Death and Destruction in the Economics of Catastrophes

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Background

- We face multiple potential catastrophes: nuclear or bioterrorism, "mega-virus," climate, ...
- Which ones to avert? If benefit of averting exceeds cost for each one, should we avert them all? No.
- Ian Martin and Robert Pindyck, "Averting Catastrophes: The Strange Economics of Scylla and Charybdis."
- Use WTP to measure benefit of avoidance, and a permanent tax on consumption, τ, to measure cost.
- Consider N "types" of catastrophes. They are independent.
- Main result: Rule for determining the set that should be averted.
- Problem: WTP based on "destruction" (loss of consumption), not death.

"Strange Economics" — Two Examples

- Suppose society faces five major potential catastrophes, and the benefit of averting each exceeds the cost.
  - You'd probably say we should avert all five.
  - You might be wrong.
  - It may be that we should avert only three of the five.
- Suppose we face three potential catastrophes. The first has a benefit w_1 much greater than the cost τ_1, and the other two have benefits greater than the costs, but not that much greater.
  - Naive reasoning: Eliminate the first and then decide about the other two.
  - Wrong. If only one is to be eliminated, we should indeed choose the first; and we do even better by eliminating all three.
  - But we do best by eliminating the second and third and *not* the first: the presence of the second and third catastrophes makes it suboptimal to eliminate the first.

Outline

- WTP to avert single catastrophe.
  - Catastrophe is Poisson arrival, rate λ.
  - If it occurs, consumption drops by random fraction ϕ.
  - Can be averted via permanent consumption tax τ.
  - Only one, so avert if WTP $> \tau$.
- *N* "types" of catastrophes.
  - Fundamental interdependence of catastrophes.
  - Which ones to avert?
  - Rough numbers: 7 catastrophes.
- But some catastrophes cause death. Focus of new paper.
  - If catastrophe occurs, random fraction ψ of population dies. For the rest, consumption unchanged.
  - What is WTP to avert catastrophe? Connection to VSL.
  - Example: Nuclear terrorism vs. "mega-virus."

WTP to Avoid One Type of Catastrophe

- First consider single type of catastrophe in isolation. (Climate change, mega-virus, your choice.) Ignore all others.
- WTP: maximum fraction of consumption, now and throughout the future, society would sacrifice to avert catastrophe.
- Without catastrophe, per-capita consumption grows at rate g, and $C_0 = 1$. Catastrophe is Poisson arrival, mean arrival rate λ, can occur repeatedly.
- When it occurs, consumption falls by random fraction ϕ.
- CRRA utility function used to measure welfare, with IRRA $=$ $\eta > 1$ and rate of time preference $= \delta$.

Event Characteristics and WTP

- Assume impact of nth arrival, ϕ_n, is i.i.d. across realizations n. So process for consumption is:

$$c_t = \log C_t = gt - \sum_{n=1}^{N(t)} \phi_n \tag{1}$$

  $N(t)$ is a Poisson counting process with arrival rate λ, so when nth event occurs, C_t is multiplied by the random variable $e^{-\phi_n}$.

- Use the *cumulant-generating function* (CGF),

$$\boldsymbol{\kappa}_t(\theta) \equiv \log \mathbb{E}\, e^{c_t \theta} \equiv \log \mathbb{E}\, C_t^{\theta}.$$

- Note c_t is a Lévy process, so $\boldsymbol{\kappa}_t(\theta) = \boldsymbol{\kappa}(\theta) t$, where $\boldsymbol{\kappa}(\theta)$ means $\boldsymbol{\kappa}_1(\theta)$. The t-period CGF scales 1-period CGF linearly in t.
- The CGF is then

$$\boldsymbol{\kappa}(\theta) = g\theta + \lambda \left(\mathbb{E}\, e^{-\theta \phi_1} - 1 \right) \tag{2}$$

Event Characteristics and WTP (Continued)

- With CRRA utility, welfare is:

$$\mathbb{E}\int_0^\infty \frac{1}{1-\eta} e^{-\delta t} C_t^{1-\eta}\, dt = \frac{1}{1-\eta}\int_0^\infty e^{-\delta t} e^{\boldsymbol{\kappa}(1-\eta)t}\, dt = \frac{1}{1-\eta}\frac{1}{\delta - \boldsymbol{\kappa}(1-\eta)}$$

- Assume $z = e^{-\phi}$ follows a power distribution:

$$b(z) = \beta z^{\beta - 1}, \quad 0 \leq z \leq 1. \tag{3}$$

  Large β implies large $\mathbb{E}\, z$ and thus small expected impact.
- WTP to avert catastrophe is value of w that solves

$$\frac{1}{1-\eta}\frac{1}{\delta - \boldsymbol{\kappa}(1-\eta)} = \frac{(1-w)^{1-\eta}}{1-\eta}\frac{1}{\delta - \boldsymbol{\kappa}^{(1)}(1-\eta)}.$$

- With power distribution for $z = e^{-\phi}$, and $\rho \equiv \delta + g(\eta - 1)$:

$$w = 1 - \left[1 - \frac{\lambda(\eta - 1)}{\rho(\beta - \eta + 1)}\right]^{\frac{1}{\eta - 1}}. \tag{4}$$

- Avoid catastrophe if $w > \tau$.

Two Types of Catastrophes

- Two types of catastrophes, arrival rates λ_1 and λ_2 and impact parameters β_1 and β_2. Assume events are independent. So

$$c_t = \log C_t = gt - \sum_{n=1}^{N_1(t)} \phi_{1,n} - \sum_{n=1}^{N_2(t)} \phi_{2,n} \tag{5}$$

$$\text{CGF}: \quad \boldsymbol{\kappa}(\theta) = g\theta + \lambda_1 \left(\mathbb{E}\, e^{-\theta\phi_1} - 1 \right) + \lambda_2 \left(\mathbb{E}\, e^{-\theta\phi_2} - 1 \right) \tag{6}$$

- WTP to avert catastrophe i satisfies

$$\frac{(1-w_i)^{1-\eta}}{1-\eta} \frac{1}{\delta - \boldsymbol{\kappa}^{(i)}(1-\eta)} = \frac{1}{1-\eta} \frac{1}{\delta - \boldsymbol{\kappa}(1-\eta)}$$

$$\text{so}: \quad w_i = 1 - \left(\frac{\delta - \boldsymbol{\kappa}(1-\eta)}{\delta - \boldsymbol{\kappa}^{(i)}(1-\eta)} \right)^{\frac{1}{\eta-1}}. \tag{7}$$

- WTP to avert both catastrophes is

$$w_{1,2} = 1 - \left(\frac{\delta - \boldsymbol{\kappa}(1-\eta)}{\delta - \boldsymbol{\kappa}^{(1,2)}(1-\eta)} \right)^{\frac{1}{\eta-1}}. \tag{8}$$

Interrelationship of WTPs

- How is WTP to avert #1 affected by existence of #2?
  - Think of Catastrophe 2 as "background risk." Two effects:
  - It reduces expected future consumption;
  - and thereby raises future expected marginal utility.
- Each event reduces consumption by some percentage ϕ. So first effect *reduces* WTP because with less (future) consumption available, event causes smaller drop in consumption.
- Second effect *raises* WTP: loss of utility is greater when total consumption is lower.
- If $\eta > 1$, second effect dominates. Existence of #2 raises WTP to avert #1. (Opposite if $\eta < 1$.)
- Linking $w_{1,2}$ to w_1 and w_2:

$$1 + (1 - w_{1,2})^{1-\eta} = (1 - w_1)^{1-\eta} + (1 - w_2)^{1-\eta}$$

- This implies $w_{1,2} < w_1 + w_2$. WTPs are not additive.

Which Catastrophes to Avert?

- Suppose $w_i > \tau_i$ for both $i = 1$ and 2. We should avert at least one catastrophe, but should we avert both?
- Useful to express costs τ_i and benefits w_i in terms of utility:

$$\begin{aligned} K_i &= (1-\tau_i)^{1-\eta} - 1 \\ B_i &= (1-w_i)^{1-\eta} - 1 \end{aligned}$$

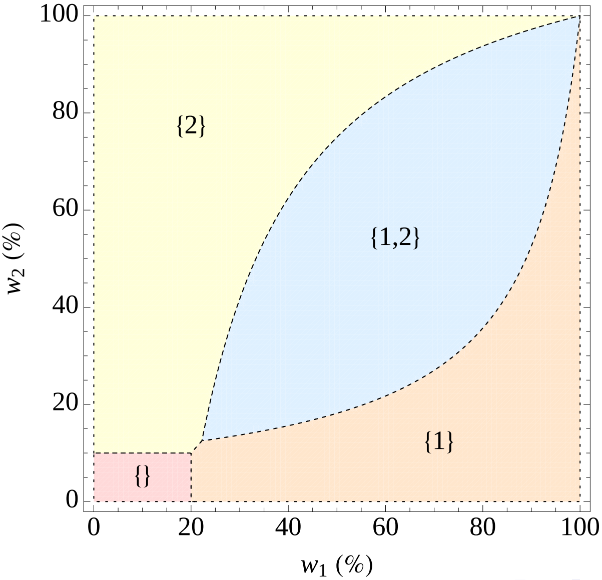
  K_i is percentage loss of utility when C is reduced by τ_i percent, and likewise for B_i. Also, $K_i/(\eta - 1)$ and $B_i/(\eta - 1)$ are absolute changes in utility (in utils).

- Suppose $B_1 \gg K_1$ so we definitely avert #1. Should we also avert #2? Only if $B_2/K_2 > 1 + B_1$.
  - Fact that we are going to avert #1 *increases hurdle rate for #2.*
  - Also applies if $B_1 = B_2$ and $K_1 = K_2$; might be we should only avert one of the two (chosen at random).

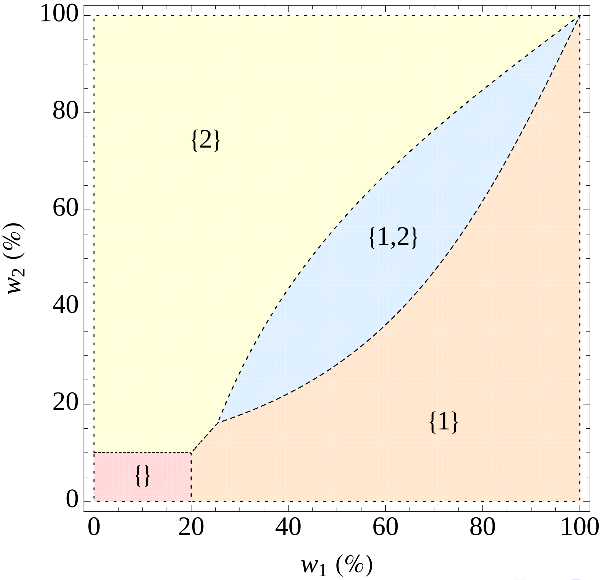
Which Catastrophes to Avert? (Continued)

- Does this seem counter-intuitive?
  - What matters is *additional* benefit from averting #2 relative to the cost.
  - In WTP terms, additional benefit is $(w_{1,2} - w_1)/(1 - w_1)$.
  - $B_2/K_2 > 1 + B_1$ is equivalent to $(w_{1,2} - w_1)/(1 - w_1) > \tau_2$.
  - Can have $w_2 > \tau_2$ but $(w_{1,2} - w_1)/(1 - w_1) < \tau_2$. Why? These are not marginal projects, so $w_{1,2} < w_1 + w_2$.
  - To avert #1, society is willing to give up fraction w_1 of C, so remaining C is lower and MU is higher. Thus utility loss from τ_2 is increased.
- Numerical example: Suppose $\tau_1 = 20\%$ and $\tau_2 = 10\%$. Figures show, for range of w_1 and w_2, which catastrophes to avert (none, one, or both).

Example: $\tau_1 = .2, \tau_2 = .1, \eta = 2$. What to Do?



Example: $\tau_1 = .2, \tau_2 = .1, \eta = 3$. What to Do?



N Types of Catastrophes

- Problem: Given a list $(\tau_1, w_1), \ldots, (\tau_N, w_N)$ of costs and benefits of averting N types of catastrophes, which ones to eliminate?
- Again, $K_i = (1-\tau_i)^{1-\eta} - 1$ and $B_i = (1-w_i)^{1-\eta} - 1$.
- Key result: (Benefits add, costs multiply.) The optimal set, S, of catastrophes to be eliminated solves the problem

$$\max_{S \subseteq \{1,\ldots,N\}} V = \frac{1 + \sum_{i \in S} B_i}{\prod_{i \in S} (1+K_i)} \tag{9}$$

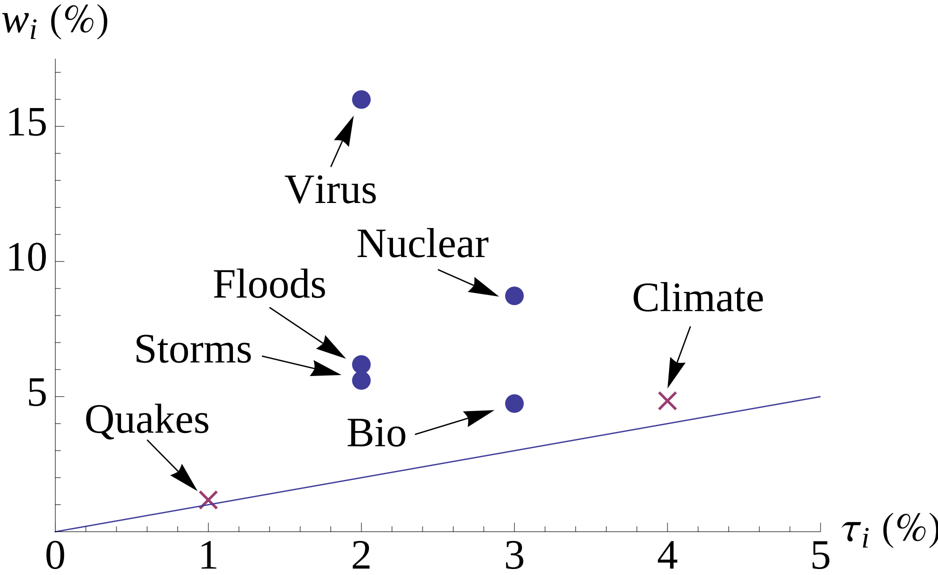
Some Rough Numbers

Characteristics of Seven Potential Catastrophes:

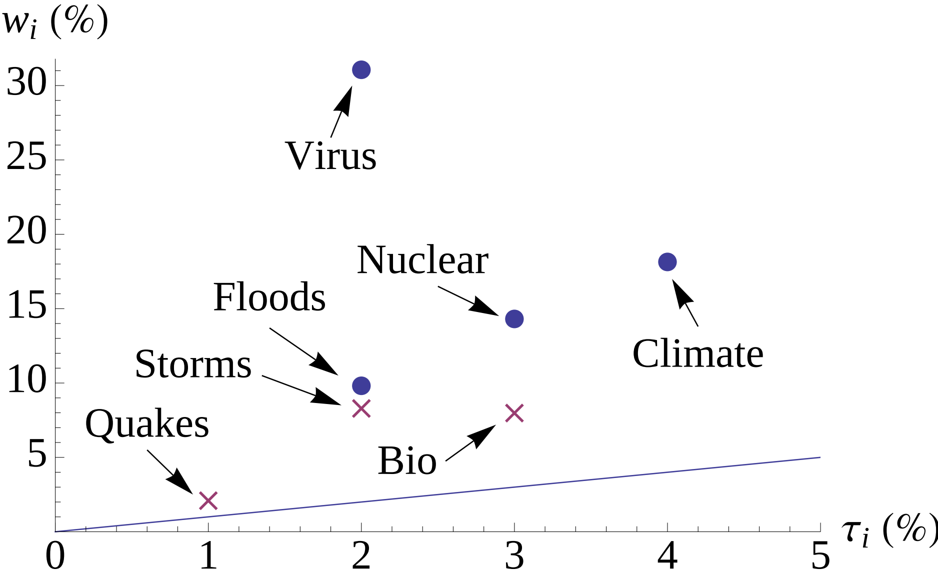
Potential Catastrophe	λ_i	β_i	τ_i	$\eta = 2$ w_i	w'_i	B_i	K_i	$\eta = 4$ w_i	w'_i	B_i	K_i
Mega-Virus	.020	5	.02	.159	.125	.189	.020	.309	.145	2.030	.062
Climate	.004	4	.04	.048	.033	.050	.042	.180	.053	.812	.130
Nuclear Terrorism	.04	17	.03	.086	.063	.095	.031	.141	.037	.580	.096
Bioterrorism	.04	32	.03	.047	.032	.049	.031	.079	.018	.280	.096
Floods	.17	100	.02	.061	.043	.065	.020	.096	.022	.356	.062
Storms	.14	100	.02	.051	.035	.053	.020	.082	.018	.293	.062
Earthquakes	.03	100	.01	.011	.008	.011	.010	.020	.004	.063	.031
Avert all Seven				.339		.513	.188	.442		4.415	.677

Note: w'_i is WTP "naively" calculated, i.e., ignoring the other six.

Which to Avert? ($\eta = 2$)



Which to Avert? ($\eta = 4$)



Framework: Death and Consumption

- N_t identical consumers who each consume C_t.
- Utility comes only from consumption, so total welfare is:

$$V_0 = \mathbb{E} \int_0^\infty \frac{1}{1-\eta} N_t C_t^{1-\eta} e^{-\delta t} dt \ , \tag{10}$$

  with $\eta > 1$. Absent catastrophes, C_t grows at rate g, N_t grows at rate n. Two types of catastrophes:
  - Consumption catastrophe: C_t falls by random fraction ϕ. Arrival rate λ_c.
  - "Death" catastrophe: N_t falls by random fraction ψ. Arrival rate λ_d. Consumption of those who remain alive unchanged.
- We want WTP to avert each type of catastrophe, and WTP to avert both.

Death: One Period

- What is welfare loss for those who die?
- One period: Is loss simply foregone utility? No, much greater.
  - Suppose $\eta = 2$ and $C_t = 1$, so utility is -1. Is welfare change just the loss of this utility, i.e., -1?
  - Suppose C falls by 75%, i.e., to .25. Then utility is -4 and welfare change is $-4 - (-1) = -3$.
  - For most, 25% of "normal" consumption is preferable to death.
- $u(C) \rightarrow -\infty$ as $C \rightarrow 0$, so what to do?
- Common approach is to add a positive constant to the utility function: $u(C) = \frac{1}{1-\eta} C_t^{1-\eta} + b$.
- Then "death" means consumption drops to some low value ϵ, such that $u(\epsilon) = 0$, i.e., $\epsilon = [(\eta - 1)b]^{1/(1-\eta)}$.

The Value of Life

- Issue is loss of welfare from death, not marginal benefits, so we retain CRRA utility without adding a constant.
- Treat death using the same framework used to treat destruction, i.e., utility loss from drop in consumption.
- So assume "death" results in a drop in consumption to low value ϵ, which implies a large drop in utility.
- At issue is what value to use for ϵ. Use VSL.
- VSL is MRS between wealth (or income, or discounted consumption over a lifetime) and probability of survival.
  - Tells us what an individual (or society) would pay in terms of a small decrease in wealth or consumption for a small increase in probability of survival.
  - Does *not* tell us what an individual or society would pay to avoid certain death, which we expect is much more.

Value of a Statistical Life

- Many studies have estimated VSL using risk-of-death choices by individuals. Find VSL $\approx$ 7 times lifetime income or consumption.
- To get ϵ, we use a simple static model for the VSL.
  - w = lifetime consumption = 40 times current consumption.
  - p = *ex ante* probability of death. Can reduce p at the cost of reducing w.
  - $u(w)$ = utility if alive, $v(w)$ = utility if dead. Then

$$\mathrm{VSL} = -\frac{dw}{d(1-p)} = \frac{dw}{dp} = \frac{u(w) - v(w)}{(1-p)u'(w) + pv'(w)} \tag{11}$$

  - $u(w)$ and $v(w)$ measured in utils, and $u'(w)$ and $v'(w)$ measured in utils/\$, so VSL measured in \$.
  - VSL is a cardinal measure, invariant to linear transformations of u or w.

VSL (Continued)

- VSL is increasing in p; if p is high, little incentive to limit spending to reduce p ("dead anyway" effect).
- *Ex ante*, p is low. And most estimates of VSL based on populations for which p is low. So evaluate VSL at $p = 0$.
- Treat lifetime consumption as a multiple m of current consumption C_t.
- Annual consumption when dead is ϵC_t, with $\epsilon << 1$, so "lifetime" consumption when dead is $m\epsilon C_t$. Then $u(w) = u(mC)$ and $v(w) = u(m\epsilon C)$.
- VSL is multiple s of lifetime consumption, so

$$\text{VSL} = smC = \frac{mC}{1-\eta}\left[1 - \epsilon^{1-\eta}\right]. \quad (12)$$

- Therefore: $\epsilon = [s(\eta - 1) + 1]^{\frac{1}{1-\eta}}$.

VSL (Continued)

- We use $s = 7$. So if $\eta = 2$, $\epsilon = 1/(s+1) = .125$, i.e, death is equivalent in welfare terms to an 88% drop in consumption. If $\eta = 3$, $\epsilon = .27$, and if $\eta = 4$, $\epsilon = .42$.
- ϵ is increasing in η because larger η implies larger utility loss from any given reduction in C.
- Death is worse than destruction:
  - Suppose $\eta = 2$ so $\epsilon = .125$.
  - Then (annual) welfare loss for those who die is $u(\epsilon) - u(C_0) = [\epsilon^{1-\eta} - 1]/(1-\eta) = -7$ utils.
  - Suppose $\phi = .10$. Then the total loss is $-7\phi = -0.7$.
  - If instead consumption of everyone falls by $\phi = .10$, total welfare loss is $u(.9C_0) - u(C_0) = -0.11$.
  - Loss from death is more than six times loss from destruction.

WTPs to Avert Catastrophes

- Social welfare function: $V_0 = \mathbb{E} \int_0^\infty \frac{1}{1-\eta} N_t C_t^{1-\eta} e^{-\delta t} dt$
- C_t and N_t evolve as: $\log C_t = gt - \sum_{k=1}^{Q(t)} \phi_k$ and $\log N_t = nt - \sum_{k=1}^{X(t)} \psi_k$, where Q_t and X_t are Poisson counting processes with mean arrival rates λ_c and λ_d.
- CGF's are linear in t, so $\kappa_C(\theta) = g\theta + \lambda_c \left(\mathbb{E}\, e^{-\theta\phi} - 1\right)$ and $\kappa_N(\theta) = n\theta + \lambda_d \left(\mathbb{E}\, e^{-\theta\psi} - 1\right)$.
- Let * denote no catastrophes, so $N_t^* = e^{nt}$ and $\kappa_N^*(\theta) = n\theta$.
- If no catastrophes are averted, total welfare is

$$V = \mathbb{E} \left\{ \int_0^\infty e^{-\delta t} \left[\frac{N_t C_t^{1-\eta}}{1-\eta} + \frac{(N_t^* - N_t)\epsilon^{1-\eta} C_t^{1-\eta}}{1-\eta} \right] dt \right\},$$

where $(N_t^* - N_t)$ is number of people that have died.

WTPs (Con't)

- C_t is an exponential Lévy process, so it evolves independently of N_t. Thus:

$$\mathbb{E}(N_t C_t^{1-\eta}) = \mathbb{E}\, N_t \, \mathbb{E}\, C_t^{1-\eta} = e^{\kappa_N(1)t} \cdot e^{\kappa_C(1-\eta)t}$$

$$\mathbb{E}\left[(N_t^* - N_t)\epsilon^{1-\eta} C_t^{1-\eta}\right] = \left(e^{\kappa_N^*(1)t} - e^{\kappa_N(1)t}\right)\epsilon^{1-\eta} e^{\kappa_C(1-\eta)t}$$

- Substituting these expressions into the integral,

$$V = \frac{1}{1-\eta}\left\{\frac{1-\epsilon^{1-\eta}}{\delta - \kappa_N(1) - \kappa_C(1-\eta)} + \frac{\epsilon^{1-\eta}}{\delta - \kappa_N^*(1) - \kappa_C(1-\eta)}\right\}$$

- Second term: welfare from guaranteed consumption stream ϵC_t (received even after death). Discounted at rate $\delta - n$.
- First term: welfare from consumption stream $(1-\epsilon)C_t$ received by those alive. Given risk of death, discounted at higher rate $\delta - \kappa_N(1) > \delta - n$.

WTP to Avoid Consumption Catastrophe

- Avert consumption catastrophe: set $\lambda_c = 0$, replace $\boldsymbol{\kappa}_C(1-\eta)$ by $\boldsymbol{\kappa}^*_C(1-\eta) \equiv g(1-\eta)$.
- If this catastrophe is averted at cost of permanent loss of fraction w_c of consumption, welfare is

$$V_c = \frac{(1-w_c)^{1-\eta}}{1-\eta}\left\{\frac{1-\epsilon^{1-\eta}}{\delta - \boldsymbol{\kappa}_N(1) - \boldsymbol{\kappa}^*_C(1-\eta)} + \frac{\epsilon^{1-\eta}}{\delta - \boldsymbol{\kappa}^*_N(1) - \boldsymbol{\kappa}^*_C(1-\eta)}\right\}$$

WTP to avoid catastrophe is w_c that equates V and V_c:

$$(1-w_c)^{1-\eta} = A \times B \times C$$

$$\begin{aligned} A &= \frac{\delta - \boldsymbol{\kappa}^*_N(1) - \boldsymbol{\kappa}^*_C(1-\eta)}{\delta - \boldsymbol{\kappa}^*_N(1) - \boldsymbol{\kappa}_C(1-\eta)} \\ B &= \frac{\delta - \boldsymbol{\kappa}_N(1) - \boldsymbol{\kappa}^*_C(1-\eta)}{\delta - \boldsymbol{\kappa}_N(1)\epsilon^{1-\eta} - (1-\epsilon^{1-\eta})\boldsymbol{\kappa}^*_N(1) - \boldsymbol{\kappa}^*_C(1-\eta)} \\ C &= \frac{\delta - \boldsymbol{\kappa}_N(1)\epsilon^{1-\eta} - (1-\epsilon^{1-\eta})\boldsymbol{\kappa}^*_N(1) - \boldsymbol{\kappa}_C(1-\eta)}{\delta - \boldsymbol{\kappa}_N(1) - \boldsymbol{\kappa}_C(1-\eta)}. \end{aligned}$$

WTP to Avoid Death Catastrophe

- If death catastrophe is averted at cost of loss of fraction w_d of consumption, welfare is

$$V_d = \mathbb{E}\left\{\int_0^\infty e^{-\delta t}\frac{(1-w_d)^{1-\eta}N_t^* C_t^{1-\eta}}{1-\eta}\,dt\right\}$$
$$= \frac{1}{1-\eta}\frac{(1-w_d)^{1-\eta}}{\delta-\boldsymbol{\kappa}_N^*(1)-\boldsymbol{\kappa}_C(1-\eta)}$$

Equating V and V_d, w_d satisfies

$$(1-w_d)^{1-\eta} = \frac{\delta-\boldsymbol{\kappa}_N(1)\epsilon^{1-\eta}-(1-\epsilon^{1-\eta})\boldsymbol{\kappa}_N^*(1)-\boldsymbol{\kappa}_C(1-\eta)}{\delta-\boldsymbol{\kappa}_N(1)-\boldsymbol{\kappa}_C(1-\eta)}$$

WTP to Avoid Both Catastrophes

- If fraction $w_{c,d}$ of consumption is sacrificed to avert both catastrophes, welfare is

$$V_{c,d} = \frac{1}{1-\eta} \frac{(1-w_{c,d})^{1-\eta}}{\delta - \kappa_N^*(1) - \kappa_C^*(1-\eta)}.$$

Equating V and $V_{c,d}$, $w_{c,d}$ satisfies

$$(1-w_{c,d})^{1-\eta} =$$

$$\frac{\delta - \kappa_N^*(1) - \kappa_C^*(1-\eta)}{\delta - \kappa_N^*(1) - \kappa_C(1-\eta)} \cdot \frac{\delta - \kappa_N(1)\epsilon^{1-\eta} - (1-\epsilon^{1-\eta})\kappa_N^*(1) - \kappa_C(1-\eta)}{\delta - \kappa_N(1) - \kappa_C(1-\eta)}$$

- Can show that $w_{c,d} > \max\{w_c, w_d\}$ and, more interestingly, $w_{c,d} < w_c + w_d - w_c w_d$.

Applying the Model

- The CGFs κ_C and κ_N apply to *any* probability distributions for the impacts ϕ and ψ.
- For numerical examples, we assume ϕ and ψ are exponentially distributed: $f_\phi(x) = \beta_c e^{-\beta_c x}$ and $f_\psi(x) = \beta_d e^{-\beta_d x}$.
- Note that $\mathbb{E}(\phi) = 1/\beta_c$ and $\mathbb{E}(z_c) = \beta_c/(\beta_c + 1)$, and similarly for ψ and z_d. So large β_c and β_d imply small expected impacts, i.e., small values of $\mathbb{E}(\phi)$ and $\mathbb{E}(\psi)$ and large values of $\mathbb{E}(z_c)$ and $\mathbb{E}(z_d)$.

CGFs and WTPs

- Given these distributions for ϕ and ψ, the CGFs are

$$\begin{aligned}
\kappa_C(1-\eta) &= g(1-\eta) - \lambda_c(1-\eta)/[\beta_c + (1-\eta)] \\
\kappa_C^*(1-\eta) &= g(1-\eta) \\
\kappa_N(1) &= n - \lambda_d/(\beta_d + 1) \\
\kappa_N^*(1) &= n
\end{aligned}$$

- Define $\rho \equiv \delta - n + g(\eta - 1)$, and

$$\begin{aligned}
\lambda'_c &\equiv \lambda_c(\eta - 1)/(\beta_c + 1 - \eta) \\
\lambda'_d &\equiv \lambda_d/(\beta_d + 1)
\end{aligned}$$

λ'_c and λ'_d are risk- and impact-adjusted arrival rates. Raising β_d reduces expected impact of death catastrophe, welfare-equivalent to reducing λ_d. λ'_c also adjusts for risk aversion; increasing η raises utility loss from reduced consumption – welfare-equivalent to increasing λ_c.

WTPs

- Substituting in the expressions for the CGFs, ρ, λ'_c and λ'_d, the WTPs are:

$$w_c = 1 - \left[\frac{(\rho - \lambda'_c)(\rho + \lambda'_d \epsilon^{1-\eta})(\rho + \lambda'_d - \lambda'_c)}{\rho(\rho + \lambda'_d)(\rho + \lambda'_d \epsilon^{1-\eta} - \lambda'_c)} \right]^{\frac{1}{\eta - 1}}$$

$$w_d = 1 - \left[\frac{(\rho + \lambda'_d - \lambda'_c)}{(\rho + \lambda'_d \epsilon^{1-\eta} - \lambda'_c)} \right]^{\frac{1}{\eta - 1}}$$

$$w_{c,d} = 1 - \left[\frac{(\rho - \lambda'_c)(\rho + \lambda'_d - \lambda'_c)}{\rho(\rho + \lambda'_d \epsilon^{1-\eta} - \lambda'_c)} \right]^{\frac{1}{\eta - 1}}$$

Recall that $\epsilon^{1-\eta} = s(\eta - 1) + 1$.

Example

- As an example, consider two catastrophes we examined earlier: a "mega-virus" and nuclear terrorism.
  - **Mega-virus:** causes death, not destruction. Spanish Flu of 1918 killed 4 to 5% of populations of Europe and U.S., but had minimal impact on GDP and consumption of those who lived.
  - **Nuclear terrorism:** Hiroshima-grade bomb in a major city might kill 200,000, but biggest impact would be economic: major shock to GDP from worldwide reduction in trade and economic activity, and vast resources devoted to averting further attacks. So this is a "consumption" catastrophe.
- Mean arrival rates and impact parameters:
  - **Mega-virus:** $\lambda_d = .02$, i.e., 10% chance of pandemic in next 10 years. Mean impact: death of 5% of population, so $\beta_d = 20$.
  - **Nuclear terrorism:** $\lambda_c = .04$, i.e., 50% chance in next 17 years. Mean impact is 5.5% drop in consumption, so $\beta_c = 17$.

WTPs: Virus (w_d) and Nuclear Terrorism (w_c)

Parameters		w_c	w_d	$w_{c,d}$	Avert:
Base Case	$\eta = 2$	.1527	.2654	.3572	Both
	$\eta = 4$	.0626	.1022	.1472	Both
$n = 0$	$\eta = 2$	.0710	.1478	.2010	Both
	$\eta = 4$	.0445	.0781	.1123	Virus
$s = 3$	$\eta = 2$	.1390	.1341	.2423	Both
	$\eta = 4$	.0564	.0493	.0969	Nuclear
$s = 10$	$\eta = 2$	.1605	.3404	.4229	Both
	$\eta = 4$	.0661	.1351	.1784	Both
$\lambda_d = 0$	$\eta = 2$	.1250	0	.1250	Nuclear
	$\eta = 4$	.0501	0	.0501	Nuclear

Note: Base case parameter: $\delta = g = n = .02$ and $s = 7$. Also, $\lambda_c = .04$, $\beta_c = 17$, $\lambda_d = .02$, and $\beta_d = 20$; $\tau_c = \tau_d = .05$.

Which Catastrophes to Avert?

- To answer that we need the cost of averting each catastrophe, which we express as a permanent tax on consumption at a rate just sufficient to pay what is required to avert the catastrophe.
- Denote these costs by τ_c and τ_d for the consumption (nuclear) and death (virus) catastrophes.
- We set $\tau_c = .05$ and $\tau_d = .05$.
- To find optimal policy, calculate net (of taxes) welfare of doing nothing (W_0), averting only nuclear (W_c), averting only the virus (W_d), and averting both ($W_{c,d}$)
- In this example, usually optimal to avert both. But reducing VSL parameter to $s = 3$, which reduces value of averting the virus, and if $\eta = 4$, optimal to only avert nuclear terrorism.

Conclusions

- Studies of potential catastrophes usually treat them in isolation. Can lead to policies that are far from optimal.
- Major catastrophes (by definition) are not marginal events. Thus inherently interdependent.
- Earlier work showed how to find set of catastrophes to be averted, but based on loss of consumption.
- Now we show how to incorporate death, using VSL estimates.
- Get WTP to avert consumption catastrophe, to avert death catastrophe, and to avert both.
- Death far worse than "destruction." In the example with "base case" parameter values, w_d is about twice as large as w_c.
- Application: valuing government subsidy for new antibiotics.