Examining Temperature Fluctuations and Soot Deposition in Nuclear Winter

by Duc Nguyen

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Abstract

This paper will synthesize the datasets simulated from two physics-based models, WACCM-4 (Coupe, 2019b, Coupe, 2021) and GISS ModelE (Coupe, 2019a), on nuclear winter to better understand temperature fluctuations and soot deposition patterns. During the first few months after a nuclear detonation, global temperatures plummeted and local temperatures may drop as low as 30K compared to the control runs. In addition, the decline in temperature varied significantly across nations and regions. A case study between New Zealand's and Australia's temperature drop is conducted to demonstrate this claim. Soot sedimentation followed a periodical pattern of 12 months, with peaks during winter periods in each hemisphere. The paper will also address how these risks may pose a threat to agriculture and human health.

Key takeaways

- Temperature decreases rapidly but disproportionately after soot is injected, which can cause an increase in heat-related diseases and agricultural disruption. A survival plan that considers regional climate responses to nuclear winter is encouraged.
- Soot sedimentation follows a 12-month pattern but with reverse peak periods in the Northern and Southern hemispheres. More research is needed to evaluate the impacts of radioactivity during peak soot sedimentation months.

1. Introduction and background

Nuclear winter, in the most literal sense of the term, is the global temperature decrease after a nuclear war. However, in a nuclear winter scenario, other severe climatic effects can arise, including extreme precipitation alteration (Coupe et al., 2019), ozone layer loss (Mills et al. 2008), and sea ice loss (Coupe et al., 2023). In this paper, I will refer to nuclear winter as every radical change in the Earth's climate as a result of nuclear war.

Foundational work on the impacts of nuclear winter by Turco et al. (1983) showed that a nuclear exchange can cause summer temperatures to plummet below zero Celsius in the Northern Hemisphere. Recent nuclear winter simulations use atmospheric models such as WACCM-4 with higher spatial resolution and more refined treatment of aerosol particles, confirming that a nuclear war by United States and Russia could produce a global temperature drop of 5K persisting 5 years after detonation (Coupe et al., 2019).

Understanding the impacts of a global nuclear war on climate and human survival is crucial in pushing global cooperation on nuclear disarmament (Robock et al., 2023). In addition, research on nuclear winter will also help us prepare if such a situation happens in the future (Vilhelmsson & Baum, 2023). In the current military conflict between Russia and Ukraine, the threat of tactical nuclear weapon usage has been employed with increasing frequency by Russian officials, which makes a study of the environmental fallout of nuclear war all the more pressing and pertinent. Since tactical nuclear weapons are closer to conventional weaponry in terms of war theater size, the model of India-Pakistan nuclear war in this paper may be able to indicate what the impact of tactical nuclear weapon usage in the Russia-Ukraine conflict would be like. As agriculture disruption is the primary consequence of nuclear winter (Robock, 2010), quantifying agricultural disruption has been the main topic of some recent papers on nuclear winter (Jagermayr et al., 2020, Xie et al., 2022). Based on climate, crop, and fishery models, Xia et al (2022) estimate that agricultural disruption can leave more than 2 billion people starving in the case of a regional nuclear war between India and Pakistan, and more than 5 billion in the case of Russia and the United States two years after the war. In addition, there have been growing efforts to identify resilient crops (Winstead and Jacobson, 2022) and optimize productivity to ensure food supply during nuclear winter (Wilson et al., 2023)

Most of the work on nuclear winter has been focusing on the general climatic and agricultural effects. However, it is equally as important to understand human health effects that could arise from a nuclear winter. Recently, Vilhemsson and Baum suggested an “interdisciplinary research and policy agenda to understand and address the public health implications of nuclear winter” (2023). While there has been an effort to relate the destruction of the ozone layer and human health (Bardeen et al., 2021), other health hazards such as global radiation fallout and temperature shock are poorly investigated.

To better understand global radiation fallout and temperature shock, I analyzed the dataset from nuclear simulations in both a regional nuclear exchange between India and Pakistan and a global nuclear war between Russia and the United States. For the temperature analysis, I focused on temperature reduction in the period of 6 months after the bombs were detonated. To examine the impacts of fallout, I analyzed the mixing ratio of soot to air at ground level, specifically focusing on the temporal pattern of soot.

2. Methods

Since there is no anecdotal evidence, and it is impossible to experiment the global climate system on the conditions of nuclear winter, current research relies on the use of modern physics-based climate models. There are two components in modeling the climatic impact of a global nuclear war. Firstly, fire modeling systems, simulations, and/or previous urban fires from nuclear bombs such as in Hiroshima are used to estimate the amount of black carbon produced and the height that black carbon resides (Reisner et al., 2018, Wagman et al., 2020). The estimated amount of black carbon is then fed into physics-based models coupled with land and ocean models to determine changes in variables such as temperature, precipitation, and surface radiation.

In this project, I mainly used WACCM-4 and GISS ModelE simulation data from Coupe et al. (2019). The data is given with values at 1.9 deg (latitude) x 2.5 deg (longitude) resolution. In both of the models, 150 Tg of soot is injected into the troposphere between 15 and 20 May, and simulation starts in January of the year when soot is injected. Additionally, to confirm the soot sedimentation pattern, I use simulations of a regional nuclear exchange between India and Pakistan, provided in the paper by Coupe and Robock (2021) in multiple scenarios: 5, 16, 27.3, 37, and 46.8 Tg.

a/ Temperature analysis

In each model, the temperature anomaly is calculated as the difference between the temperature of the nuclear detonation run minus the temperature of control runs (averaged over three ensemble members) at that particular time. Regional temperatures are calculated using a weighted area average for the sphere.

For temperature analysis, I focused on each region’s response after 1, 2, 3, and 6 months after the injection of soot into the atmosphere. Temperature biases of the model is estimated as the average of the temperature anomaly of the four months before detonation. For the world average temperature, the WACCM-4 model has negligible temperature bias (+0.06 K) and is more stable, whereas the GISS ModelE has a considerable bias of -0.50 K.

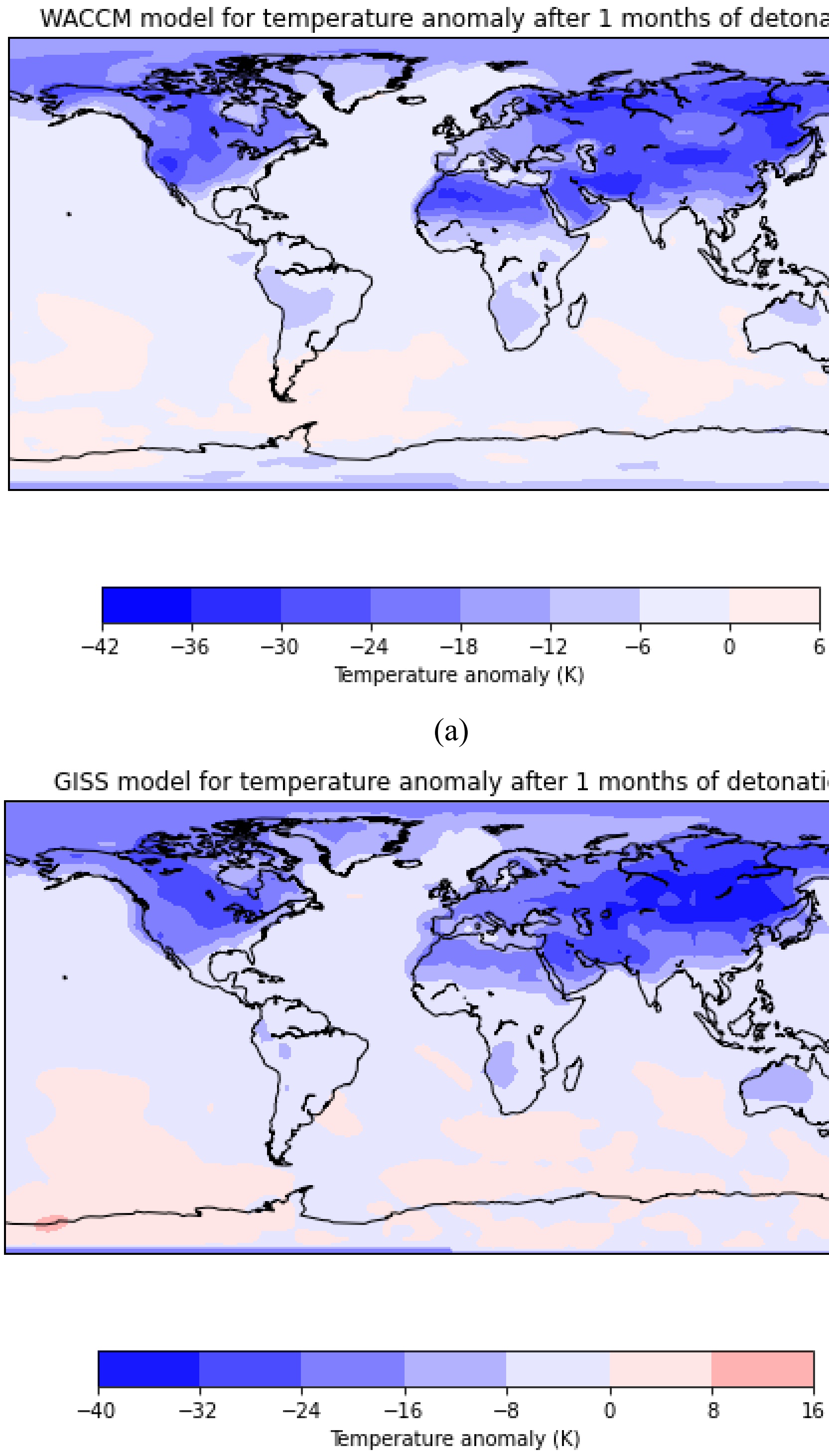
b/ Soot analysis

I use WACCM-4 simulations to analyze the mass mixing ratio of soot at surface level. Since soot in the air near the ground will fall down quickly, the mass mixing ratio at surface level is indicative of the soot sedimentation pattern. Since the WACCM-4 data only provides soot mass mixing ratio at fixed levels of pressure, surface level soot mass mixing ratio is interpolated/extrapolated. Interpolation/extrapolation follows a quadratic fit of soot levels data points near the surface level.

3. Results & Explanation

a. Temperature response after soot injection in the atmosphere

In both WACCM-4 and GISS ModelE simulations, temperature in the Northern Hemisphere plummeted right after soot was injected into the atmosphere. In a month after the soot injection, some areas can experience a monthly averaged temperature decrease of 30K, as shown in Fig. 1. This rapid decrease is detrimental to crops and human survival.



(a)

(b)

Fig 1: WACCM-4 (a) and GISS ModelE (b) global temperature anomaly map, 1 month after detonation

Surprisingly, while New Zealand and Australia are close to each other geographically, temperature changes right after injection are massively different. Australia experienced a significant drop immediately following the detonation event. After month 3, Australia's temperature dropped an average of -4.7 K in the WACCM-4 model compared to the control run. On the other hand, New Zealand only experienced a slight drop of 0.5 K in the first four months, and then followed by a gradual drop to -2.2 K during month 6 (Fig. 2). This may be due to the two following reasons, both coming from the fact that despite close proximity, Australia belongs to the subtropical latitudes, whereas New Zealand belongs to middle latitudes.

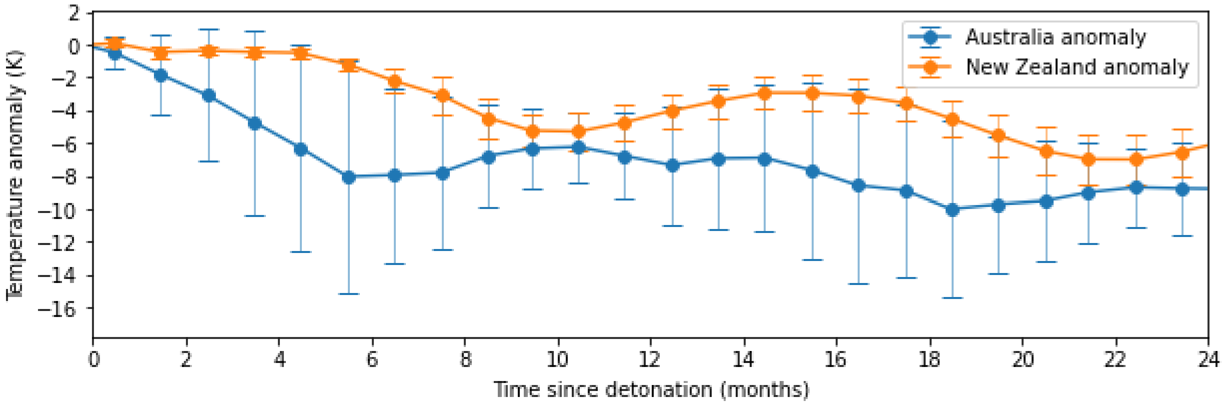
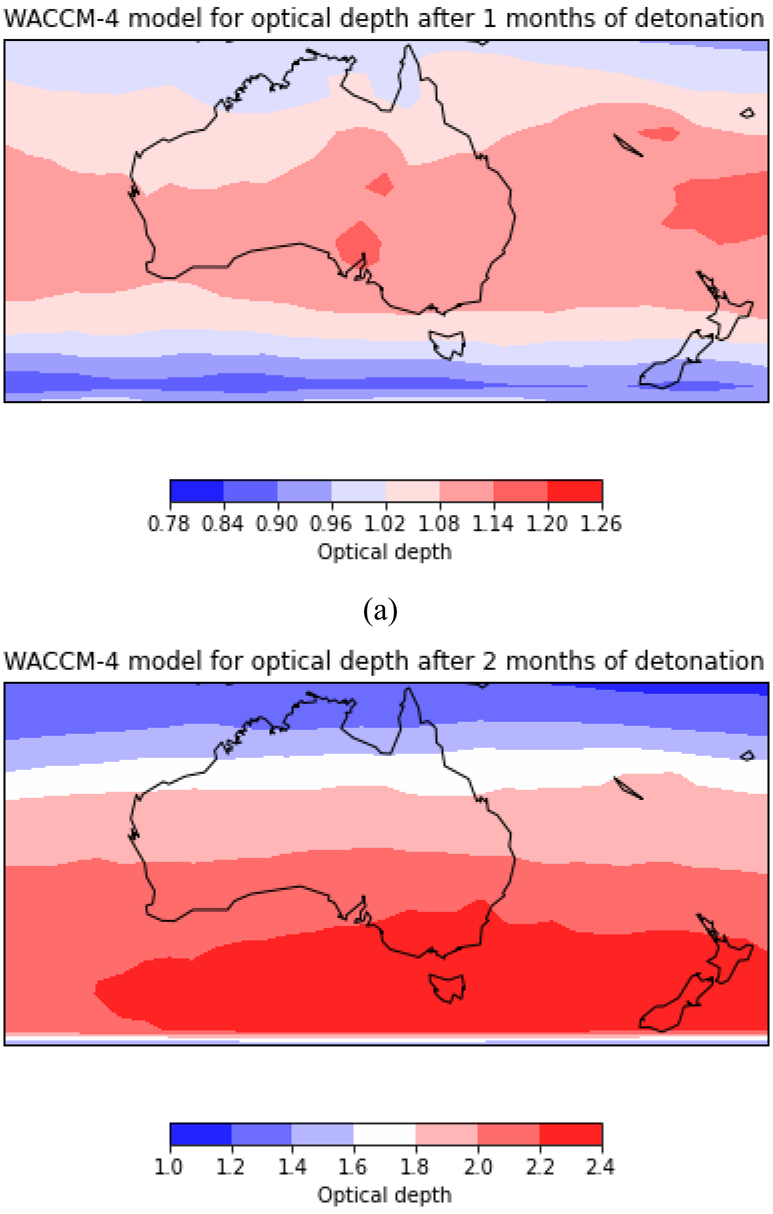


Fig. 2: Australia and New Zealand average temperature anomaly and standard deviation. 0 is set at detonation time.

Humidity: Since Australia is in the subtropical latitudes, dry air from the Hadley cell descends, causing low rainfall and more desert-like climate in the inshore area of the continent (Head et al., 2013). Low water content means heat is more likely to escape, causing a sharper drop in temperature. This effect is also evident when we consider how temperature in Australia changes according to region after nuclear detonation: the more coastal a region is (especially the southeast part of Australia), the less extreme the temperature drop will be.

Delay in soot circulation across the globe: In the first month after detonation of the bombs, a higher concentration of soot resided between the subtropics latitude than the middle latitudes, which meant less light was able to reach the surface of Australia than New Zealand. This is reflected in the aerosol optical depth difference in Fig. 3. However, due to Brewer-Dobson circulation higher in the stratosphere, soot began to circulate poleward from month two until 12 months after detonation, which contributed to a sharper decline in New Zealand’s temperature in later months.



WACCM-4 model for optical depth after 1 months of detonation

(a)

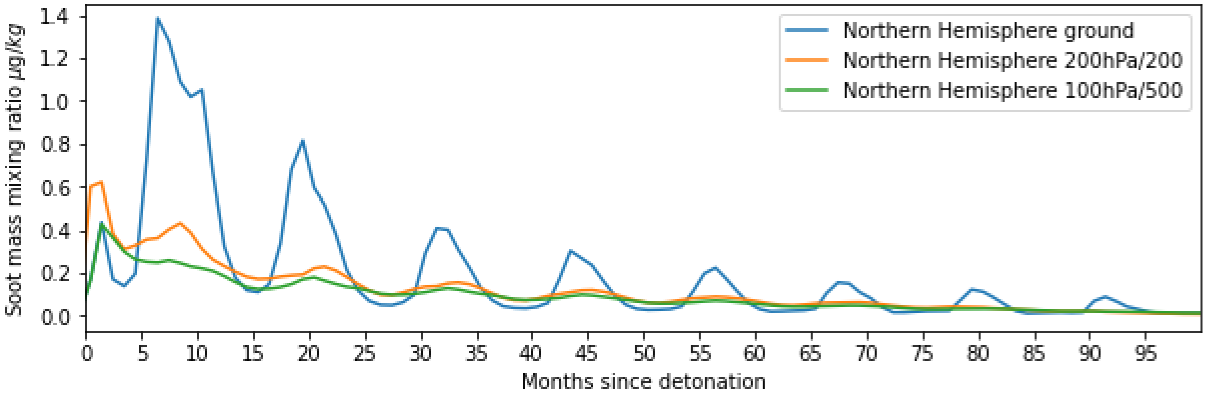
WACCM-4 model for optical depth after 2 months of detonation

(b)

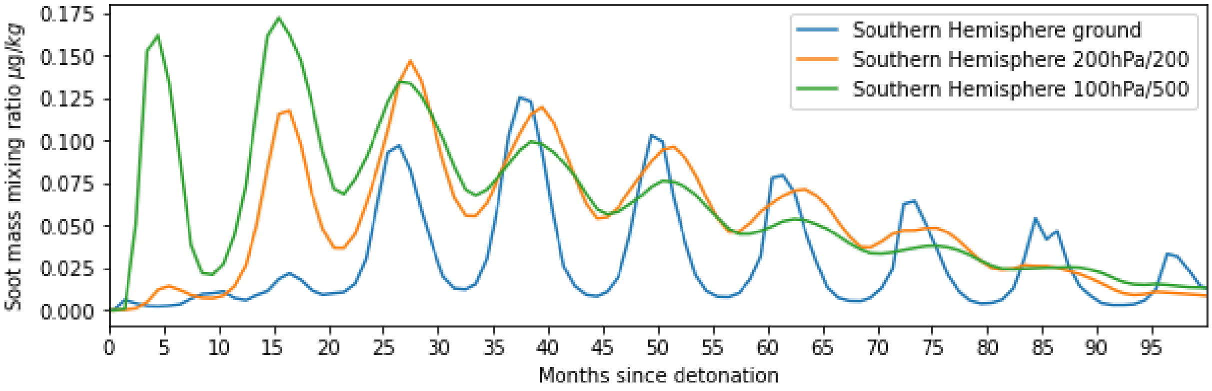
Fig 3: Optical depth in Australia and New Zealand after 1 (a) and 2 (b) months of detonation

b. Soot sedimentation pattern

In the case of a global nuclear winter injecting 150Tg of soot into the atmosphere, the Northern and Southern hemispheres both display a 12-month periodical sedimentation pattern, as shown in Fig. 4. However, the peaks and troughs of the pattern differ by 6 months. In the Northern Hemisphere, soot sediments mostly during boreal winter, explaining the higher mass mixing ratio at surface level and a peak during winter months. On the other hand, in the Southern Hemisphere, soot sediments during the southern winter, which is the summer in the Northern Hemisphere. Since more soot accumulates in the Northern Hemisphere than the Southern Hemisphere for the first few years, the globally averaged sedimentation depends on the Northern Hemisphere's oscillation pattern. This sedimentation pattern is similar in both hemispheres at 100hPa and 200hPa. Another point of interest is the time of maximum soot mass mixing ratio in the Northern Hemisphere and the Southern Hemisphere, which is not right after the nuclear war but after 5 and 36 months, respectively.



(a)



(b)

Fig 4: Soot mass mixing ratio, averaged across the Northern (a) and Southern Hemisphere (b). To allow easier visualization, a factor of 200 and 500 has been divided off of the soot at 200hPa and 100hPa, respectively.

To compare the soot sedimentation pattern in a global nuclear war versus a regional one, I focused on the region encompassing India and Pakistan. This is due to the fact that more soot is concentrated in this area in a regional war scenario between these two countries. Therefore, it is easier to extract a sedimentation pattern, given that a local nuclear exchange produces significantly less soot into the stratosphere. The soot mass mixing ratio for all of the cases at surface level is shown in Fig. 5. For easier comparison with policy regulations on fine particulate pollution, uniform air density of 1.226 kg/m^3 (288 K, 101.325 kPa) is assumed to convert mass mixing ratio unit from kg/kg to micrograms/m^3. The threshold for fine particulate pollution (PM2.5), as EPA is pushing towards, is between 9.0 and 10.0 micrograms/m^3 annually (United States Environmental Protection Agency, 2023), and a maximum of 35 micrograms/m^3 per day. In the India-Pakistan region, three of the scenarios (150Tg, 37Tg, 46Tg) have the peak monthly average nearing the annual pollution level at 7.94, 7.07, and 7.95 micrograms/m^3, respectively. In the 150Tg global nuclear war scenario, soot mass mixing ratio reached its peak about 10 months after detonation, whereas in all local exchanges scenarios, soot mass mixing ratio is maximum right after detonation. In both global and local scenarios, although the detonation sites are different, soot mass mixing ratio at surface level followed the same oscillation pattern between year 1 and year 4 after detonation.

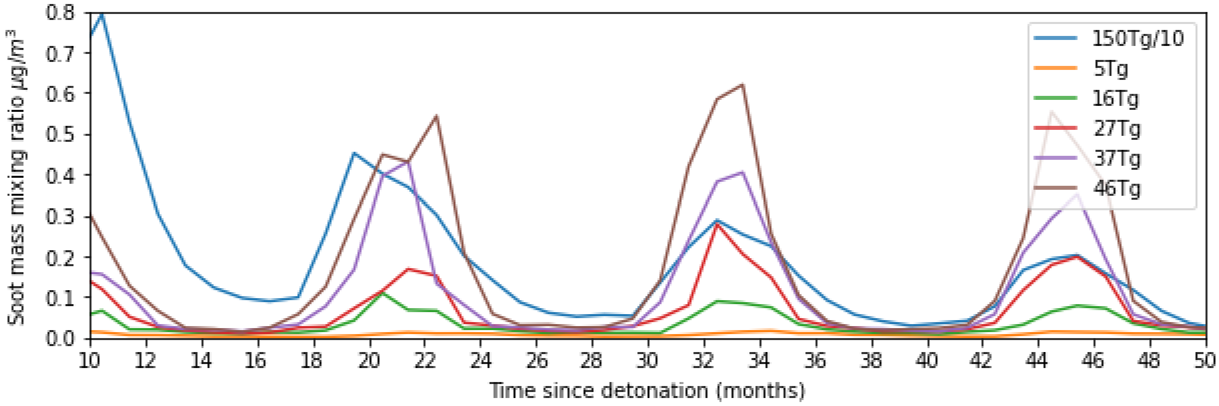


Fig. 5: Soot mass mixing ratio (in micrograms/m^3) in the India-Pakistan region, from 10 months to 50 months after detonation at ground level. The soot mass mixing ratio for the 150Tg case has been reduced by a factor of 10.

An explanation for this oscillation effect might lie in the correlation between colder temperatures and more soot sediment. As solar heating is reduced during winter, soot will gradually fall down due to colder air providing less buoyancy, causing sedimentation increase in the hemisphere experiencing winter. In addition, the changes in circulation between summer and winter can come into play. In the stratosphere, the Brewer-Dobson circulation transported soot polewards, where it would be slowly removed from this layer. The upper branch of the Hadley cell helps with transporting soot across the equator in the troposphere, with peak meridional velocity at approximately 300-400 hPa. A significant correlation (|r| ~ 0.5-0.6) is found between the equator's meridional velocity and soot mass mixing ratio at 8-10 degrees north and south at around 300-400 hPa. This correlation shows that soot moves across the equator following the meridional wind into the tropical latitudes.

4. Discussion

My results show that there is a sharp decrease in temperature immediately after nuclear winter globally. This decrease may lead to devastating consequences for human health. While direct deaths from cold temperatures are low, cardiovascular and respiratory diseases resulting from a sudden decline in temperature are detrimental to life expectancy (Deschenes & Moretti, 2009). Just an extreme cold day in a month may lead to a cumulative 10% increase in mortality rates (Deschenes & Moretti, 2009). In addition, the monthly temperature averages during the first winter after the war may fall below zero degrees Celsius in hot regions, which can lead to frost damage on tropical plants, inhibition of photosynthesis, and thus a reduction in agricultural productivity (Bhattacharya, 2022). Recent events, including the Covid-19 pandemic and wheat shortage, show how the global economy can collapse following a health and agricultural crisis.

The decrease in temperature is disproportionate across the globe. As my case study of Australia and New Zealand shows, even countries with close proximity to each other can have vastly different temperature fluctuations due to their distinct climates. Given that both countries are potential island refuges in a nuclear winter scenario because of their location and abundant food supply (Boyd & Wilson, 2022), a plan that accounts for differences in climate in both countries is necessary in order to ensure human survival during nuclear winter.

While soot fallout doesn't exceed the threshold for fine particulate matter pollution in places distant from the detonation sites, radioactivity from the soot might pose a substantial threat. Isotopes with a longer half-life, such as Cesium-137 (30 years) and Carbon-14 (about 5700 years), can produce significant radiation years after a nuclear bomb is detonated (U.S. Arms Control and Disarmament Agency, 1975). These isotopes might enter drinking water, livestock, and breathing air during a fallout, which will cause internal contamination when introduced inside the body. Once internal contamination occurs, there is an increased risk of cancer due to lack of protection inside the body (United States Environmental Protection Agency, 2023). Therefore, understanding the period of soot sedimentation will help plan safety responses, for example restrictions on outside travel during high radioactivity periods. Unfortunately, the simulations can't account for radioactivity of the smoke produced, so I can't estimate the impact of radioactivity fallout in a nuclear winter. Future work might be able to correlate between soot concentration and radiation produced, which will provide a more concrete course of action to minimize the effects of radiation fallout.

5. Acknowledgements

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6. References

Bardeen, C. G., Kinnison, D. E., Toon, B., Mills, M. J., Vitt, F., Xia, L., et al. (2021). Extreme ozone loss following nuclear war results in enhanced surface ultraviolet radiation. *Journal of Geophysical Research: Atmospheres*, *126*(18). https://doi.org/10.1029/2021jd035079

Bhattacharya, A. (2022). Effect of Low-Temperature Stress on germination, growth, and phenology of plants: a review. In *Springer eBooks* (pp. 1–106). https://doi.org/10.1007/978-981-16-9037-2_1

Boyd, M., & Wilson, N. (2022). Island refuges for surviving nuclear winter and other abrupt sunlight-reducing catastrophes. *Risk Analysis*. https://doi.org/10.1111/risa.14072

Coupe, J., & Robock, A. (2021). The influence of stratospheric soot and sulfate aerosols on the northern hemisphere wintertime atmospheric circulation. *Journal of Geophysical Research: Atmospheres*, *126*(11). https://doi.org/10.1029/2020jd034513

Coupe, J., Bardeen, C. G., Robock, A., & Toon, B. (2019). Nuclear Winter Responses to nuclear war between the United States and Russia In the whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE. *Journal of Geophysical Research: Atmospheres*, *124*(15), 8522–8543. https://doi.org/10.1029/2019jd030509

Coupe, J., Harrison, C. S., Robock, A., DuVivier, A. K., Maroon, E., Lovenduski, N. S., et al. (2023). Sudden reduction of Antarctic sea ice despite cooling after nuclear war. *Journal of Geophysical Research: Oceans*, *128*(1). https://doi.org/10.1029/2022jc018774

Deschenes, O., & Moretti, E. (2009). Extreme weather events, mortality, and migration. *The Review of Economics and Statistics*, *91*(4), 659–681. https://doi.org/10.1162/rest.91.4.659

Head, L., Adams, M., McGregor, H., & Toole, S. (2013). Climate change and Australia. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(2), 175–197. https://doi.org/10.1002/wcc.255

Jägermeyr, J., Robock, A., Elliott, J., Müller, C., Xia, L., Khabarov, N., et al. (2020). A regional nuclear conflict would compromise global food security. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(13), 7071–7081. https://doi.org/10.1073/pnas.1919049117

Körner, C. (2016). Plant adaptation to cold climates. *F1000Research*, *5*, 2769. https://doi.org/10.12688/f1000research.9107.1

Mills, M. J., Toon, O. B., Turco, R. P., Kinnison, D. E., & Garcia, R. R. (2008). Massive global ozone loss predicted following regional nuclear conflict. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(14), 5307–5312. https://doi.org/10.1073/pnas.0710058105

Reisner, J., D'Angelo, G., Koo, E., Even, W., Hecht, M., Hunke, E., et al. (2018). Climate Impact of a Regional Nuclear Weapons Exchange: An Improved Assessment Based On Detailed Source Calculations. *Journal of Geophysical Research: Atmospheres*, *123*(5), 2752–2772. https://doi.org/10.1002/2017jd027331

Robock, A. (2010). Nuclear winter. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(3), 418–427. https://doi.org/10.1002/wcc.45

Robock, A., Xia, L., Harrison, C. S., Coupe, J., Toon, O. B., & Bardeen, C. G. (2023). Opinion: How Nuclear Winter has Saved the World, So Far. *Atmospheric Chemistry and Physics*. https://doi.org/10.5194/acp-2022-852

Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B., & Sagan, C. (1983). Nuclear Winter: Global consequences of multiple nuclear explosions. *Science*, *222*(4630), 1283–1292. https://doi.org/10.1126/science.222.4630.1283

United States Environmental Protection Agency. (2023, July 3). Radioactive fallout from nuclear weapons testing. Retrieved August 8, 2023, from https://www.epa.gov/radtown/radioactive-fallout-nuclear-weapons-testing

United States Environmental Protection Agency. (2023, February 3). Proposed decision for the reconsideration of the National Ambient Air Quality Standards for Particulate Matter (PM). Retrieved August 11, 2023, from https://www.epa.gov/pm-pollution/proposed-decision-reconsideration-national-ambient-air-quality-standards-particulate

U.S. Arms Control and Disarmament Agency. (1975). Radioactive fallout. Retrieved August 8, 2023, from https://www.atomicarchive.com/resources/documents/effects/wenw/chapter-2.html

Vilhelmsson, A., & Baum, S. D. (2023). Public health and nuclear winter: addressing a catastrophic threat. *Journal of Public Health Policy*. https://doi.org/10.1057/s41271-023-00416-7

Wagman, B. M., Lundquist, K. A., Tang, Q., Glascoe, L., & Bader, D. C. (2020). Examining the climate effects of a regional nuclear weapons exchange using a multiscale atmospheric modeling approach. *Journal of Geophysical Research: Atmospheres*, *125*(24). https://doi.org/10.1029/2020jd033056

Wilson, N., Payne, B., & Boyd, M. (2023). Mathematical optimization of frost resistant crop production to ensure food supply during a nuclear winter catastrophe. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-35354-7

Winstead, D., & Jacobson, M. G. (2022). Food resilience in a dark catastrophe: A new way of looking at tropical wild edible plants. *Springer Link*, *51*(9), 1949–1962. https://doi.org/10.1007/s13280-022-01715-1

Xia, L., Robock, A., Scherrer, K., Harrison, C. S., Bodirsky, B. L., Weindl, I., et al. (2022). Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection. *Nature Food*, *3*(8), 586–596. https://doi.org/10.1038/s43016-022-00573-0

Coding references:

Harris, C. R., Millman, K. J., Van Der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., et al. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hunter, J. D. (2007). MatPlotLib: a 2D Graphics environment. *Computing in Science and Engineering*, *9*(3), 90–95. https://doi.org/10.1109/mcse.2007.55

Slocum, C. (n.d.). NetCDF example. Retrieved August 10, 2023, from http://schubert.atmos.colostate.edu/~cslocum/netcdf_example.html

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., et al. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2

Dataset References:

Coupe, J. (2019, February 19). GISS ModelE 150 Tg US-Russia (Version 1). figshare. https://doi.org/10.6084/m9.figshare.7742732.v1

Coupe, J. (2019, February 20). WACCM4 150 Tg US-Russia (Version 2). figshare. https://doi.org/10.6084/m9.figshare.7742735.v2

Coupe, J. (2021, April 4). WACCM4 5Tg-46.8Tg India-Pakistan Cases (Version 1). figshare. https://doi.org/10.6084/m9.figshare.14370785.v1

7. Appendix

To better visualize the transportation of soot and how it correlates with atmospheric circulation, an animation has been made, which can be found here https://drive.google.com/file/d/1WOO9rVxKKCDGJM4kcU32Ixtwp05Mcjki/view?usp=sharing