Joint Allocation of Climate Control Mechanisms is the Cheapest Way to Reduce Global Climate Damage.

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John Deutch, Department of Chemistry, MIT

jmd@mit.edu

Today's Climate Circumstance

- 2015 Paris Agreement moved 2100 δT target from 3^0C to 2^0C. (perhaps 1.5^0C)
- [2020 INDC Commitments will not be met.]
- *Emission Reduction* cannot do it alone.
- Paris COP underscored need for attention to *Adaptation.*
- New interest in *Negative Emission Technologies*
- What is the role for *Geoengineering?*

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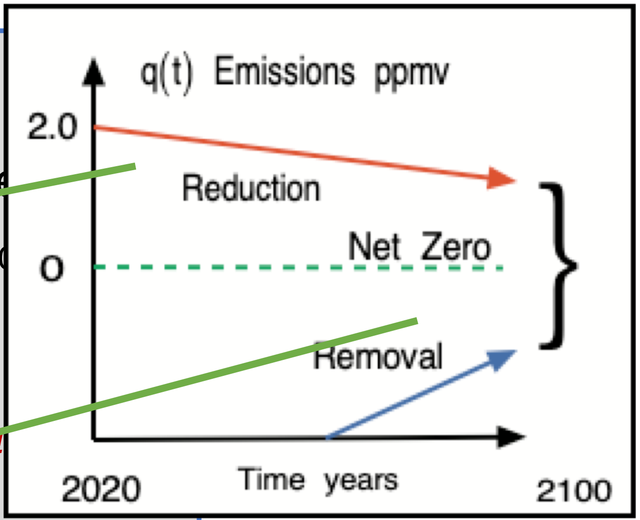


The Joint Model

- Damage $D\left[\delta T(t)\right]$ is a monotonically increasing function of δT
- In the limit: $D\left[\delta T(t)\right] \to \beta \delta T(t)^2$ as $\delta T(t) \to 0$

$$\boxed{D\left[\delta T(t)\right] \to D\left[\delta T_{\varphi(t),\phi(t)}(t)\right] = \left(1-\chi(t)\right)\beta\left\langle \delta T_{\varphi(t),\phi(t)}(t)^2 \right\rangle \left(1-\lambda(t)\right)^2}$$

- $\varphi(t)$ *Emission Reduction.* $\phi(t)$ *CO_2 Removal*

  $\lambda(t)$ *Geoengineering.* $\chi(t)$ *Adaptation*

- All variables $\alpha(\tau) = \{\varphi(\tau), \phi(\tau), \lambda(\tau), \chi(\tau)\}$ [0,1]

0 = no abatement, 1 = full abatement

Atmospheric Dynamics: $q(t) \rightarrow c(t) \rightarrow T(t)$

$q(t) \rightarrow c(t)$

$$c_0(t) = c_0(t_0) + \int_{t_0}^{t} d\tau q(\tau) \qquad c_{\varphi,\phi}(t) \rightarrow c_0(t) - \int_{t_0}^{t} d\tau \left[\varphi(\tau) q(\tau) + \phi(t) c_0(t_0)\right]$$

$c(t) \rightarrow T(t)$

Equilibrium Climate Sensitivity $\quad \delta T(t) - \delta T(t') = \varepsilon \ln\left(c(t)/c(t')\right)$

$T(t) \rightarrow D[\delta T(t)]$

$$D\left[\delta T_{\varphi(t),\phi(t)}(H)\right] \simeq \left(1-\chi(H)\right)\beta \left\langle \left(\delta T_0(H) + \varepsilon \ln\left(1 - \frac{\int_{t_0}^{H} \varphi(\tau) q(\tau) + c_0(t_0)\phi(t)}{c_0(t_0) + \int_{t_0}^{H} d\tau q(\tau)} \right)\right)^2 \right\rangle \left(1-\lambda(H)\right)^2.$$

t_0 initial time, H horizon time

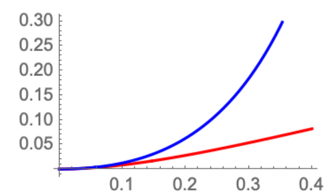
$\langle \cdots \rangle$ Possible stochastic behavior of $q(t)$

Optimization: Determine $\{\alpha(t)\}$ that minimizes $D[\delta T(H)]$ for a given Budget Constraint

$$B = C_\varphi(\varphi(t)) + C_\phi(\phi(t)) + C_\lambda(\lambda(t)) + C_\chi(\chi(t))$$

- No empirical or engineering studies on $C_\alpha(\alpha(t))$
- <u>For illustration</u> Choose the same functional forms differing by only a scale factor $C_\alpha(\alpha(t)) = \tilde{C}_\alpha f(\alpha(t))$ and two cases $f_\alpha(\alpha)_{high} = (\alpha/1-\alpha)^2$ $f_\alpha(\alpha)_{low} = (\alpha/1+\alpha)^2$

$\tilde{C}_\varphi = \$50\ T$ $\tilde{C}_\phi = \$100\ T$ $\tilde{C}_\lambda = \$150\ T$ $\tilde{C}_\chi = \$150\ T$



Addressing Policy Questions:
Minimum Cost to achieve $\delta T(2100) = 2^0C$, 1.5^0C,

$$D\left[\delta T(H)\right]/\beta = (1-\chi)\left[\delta T(t_0) + \varepsilon \ln\left(1 - aq(1-\varphi)\right) - \phi\right]^2 (1-\lambda)^2$$

	$\delta T(2100)$		$\delta T(2100)$	Low Cost	High Cost
Paris Goal					
Deeper Goal	3.0^0C	$\rightarrow$	2.0^0C	\$3.9T	\$7.1T
Wrong Horizon	3.0^0C	$\rightarrow$	1.5^0C	\$7.3T	\$17.1T
Estimate	4.0^0C	$\rightarrow$	2.0^0C	\$13.8T	\$70.0T

Linear Assumptions.

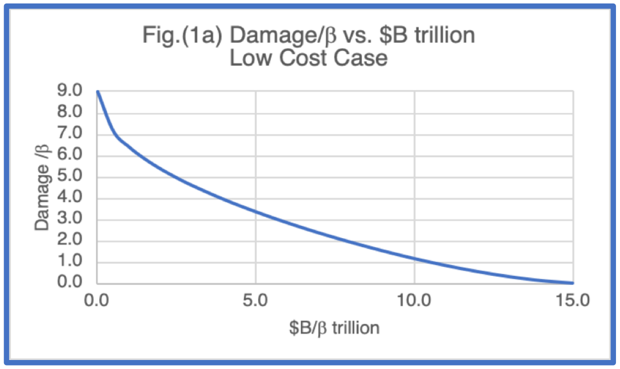
$t_0 = 2020$ $H = 2100$ $c_0 = 400$ ppmv $c_H = 560$ (2x c_{pre})

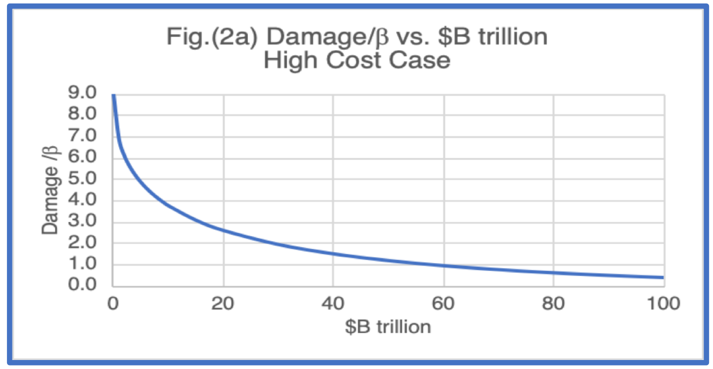
$q = 2$ppmv/yr $\varepsilon = 4.34$ $a = q(H-t_0)/c_0 = 0.4$

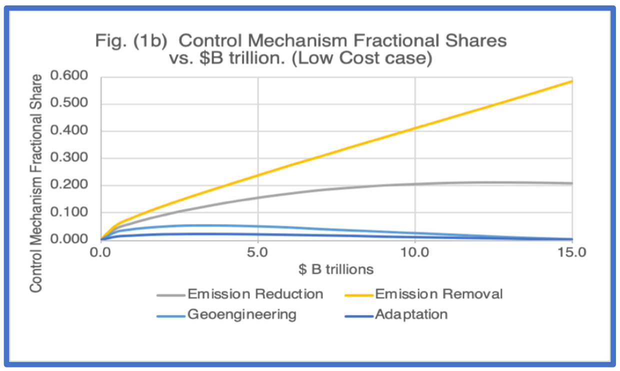
Minimum Cost to achieve $\delta T(2100) = 2^0C$

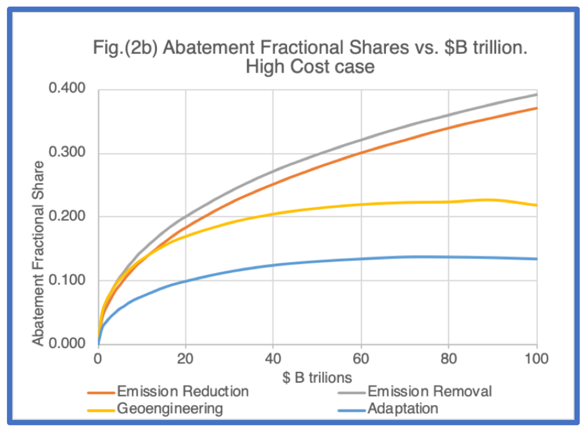
Table (1) Budget \$B T and Allocation to Control Measures to reduce global temperature anomaly from $\delta T(2100) = 3^0C$ to $\delta T(2100) = 2^0C$					
Cost Functions	Total	Emission Reduction φ	CO_2 Removal ϕ	Geo-Engineering λ	Adaptation χ
Low Cost Budget \$ T	\$3.91 T	\$0.71	\$2.73	\$0.39	\$0.08
%	100%	18%	70%	10%	2%
Control Shares	--	0.135	0.198	0.054	0.024
Individual		\$8.79T	\$5.02	\$9.38T	\$19.13T
High Cost Budget \$ T	\$7.13 T	\$1.33 T	\$3.74 T	\$1.61T	\$0.43T
%	100%	19%	52%	23%	6%
Control Shares		0.140	0.162	0.094	0.051
Individual		\$336.5 T	\$16.47T	\$37.49	\$234.5 T

Damage/β vs Budget Relationship, (Linear Assumptions)









Joint Optimization With Three Climate Control Measures

- Optimization among pairs or triplets of the four adaptation measures will close the gap between the result for individual and all measures.
- Drop Geoengineering: Low TRL and Significant Governance Issues.
- Cost of lower $\delta T(2100)$ from 3^0C to 2^0C: (linear assumptions)

	Low Budget	High Budget	
4 Measures	\$3.91	\$7.3T	
3 Measure	\$4.25T	\$9.3T.	(No Geoeng.)

Variation of $\delta T(H)$ with emission rate, q, (Linear Assumptions)

As q increases (at fixed budget) $\delta T(H)$ increases

Table (3) Variation of Damage/ β and Control Mechanism Share with Emission at Low and High Cost

	Low Cost \$3.91 T					High Cost \$7.13 T				
q emission ppmv/yr	$\delta T(H)^2$	φ	ϕ	λ	χ	$\delta T(H)^2$	φ	ϕ	λ	χ
q = 0.0	3.04	0.000	0.240	0.030	0.014	3.48	0.000	0.193	0.080	0.043
q = 0.2	3.72	0.058	0.227	0.044	0.020	3.89	0.095	0.178	0.091	0.050
q = 0.4	4.00	0.135	0.198	0.054	0.024	4.00	0.140	0.162	0.094	0.051
q = 0.6	4.01	0.219	0.156	0.054	0.024	4.00	0.167	0.149	0.094	0.051

Social Cost of Carbon – SCC

SCC definition: *Damage increase from addition of 1 MT CO_2 to the atmosphere.* $SCC(t) = \partial D[\delta T(t)]/\partial q > 0$

Joint optimization→

$$\boxed{SCC_q(H) = \partial D[\delta T(H)]/\partial q = (1-\chi(B))2\beta\left(\delta T(t_0) + \varepsilon \ln\left(1 + a(1-\varphi(B)) - \phi(B)\right)\right) \frac{\varepsilon a(1-\varphi(B))}{\left(1 + a(1-\varphi(B)) - \phi(B)\right)q}(1-\lambda(B))^2}$$

$a = q(H-t_0)/c_0$

Emissions only→

$$\boxed{SCC_0(H) = 2\beta\left(\delta T(t_0) + \varepsilon \ln(1+a)\right)\frac{\varepsilon a}{(1+a)q}}$$

q_m = 1ppmv = 2.13 GT

Low Cost $SCC_2(2100) / SCC_0(2100) = 1.71/2.92$

High Cost $SCC_2(2100) / SCC_0(2100) = 1.59/292$

Linear assumptions @ $\delta T(2100) = 2^0 C$

Variable Emission Rate q(t)

- Desirable to determine minimum cost emission trajectory to support discounted damage in joint climate measures context.
- Minimization solution will involve time dependent climate shares.
- Simple example: assume that the interval $[t_0, H]$ is divided into two equal periods that have different emission rates, q_1 and q_2

Table (2) Temperature Increase from $\delta T(2020) = 3^0C$ to $\delta T(2100) = 2^0C$ at Different Emission Rates (ppmv) in Equally Divided period with Associated Control Shares and Budgets

Low Cost Budget $4.245 T q_1	q_2	$\delta T(H)$ ^0C	Emission Reduction φ_1	Emission Reduction φ_2	CO_2 Removal ϕ	Geo-Engineering λ	Adaptation χ
0.2	0.2	4.00	0.0580	0.0580	0.2254	0.0590	0.0259
0.3	0.1	3.95	0.0960	0.0263	0.2217	0.0576	0.0254
0.2	0.3	4.13	0.0561	0.0934	0.2121	0.0653	0.0283
0.2	0.1	3.85	0.0589	0.0268	0.2315	0.5160	0.0231
High Cost Budget $7.94 T q_1	q_2	$\delta T(H)$ ^0C	Emission Reduction φ_1	Emission Reduction φ_2	CO_2 Removal ϕ	Geo-Engineering λ	Adaptation χ
0.2	0.2	4.00	0.0916	0.0916	0.1729	0.1035	0.0572
0.3	0.1	3.96	0.1230	0.0518	0.1723	0.1020	0.0563
0.2	0.3	4.05	0.0871	0.1179	0.1660	0.1048	0.0580
0.2	0.1	3.90	0.0963	0.0551	0.1799	0.1005	0.0554

Major Points

- Emission Reduction Cannot Do It Alone.
- There Four Climate Control Mechanisms (emission reduction, CO_2 removal, abatement, geoengineering).
- Least Cost Solution Involves All Four Control Measures.
- No Information on Cost of Climate Control Measures.
- Balance spending on Emission Reduction and the Other Climate Control measures

Next Steps

- Generalize optimization to time dependent q(t)
- Research on cost functions for climate control measures.
  (web tool: optimization of cost functions)
- Launch serious geoengineering R&D program.
- Speculate on different paths to raise and manage ~ 1 T$/yr for climate programs
- Educate public about magnitude of the challenge.