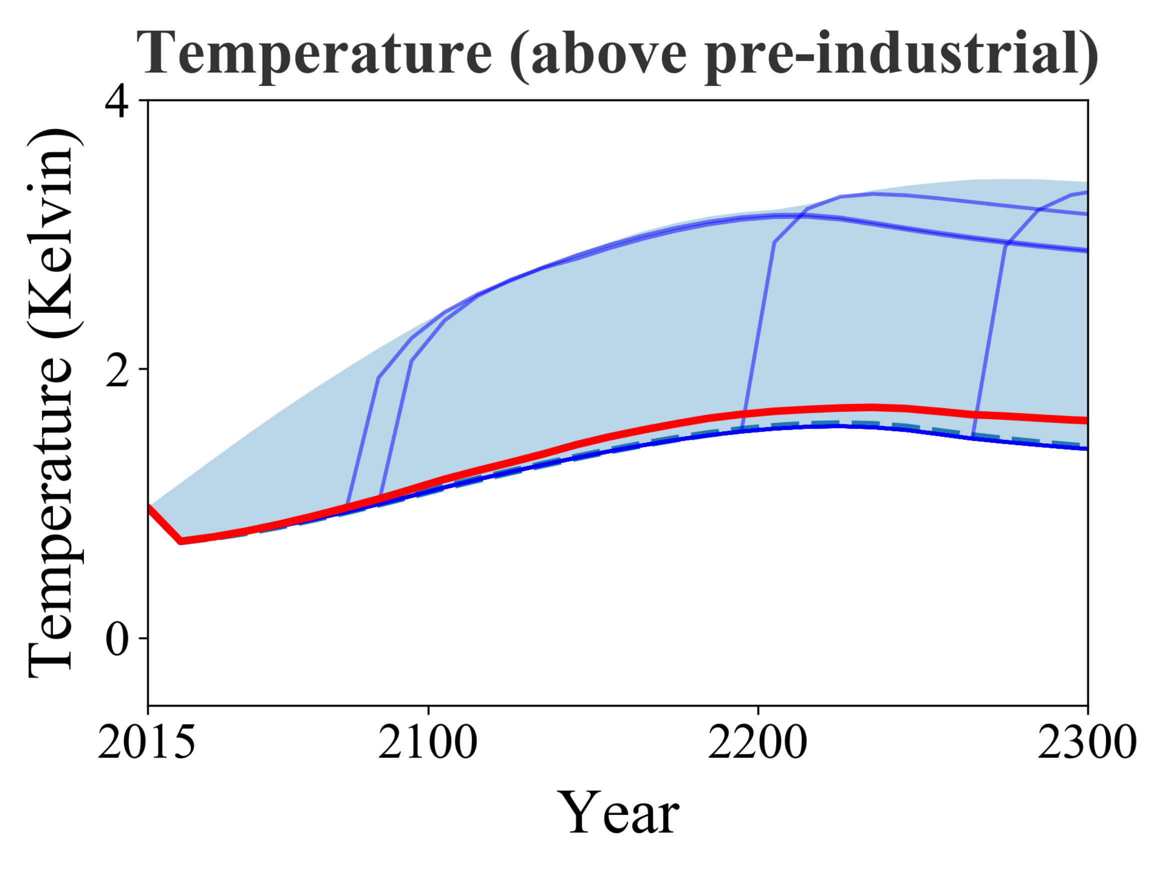
Abate-Only



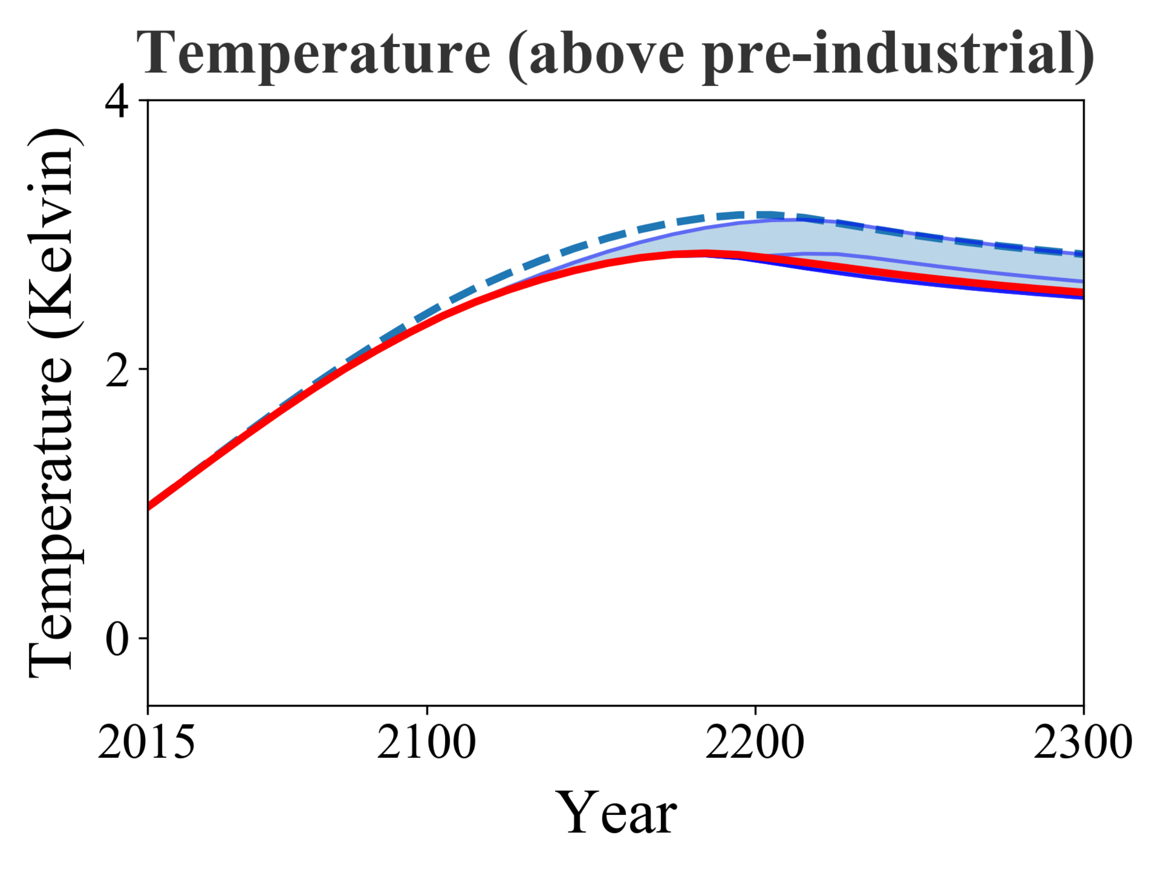
Allowing SRM does *not replace* abatement, but delays by 30-40 years

Optimal Policy: Abate+SRM vs Abate-only

Abate+SRM



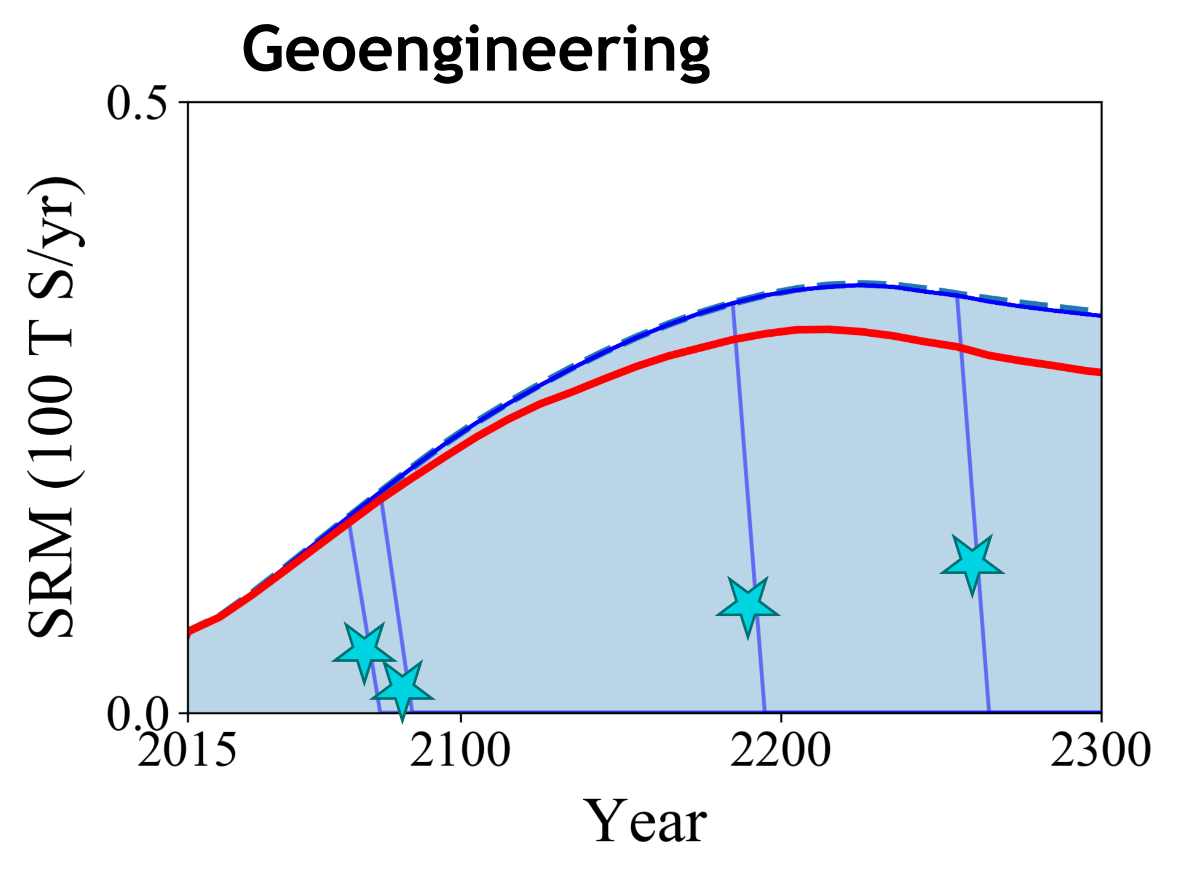
Abate-Only



Abatement-only does not stabilise T below 2K.

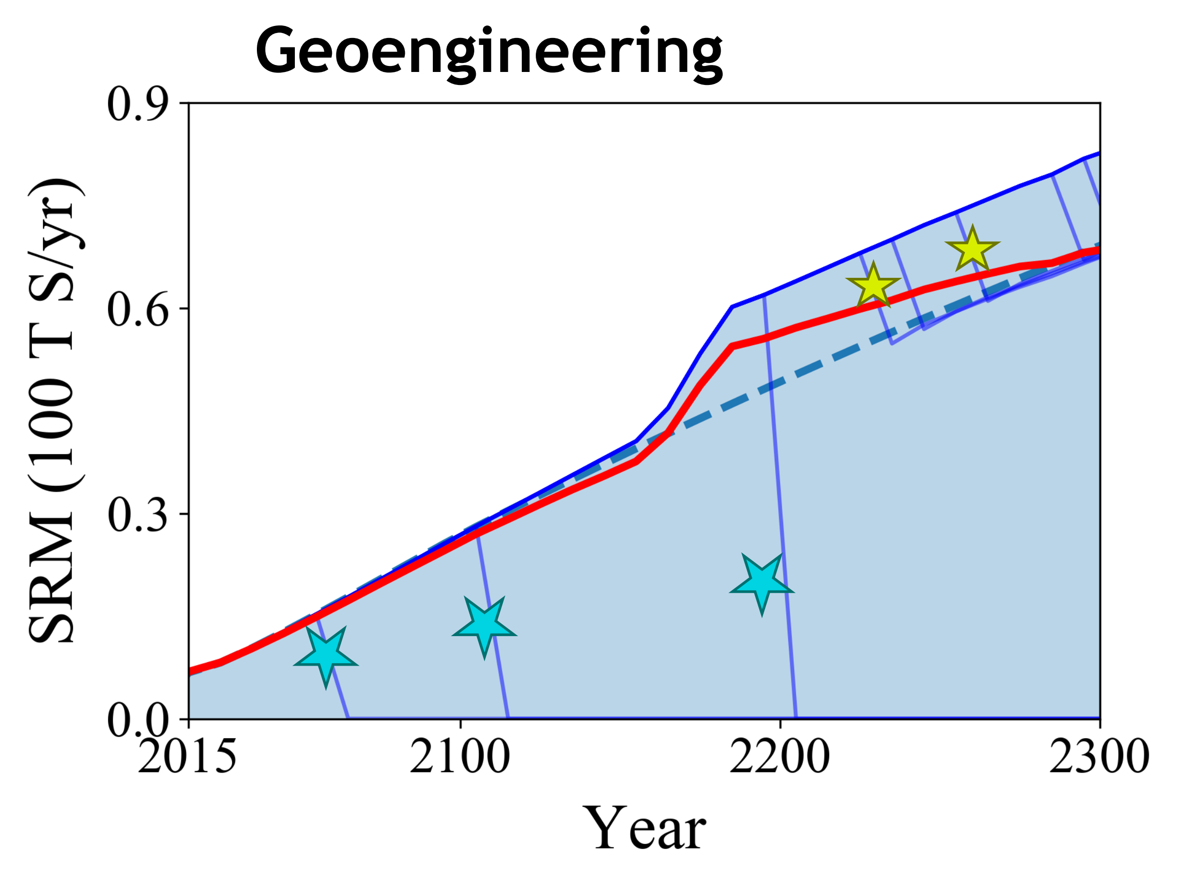
Optimal Policy: Abate+SRM vs SRM-only

Abate+SRM



Note different y-axis scales

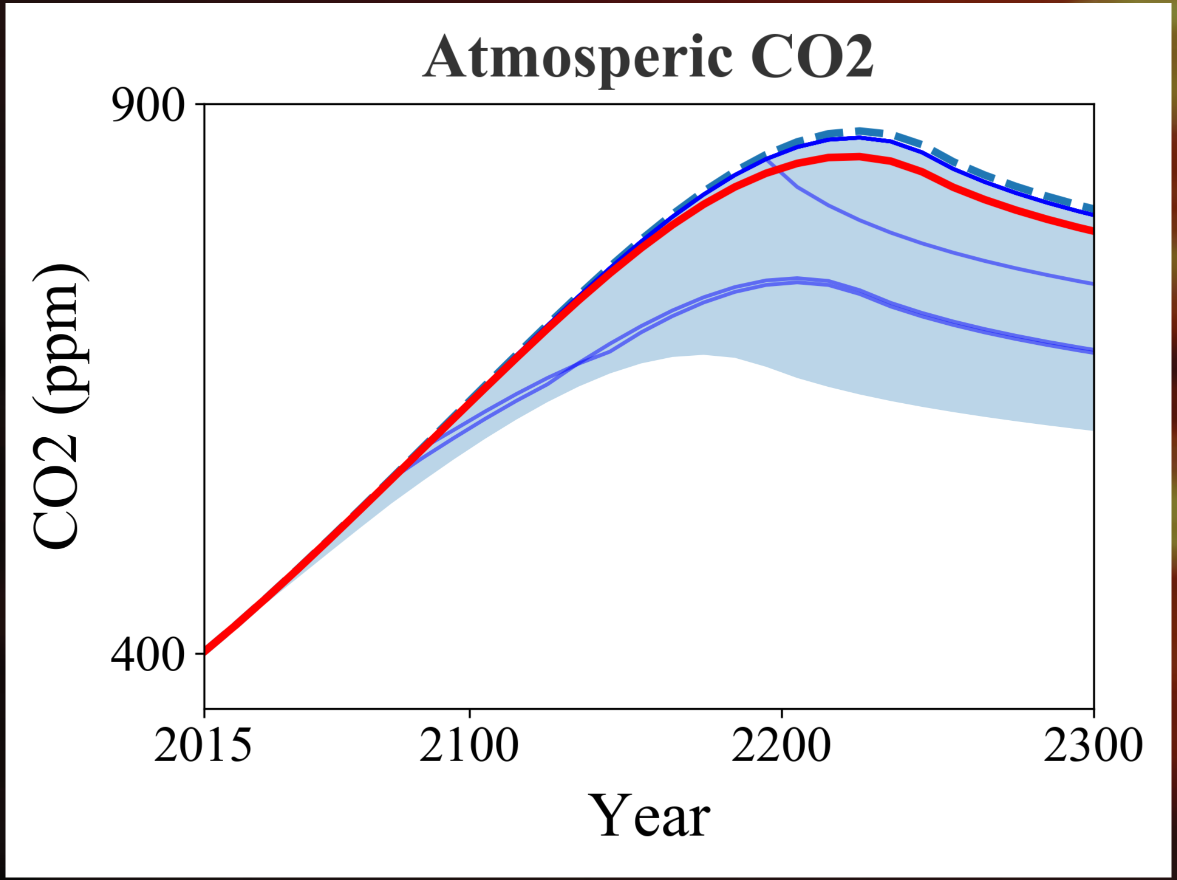
SRM-only



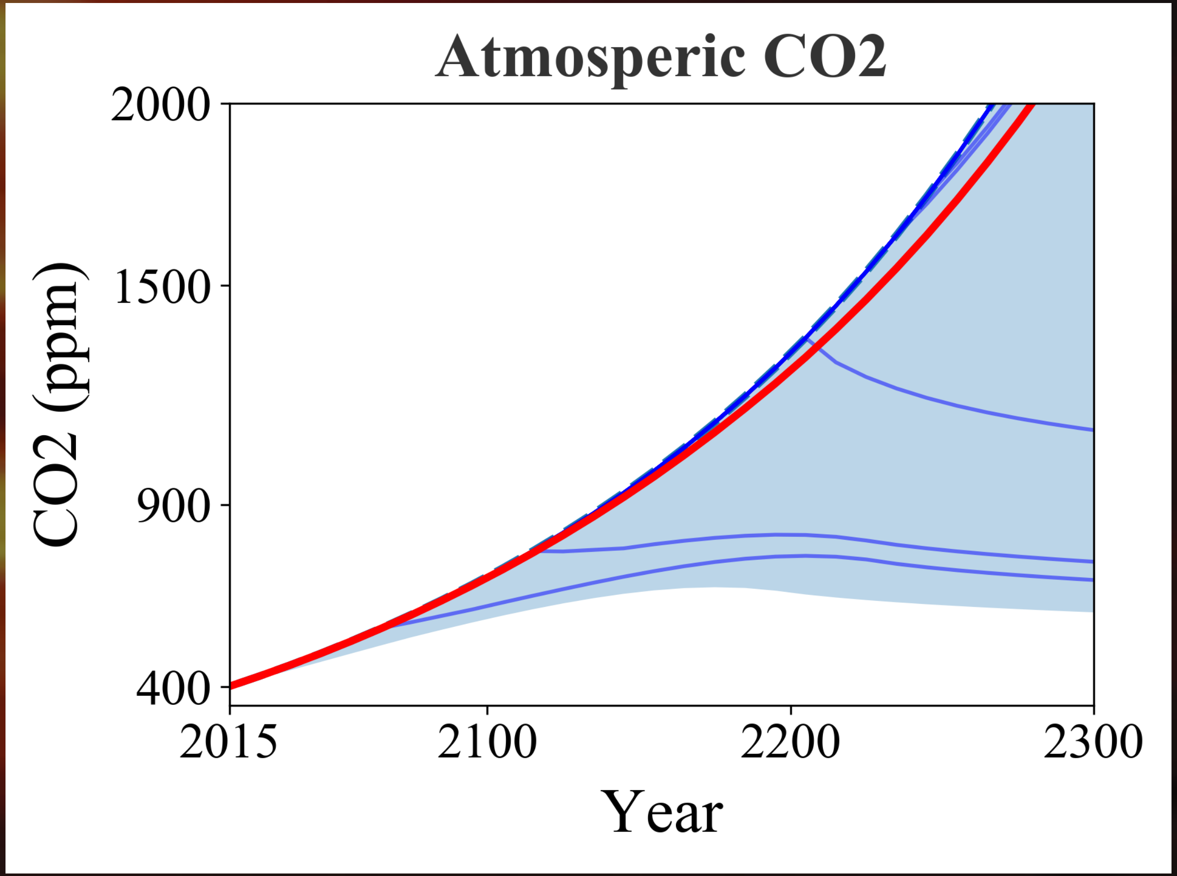
For SRM-only, very high injection rates are needed

Optimal Policy: Abate+SRM vs SRM-only

Abate+SRM



SRM-Only

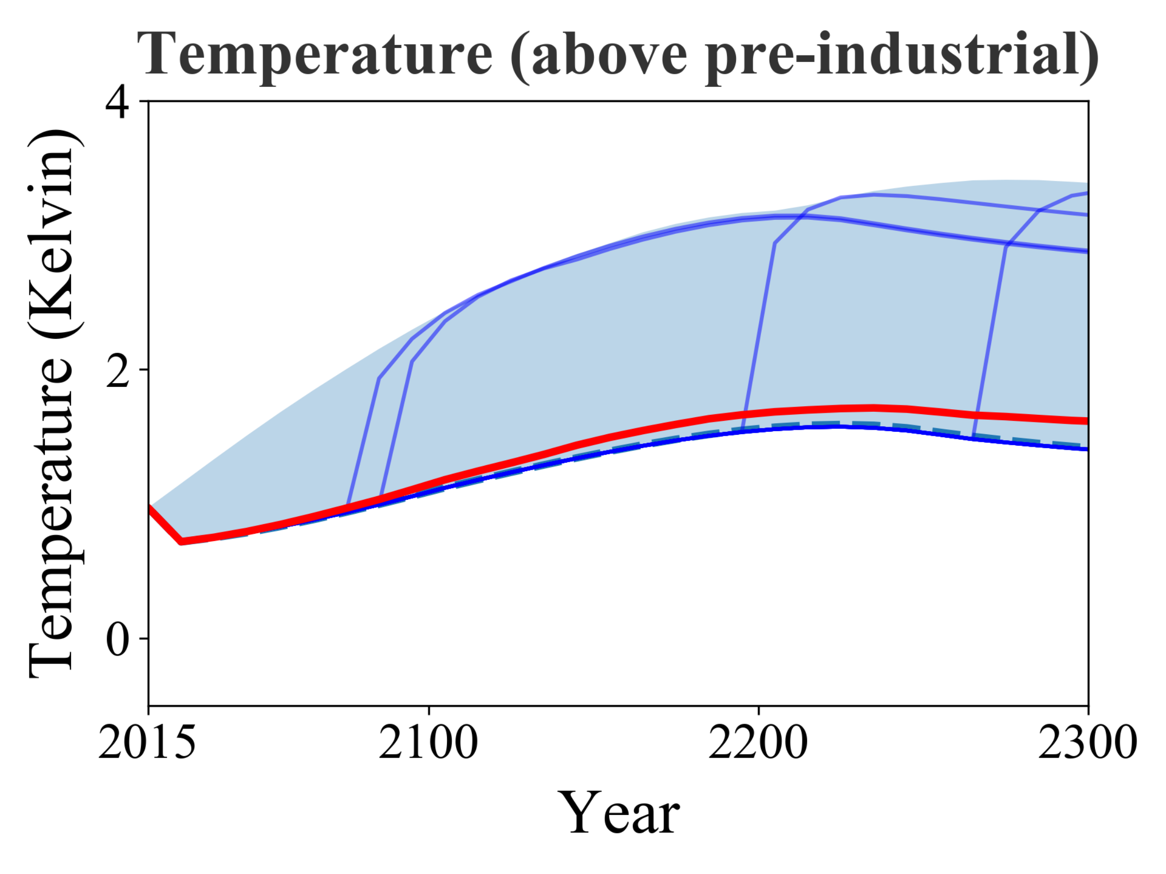


Note different y-axis scales

For SRM-only, CO2 concentrations keeps increasing beyond 2000 ppmv

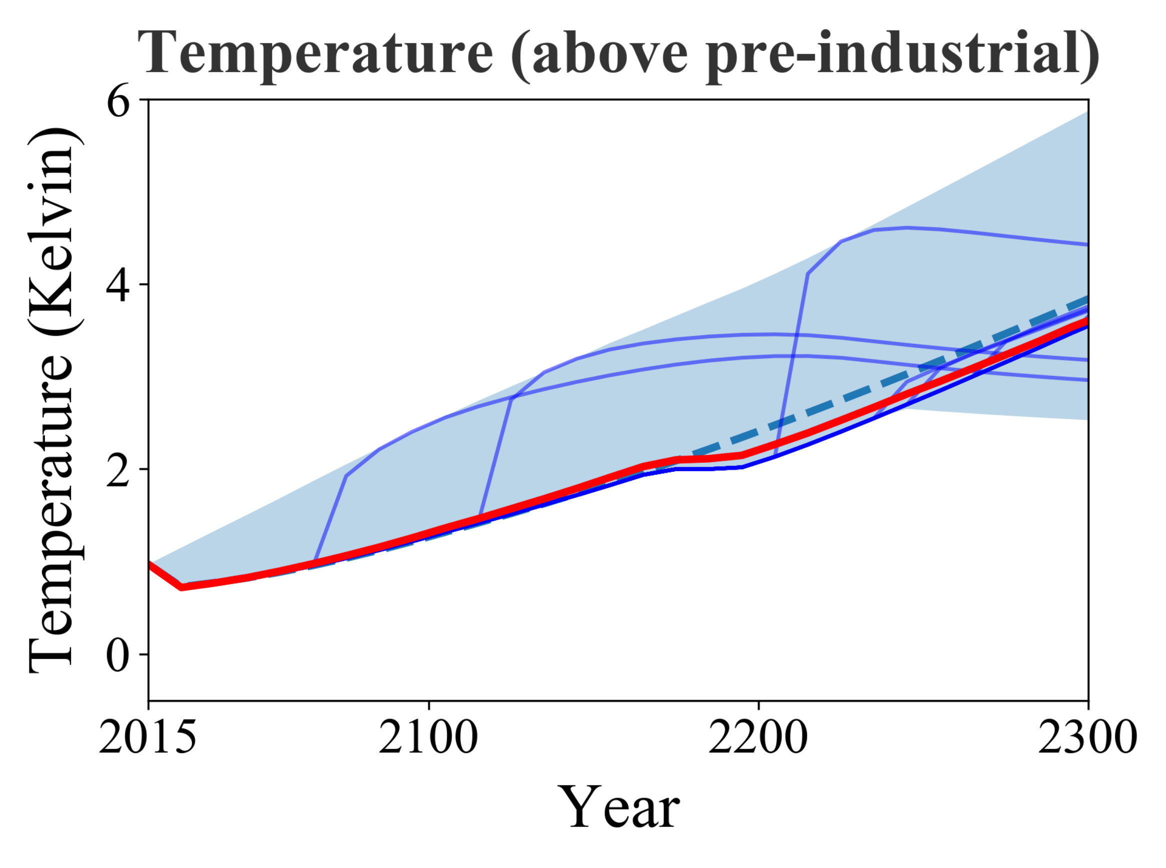
Optimal Policy: Abate+SRM vs SRM-only

Abate+SRM



Note different y-axis scales

SRM-Only



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

Optimal Policy: Comparison

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

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

-- Abate+SRM limits SO2 injections to 30Mt(S)/yr
SRM-Only goes beyond 80Mt(S)/yr (without stabilising T!)
-> Abatement needed to limit warming in long-term.

Summary: stochastic case

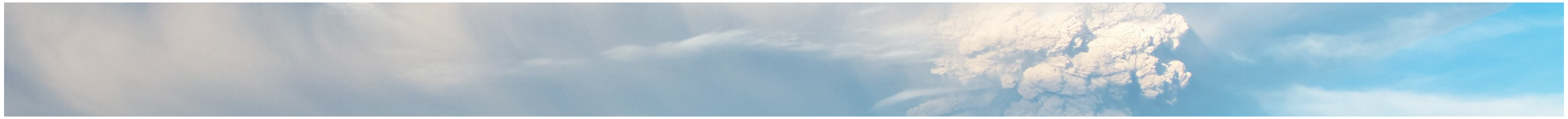
$$\zeta(\pi) = 100\,\% \times \frac{W_\pi - W_0}{W_{\mathrm{AD}} - W_0},$$

AD: Abatement-only, deterministic
0 : no-action policy

Policy	ζ	ζ_{10}	ζ_{90}	SRM fail	Tipping	Peak SRM	Ab. 50 %	Ab. 99 %	SCC
No-action case	0 %			n/a	96.2 %	n/a	n/a	n/a	45
Abatement-only case (det. policy[2])	100 %			n/a	49.5 %	n/a	2114	2212	42
Abatement-only case	105 %	77 %	121 %	n/a	37.8 %	n/a	2095	2215	41
SRM-only case	181 %	179 %	185 %	19.8 %	60.96 %	none[1]	n/a	n/a	23
Abatement+SRM case	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

[1] SRM does not peak but keeps increasing until the upper limit of $100\,\mathrm{Mt(S)}\,\mathrm{yr}^{-1}$. [2] Tipping can occur but the policy maker ignores this and chooses the policy which would be optimal in the deterministic (det.) case. n/a means not applicable.

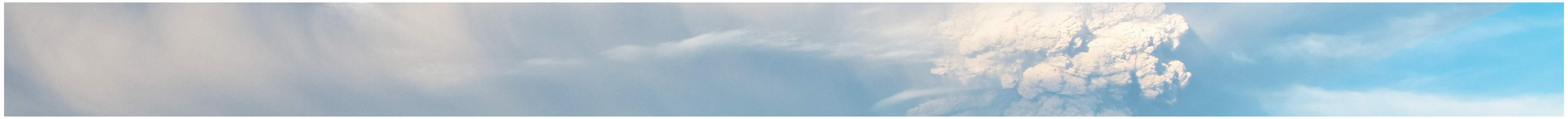
Conclusions



Sulphate SRM has the potential to greatly enhance future welfare and should therefore be taken seriously as possible policy option. It is crucial to reduce/quantify the considerable uncertainties by future research.

Even if successful, SRM does not replace CO2 abatement, but only supplements it.

Further reading



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Complementing CO_2 emission reduction by solar radiation management might strongly enhance future welfare

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Sensitivity of results

Scenario	Abate 50 %	Peak SRM	SCC
Abatement-only scenario, standard	2095	n/a	41
Ab.+SRM, standard	2139	35.0	20
Abatement-only scenario, low rate of pure time preference ($\rho = 0.5\,\%$)	2068	n/a	70
Ab.+SRM scenario, low rate of pure time preference ($\rho = 0.5\,\%$)	2116	31.1	30
Faster decline abatement cost ($\lambda_2 \to 2$; $\lambda_3 \to 0.015$)	2112	29.0	21
Ab.+SRM scenario, less temp. damage, more precip.damage ($\psi_T \to \psi_T/2$, $\psi_P \to \psi_P \times 2$)	2143	32.6	17
Ab.+SRM scenario, lower tipping threshold ($T_{\mathrm{tipp}} = 2\,\mathrm{K} \to 1\,\mathrm{K}$)	2139	35.6	21
Ab.+SRM scenario, double damage from tipping ($\Omega = 0.8$)	2136	34.8	20
Ab.+SRM scenario, double climate tipping probability ($\kappa_{\mathrm{tipp}} \to \kappa_{\mathrm{tipp}} \times 2$)	2137	34.9	20
Ab.+SRM scenario, quadrupled SRM failure probability ($\kappa_{\mathrm{fail}} \to \kappa_{\mathrm{fail}} \times 4$)	2121	34.3	23
Ab.+SRM scenario, double damage from SRM ($\psi_S \to \psi_S \times 2$)	2133	26.8	22
Ab.+SRM scenario, half damage from SRM ($\psi_S \to \psi_S/2$)	2143	43.6	20