How bad would nuclear winter caused by a US-Russia nuclear exchange be?

Luisa Rodriguez | June 2019 | Rethink Priorities

Summary

In this post, I quantify the severity of the nuclear winter we might expect to result from a nuclear war between the US and Russia ([Guesstimate model here](#)).

Researchers who have studied nuclear winter estimate that a nuclear war that produced between 50 and 150 teragrams of smoke would make agriculture nearly impossible, causing most people on Earth to starve to death and leaving humanity on the brink of extinction.

But most of the research into nuclear winter was done at the height of the Cold War when the US and Russian nuclear arsenals and nuclear policies looked quite different. I [previously argued](#) that the US and Russia would be more likely to target each others' nuclear forces during a nuclear war, rather than target each others' cities as they would have done during the Cold War. This makes a big difference in whether a US-Russia nuclear exchange would lead to a severe nuclear winter.

Nuclear attacks on cities would likely produce much more smoke than attacks on missile silos, military bases, and other nuclear arsenal targets. This is mainly because cities have much more flammable material to burn than the remote wildlands — mostly cropland and grasslands — that surround, for example, missile silos.

This leads me to conclude that a nuclear war between the US and Russia would likely produce closer to 31 teragrams of smoke (90% confidence interval: 14 Tg to 68 Tg of smoke) — suggesting that nuclear winter is not as synonymous with US-Russia nuclear war as many effective altruists seem to assume. The ~31 teragrams of smoke that would be vaulted into the atmosphere would undoubtedly produce severe climate effects, likely leading to food shortfalls and regional famines, and killing between 36% and 96% of the world population.

I think the finding points us toward being a bit more skeptical of the idea that some effective altruists seem to hold — that a nuclear war between the US and Russia would necessarily lead to a nuclear winter that posed a large risk of extinction. There's about an 11% chance that 50 Tg of smoke — the threshold at which the literature suggests the resulting nuclear winter would be catastrophic — are released into the atmosphere by a Russia-US nuclear war. To be clear, this 11% risk is non-trivial, and it's plausible that even a so-called nuclear autumn (the result of between ~5 and ~50 Tg of smoke) would pose some sort of x-risk.

As a final point, I'd like to emphasize that the nuclear winter is quite controversial (for example, see: [Singer, 1985](#); [Seitz, 2011](#); [Robock, 2011](#); [Coupe et al., 2019](#); [Reisner et al., 2019](#); [Pausata et al., 2016](#); [Reisner et al., 2018](#); Also see the summary of the nuclear winter controversy in [Wikipedia's article on nuclear winter](#)). Critics argue that the parameters fed into the climate models (like, how much smoke would be generated by a given exchange) as well as the assumptions in the climate models themselves (for example, the way clouds would behave) are suspect, and may have been biased by the researchers' political motivations (for example, see: [Singer, 1985](#); [Seitz, 2011](#); [Reisner et al., 2019](#); [Pausata et al., 2016](#); [Reisner et al., 2018](#)). I take these criticisms very seriously — and believe we should probably be skeptical of this body of research as a result. For the purposes of this

estimation, I assume that the nuclear winter research comes to the right conclusion. However, if we discounted the expected harm caused by US-Russia nuclear war for the fact that the nuclear winter hypothesis is somewhat suspect, the expected harm could shrink substantially.

December 19, 2019 Update

In light of feedback from Carl Schulman, Kit Harris, MichaelA, David Denkenberger, Topher Brennan, and others, I've made several revisions to this post that are now reflected in the text, figures, and estimates in the body of this post. The original post can still be found [here](#).

The changes that had the largest bearing on my results included:

- Correcting three typos in the formulas in my Guesstimate model (details [here](#))

- Changing the way I estimate the number of nuclear weapons that would be used in a countervalue nuclear exchange in expectation so that I don't accidentally truncate the tails of the distributions (details [here](#))

- Accounting for the fact that the US and Russia would probably detonate multiple nuclear bombs on large cities in the event of countervalue targeting (details [here](#))

- Accounting for the fact that counterforce targeting would likely involve nuclear detonations in and around some very large population centers, despite those cities not being the primary targets of the detonations (details [here](#))

After making these revisions and corrections, my estimate of the amount of smoke that would be lofted into the atmosphere went up from 20 Tg of smoke (90%CI: 7.9 Tg to 39 Tg of smoke) to 30 Tg of smoke (90%CI: 14 Tg to 66 Tg of smoke). Given this, the probability that a US-Russia nuclear exchange would cause a severe nuclear winter — assuming 50 Tg of smoke is the threshold for severe nuclear winter — goes up from just under 1% to about 11%.

Total smoke generated by a US-Russia nuclear exchange (teragrams)

31
13 to 67

50.09
87.70th percentile

0   10   20   30   40   50   60   70   80   90   100
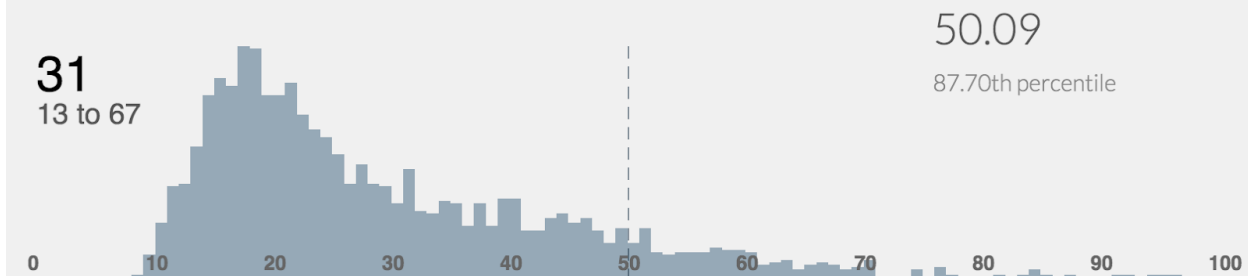
The impacts that each individual change had on my results can be seen [here](#).

Thanks again to those who offered feedback, and also to Jaime Sevilla, Ozzie Gooen, Max Daniel, and Marinella Capriati for feedback and support implementing the revisions.

Project Overview

This is the fourth post in [Rethink Priorities](#)' series on nuclear risks. In the [first post](#), I look into which plausible nuclear exchange scenarios should worry us most, ranking them based on their potential to cause harm. In the [second post](#), I explore the make-up and survivability of the US and Russian nuclear arsenals. In the [third post](#), I estimate the number of people that would die as a direct result of a nuclear exchange between NATO states and Russia. In this post, I estimate the severity of the nuclear famine we might expect to result from a NATO-Russia nuclear war. In [the fifth post](#), I get a rough sense of the probability of nuclear war by looking at historical evidence, the views of experts, and predictions made by forecasters. Future work will explore scenarios for India and Pakistan, scenarios for China, the contradictory research around nuclear winter, the impact of several nuclear arms control treaties, and the case for and against funding particular organizations working on reducing nuclear risks.

Modeling the impacts of a nuclear famine following a US-Russia nuclear exchange

In addition to the direct harm caused by a nuclear US-Russia nuclear exchange — which [I expect would kill between 30 million and 75 million people](#) — some experts believe that a large-scale nuclear war would have even more devastating effects than those caused by the initial explosion (see, for example, [Robock, 2010](#)). Following a nuclear detonation, all of the surrounding plant-life and infrastructure within the radius of the resulting fireball would be

burned up. In the event that many nuclear weapons were detonated, the resulting fires would be massive, producing huge amounts of smoke. And as the smoke rose into the sky, upward moving winds caused by the detonation would force the smoke high into the atmosphere — so high that the smoke might not be affected by the weather. Too high to be rained out of the atmosphere, the smoke could take 5-10 years to dissipate.

In a large scale nuclear exchange where several thousands of nuclear weapons are detonated, the smoke would spread enough to cover the entire Earth, eventually blocking out thermal radiation from the sun. Simultaneously, the smoke would disrupt the water cycle, causing annual rainfall to decrease globally. During the 5-10 years when the smoke is stuck up there, ice age-like temperatures would kill most crops, and a combination of the temperature and precipitation changes would make almost all agriculture impossible. If this phenomenon, known as "nuclear winter," came to pass, it would likely to lead to unprecedented global famine (Robock, 2010). According to the work by Toon et al. (2007) on the climate effects of nuclear war, similar effects, though more limited in scale, would result from a smaller scale nuclear exchange.

But it turns out that the amount of smoke that would be lofted into the atmosphere — the key mechanism in the nuclear winter hypothesis — depends a lot on whether the US and Russia would primarily target each other's nuclear forces during a first strike (counterforce targeting) or each other's cities and industry (countervalue targeting). For several reasons, nuclear attacks on cities would likely produce much more smoke than attacks on missile silos, military bases, and other targets associated with counterforce targeting. Most importantly, cities have much more flammable material to burn than the remote wildlands — mostly cropland and grasslands — that surround most counterforce targets.

Minimal flammable material in wildlands surrounding typical missile silo

Enormous amount of flammable material in cities

What is more, I'm told by experts that cities are more ignitable than the wild areas around a majority of counterforce targets. Even forests, the ecosystems that would produce the most smoke, aren't nearly as likely to catch fire as the non-organic material in cities. Moreover, the combustible material in forests would burn _cleaner _than that in cities, making the smoke less opaque ([Crutzen, Galbally & Bruhl, 1984](#)). Because the smoke generated by wildland fires would block less thermal radiation than the smoke produced in cities, the climate impacts of wildland fires would be much less severe relative to those caused by city fires.
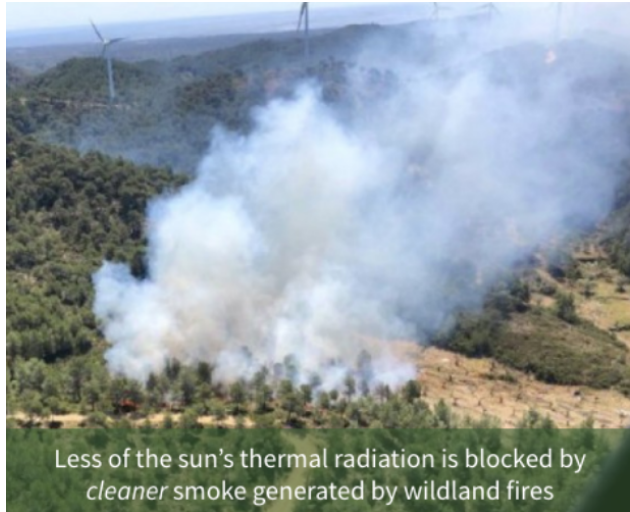
Less of the sun's thermal radiation is blocked by *cleaner* smoke generated by wildland fires

More thermal radiation is blocked by more opaque smoke generated by wildland fires

On the other hand, I've learned from experts that buildings that topple over would create rubble piles that would actually shield some flammable material from the fires, meaning that a smaller proportion of the flammable material in cities would actually burn relative to that in wild areas. But even taking this into account, my understanding is that the sheer volume of material would lead detonations in population centers to produce orders of magnitude more smoke.

As I've argued [previously], I expect that a first strike by either the US or Russia would focus on counterforce targeting, and that the exchange would be somewhat unlikely to escalate to the point of limited countervalue targeting, and even more unlikely to escalate to full-scale countervalue targeting. Consequently, this means that the amount of smoke generated by a US-Russia nuclear exchange may be less substantial in expectation than previously believed.

To understand this more concretely, I crudely quantify the severity and impacts of the nuclear famine we might expect to result from a US-Russia nuclear exchange (see my [Guesstimate model]). To do this, I look at each step in the causal chain in turn.

First, I explore the specifics of the relationship between the number of civilian and military targets that might be attacked and the amount of smoke that's generated.

I then look at the relationship between smoke in the atmosphere and the climate — for example, the effects on growing seasons and rainfall — to understand the impact of the resulting environmental effects on agriculture.

Finally, I'll consider the number of people we might expect to starve to death as a result of those agricultural effects.

Along the way, I'll note how uncertainty, and the simplifying assumptions I make to deal with that uncertainty, might bias my results.

The scale of a US-Russia nuclear exchange

I expect that a US first strike against Russia would involve around 1,300 nuclear weapons used exclusively on counterforce targets (90% confidence interval: 670 – 1,700), and that a Russian first strike against the US/NATO would involve around 1,100 nuclear weapons (90% confidence interval: 750 – 1,200), also exclusively used on counterforce targets.

I expect that a counterforce second strike would look pretty similar to a first strike, though it's possible that a second strike by Russia would be somewhat smaller than its first strike.[1]

As I discussed in my previous post, I also put _some _probability on the US or Russia electing to engage in countervalue targeting. I think the chances that Russia uses countervalue targeting against the US (conditional on Russia using a nuclear strike of any kind) are somewhere between 7% and 81%, and that the chances that the US uses countervalue targeting against Russia are about half that — somewhere between 5% and

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[1] As I've argued previously, if the US or Russia detected an imminent first strike — especially one large enough to take out a significant portion of their arsenal — they would almost certainly decide to retaliate in kind before their arsenal was destroyed (this incentive is called "Use it or Lose it"). To do this, each country would have to decide, in a very short amount of time, to "launch on warning," (LOW) (as opposed to "launch under attack," which basically just means waiting until the bombs starts hitting before you retaliate). Given just a short amount of time, the country under attack wouldn't have much time to tailor its second strike based on factors like which ICBM silos are now probably empty. Given this, I expect that their second strike would probably look reasonably similar to a first strike. What is more, to ensure the 'survivability' of their nuclear forces, both the US and Russia have divided their nuclear capabilities across three forms of deployment: land-based intercontinental ballistic missiles (ICBMs), sea-launched ballistic missiles (SLBMs), and air-based strategic bombers. This is known as the nuclear triad. The different deployment types make it possible to conceal and move nuclear weapons around, making them harder to detect and destroy, which in turn makes them more likely to survive a counterforce strike. I looked into the survivability of the US and Russian nuclear arsenals and found that as somewhere between ~990 and ~1,500 of the US's nuclear warheads and ~450 and ~1,420 of Russia's nuclear warheads could plausibly survive a counterforce first strike. This makes me think that the US would have enough surviving warheads to execute a second strike that would look similar to a first strike even in the case that Russia did destroy the US's vulnerable nuclear forces. Because Russia's nuclear arsenal is a bit more vulnerable, its second strike might be around the same size as its first strike, or it might be smaller — perhaps half the size of its first size. This means that simple addition might lead me to overestimate the number of deaths caused by counterforce targeting, though I suspect it wouldn't be by much. This is because whether a counterforce second strike by Russia would actually cause fewer deaths than a first strike is conditional on 1) the US striking first, 2) Russia choosing not to launch on warning, and 3) Russia being substantially under-prepared for a first strike. My best guess is that the probability of all three of these being the case is fairly low. If we naively assume that the probability that the US strikes first is 50%, the probability that Russia chooses not to launch on warning is also 50%, and that the US counterforce strike destroyed the 'center value' of the range for the number of nuclear weapons that might be destroyed (870), or 79% of the number of warheads I expect Russia would use against the US during a counterforce _first _strike (1,100), I would expect that a second strike would only use about 5% fewer nuclear weapons than Russian first strike (0.50.50.21). See my post on the survivability of the US and Russian nuclear arsenals for more details.

59%.

Assuming the US or Russia did decide to target the others' cities, I expect it's most likely that their countervalue strikes would be limited to 1-20 nuclear detonations (see my [previous post](#) for details). That said, I also put some weight on the probability that countervalue targeting would escalate. If this did happen, I expect it would escalate to full-scale countervalue targeting, to the point of using hundreds of nuclear weapons to target US cities and industry, rather than stay moderate in scale. Below, I express my views on the probability of limited, moderate, and full-scale nuclear war quantitatively.

I then aggregate these three scenarios into a single nuclear exchange scenario, which reflects the number of nuclear weapons I'd expect to be detonated in a countervalue attack against the US in expectation (so taking into account the probability that an exchange stays limited, escalates a moderate amount, or escalates to a full-scale nuclear war).

Countervalue targeting scenarios	US countervalue strike(s) against Russia		Russian countervalue strike(s) against the US	
	Number of nuclear weapons used	Probability that countervalue targeting stays at this scale	Number of nuclear weapons used	Probability that countervalue targeting stays at this scale
Limited countervalue targeting				
Average	~7	0.5	~7	0.5
95% confidence interval	~1 – 23	0.14 – 0.86	~1 – 23	0.14 – 0.86
Moderate countervalue targeting				
Average	33	0.14	33	0.14
95% confidence interval	20 – 50	0 – 0.47	20 – 50	0 – 0.47
Full-scale countervalue targeting				
Average	250	0.36	240	0.36
95% confidence interval	230 –1,300	0.12 – 0 .67	180 –1,200	0.12 –0 .67
Scale of countervalue targeting, in expectation				
Average	270	1	230	1
95% confidence interval	3.5 – 1,100	–	3.4 – 1,000	–

(See notes on the 95% CI for number of weapons used by the US[2] and Russia.[3] Also note that I do this aggregation by having Guesstimate sample the number of nuclear weapons likely to be used from the three escalation scenarios (limited, moderate, and full-scale) in proportion to the range of probabilities of each scenario.)

There's a fair amount of academic literature on the relationship between the number and size of the bombs detonated in specific countries and the smoke generated by those detonations based on the amount of flammable material in key cities in those countries. I can use this literature to estimate the amount of smoke that is likely to be produced by the counterforce and countervalue targeting I expect to see during a US-Russia nuclear exchange.

The amount of smoke generated by nuclear detonations

In the 80s and 90s, climate scientists Alan Robock, Brian Toon, Richard Turco, J.B. Pollack, and Carl Sagan modelled the amount of smoke and resulting climate effects that would be caused by the type of nuclear exchange that was feared during the Cold War: a full-scale nuclear war with extensive countervalue targeting using the enormous, high-yield nuclear arsenals of the 80s (see for example [Turco, 1983](#)). They found that this type of full-scale nuclear exchange between the US and Russia would generate hundreds of megatons of smoke — enough to cause substantial worldwide climate effects.

These nuclear war scenarios are no longer plausible, as the US and Russian nuclear arsenals are much smaller, lower-yield, and more likely to be used for counterforce targeting rather than countervalue targeting. As a result, the early nuclear winter papers don't tell us much about how bad the nuclear famine that be if the US and Russia were to have a nuclear exchange today.

More recently though, Toon et al. ([2007](#)) published an updated paper estimating the amount of smoke that would be produced by 50 low-yield bombs detonated in major cities in thirteen key countries. Their research showed that, under certain assumptions (discussed

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[2] To generate the parameters of the lognormal distribution I think best fits the number of nuclear weapons that might be used in a full-scale countervalue attack (/series of attacks) on Russia, I enter what I believe to be the median value, the lower bound, the upper bound, the 0.05th percentile, and the the 0.95th percentile. With help from [SHELF](#), I generated the lognormal distribution, lognormal(6.31,0.524), which approximates the values I've entered.

[3] To generate the parameters of the lognormal distribution I think best fits the number of nuclear weapons that might be used in a full-scale countervalue attack (/series of attacks) on the US, I enter what I believe to be the median value, the lower bound, the upper bound, the 0.05th percentile, and the the 0.95th percentile. With help from [SHELF](#), I generated the lognormal distribution, lognormal(6.1,0.567), which approximates the values I've entered.

in "Appendix B"), the amount of smoke generated by a nuclear exchange of a given size can be represented reasonably well by simple algebraic functions.
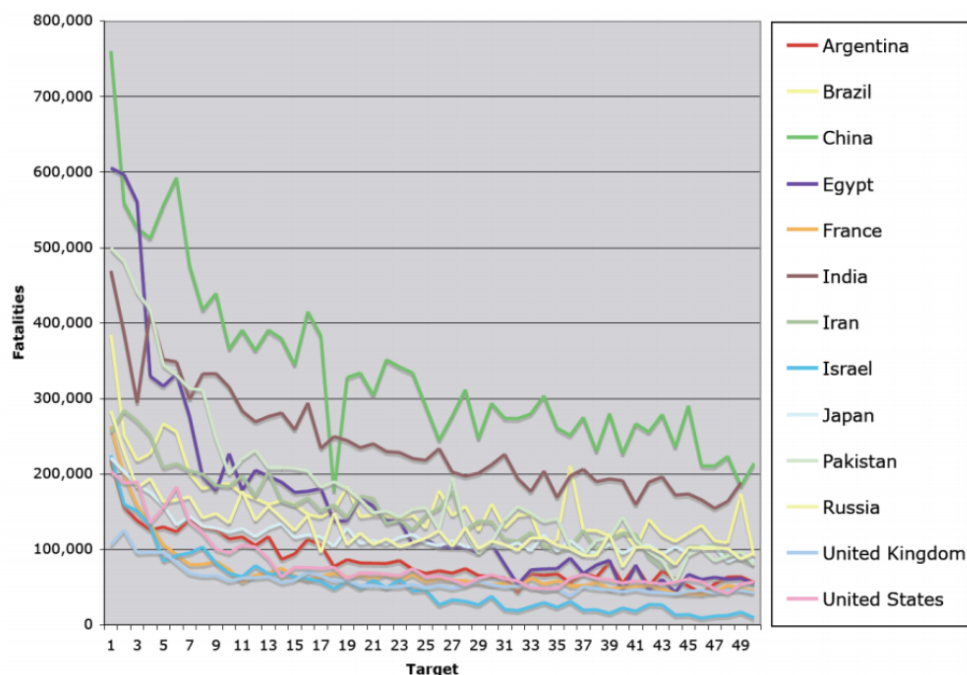

Fig. 6. Potential fatalities caused by airbursts of 15-kt yield on each of 50 targets in the countries listed ([Toon et al., 2007](#))

Source: Figure 12 from Toon et al. ([2007](#))

While the authors didn't publish the data used to generate these functions, I was able to reconstruct the figure above, which allowed me to estimate the country-specific functions on my own (again, see "Appendix B" for details). After adapting the US- and Russia-specific functions to account for the fact that the bombs detonated during a US-Russia exchange wouldn't necessarily be as small as the ones modeled by Toon et al. ([2007](#)), I find that the amount of smoke expected to result from a countervalue attack using x nuclear weapons against the United States can be represented by the following function:

$$Total\ Smoke\ (Tg)_{US} = 0.664x^{0.63}$$

Similarly, the amount of smoke expected to result from a countervalue attack of a given size in Russia can be represented by the following function:

$$Total\ Smoke\ (Tg)_{Russia} = 0.554x^{0.74}$$

The amount of smoke generated by countervalue targeting

If I make two assumptions about US and Russian countervalue targeting, I can use these functions to estimate the amount of smoke that would be produced by the countervalue targeting scenarios discussed earlier.

First, I have to be able to assume that targets would be prioritized on the basis of population size — as this was a key assumption in Toon et al.'s ([2007](#)) work. This assumption seems reasonable to me. If the US or Russia decided to target each other's population centers, I expect they would be trying to maximize fatalities by targeting the most densely populated cities. The exception to this would be if the US or Russia were selecting countervalue targets on the basis of causing economic harm. If this were the case, using the equations I derived from Toon et al. ([2007](#)) would overestimate the amount of smoke produced as industry cities aren't necessarily the most populated cities in either the US or Russia.

I also have to be able to assume that only one nuclear bomb would be dropped on each city targeted. This would not necessarily be the case. But because the first nuclear detonation produces more smoke that subsequent nuclear detonations in the same city, I don't think the assumption is completely unreasonable. Nonetheless, the assumption will likely bias my estimate downward a moderate amount.

Given that the assumptions are at least tolerable, I go ahead and plug in the probability distribution of the number of nuclear weapons I expect to be used in a countervalue exchange between the US and Russia. I find that about 30 Tg of smoke would be generated by the expected countervalue attack against Russia in the event that the US pursued countervalue targeting (90% confidence interval: 1.3 – 100 Tg of smoke). I also find that about 15 Tg of smoke would be produced by the expected countervalue attack against the US, assuming Russia decides to execute countervalue targeting against the US at all (90% confidence interval: 1.4 — 49 Tg of smoke).

However, as I've discussed [previously](#), if the US and Russia did decide to target each others' cities, they would probably choose to drop more than one nuclear bomb on big cities and/or economically important cities to maximize casualties and economic disruption. I roughly estimated the number of nuclear weapons that would be dropped on the four largest US cities and five largest Russian cities. Using the formulas above, I can then calculate the amount of additional smoke that would be caused by the detonation of multiple bombs on particularly big cities. When I did this, I found that multiple detonations on large cities in Russia would lead to an additional ~20 Tg of smoke, and detonations on large cities in the US would probably lead to an additional ~5 Tg of smoke.

When I add this to the estimates above, I find that countervalue targeting in Russia would produce about 49 Tg of smoke (90% confidence interval: 21 Tg – 120 Tg of smoke). Similarly, I find that countervalue targeting against the US would generate about 20 Tg of smoke (90% confidence interval: 6.1 Tg – 53 Tg of smoke).

I then multiply the amount of smoke generated by countervalue targeting against Russia by the probability that the US actually executes countervalue targeting against Russia. This tells me the amount of smoke that would be produced, in expectation. I find that between 0.98 Tg and 20 Tg of smoke would be generated as a result of US countervalue targeting against Russia (6.8 Tg in expectation).

Similarly, when I account for the probability that Russia engages in countervalue targeting, I find that Russian countervalue targeting would produce between 0.83 Tg and 32 Tg of smoke (8.2 additional Tg in expectation).

When I add together the smoke generated by US and Russian countervalue targeting, I find that between 5.1 and 58 Tg of smoke would be generated by countervalue targeting by the US and Russia in expectation:
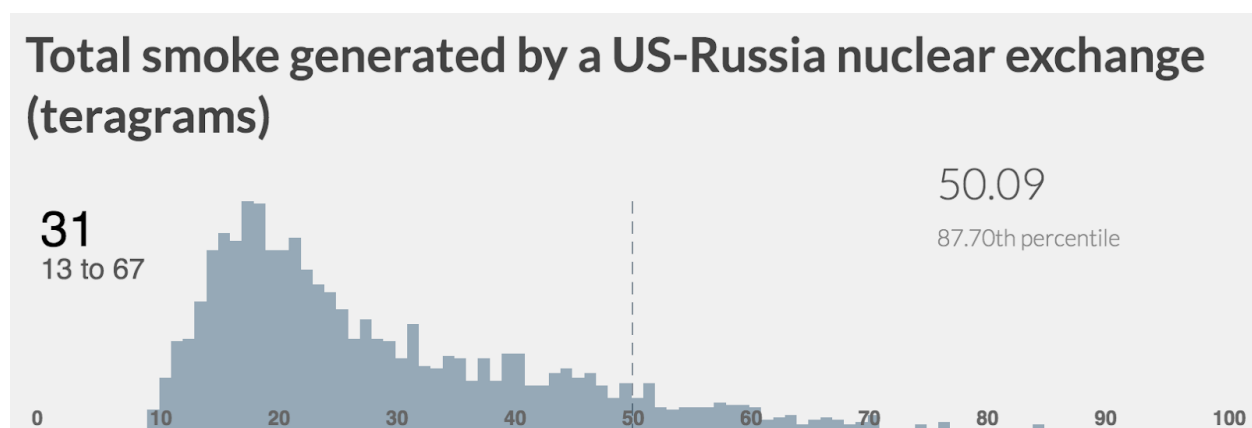
The amount of smoke generated by counterforce targeting

Estimating the amount of smoke generated by counterforce targeting is more difficult. There's also been far less research on counterforce nuclear exchanges; there are only a few papers that speak directly to the amount of smoke that would be generated by counterforce targeting. And the research that has been done has modeled the impacts of counterforce strikes that would be implausible today — much larger than what the US and Russia would actually be able to execute (Turco, 1983; Crutzen & Birks, 1982; Crutzen et al., 1984; Small & Bush, 1985).

Further, most estimates of the amount of smoke that would be produced by a counterforce exchange suffer from methodological problems that likely led to gross overestimates. In particular, the models assume that the areas surrounding (most) counterforce targets would have much more fuel loading — the amount of flammable material (fuel) per unit area — than they actually do (Turco, 1983; Crutzen & Birks, 1982; Crutzen et al., 1984).

Given this, I decided to manipulate the data functions I derived using Toon et al.'s (2007) work to estimate the smoke that would be generated by counterforce targeting while accounting for two factors:

1. As I discussed above, the amount of smoke that would be produced by the burning of the wildlands that surround counterforce targets (like missile silos and military

bases) would be just a fraction of the amount that would be produced by city fires.

2. Assuming that countervalue targeting prioritizes cities in order of population density, the amount of smoke produced by countervalue targeting decreases sublinearly as the number of bombs detonated increases. In contrast, the smoke generated by counterforce targeting would increase linearly. Unlike in countervalue targeting, there's no reason that the 10th counterforce target would produce a different amount of smoke than the 100th counterforce target.

To do this, I first estimate the total amount of smoke that would be generated by fires in the US and Russia assuming a linear relationship between the number of detonations and smoke produced. I then multiply those estimates by the factor by which the areas surrounding counterforce targets have smaller fuel loadings than cities do. I estimate that factor by dividing the fuel loading of the wildlands (0.03 g/cm2 – 0.55 g/cm2) around counterforce targets by the fuel loadings of cities in the US and Russia (18 g/cm2 and 12 g/cm2, respectively) (See "Appendix C" for details).

When I plug in the number of targets the US and Russia would each target during a counterforce first strike and then adjust for the factor by which wildland fires wouldn't produce as much smoke as city fires would, I find that counterforce targeting by the US against Russia would produce between 0.11 Tg and 2.5 Tg of smoke and counterforce targeting by Russia against the US would produce between 0.31 Tg and 6.1 Tg of smoke.

There is an important exception to the general rule that counterforce targets tend to be in more remote areas. It's fairly likely that a key component to a US or Russian counterforce strike would be to hinder the others' leadership command, control, and communications systems (LC3) — in other words, the people and systems responsible for authorizing and carrying out nuclear attacks. To do this successfully, both countries would likely target each others' capitals. Because Moscow and Washington DC are relatively dense cities, the nuclear detonations would generate a fair amount of smoke — more than other counterforce targets and more than I'm accounting for in the smoke estimation above.

To better account for this, I separately estimate the smoke generated by multiple nuclear detonations in both Washington DC and Moscow. I do this by using equations I derived from Toon et al. ([2007](#)), which can be used to estimate the amount of smoke generated by the nth target hit in a nuclear attack on US and Russian cities (see "Appendix C" for details). Because I assume that cities will be targeted in order of population size, I can plug in the population size ranking for n to estimate the amount of smoke generated by a detonation on each city. I find that, if both the US and Russia both definitely targeted each others' capital cities, between 2.3 Tg and 5.4 Tg of smoke would be generated.

I then multiply this by the probability that the US and Russia would target each others' capital cities, which gives me the expected amount of smoke generated by attacks on both Moscow and Washington DC. I put this probability somewhere between 50% and 100%, because I think they're more like to target each others' capitals than not, but have some uncertainty about exactly how likely it is that they do so. I find that a counterforce attack on Moscow and Washington DC would generate between 1.5 Tg and 4 Tg of smoke (2.6 Tg in expectation).

Similarly, there are a number of military targets that are within or close enough to populated cities that detonations on those military targets would have substantial effects on surrounding urban areas. Fires in cities near military sites that were targeted during a counterforce strike would be smaller, and thereby produce somewhat less smoke, relative to a nuclear bombs detonated directly over cities. However, there would be enough additional smoke generated that it's important to account for it in the model.

I accounted for this by looking into the nuclear weapons-related military sites that are in or near cities in the US and Russia with populations greater than 50,000, and then estimating the amount of smoke that would be generated as a result of detonations on those sites. To do this, I again use the equations derived from Toon et al. ([2007](#)), which estimate the amount of smoke generated by the nth target (and because I assume cities are prioritized in order of population size, population size ranking can be plugged into the equation for n). When I do this for all of the cities near likely military targets, I estimate that counterforce targeting near cities would cause an additional 3 Tg of smoke to be generated in Russia and an additional 2 Tg of smoke to be generated in the US.

Because it's unclear how much less smoke will be produced by nuclear detonations on military targets in or near cities, I make the simplifying assumption that the smoke would be the same as that generated by a nuclear detonation directly on that city.

When I add up the smoke generated by counterforce targeting in remote areas plus the counterforce targeting on Washington DC and Moscow and cities near key military targets, I find that counterforce targeting by the US and Russia would generate between 7.1 Tg and 12 Tg of smoke, or 8.8 Tg in expectation.
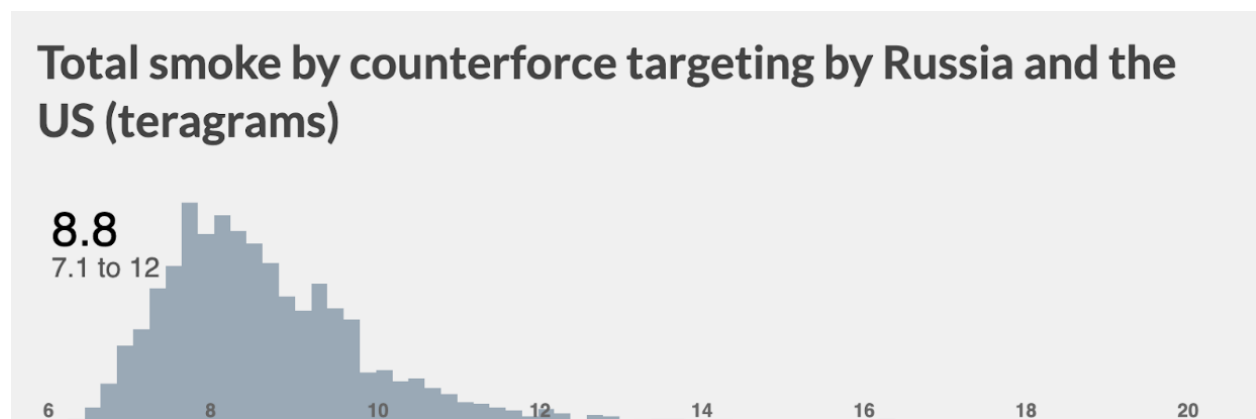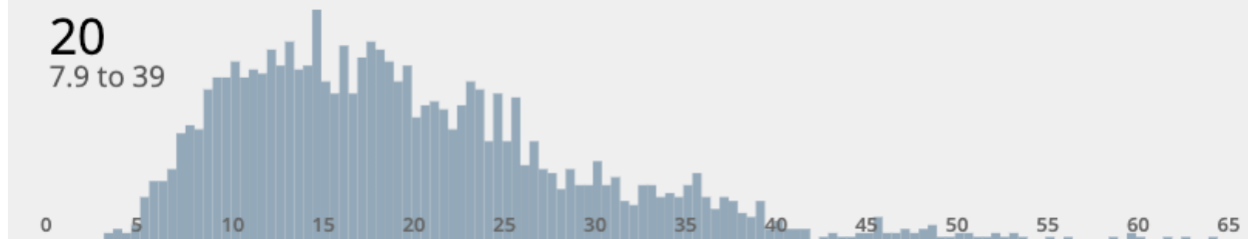

The total amount of smoke generated by a US-Russia nuclear exchange

When I combine the smoke that would be generated by counterforce and countervalue targeting by both the US and Russia, I find that between 13 Tg and 67 Tg of smoke would be emitted into the atmosphere in expectation:[4]

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[4] There are a few problems with adding the number of deaths caused by counterforce and

Total smoke generated by a US-Russia nuclear exchange (teragrams)

20
7.9 to 39

But this range is quite sensitive to conclusions I've drawn that well-informed experts seem to disagree on. In particular, whether the US and Russia would target each others' cities makes a big difference to the amount of smoke generated by a US-Russia nuclear exchange. The results are also sensitive to the probability that countervalue targeting would escalate, eventually reaching the point where hundreds of nuclear bombs were dropped on US and Russian cities and industry. To understand how my results change if you hold the view that countervalue targeting or countervalue escalation is inevitable, see Appendix D.

## The relationship between the smoke generated and the climate

From there, I can draw from climate simulations done by the same researchers to explore the climate effects of the smoke generated by the nuclear exchange. Importantly, this research is controversial. Critics argue that the parameters fed into the climate models (like, how much smoke would be generated by a given exchange) as well as the assumptions in the climate models themselves (for example, the way clouds would behave) are suspect, and may have been biased by the researchers' political motivations. I take these criticisms very

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countervalue targeting together. First, as discussed earlier, Russia's second strike may not involve as many nuclear weapons as its first strike, as its nuclear arsenal is somewhat vulnerable. This means adding together the smoke generated by a US and Russian counterforce strike modeled on what I expect a first strike would look like may overestimate the amount of smoke produced. That said, Russia would have at least 450 or so nuclear warheads left. Assuming that cities are prioritized in order of population density, the marginal amounts of smoke produced by nuclear detonations in the 450th city and beyond is basically negligible. I therefore don't expect this to have much bearing on my results. A second problem comes from the fact that the counterforce and countervalue scenarios were considered independently — they're not comprehensive or mutually exclusive. This means that, the probability of all the scenarios in here might be more or less than 1. It also means that the number of nuclear weapons used in both counterforce and countervalue targeting might sometimes be greater than the number of nuclear weapons currently deployed by the US and Russia. Because the probability of countervalue targeting is pretty low, I don't expect this to be the case.

seriously — and believe we should probably be skeptical of this body of research as a result — but for the purposes of this estimation, I assume that the nuclear winter research comes to the right conclusion.

Toon, Robock, and Turco (2014) estimated the climate effects of four nuclear war scenarios — one where 1 Tg of smoke is generated, another where 5 Tg is generated, a third with 50 Tg, and the final with 150 Tg.

For each of these scenarios, they plotted the effects of the smoke on precipitation, temperature, and the length of growing season in key regions in the United States and Eastern Europe. Note that the effects that Toon et al. (2014) report in this graph reflect the magnitude of the effects that we'd see in the years immediately after the nuclear exchange — the period during which the climate effects would be the worst. So, we should think of these effects as an upper bound on the severity of the climate effects, not the average effects across the 10 years over which the authors predict some level of climate disturbances will persist:
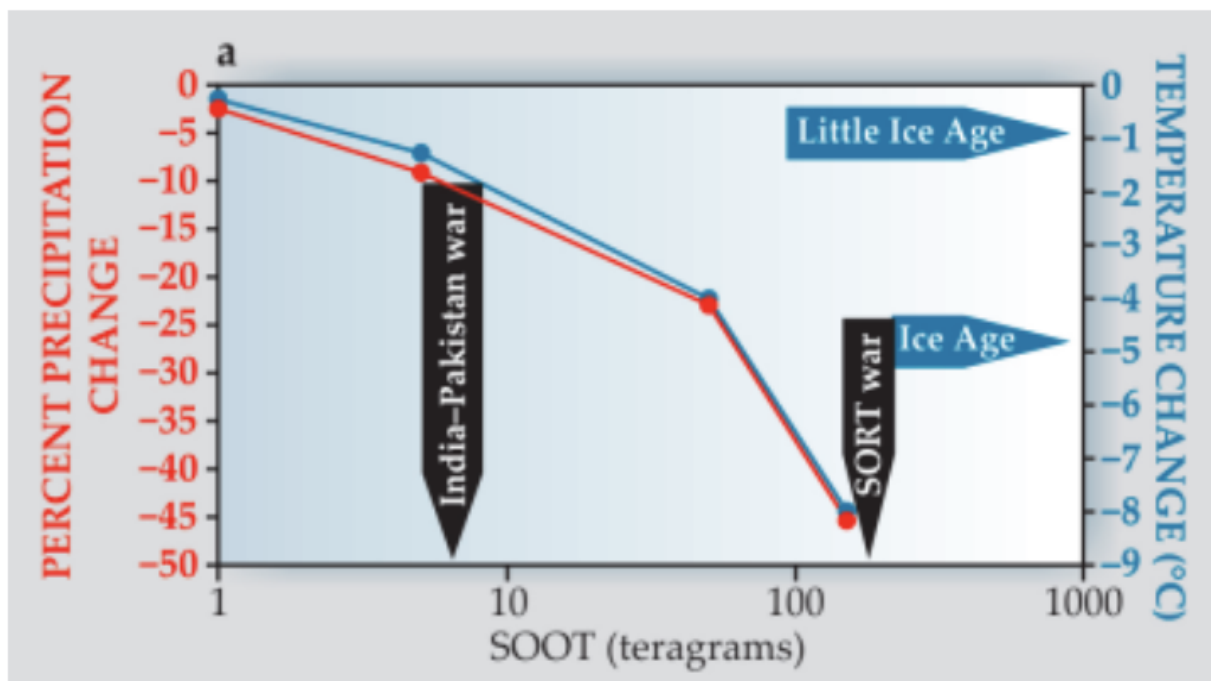
Source: Figure 3a from Toon et al. (2014)

I recreated the figures published in Toon et al. (2014) (see my work here), and estimated functions that roughly fit those curves. The effect of smoke on global precipitation can be approximated using the following equation:
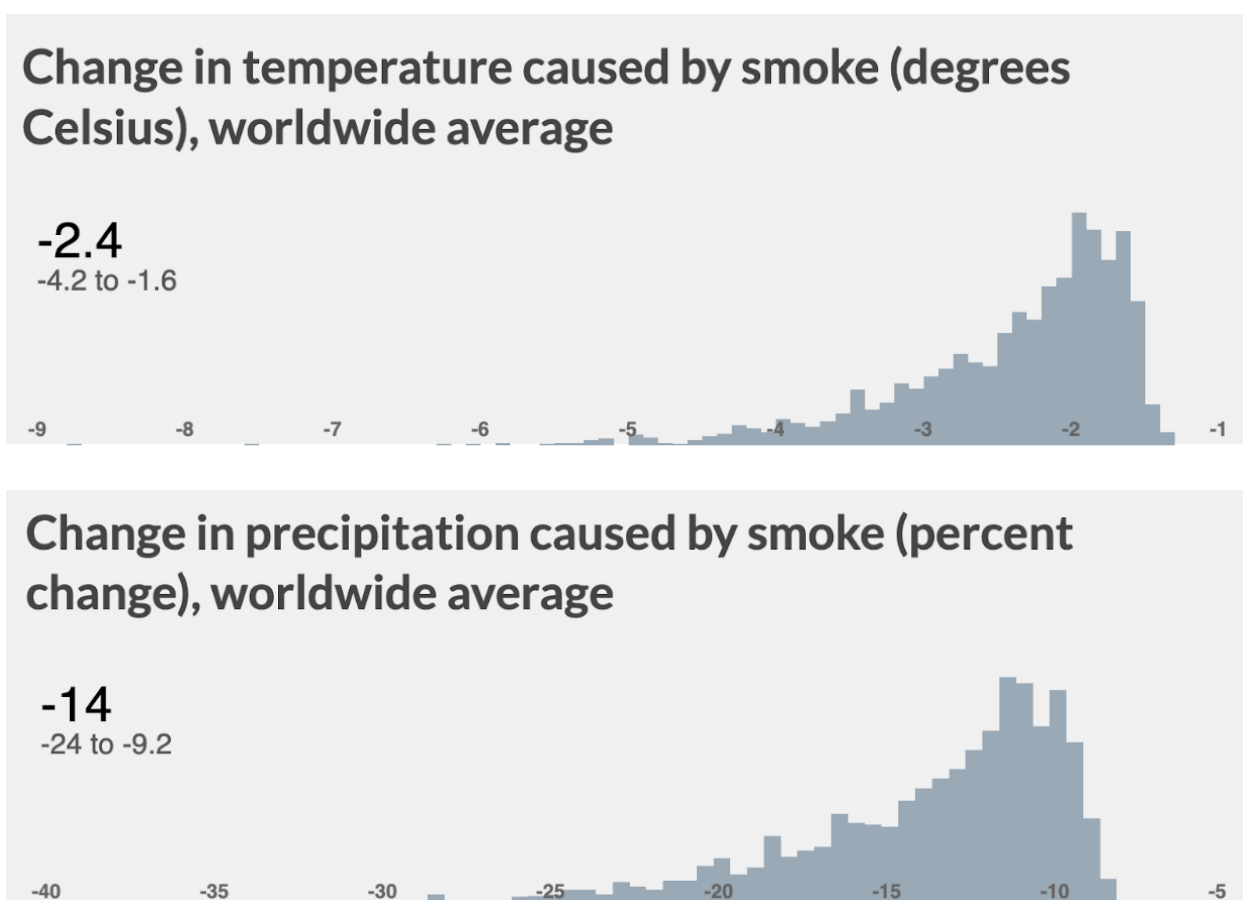
$$Percent\ change\ in\ precipitation_{Global} = -0.0485 * Smoke(Tg) - 0.938$$

Similarly, the effect of smoke on global temperatures (in degrees Celsius) can be

approximated by the equation:

$$Percent\ change\ in\ temperature_{Global} = -0.276 * Smoke(Tg) - 5.55$$

I can then plug in the probability distribution of the amount of smoke expected to be produced during a US-Russia nuclear exchange. This offers a glimpse at the worst climate effects we might expect to see:

Change in temperature caused by smoke (degrees Celsius), worldwide average

-2.4
-4.2 to -1.6

Change in precipitation caused by smoke (percent change), worldwide average

-14
-24 to -9.2

In effect, there's a 90% chance that the actual change in temperature caused by a nuclear exchange between the US and Russia will be between -1.6 degrees Celsius and -4.2 degrees Celsius at its most severe. Similarly, there's a 90% chance that the actual change in precipitation caused by a US-Russia nuclear exchange would be between -9.2% and -24% during the worst period of climate disturbances.

The effects of the climate change on agriculture

Less work has been done to estimate the severity of the effects of nuclear smoke on food production. Harwell and Harwell ([1986](#)) published a pretty extensive review of what we

know about the variations in the climate that we expect to result from a nuclear exchange, and how these variations tend to affect different ecosystems — including agricultural systems.

Because climate effects of the magnitude of those caused by large-scale nuclear war are unprecedented — at least in the context of modern society — it's difficult to create precise models to predict what would happen to modern-day agricultural systems when faced with huge drops in temperature and precipitation. In light of this, Harwell and Harwell (1986) used a bunch of different methods to make broad generalizations about which ecosystems would be affected by various climate fluctuations, and by how much. Specifically, their analysis makes use of historical analogs, statistical analyses, laboratory physiological studies, simulation models, and expert judgment.

Their analyses assumed that the nuclear exchange would cause a decline in temperature of a few degrees [Celsius] over the entire growing season, a decline in sunlight of about 5-20%, and "possible decreases in precipitation." When looking at the effects on agricultural systems specifically, they focused on grain crops, which make up a majority of the calories in the average diet (globally) and are the easiest crops to store.

They found that most ecosystems would be moderately affected by the climate effects, and that agriculture would be substantially affected, though they only offer qualitative comments on how large those effects would be. A drop in temperature of a few degrees was reported to have "extremely large effects" on agricultural systems, and a drop in precipitation was expected to have "large effects."

| System Type	Temperature	Light	Precipitation	Radiation	Ultraviolet-B	Air Pollutants	Fire
Agriculture	●●●●	●	●●●	●●	●	●●	●
○ = essentially no effect ● = low effect ●● = medium effect ●●● = large effect ●●●● = extremely large effect							

Source: Adapted from Table 3 in Harwell and Harwell (1986)

Analyses reported in Toon et al. (2014) make it possible to roughly quantify some of these effects. The authors modeled the effects of temperature and precipitation on the duration of the average growing season in two key agricultural regions, Iowa and Ukraine, plotted here:
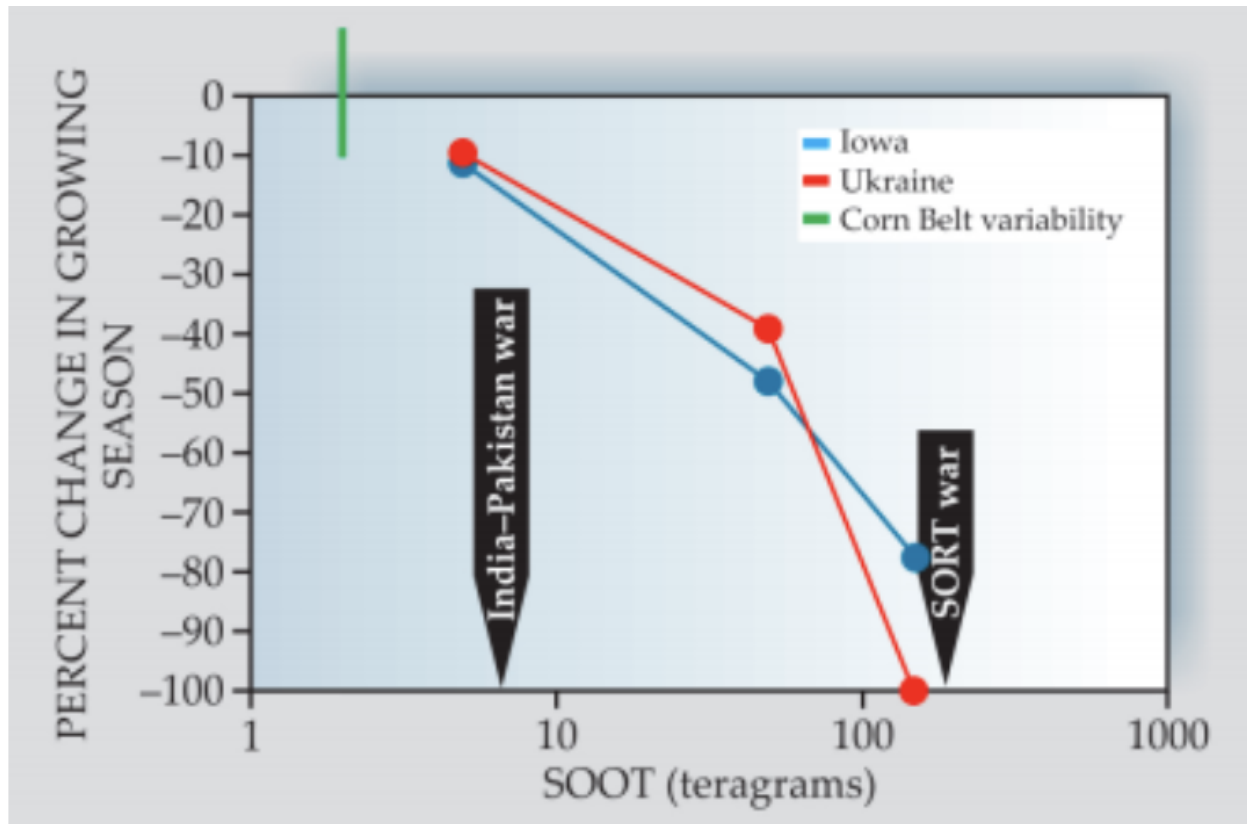
Source: Figure 4 from Toon et al. ([2014](#))

Like above, I was able to extract the data from the figure, plot it, and estimate the functions that reflect the relationship between the amount of smoke produced by a nuclear exchange and the percent change in the growing seasons in both regions (see my work [here](#)). Note that the graph looks a bit different below, because I chose not to present the horizontal axis using a logarithmic scale as the original figure does.

The Effects of Nuclear Smoke on Growing Seasons
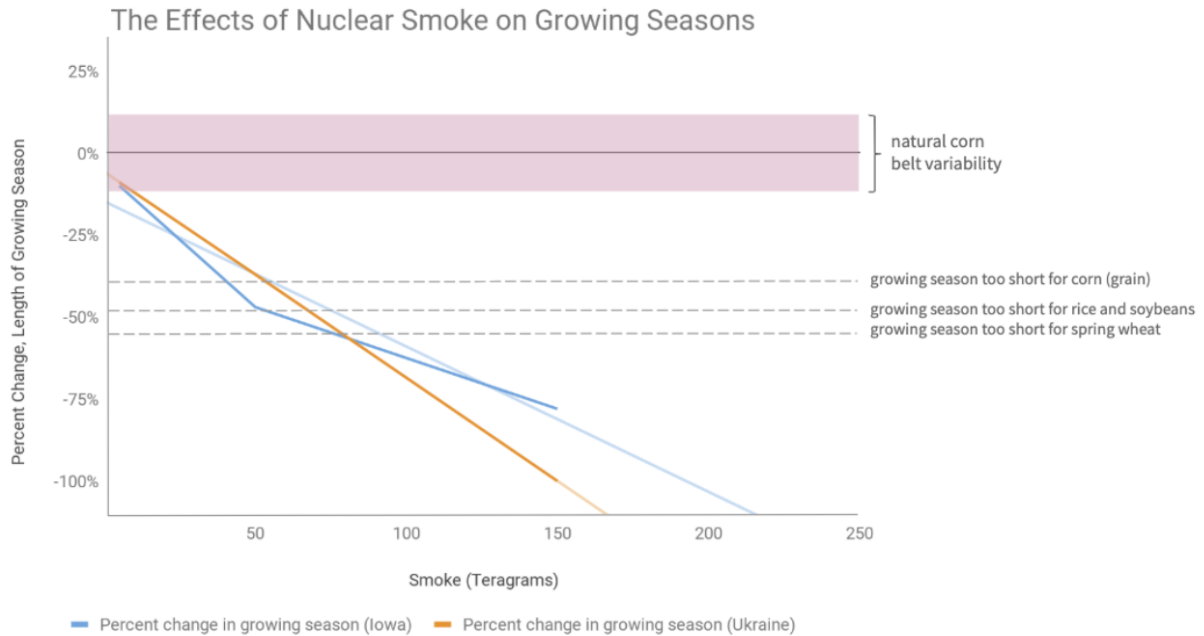
The effect of smoke on the length of the growing season in Iowa can be estimated using the function:

$$Percent\ change\ in\ growing\ season_{Iowa} = -0.443 * Smoke(Tg) - 14.8$$

And the effect of smoke on the length of the growing season in Ukraine can be estimated using the function:

$$Percent\ change\ in\ growing\ season_{Ukraine} = -0.628 * Smoke(Tg) - 5.75$$

Using these equations, I can estimate the probability distributions of the percent change in the duration of the growing season in Iowa and Ukraine. My modeling suggests that there's a 90% chance that the growing season in Iowa will fall by between 21% and 44%, and that the growing season in Ukraine will fall by between 14% and 48%. These estimates are only directly relevant to crop yields in the United States and Eastern Europe, but nonetheless, offer a glimpse of the types of effects we might expect to see.

Change in growing season (Iowa) caused by smoke (percent change)

-24
-32 to -18

-44 -42 -40 -38 -36 -34 -32 -30 -28 -26 -24 -22 -20 -18 -16
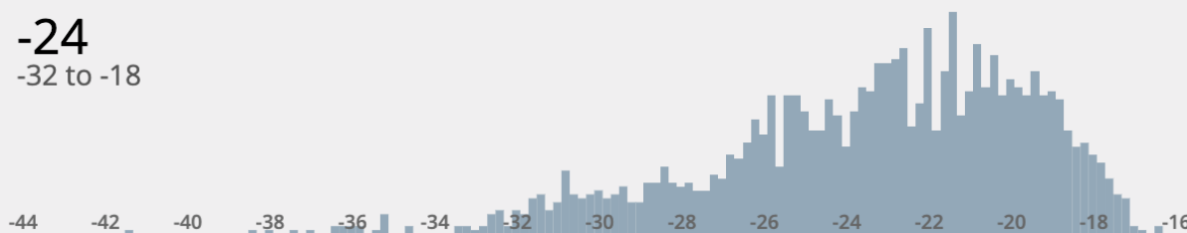
Change in growing season (Ukraine) caused by smoke (percent change)

-18
-30 to -11

-50 -45 -40 -35 -30 -25 -20 -15 -10 -5
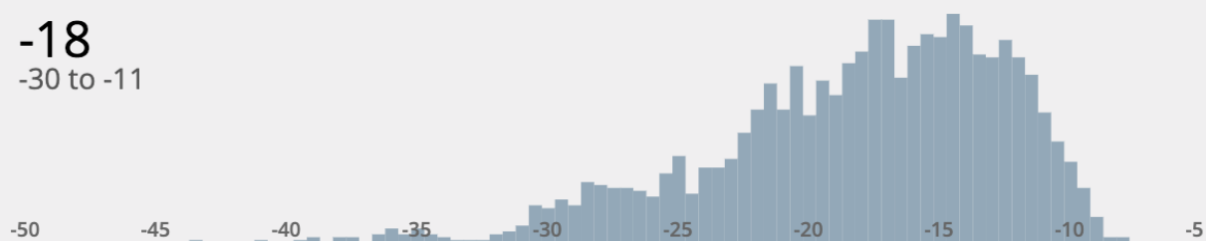
To help interpret these distributions, I estimated the [percent change in the growing season that would prevent the maturation of](#) — and therefore make it impossible to grow — several key crops, given the fact that both regions have average annual growing seasons lasting about 190 days on average (ranging from [160 to 210 days in Des Moines, Iowa](#), and from [170 to 210 days in Kiev, Ukraine](#)).

| Crop | Percent change in the growing season that would make cultivation impossible | |
	Iowa	Ukraine
Corn (Grain)	41%	42%
Soybeans (dried)	47%	47%
Spring Wheat	52%	53%
Rice	44%	45%

Given that it's likely that the growing season would shorten by 28% in Iowa and 25% in Ukraine in expectation, the annual supply of corn, soybeans, spring wheat, and rice will probably fall a fair amount. Additionally, it's plausible, though pretty low-probability (~5%), that growing some of them would become impossible.

Again, these effects are specific to particular regions in the United States and Eastern Europe. Regions closer to the poles would be more likely to lose the ability to cultivate certain crops, and regions closer to the equator would be less likely to be affected.

For example, according to Harwell and Harwell ([1986](#)), most agriculture would become impossible in Canada with temperature changes of between 2 and 3 degrees Celsius. Based on my estimation of the temperature effects we might see result from a nuclear exchange, it seems quite likely that Canada (and other countries with similar climates) would face crop failures immediately following a US-Russia exchange. On the other hand, the drop in temperature would have to be between 4 and 6 degrees Celsius to cause crop failures in southern US, and would have to be even larger to cause crop failures in the tropics ([Harwell & Harwell, 1986](#)).

Importantly though, even if crops don't fail completely, fluctuations in temperature, precipitation and sunlight would cause reductions in crop yields. For example, analyses using the historical record and computer simulations revealed that 25% less precipitation was associated with a 25% percent reduction in Australian crop yields ([Harwell & Harwell, 1986](#)). The relationship between rainfall and crop yields likely varies enormously in different regions: in some areas, it might be sub-linear, and in others, super-linear. But the Australian example is nevertheless instructive, offering a glimpse at the magnitude of the reductions in agricultural productivity we might see, even with moderate climate impacts.

What is more, all of these effects would be exacerbated by the reduction or elimination of the availability of agricultural technologies like fertilizer and machinery caused by breakdowns in the transportation systems in the US and Russia. The same technologies would also be unavailable for any countries who import them from either the US or Russia.

An elimination of technological inputs to agriculture — fertilizers, pesticides, herbicides, fuel for tilling and harvesting, machinery — may lead to a decrease in agricultural productivity of up to 50% (Harwell & Harwell, 1986).

Unfortunately, while we can get a general sense of the types of food shortages we might see in the aftermath of a US-Russia nuclear exchange, the exact effects on the global food supply are almost impossible to know for several reasons.

For one, the actual impacts of the climate effects on crop yields would vary a lot by region, which makes estimating those impacts really complicated. And even if we knew exactly how agricultural productivity would be affected, there are a number of things that could be done to mitigate those impacts — measures like shifting from meat-based diets to plant-based ones, and from high-maintenance crops to more robust ones (World Resources Institute, 2016). Those mitigation strategies would probably reduce food shortages to some extent, but it's really hard to know by how much.

Given these complexities, I estimate the severity of the famine we might expect to see by looking at instances where experts have commented directly on the relationship between the smoke produced by nuclear war and the number of people expected to die during the resulting famine.

The relationship between smoke and famine

To date, there have been only a few studies that have commented on the severity of a nuclear famine based on the amount of smoke generated by a nuclear exchange. Below, I summarize their results, focusing on the studies that use the most modern climate models:

Smoke produced (teragrams)	Temperature decrease (degrees Celsius)	Duration of impacts (years)	Precipitation decrease (% change)	Effects on crops	Famine Fatalities
1-5 Tg	-0.25°C (global average)	"several" years	-2% (global average)	not reported	not reported
5 Tg	-1.25°C (global average)	Decreasing effects over 10 years	-10% (global average)	- 10– 30% (China and the Midwestern United States)	Between ~873 million and ~2 billion people
50 Tg	-4°C (global average)	Decreasing effects over 5-10 years	~ -23% (global average)	No food production for "many years" (possibly a decade)	~everyone in the world, except some people in Australia and New Zealand (~7.5 billion people)
75 Tg	~-5°C (global average)	not reported	-25% (global average	not reported	not reported
150 Tg	-8°C (global average) >-20°C (North America) >-30°C (Eurasia)	Decreasing effects over 5-10 years	-45% (global average)	No food production for "many years" (possibly a decade)	~everyone in the world, except some people in Australia and New Zealand (~7.5 billion people)

Sources for this table include Robock et al., 2006; Robock et al., 2007; Robock, 2010; Robock, 2011; Xia & Robock, 2012; Helfand 2013; Toon et al, 2014; and Baum, 2015.

Some of the studies I'm relying on have serious limitations. In particular, the links that Helfand (2013) makes between agricultural shortfalls and famine is (understandably) un-rigorous. To justify his claims that a limited nuclear exchange could lead to 873 million – 2 billion deaths, Helfand (2013) points out that 873 million people are already food insecure, and that another 1 billion plus people in China could become food insecure. He then notes that, historically, food shortages have caused sharp increases in food prices — suggesting that the world's food systems weren't able to compensate for those shortages. Further, he notes that this relationship is super-linear. The larger the shortage, the bigger the impact on the price of food. So it makes sense that food shortages would price out the world's most food insecure — people who are already unable to afford enough food, and who would become even more malnourished if food became more expensive.

All that in mind, I think it's plausible that the 870 million – 2 billion people who are already vulnerable to food insecurity will starve to death, but the relationship between food shortfalls and famine is too complicated to know with any certainty. The world is just really complex. And, as I mentioned, there are a bunch of things we could do to adapt to the altered climate: switch from meat-based diets to plant-based ones and from crops that are more vulnerable to climate variation to crops that are more robust (World Resources Institute, 2016).

Further, with just the couple of data points in that table, I can make educated guesses about

the relationship between the amount of smoke generated by a nuclear exchange and the severity of the resulting famine, but those guesses come with a lot of uncertainty.

As a result, all of my modeling from here on out should be taken as extremely speculative.

I hypothesize that the relationship is best represented by a logistic function (s-curve). This is because, at very small amounts of smoke, our food system would likely be able to compensate for a slight cooling of the climate through the implementation of easy and cheap mitigation strategies.

At somewhat higher amounts of smoke — beyond the level we could easily mitigate — I'd expect the number of people that would starve to death as a result of food shortages to increase rapidly, as the billion or so people that already face food insecurity would be extremely vulnerable to disturbances in the food supply (Food and Agriculture Organization, 2018).

At even higher amounts of smoke, I expect the number of people that would starve to death to increase steadily as colder temperatures had proportionately large impacts on crop yields. At some point, the amount of smoke would lead to Ice Age-like conditions, at which point it seems like just about everyone in the world would die (Robock, 2010).

Because the climate impacts would be somewhat less severe in the Southern Hemisphere, and because warm ocean winds would reduce the temperature effects on islands, it's possible that people living in New Zealand and Australia might survive (80,000 Hours podcast with Dave Denkenberger, 2018).
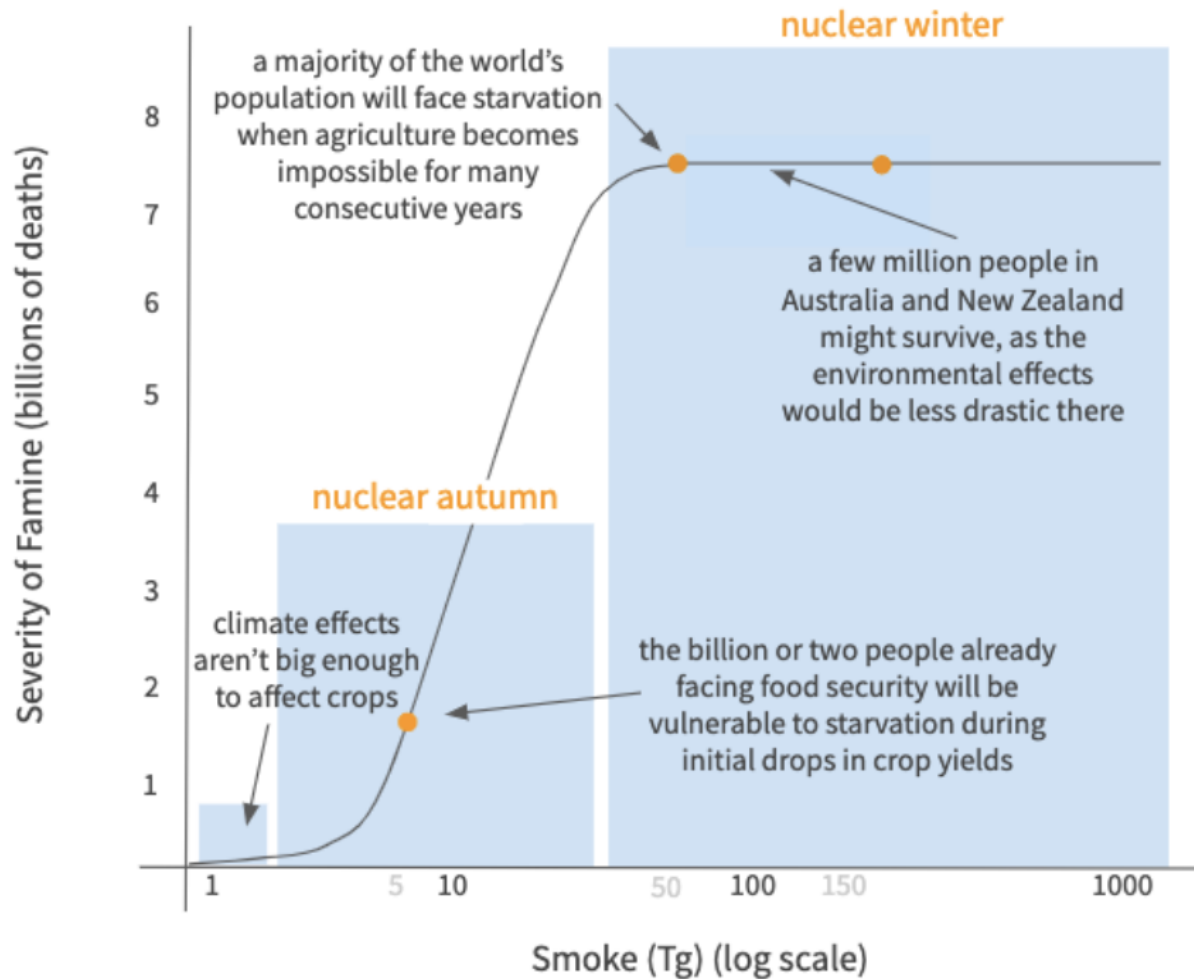
Based on this reasoning, I generated optimistic, pessimistic, and best guess logistic functions that roughly fit the available data points. Again, because there are so few academic papers that comment on this relationship, my estimation of these functions involved a lot of subjective judgment; the optimistic, pessimistic, and best guess curves correspond to my personal interpretation of the information available on nuclear winter. For more details, see my work here.

The amount of nuclear smoke generated and severity of the resulting nuclear famine

Legend: Deaths — Optimistic | Deaths — Best Guess | Deaths — Pessimistic | ● Predicted in Academic Literature
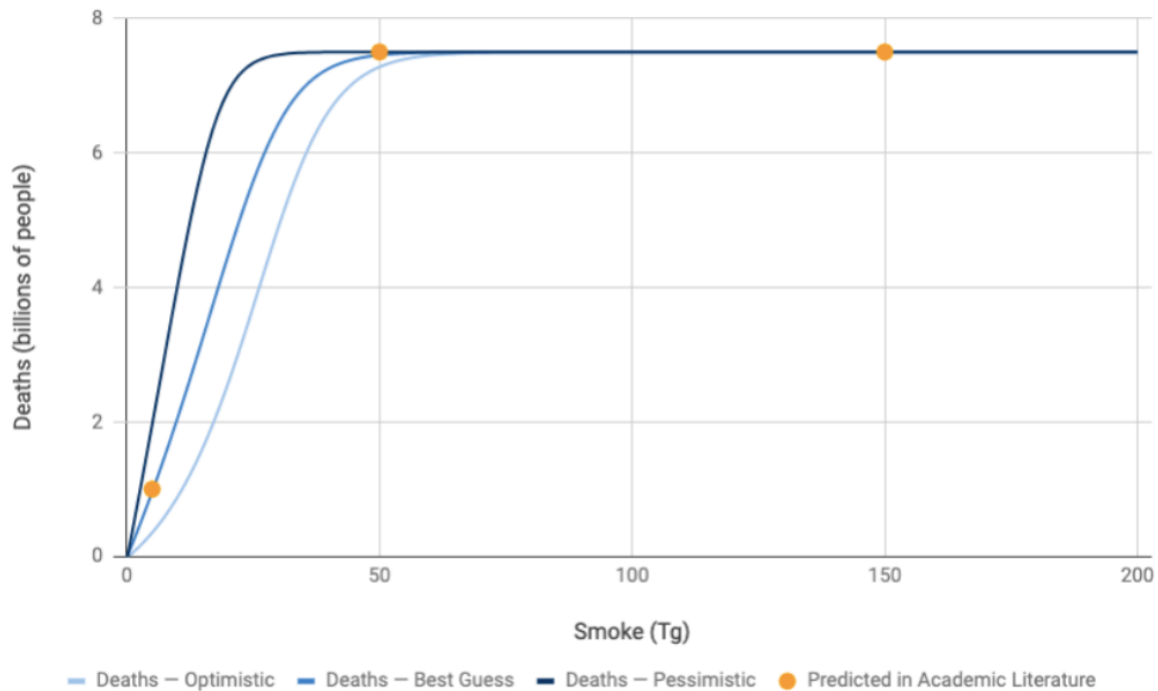
I can then plug in the probability distribution of the amount of smoke we might expect to be generated by a US-Russia nuclear exchange into each function to estimate an optimistic, pessimistic, and best guess estimate of the number of deaths that might be caused by the resulting nuclear famine. I just report the best guess here, but you can see the optimistic and pessimistic estimates in my Guesstimate model.

Total deaths caused by the nuclear famine that would follow a US-Russia nuclear exchange

By my estimation, a nuclear exchange between the US and Russia would lead to a famine that would kill 5.5 billion people in expectation (90% confidence interval: 2.7 billion to 7.5 billion people).

Number of people that would die of starvation as a result of a famine caused by a US-Russia nuclear exchange

5.5B
2.7B to 7.5B

1.5B 2B 2.5B 3B 3.5B 4B 4.5B 5B 5.5B 6B 6.5B 7B 7.5B

A famine killing between 2.7 billion and 7.5 billion would be absolutely horrible. Between 36% and 96% of the world population would die an excruciating and prolonged death.

I don't feel like I have a full grasp of the implications of this yet. On the one hand, I think the finding points us toward being a bit more skeptical of the idea that some effective altruists seem to hold — that a nuclear war between the US and Russia would necessarily lead to a nuclear winter that posed a large risk of extinction. There's about an 11% chance that 50 Tg of smoke — the threshold at which the literature suggests the resulting nuclear winter would be catastrophic — are released into the atmosphere. On the other hand, 11% is non-trivial, and it's likely that even a moderate nuclear winter (the result of between 5 and 50 Tg of smoke) would pose some sort of x-risk.

Either way, the effects, some of which I don't yet completely understand, are potentially really, really terrible — possibly worth investing substantial resources to avert from an x-risk perspective, especially if there are particularly tractable ways to do so or if we expect geopolitical conditions around the likelihood of nuclear war and method of nuclear targeting to change over time.

As a final note, I want to flag that a US-Russia nuclear exchange could have other x-risk-related implications not explored in this work. For example, I don't consider here the risk of famine resulting from nuclear fallout contaminating crops, or the threat posed by a high-altitude electromagnetic pulse (EMP) that could be generated by the detonation of a nuclear bomb at a high altitude (Foster et al., 2008). I hope to do so in future work.

Appendix A: Simplifying assumptions and how they might bias my model

I want to be transparent about the fact that many aspects of my model, especially the probabilities of countervalue targeting and escalation, are very speculative and involved a lot of subjective judgment. Below, I summarize 1) all of the simplifying assumptions I made, 2) the ways they might bias my model, 3) how much those biases might affect my

results, and 4) how hard it would have been to replace that assumption with actual data:

Considerations excluded from the model	If I were wrong about this, my estimate would be an:	Magnitude of bias	How hard it would be to address
I only consider human suffering	Unknown[7] (0)	Unknown (0)	Very hard
The US and Russia would likely only use counterforce targeting during a first strike	Underestimate (-1)	Large (3)	Very hard
The US and Russia would both target *most* of their enemy's nuclear forces during a counterforce strike to reduce the risk and severity of retaliation (rather than execute a more limited counterforce strike)	Overestimate (1)	Small (1)	Pretty hard
I assume zero 'overkill,' which is where multiple nuclear weapons are detonated on the same site to make sure a target is destroyed	Overestimate (1)	Small (1)	Kind of hard
Only deployed nuclear weapons would be used in a US-Russia nuclear exchange	Underestimate (-1)	Large (3)	Very hard
The US and Russia haven't deployed any secret technologies allowing them to track each other's SLBMs, road-mobile ICBMs, or strategic bombers	Overestimate (1)	Large (3)	Very hard
In many cases, a second strike would look pretty similar to a first strike	Overestimate (1)	Moderate (2)	Very hard
A second strike would be proportionate to the first strike	Unknown (0)	Moderate (2)	Pretty hard
A nuclear war would escalate (or not) in the same way and for the same reasons conventional wars escalate	Probably underestimate (-0.5)	Moderate- Large (2.5)	Very hard
In most cases, the costs of escalation to countervalue targeting would outweigh the benefits	Underestimate (-1)	Moderate (2)	Pretty hard

In the context of retaliation and escalation, revenge would usually be a weaker motivation than strategy	Underestimate (-1)	Small (1)	Pretty hard
Russia would only execute countervalue targeting against the US — not other NATO countries	Underestimate (-1)	Moderate (2)	Not hard but time-consuming
Within each countervalue targeting scenario, the number of nuclear weapons used is assumed to be uniformly distributed	Probably underestimate (-0.5)	Small- Moderate (1.5)	Pretty hard
In countervalue targeting where multiple nuclear weapons are dropped on one city, the second, third, etc., nuclear weapons detonated would generate the same amount of smoke as the first	Overestimate (1)	Moderate (2)	Pretty hard
Both Russia and the US would allocate additional nuclear weapons to a given city until the point where an additional nuclear bomb would kill fewer people than the former (in effect, the point at which the surviving population would be smaller than the maximum potential deadliness of another nuclear weapon)	Underestimate (-1)	Small-Moderate (1.5)	Kind of hard
Civilian targets would be selected on the basis of population and would be prioritized in descending order from most to least populated. This wouldn't hold if industrial areas were targeted instead, or if countervalue targeting was used for signaling purposes, like it (arguably) was in Japan.	Overestimate (1)	Moderate (2)	Pretty hard
Nuclear bombs detonated on military targets would be detonated at ground level (surface/ground bursts)	Underestimate (-1)	Small (1)	Pretty hard
Nuclear bombs detonated on civilian targets would be detonated in the air (airbursts)	Overestimate (1)	Small (1)	Pretty hard
The US and Russia would use the median-sized nuclear bomb in their arsenals during a countervalue strike (or the bombs they actually use would roughly equal out to the median).	Unknown (0)	Unknown (0)	Pretty hard

The relationship between target number and smoke can be extrapolated out beyond 50 nuclear detonations.	Unknown (0)	Probably small (1)	Pretty hard
Because both the relationships between bomb size and fatalities and bomb size and smoke generated are both functions of population density, I can use the same scaling factors estimated in my post on the number of deaths we'd expect to be caused directly by nuclear detonations[2]	Unknown (0)	Unknown (0)	Very hard
There is a negligible amount of smoke generated by the detonation of nuclear weapons on counterforce targets near cities with populations under 50,000.	Underestimate (-1)	Small (1)	Pretty hard
The smoke generated by the detonation of nuclear bombs on military targets near cities would be the same as that generated by a nuclear detonation directly on those cities.	Overestimate (1)	Moderate (1)	Pretty hard
The factor by which wildland fires would produce less smoke than fires in the US and Russia can be approximated by dividing the amount of fuel loading in US and Russian cities by the fuel loading in wildlands	Underestimate (-1)	Small (1)	Pretty hard
The fuel loadings of cities with lower population densities than the 50th most dense city in the US and Russia can be approximated by the fuel loadings in the 50 most dense cities	Overestimate (1)	Small (1)	Pretty hard
Subsequent nuclear detonations in Washington DC and Moscow will produce the same amount of smoke as the first. In other words, the detonation radii are non-overlapping and the population densities of the areas hit are the equivalent.	Overestimate (1)	Small-Moderate (1.5)	Pretty hard

The smoke generated by counterforce and countervalue targeting can be added together. In effect, the cities targeted during countervalue targeting would not have already been affected by counterforce targeting.	Overestimate (1)	Moderate (2)	Kind of hard
The nuclear winter research offers an accurate representation of what would happen following a large scale nuclear war	Overestimate (1)	Large (3)	Very hard
The relationship between the amount of smoke generated by a nuclear exchange and the severity of the resulting famine is represented by a logistic function.	Unknown (0)	Unknown (0)	Pretty hard
Helfand's estimates of the number of people that would die as a result of a nuclear famine can be taken as given	Overestimate (1)	Large (3)	Kinda hard
We wouldn't be able to mitigate the agricultural impacts of the climate changes	Overestimate (1)	Moderate – Large (2.5)	Pretty hard
I don't take account of the fact that the people that died during the nuclear exchange can't then die during the nuclear famine.	Overestimate (1)	Small (1)	Kinda hard
Russia and the US wouldn't attack non-nuclear weapons-possessing countries with nuclear weapons	Underestimate (-1)	Moderate (2)	Pretty hard
No other nuclear weapons possessing countries would get involved in a US-Russia nuclear exchange	Underestimate (-1)	Large (3)	Very hard

(Endnotes from the table: note on nonhuman animals,[5] note on prior work,[6] note on counterforce + countervalue overlap).[7]

I aggregate these to try to get a crude sense of how my assumptions will bias my estimate on net:

To do this I first assign a value of -1 to an assumption that would lead my model to produce underestimates, +1 to an assumption that would lead to an overestimate, 0 to an assumption with unknown implications. I then multiply each of those directional values by 1, 2, or 3,

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[5] I consider the effect on wild and domestic animals ambiguous. This is because I'm not sure if most sentient animals are living net positive or net negative lives, so I'm not sure whether it's a good or a bad thing for them to die en masse.

[6] My post on the number of deaths we'd expect to be caused directly by nuclear detonations can be found here.

[7] Because I've considered counterforce and countervalue targeting relatively independently, it may be the case that the number of nuclear weapons used in counterforce and countervalue targeting would sometimes be greater than the number of nuclear weapons currently deployed by the US and Russia.

depending on the magnitude of the bias (i.e. a small bias would be multiplied by 1, a large bias by 3). I can then add the values up to see a rough indication of the direction and magnitude of the bias in my model.

A score of zero would indicate that there are no biases in my model, or equivalently, that all of the biases in my model likely cancel out. Because there are 34 assumptions in my table, a score (in this case) of 102 would indicate that my estimate is likely enormously inflated. In this case, I get a score of 12, which tells me that there's some risk that my estimate is an overestimate.

It's worth noting that this aggregation scheme doesn't take into account the strength of each assumption. Theoretically, the scheme should weigh the magnitude of the bias by how likely the assumption is to be wrong. Because I don't take this into account, I suspect that in this case the extent to which my model systematically overestimates the amount of smoke that would be generated by a US-Russia nuclear war is somewhat overstated.

Appendix B: Estimating the amount of smoke caused by nuclear detonations

Toon et al. (2007) estimated the amount of smoke that would be produced by 50 15-kiloton (kt) bombs detonated in thirteen key countries. The authors found that the amount of smoke generated by a nuclear exchange varies considerably depending on which country the bombs are detonated in — the result of the fact that cities in different countries differ substantially in the amount of flammable material they have (mostly a function of population density):
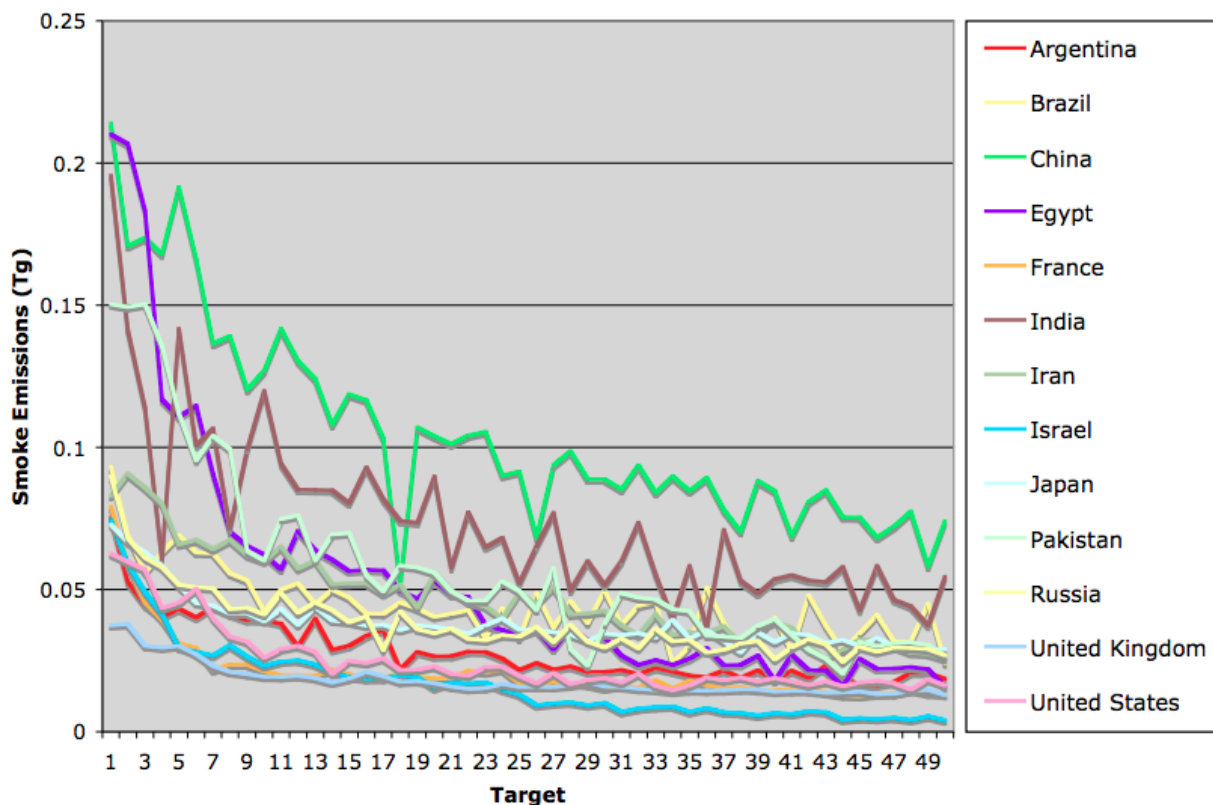
Source: Figure 12 from Toon et al. ([2007](#))

Their research showed that the amount of smoke generated by a nuclear exchange of a given size can be represented reasonably well by simple algebraic functions.

While the authors didn't publish the data used to generate these functions, I was able to reconstruct the figure above, which allowed me to estimate the country-specific functions independently (see my work [here](#) and [here](#)).

But extrapolating from Toon et al. ([2007](#)) relies on three assumptions:

First, I have to be able to assume that targets would be prioritized on the basis of population size — as this was a key assumption in Toon et al.'s ([2007](#)) work. This assumption seems reasonable to me. If the US or Russia decided to target each other's population centers, I expect they would be trying to maximize fatalities by targeting the most densely populated cities. The exception to this would be if the US or Russia were selecting countervalue targets on the basis of causing economic harm. If this were the case, using the equations I derived from Toon et al. ([2007](#)) would overestimate the amount of smoke produced as industry cities aren't necessarily the most populated cities in either the US or Russia.

I also have to be able to assume that only one nuclear bomb would be dropped on each city targeted. This would not necessarily be the case, and assuming so biases my estimate downward a moderate amount. (Note: I'm currently in the process of revising my model to account for the fact that it is likely that more than one bomb would be detonated in many

cities during a countervalue strike).

Finally, I'd have to assume that the bombs detonated during US and Russian countervalue targeting would have an explosive yield of 15 kilotons. Rather, as discussed in my previous post, we should actually expect them to be a fair bit bigger. The median bomb in the nuclear arsenals of the United States and Russia are probably around 300 kt and 500 kt, respectively (Kristensen & Norris, 2018; Kristensen & Korda, 2019).

To account for this, I adapted the functions to account for the fact that the bombs detonated during a US-Russia exchange wouldn't necessarily be 15 kt bombs. I did this by multiplying the estimates generated by the Toon et al. (2007) functions by a factor that accounts for how a 300 kt or 500 kt bomb would generate more smoke than a 15 kt bomb.

Because both the relationships between (a) bomb size and fatalities and (b) bomb size and smoke generated are both functions of population density, I can use the same scaling factor estimated in my previous post on the number of deaths we'd expect to be caused directly by nuclear detonations.[8] According to that estimation, there would be 6.4 times as many US fatalities if Russia were to detonate a 500 kt bomb in a population center instead of a 15 kt bomb. Similarly, a 300 kt bomb would kill about 5.5x as many Russians as a 15 kt bomb.

When I transform the functions, and then extrapolate to larger exchanges, I get the following functions:

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[8] "Surveys of a few large US cities and the centers of cities such as Hamburg, Germany, after World War II, along with the known quantity of flammable material stored in the world, suggest that the amount of fuel per unit area in the urban developed world, Mf, is a linear function of the population density." (Toon, Robock & Turco, 2014, p. 67).

Smoke Generated by Nth Target
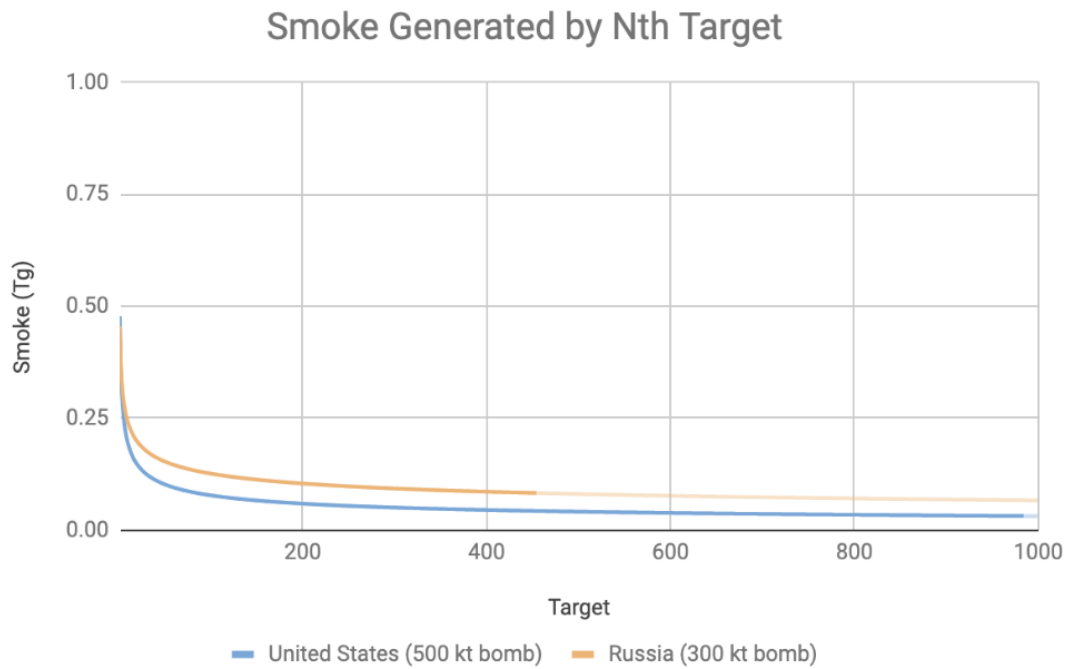
Source: Adapted from Toon et al. ([2007](#))

$$Smoke\ (Tg)_{US} = 0.477 * target\_number^{-0.395}$$

$$Smoke\ (Tg)_{Russia} = 0.455 * target\_number^{-0.279}$$

I transform the functions one more time so that I can estimate the total amount of smoke generated by n targets (i.e., cumulative smoke), rather than the amount of marginal smoke generated by just the nth target. When I do this, I find that the amount of smoke expected to result from a nuclear attack of a given size in the United States can be represented by the following function:

$$Smoke\ (Tg)_{US} = 0.664x^{0.63}$$

Similarly, the amount of smoke expected to result from a nuclear attack of a given size in Russia can be represented by the following function:
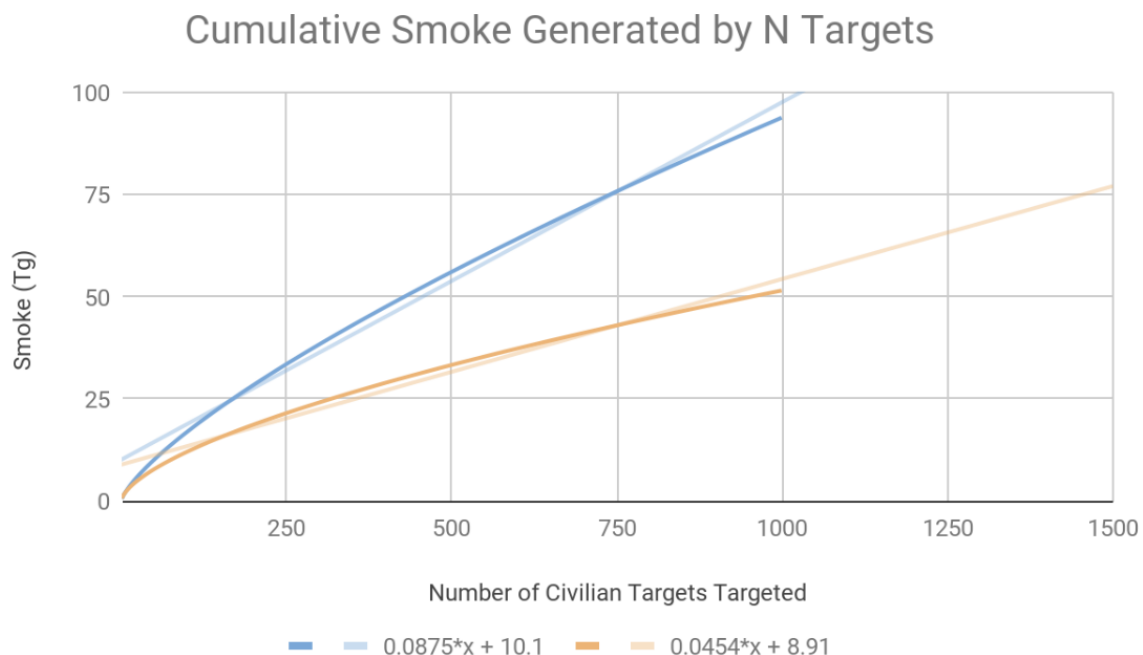
$$Smoke\ (Tg)_{Russia} = 0.554x^{0.74}$$

Appendix C: Estimating the amount of smoke caused by counterforce targeting

To estimate the smoke that would be generated by counterforce targeting, I manipulate the data functions I derived using Toon et al.'s ([2007](#)) work to accounting for two factors that make Toon et al. not directly applicable to counterforce targeting:

1. As I discussed above, the amount of smoke that would be produced by the burning of the wildlands that surround counterforce targets (like missile silos and military bases) would be just a fraction of the amount that would be produced by city fires.

2. Assuming that countervalue targeting prioritizes cities in order of population density, the amount of smoke produced by countervalue targeting decreases sublinearly as the number of bombs detonated increases. In contrast, the smoke generated by counterforce targeting would increase linearly. Unlike in countervalue targeting, there's no reason that the 10th counterforce target would produce a different amount of smoke than the 100th counterforce target.

To do this, I first estimate the total amount of smoke that would be generated by fires in the US and Russia assuming a linear relationship between the number of detonations and smoke produced (see my work [here](#)):

I find that the smoke generated by x nuclear detonations in US and Russian cities can be approximated by the linear functions:

$$Total\ Smoke\ (Tg)_{US} = 0.0875x + 10.1$$

$$Total\ Smoke\ (Tg)_{Russia} = 0.0454x + 8.91$$

I then add a term to these equations to account for the factor by which the areas surrounding counterforce targets have smaller fuel loadings — again, this is the amount of flammable material (fuel) per unit area — than cities do. I estimate that factor by dividing the fuel loading of the wildlands around counterforce targets by the fuel loadings of cities in the US and Russia.

To understand the fuel loadings of cities in the US and Russia, I draw from the work of Toon et al.(2007). Toon and his colleagues assumed that, in cities, there is a direct relationship between the amount of fuel in a given city area and the city's population density.[9] To understand that relationship, Toon et al. (2007) reviewed the literature on the known fuel loadings of other cities, including San Jose, Hamburg, and a few other cities in the US.

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[9] To estimate fuel loadings for the present work, we make a basic assumption that within urban zones there is a direct relationship between the quantity of fuel available and the local population density. Contributing to the fuel load would be dwellings, offices, industries and infrastructure such as schools, transport and fuel depots, shopping malls, and so on. Given the relationship between fuel loading and population density we can use population density data as a surrogate for fuel loading data (Toon et al., 2007, 1989)
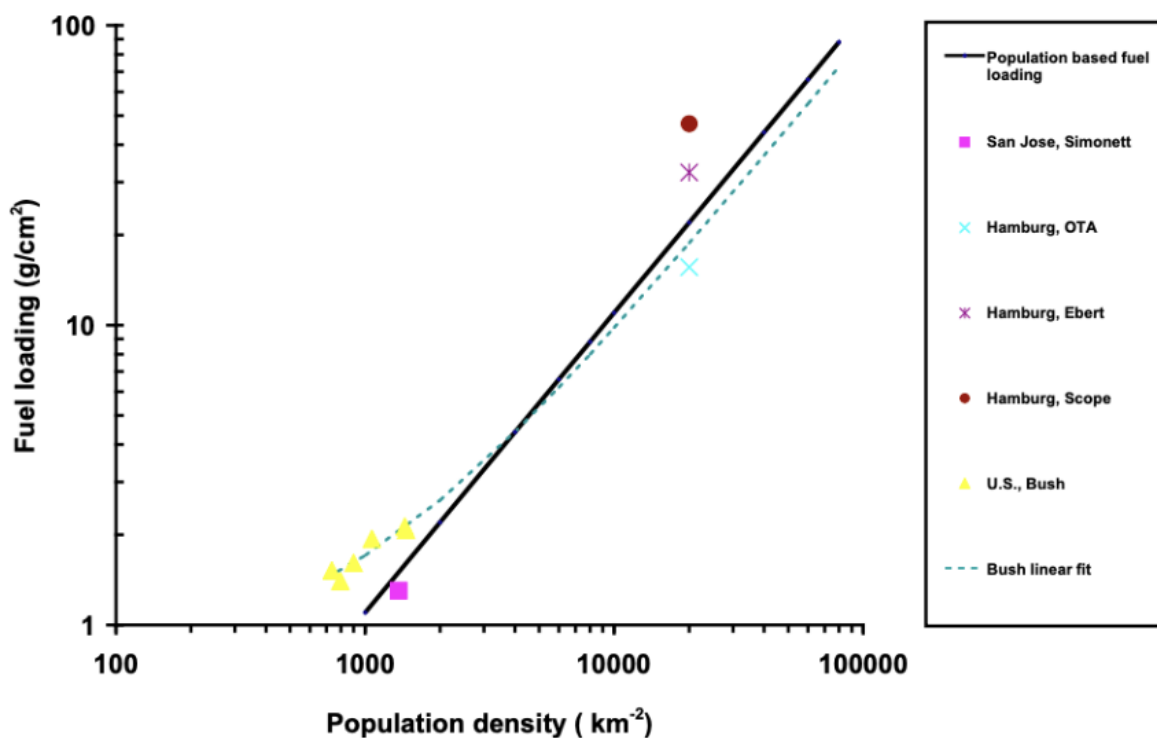
Source: Figure 9 from Toon et al. (2007)

Toon et al. (2007) found that population density did seem to predict the fuel loading found in past research reasonably well — albeit not perfectly. The authors then used this method to predict the fuel loadings in the 50 most densely populated cities in thirteen key countries, including the US and Russia:[10]

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[10] Because the fuel loadings estimated by Toon et al. (2007) reflect the average fuel loadings of the 50 most densely populated cities, using Toon et al.'s fuel loading figures will lead me to overestimate the amount of smoke generated by countervalue targeting scenarios involving more than 50 targets.

Country	Average Fuel Loading (g/cm^2)
Argentina	13
Brazil	21
China	50
Egypt	25
France	10
India	35
Iran	23
Israel	8
Japan	19
Pakistan	28
Russia	18
UK	9
US	12

Source: Adapted from Table 13 from Toon et al. ([2007](#))

I then draw on the work of Small and Bush ([1985](#)), who I believe have done the best work on the smoke generated by counterforce scenarios. Small and Bush report the fuel loadings of wildlands surrounding counterforce targets in both the US and Russia. They begin by identifying plausible counterforce targets in the US and Russia, and then categorized surrounding areas by ecosystem type. They then used data published by the US Forest Service National Fire Danger Rating System (NFDRS) to understand the fuel loadings in

each of the ecosystem types.

| Area	Number of targets	Percent of targets	Fuel loading (g/cm2)
Wasteland	204	6%	Unknown
Forest	481	14%	0.17
Grassland	702	20%	0.01 – 0.06
Cropland	2,072	60%	0.0, 50 weeks/year 0.2 week/year
Total	3,459	100%	–

Source: Adapted from Table 1 from Small and Bush (1985)

I then take the average of these fuel loadings — which each fuel loading weighted bv the percentage of counterforce targets that are surrounded by a particular ecosystem — to get the range of possible fuel loadings for areas surrounding the counterforce targets overall: 0.03–0.17 g/cm2.

Small and Bush (1985) point out that previous estimates of the amount of smoke generated during counterforce targeting use much higher fuel loadings — erroneously, they argue. Citing models well-regarded models for predicting fire behavior in wildlands, Small and Bush (1985) claim that "...the loading factors used by Crutzen and Birks and by Turco et al...are more appropriate for logged forests with extensive ground litter ('slash') than for naturally occurring vegetation. Such values greatly overestimate the amount of fuel that can be burned in a nuclear exchange" (p. 469).

Study	Loading (g/cm2)
Crutzen and Birks (1982)	0.3 – **0.55**
Turco et al. (1983)	0.5
Crutzen et al. (1984)	0.4
The National Academy of Sciences (1985)	0.4
Small and Bush (1985)	0.01 – 0.02

I'm inclined to agree with Small and Bush ([1985](#)), but I'm pretty uncertain. I therefore use a range of possible fuel loadings in my model. The 5th percentile value comes from the lower bound on the weighted average I estimated using the data reported by Small and Bush: 0.03 g/cm3. The 95th percentile comes from the upper bound of the highest fuel loading value assumed by author researchers: 0.55 g/cm2 (bolded in the table above).
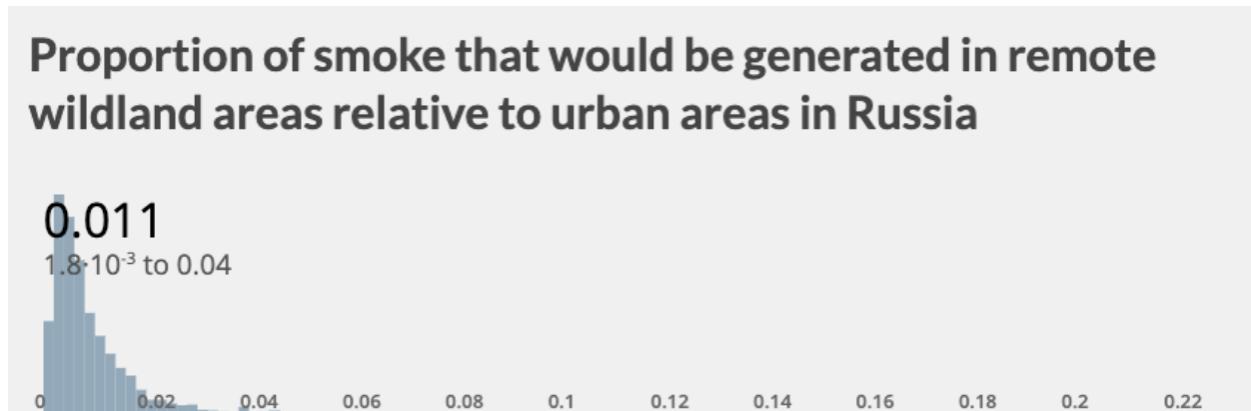
Because I put more weight on the fuel loadings reported by Small and Bush ([1985](#)), I assume the distribution of fuel loadings is lognormally distributed. The resulting probability distribution looks like this:

Fuel loading in wildland areas (g/cm^2)
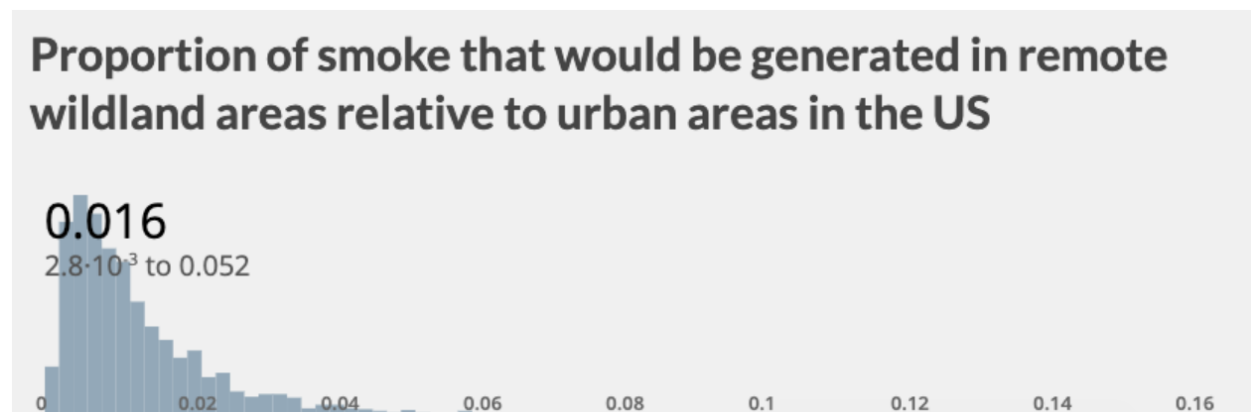
0.19
0.033 to 0.71
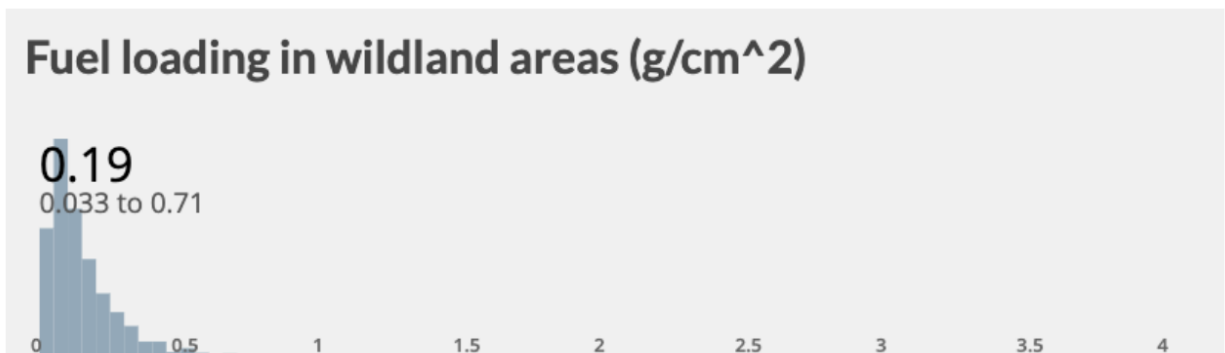
Finally, I estimate that factor by which wildland around counterforce targets fuel loadings are smaller than fuel loadings in US and Russian cities by dividing the fuel loading of wildlands that surround counterforce targets (0.03 g/cm2– 0.55 g/cm2) by the fuel loadings of cities in the US and Russia (18 g/cm2 and 12 g/cm2, respectively). I call this the

Counterforce Fuel Loading Factor (CFL).

I find that fires in wildlands around counterforce targets would only produce around 1.1% of the smoke that would be generated by fires in Russian cities (CFL of 0.011 on average).

Proportion of smoke that would be generated in remote wildland areas relative to urban areas in Russia

0.011
$1.8 \cdot 10^{-3}$ to 0.04

Similarly, I find that fires in wildlands would produce about 1.6% of the smoke that would be generated by fires in US cities (CFL of 0.016 on average).

Proportion of smoke that would be generated in remote wildland areas relative to urban areas in the US
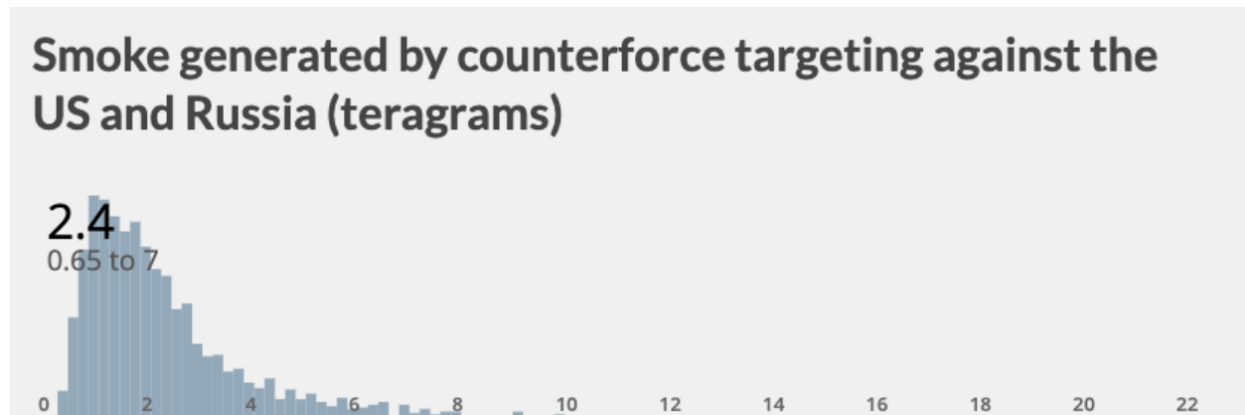
0.016
$2.8 \cdot 10^{-3}$ to 0.052

I can add these terms to my equations, which can then be used to estimate the amount of smoke produced by counterforce targeting against the US and Russia.

$$Total\ Smoke\ (Tg)_{US} = (0.0875x + 10.1) * CFL_{US}$$

$$Total\ Smoke\ (Tg)_{Russia} = (0.0454x + 8.91) * CFL_{Russia}$$

When I plug in the number of targets the US and Russia would each target during a counterforce first strike, I find that counterforce targeting by the US against Russia would produce between 0.11 Tg and 2.5 Tg of smoke and counterforce targeting by Russia against

the US would produce between 0.31 Tg and 6.1 Tg of smoke. In total, I expect counterforce targeting between the US and Russia would produce around 2.4 Tg of smoke:

Smoke generated by counterforce targeting against the US and Russia (teragrams)

2.4
0.65 to 7

But there is an important exception to the general rule that counterforce targets tend to be in more remote areas. It's fairly likely that a key component to a US or Russian counterforce strike would be to hinder the others' leadership command, control, and communications systems (LC3) — in other words, the people and systems responsible for authorizing and carrying out nuclear attacks. To do this successfully, both countries would likely target each others' capitals. Because Moscow and Washington DC are relatively dense cities, the nuclear detonations would generate a fair amount of smoke — more than other counterforce targets and more than I'm accounting for in the smoke estimation above.

To better account for this, I estimate the smoke generated by multiple nuclear detonations in both Washington DC and Moscow. I do this by again using the equations I derived from Toon et al. ([2007](#)), that I used to estimate the amount of smoke generated based on the scale of the attack on cities.

Unlike above, where I used functions that reflect the relationship between the total number of nuclear detonations and smoke, the following transformations of those formulas represent the relationship between the target number — which is based on the assumption that cities would be prioritized on the basis of population density — and smoke:

$$ Smoke \ (Tg)_{US} = 0.477 * target\_number^{-0.395} $$

$$ Smoke \ (Tg)_{Russia} = 0.455 * target\_number^{-0.279} $$

Because the target number is assumed to be based on population density, I can use demographic data about Russian and US cities to understand which target number Moscow and Washington DC would be. [Washington DC is the US's 17th highest population density](#), and [Moscow is the biggest city in Russia](#), and presumably the densest. I can therefore plug

in 17 and 1 into the respective countries above to understand how much smoke would be generated by counterforce targeting against Russia. When I do this, I find that each 500 kt nuclear detonation on DC and each 300 kt nuclear detonation on Moscow generate about 0.11 Tg and 0.455 Tg of smoke, respectively.

I expect that the US and Russia would both detonate multiple nuclear weapons on each others' capitals to increase the likelihood of decapitating the others' LC3. To account for this, I multiply the amount of smoke generated by one nuclear detonation in each city by total number of bombs I expect to be detonated — I would guess somewhere between 3 and 10 each.[11] I find that, if both the US and Russia both targeted each others' capital cities, between 2.3 Tg and 5.4 Tg of smoke would be generated.

I then multiply this by the probability that the US and Russia would target each others' capital cities, which gives me the expected amount of smoke generated by attacks on both Moscow and Washington DC. I put this probability somewhere between 50% and 100%, because I think they're more like to target each others' capitals than not, but have some uncertainty about exactly how likely it is than they do so. I find that a counterforce attack on Moscow and Washington DC would generate between 1.5 Tg and 4 Tg of smoke (2.6 Tg in expectation).

When I add up the smoke generated by counterforce targeting in remote areas plus the counterforce targeting on Washington DC and Moscow, I find that counterforce targeting by the US and Russia would generate between 2.2 Tg and 7.3 Tg of smoke, or 3.9 Tg in expectation.

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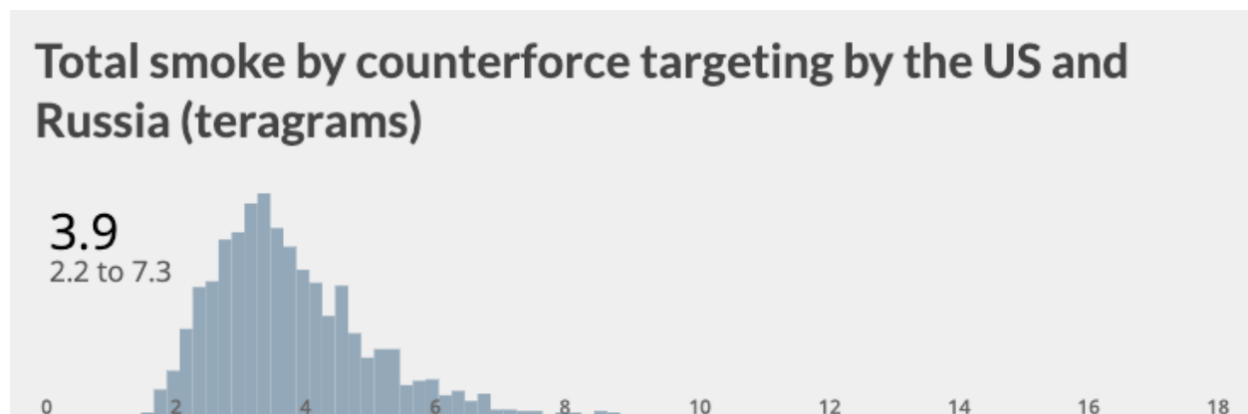
[11] To generate the parameters of the lognormal distribution I think best fits the number of in a counterforce attack on Moscow and Washington DC, I enter what I believe to be the median value, the lower bound, the upper bound, the 0.05th percentile, and the the 0.95th percentile. With help from SHELF, I generated the lognormal distribution, lognormal(1.62,0.343), which approximates the values I've entered.

Appendix D: If you believe countervalue targeting is inevitable

As discussed above, the amount of smoke generated by a nuclear war between the US and Russia is quite sensitive to parameters that well-informed experts reasonably disagree on. In particular, whether the US and Russia would target each others' cities makes a big difference to the amount of smoke generated by a US-Russia nuclear exchange. The results are also sensitive to the probability that countervalue targeting would escalate, eventually reaching the point where hundreds of nuclear bombs were dropped on US and Russian cities and industry.

Below, I explore two alternative scenarios that illustrate how my results would change if you held relatively extreme views about the likelihood of countervalue targeting and the likelihood that countervalue targeting would escalate.

In scenario 1, I assume that neither the US or Russia would use any counterforce targeting — instead focusing exclusively on a countervalue targeting strategy. I assume that the probability of countervalue escalation is the same as in my base case model.

Scenario 1: Countervalue targeting used instead of counterforce targeting; countervalue targeting is equally likely to escalate relative to the base case				
US-Russia Nuclear Exchange Scenarios	Targeting by the US against Russia		Targeting by Russia against the US	
	Base Case	Scenario 1	Base Case	Scenario 1
Probability of counterforce targeting				
Average	1	0	1	0
95% confidence interval	–	–	–	–
Probability of countervalue targeting				
Average	0.27	1	0.41	1
95% confidence interval	0.05 – 0.58	–	0.07 – 0.81	–

This scenario would generate 79 Tg of smoke in expectation, increasing the chances of a nuclear winter severe enough to likely cause human extinction to about 77% (conditional on there being a US-Russia nuclear war in the first place).

Smoke that would be generated as a result of countervalue targeting by both the US and Russia (teragrams) [Scenario 1]

79
37 to 150
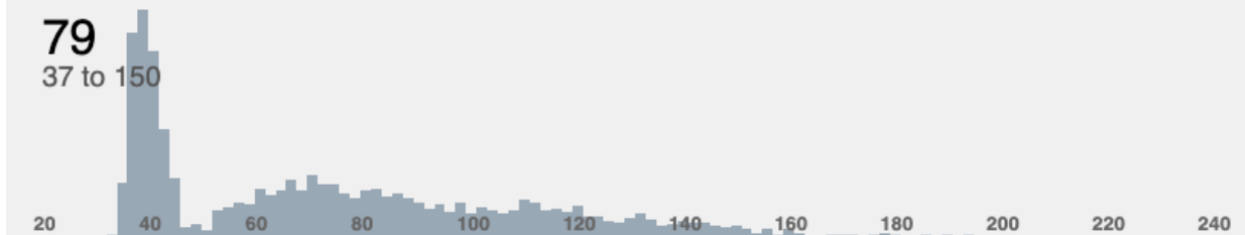
In Scenario 2, I assume that — in addition to exclusively relying on countervalue targeting — the countervalue nuclear exchange would be less likely to stay limited or escalate a moderate amount, and much more likely to instead escalate to a full scale countervalue nuclear war.

Scenario 2: Countervalue targeting used instead of counterforce targeting, and countervalue targeting is more likely to escalate than not				
US-Russia Nuclear Exchange Scenarios	Targeting by the US against Russia		Targeting by Russia against the US	
	Base Case	Scenario 2	Base Case	Scenario 2
Probability of counterforce targeting				
Average	1	0	1	0
95% confidence interval	–	–	–	–
Probability of countervalue targeting				
Average	0.27	1	0.41	1
95% confidence interval	0.05 – 0.58	–	0.07 – 0.81	–
Probability of full-scale countervalue targeting, conditional on any countervalue targeting				
Average	0.36	0.75[12]	0.36	0.75[13]
95% confidence interval	0.11 – 0.67	0.36 – 0.98	0.11 – 0.67	0.36 – 0.98

(See endnotes in table on distributions).[12]

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[12] This parameter is represented by the beta distribution, beta(3.2,1.09). Because I increased the probability of full-scale countervalue targeting, I had to also decrease the probability of limited and moderate countervalue targeting. I decreased the probabilities of each in proportion to their initial values. After doing so, the probability of limited countervalue targeting became 0.2 (90% confidence

I find that Scenario 2 would generate much more smoke than either Scenario 1 or the base case — about 94 Tg in expectation. At that amount of smoke, Scenario 2 would be quite likely (~85%) to cause a nuclear winter severe enough as to pose an extinction threat. For those who hold the view that countervalue targeting is both inevitable and very likely to escalate, this finding supports the conclusion that a US-Russia nuclear war poses an extinction risk.

Smoke that would be generated as a result of countervalue targeting by both the US and Russia (teragrams) [Scenario 2]

99
39 to 160
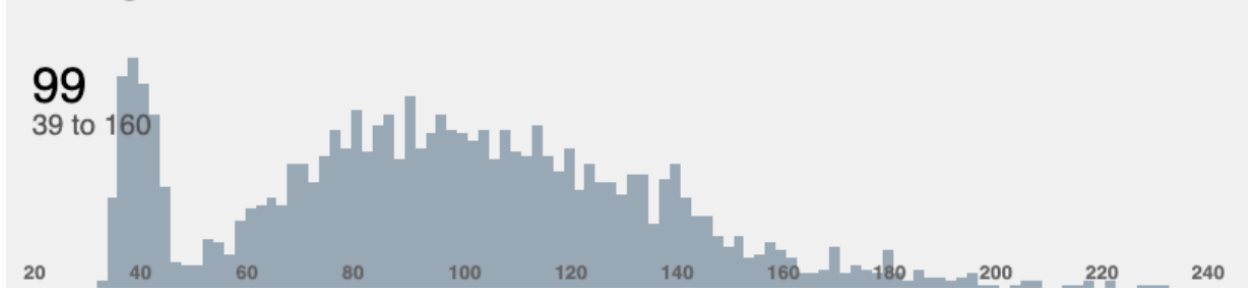
Edits and Corrections

December 19, 2019 — I found a typo in a formula in my Guesstimate model which caused the node calculating the amount of smoke that would be generated as a result of full-scale countervalue targeting against the US to refer to an incorrect node. Originally written "0.664(NON^0.63)," the formula referred to the number of nuclear weapons likely to be used in counterforce targeting against Russia, rather than the number of nuclear weapons likely to be used in a full-scale counterforce strike against the US, which would have read "0.664(NON7^0.63)." When I corrected this, the amount of smoke generated by a US-Russia nuclear exchange went down from 20 Tg to 16 Tg.

December 19, 2019 — I found typos in the formulas in my Guesstimate models that I use to estimate the change in temperature and precipitation that would be caused by a given amount of smoke. Rather than enter the correct formulas — "-0.276TSG1-5.55" and "-0.0485TSG1-0.938" — I entered "-0.085TSG1-0.938" and "-0.276TSG1-0.938." When I corrected this, the change in temperature went from down from -2.3 degrees Celsius to -1.7 degrees Celsius, and the percent change in precipitation went up from -5.4% to -10%. November XX, 2019 — Kit pointed out that the way I originally accounted for the fact that a US-Russia nuclear exchange could stay limited, escalate a moderate amount, or escalate to a large-scale nuclear war causes my probability distributions representing the amount of smoke produced during each scenario to be artificially narrow. This happened because I

interval: 0.02 – 0.53), represented by the beta distribution, beta(1.2,4.73). The probability of moderate countervalue targeting became 0.05 (90% confidence interval: 0.0 –0.28), represented by the beta distribution, beta(0.343,6.49).

estimated the expected number of nuclear warheads that would be used in the three nuclear exchange scenarios rather than sampling the number of warheads used in the various scenarios in proportion to the probability that a given escalation scenario would occur (see Kit's comment for more details). More concretely, I approximated the size of the nuclear exchange in expectation by taking the sumproducts of the number of warheads used in each scenario and probability that each scenario would occur. This approach was problematic in that the "expected" nuclear exchange scenario never took on the values at the upper extreme of the large-scale exchange scenario (i.e. cases in which many hundreds of nuclear warheads are used). And because the relationship between the number of warheads detonated and the amount of smoke ejected into the atmosphere is nonlinear, the truncation of the extreme values in the right tail gets further exacerbated when I estimate the amount of smoke generated by the "expected" nuclear exchange. Ozzie Gooen helped me find a workaround for this in Guesstimate. As a result of the change, my estimate of the amount of smoke we'd expect to be generated went up to 16 Tg to 18 Tg of smoke. Additionally, the upper and lower bounds on the confidence interval also got bigger, as well as slightly wider (indicating higher uncertainty than the original model did).

December 19, 2019 — My original model assumed that all cities targeted during countervalue targeted would be hit with a single nuclear bomb (of the median size in the US/Russian arsenal). This assumption led me to underestimate the amount of smoke that would be generated by a US-Russia nuclear exchange. I now assume that the US and Russia would drop additional nuclear bombs on large cities, insofar as additional bombs would meaningfully increase the death toll. When I made this change, the amount of smoke expected to be generated by a US-Russia nuclear exchange increased from 18 Tg to 25 Tg of smoke.

December 19, 2019 — My original model assumed that all counterforce targets — aside from leadership command, control, and communications systems (LC3) in Washington DC and Moscow — would be in rural areas. In reality, some counterforce targets, like air and naval bases, would be in or near populated cities, where the amount of smoke generated by nuclear detonations would be orders of magnitude greater than that generated by detonations in rural areas. Failing to account for this caused me to underestimate the amount of smoke that would be lofted into the atmosphere in a counterforce targeting scenario. When I revised my model to account for the fact that a number of large cities would likely be affected by nuclear detonations in urban counterforce targets, the amount of smoke I expect would be generated by a US-Russia nuclear war in expectation went up from 25 Tg of smoke to 30 Tg of smoke.

Credits

This essay is a project of [Rethink Priorities](#). It was written by Luisa Rodriguez. Thanks to Peter Hurford, Marinella Capriati, Ida Sprengers, Marcus A. Davis, and Neil Dullaghan for their valuable comments. Thanks also to Matt Gentzel, Carl Schulman, and Seth Baum for providing guidance and feedback on the larger project.

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Appendix B: Text exemplars and sample performance tasks (n. d.) Common core state standards for English language arts & literacy in history/social studies, science, and technical subjects. Retrieved from http://www.corestandards.org/assets/Appendix_B.pdf

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