Proposal to the Open Philanthropy Project

Environmental and Human Impacts of Nuclear War

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Abstract

We propose to calculate in detail for the first time the impacts of nuclear war on agriculture, the oceanic food chain, and the human impacts through availability of food and pressure on migration. To do this, we will use various scenarios of nuclear war, and calculate how much smoke will be produced from fires initiated in modern cities by nuclear blasts. For the first time we will model these city firestorms in detail. We will then calculate how the climate will respond to this smoke, and how the resulting climate change will impact global agriculture, the oceanic food chain, and the availability of food worldwide, through the impacts on food prices and food trade. The results will be crucial for the debate on the humanitarian impacts of nuclear war, and will be influential on the targeting plans for nuclear nations, allowing them for the first time to quantify these effects. The results will also be of great interest in international campaigns and negotiations to reduce the number of nuclear weapons on the planet.

Introduction

Crutzen and Birks [1982] suggested that a nuclear war would start massive forest fires, creating toxic air and darkening smoke clouds over much of the war zone. *Turco et al.* [1983] recognized that burning cities would produce even more soot than burning forests, and that the soot would rise into the stratosphere where it would cover the Earth and produce global climate change so large that the climatic consequences were described as “nuclear winter.” *Aleksandrov and Stenchikov* [1983] conducted the first three-dimensional global climate modeling, and found the large climate changes over the land were not moderated by the oceans. This new research confronted the world with the prospect of potential indirect effects of nuclear war much larger than the direct effects. While the direct effects might kill hundreds of millions in combat zones, the indirect effects would lead to collapse of world agriculture and starvation of billions of people even in regions that were not involved directly in the war. By 1990 the arms race and Cold War ended. Since then, the global nuclear arsenal has been reduced by a factor of four.

The world currently possess about 15,000 nuclear weapons, distributed among nine nations (http://www.ploughshares.org/world-nuclear-stockpile-report, accessed January 12, 2017). When exploded on cities and industrial areas, the acknowledged targets of these nations, they would start fires, producing massive amounts of smoke. That smoke would block out sunlight, making it cold and dark at the surface for many years, as well as destroy ozone, enhancing ultraviolet radiation reaching the surface. The size of these impacts would depend on the number and yield of the nuclear weapons used, as well as the specific targets.

Until *Robock et al.* [2007a], all previous simulations of the climatic response to the smoke generated from a nuclear war were limited by computer power and the available climate models. Each simulation addressed certain aspects of the climate model response with simple climate models or with short simulations of low-resolution atmospheric general circulation models (GCMs), but *Robock et al.* [2007a] for the first time used a coupled atmosphere-ocean GCM run continuously for multiple 10-yr simulations and with a model top at the mesopause.

Thompson and Schneider [1986] use the term "nuclear autumn" to describe the results of a climate simulation they did. Their simulation was primitive by today's standards and was not published in a scientific peer-reviewed journal. They simulated for only a few weeks of time, not even one season. Their model had no ocean, and the atmosphere was capped in the lower stratosphere. Even though the authors made clear that the climatic consequences would be large, some in policy circles used the *Thompson and Schneider* [1986] paper to claim the theory of nuclear winter was exaggerated and disproved [e.g., *Martin*, 1988].

Robock et al. [2007a] conducted climate model simulations with a then state-of-the-art general circulation model, ModelE from the National Aeronautics and Space Administration Goddard Institute for Space Studies [*Schmidt et al.*, 2006], which includes a module to calculate the transport and removal of aerosol particles [*Koch et al.*, 2006]. The atmospheric model is connected to a full ocean general circulation model with calculated sea ice, thus allowing the ocean to respond quickly at the surface and on yearly time scales in the deeper ocean. We ran the atmospheric portion of the model at 4°x5° latitude-longitude resolution, with 23 vertical layers extending to a model top of 80 km. The coupled oceanic general circulation model [*Russell et al.*, 1995] has 13 layers and also a 4°x5° latitude-longitude resolution. Simulations were run over a decade, not just a few weeks.

Using simple scenarios of 50 Tg and 150 Tg of soot injected into the upper troposphere, *Robock et al.* [2007a] found that indeed the 150 Tg scenario, an injection of soot which is still possible from the use of the current U.S. and Russian nuclear arsenals [*Toon et al.*, 2008], would produce a nuclear winter. And they found that the climate effects would last for more than a decade, as for the first time they were able to realistically simulate the lifetime of the soot particles in the upper atmosphere. The simple physics of it getting cold at Earth's surface if you block out sunlight is not in doubt. But we now have better climate models, more sophisticated treatment of soot aerosols, and the opportunity to refine the emission of soot given more credible nuclear war scenarios. We propose to repeat these simulations to produce a better understanding of the climate response, and to provide input to agricultural and economic models.

The most surprising recent result is that a nuclear war between new nuclear states, such as India and Pakistan, using much less than 1% of the current global nuclear arsenal, could produce climate change unprecedented in recorded human history [*Toon et al.*, 2007a, 2007b; *Robock et al.*, 2007b; *Stenke et al.*, 2013; *Mills et al.*, 2014; *Pausata et al.*, 2015], global-scale ozone depletion [*Mills et al.*, 2008, 2014], and widespread famine [*Özdoğan et al.*, 2013; *Xia and Robock*, 2013; *Xia et al.*, 2015]. This surprising conclusion is the result of research by our team of scientists, many of the same people who produced the pioneering work on nuclear winter in the 1980s, and new colleagues. And the effects of regional nuclear war would also last for more than a decade. Nuclear winter is such a severe climate change that its impact would clearly be a global catastrophe. However, the global impacts of the use of small parts of the nuclear arsenal are much more difficult to evaluate. Using more credible nuclear war scenarios, better soot emissions from city fires, better agricultural models, and models of the impacts on the availability of food, here we propose to produce a much better understanding of these effects.

Nuclear proliferation continues, with nine nuclear states now, and more working to develop or acquire nuclear weapons. The continued existence of nuclear weapons implies a grave threat to life on Earth not just from the direct effects of the weapons, but also from the potentially much larger environmental threats. The exact nature of these threats is not well known. For the nations of the world to make informed policy decisions regarding their own nuclear arsenals and nuclear proliferation, and for the United States to plan for its "homeland security," a clearer picture of the environmental and societal consequences of the use of even a small number of these weapons needs to be produced and widely disseminated. In fact U.S. policy requires that targeting plans consider proportionality and distinguish between military and civilian impacts [*Bellinger and Haynes*, 2007]. The tools we will develop will allow them to do this for the first time.

We propose a research program, updating the nuclear winter studies from 30 years ago, taking into consideration the current nuclear arsenals and structures of megacities that would be targets, and taking advantage of advanced modern climate models and computer capabilities. While we have produced preliminary analyses of the climate response to one particular scenario of smoke injection, and the effects on some crops of the changes of temperature, precipitation, and sunlight, there are many details and impacts that need further study. In particular we need better information on the amount of smoke that would be injected into the atmosphere, the impacts on the ocean of the climate and ultraviolet changes, the impacts on agriculture of changing diffuse sunlight and ultraviolet radiation, and the subsequent threat to the world food supply, possibly resulting in global famine.

Using much more realistic scenarios, emissions from fires, climate models, agricultural models, and world food trade models, we will for the first time quantify the impacts of small and medium-size nuclear wars on the global food supply. This will not only inform policy makers and the public around the world of the impact on their local crops from a potential nuclear war on the other side of the world, but also of the potential for global famine. And for the first time, using modern climate models and surveys of modern cities, we will quantify the global impact of a first-strike nuclear attack by either the U.S. or Russia on each other or on other nations.

The work we propose to do will be conducted by leading scientists who specialize in the various aspects of the problem. They will use state-of-the-art techniques, and recognized national computer models to conduct this work. All the proposed work will be documented in peer reviewed journals, and the data will be made available to others using standard data repositories.

Our recent, more simplistic, results have already informed the movement on the Humanitarian Impacts of Nuclear War, which led in 2016 to the United Nations (UN) Open Ended Working Group meetings and to the vote in the UN General Assembly for a set of meetings in 2017 toward a global ban on nuclear weapons. That ban will surely pass, as it will only require a majority vote of UN members, but the nine nuclear nations, along with some nations who have military alliances with them, have so far voted against these measures. For a ban to come into effect, the reality of the impacts of the use of nuclear weapons will have to be widely disseminated, with very specific information that will be understandable to the public and governments, to support the next step in pushing the nuclear nations to work toward much more rapid reductions in nuclear arsenals.

The scientific questions we propose to answer are:

A. What are the likeliest scenarios of nuclear war? How many weapons, of what size, would be used on what targets?

B. What is the inventory of flammable material in potential target zones? How much soot would be produced from fires and firestorms after nuclear attack? Would multiple discrete fires in a large megacity coalesce into a larger firestorm, which would produce more soot than assumed by the recent studies? What fraction of the soot would be placed in the upper atmosphere where it can produce global climate change?

C. How do soot particles get transported and modified by the atmosphere? What can we learn from the observed behavior of soot from forest fires? How would chemical and physical processes alter the particles in the stratosphere, and how would this affect their lifetimes and effects on radiation and climate? How sensitive are the amount and properties of the smoke to prevailing winds, season of the conflict, and duration of the conflict?

D. What would be the climate response to a variety of nuclear conflict scenarios? How does the effect vary with different combatant groups and different attack scenarios? How would temperature, precipitation, sunlight, and ultraviolet radiation change? Are the preliminary results described above robust when tested with different climate models?

E. How would agricultural production, water resources, and the ocean food chain change in response to the resulting climatic disruption and enhanced ultraviolet radiation?

F. How would the availability of food and water in each nation, including the United States, change as global markets and distribution systems react?

The specific research we propose to answer these questions is described below:

A. What are the likeliest scenarios of nuclear war? There has only been one nuclear war in the history of Earth, and it was 72 years ago. Based on such a small sample, it is impossible to quantify the probability of future nuclear war, and if one started, how it might progress. Clearly, the probability is low, but the probability is not zero given the continued existence of nuclear weapons, the complete lack of interest from the nuclear nations in abiding by Article VI of the Nuclear Non-Proliferation Treaty ("Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control."), accidents, close calls, the threat of hackers, the potential for unstable leaders to control nuclear weapons, and the desire of some non-nuclear nations, such as Iran, to gain a nuclear arsenal.

So far we have considered only two scenarios, a war between India and Pakistan using 100 Hiroshima-size 15 kiloton atomic bombs, and an all-out nuclear war between the U.S. and Russia. What other scenarios would be important to consider? We will convene a meeting of nuclear experts to develop scenarios that the defense establishment should consider credible. We have been in discussions with Daniel Ellsberg, Zia Mian, Bruce Blair, Daryl Kimball, Matthew McKinzie, and Frank von Hippel, as well as former military leaders, including retired U.S. Air Force General C. Robert Kehler (Former Commander, U.S. Strategic Command), to outline approximately five credible scenarios to consider. These scenarios will range from a very small number of weapons, perhaps used by terrorists in a region other than India and Pakistan, to the "limited" use of nuclear weapons by major nuclear states, up to scenarios that would use substantial portions of the current arsenals. These scenarios will include a first strike by the U.S. on Russia with no retaliation, and a first strike on the U.S. by Russia with no retaliation, as well as a nuclear war between the U.S., Russia and their allies such as Britain, China, and France, with each using their current arsenals. This meeting would take place soon after the project began and would result in one journal article outlining the scenarios we will study.

B. What is the inventory of flammable material in potential target zones? Will fires spread once started or remain in the target zone? How much soot would be produced from fires and firestorms after nuclear attack? The character of cities and industrial areas has changed drastically since studies in the 1980s that estimated the fuel loading in typical structures in typical cities. With the growth of megacities and new construction materials, the amount and flammability of material has changed. In our preliminary studies we used old data and made simple estimates of fuel loading based on the level of development of nations, and on population density. What is needed are modern inventories of building contents, building materials, and flammable infrastructure, such as asphalt roads. For example, how common are the aluminum-clad sidings that have been engulfed in flames in the six spectacular skyscraper fires in Dubai in the past two years? Several of those buildings were 60-80 stories high.

Our first approach to estimating fuel loads will be to determine the population living in the target zone. Fortunately, there are highly detailed population databases for most of the world that are maintained by the Department of Energy, such as the most recent version of the 1 km^2 resolution *Landscan* (2012). Given an amount of fuel per person, the fuel loading can be computed using the population database. The amount of fuel per person can be determined from surveys of fuel loadings in various cities or countries of interest. An example of this approach, mainly based on fuel loading studies prior to 1990s, is presented in *Toon et al.* [2007b]. We will use this approach in each of the areas targeted in the war scenarios. This work would be done by a student at the University of Colorado familiar with Geographical Information System (GIS) techniques.

The second approach we will use is similar to that of *Bush et al.* [1991]. The new work will be conducted by Professor Yunping Xi (http://spot.colorado.edu/~xiy/) in the Department of Civil, Environmental and Architectural Engineering at the University of Colorado in Boulder. Professor Xi, the author or coauthor of more than 75 papers in the peer-reviewed literature, is an expert on building and construction materials, including the effects of radiation on such structures and fire damage. He will assess the amount of flammable building material in modern cities in various parts of the world, as well as the flammable contents of these buildings. Surveys will be conducted by graduate students of the contents of buildings in various different cities. It is not practical to survey even modest numbers of buildings. Instead, estimates will be made of the contents and construction of typical buildings. These will then be expanded up to the scale of Landscan population areas using either remote sensing or local maps of the sizes and types of buildings in a given area. The fuel loading computed in this manner, will then be compared with that found in the first approach based on population.

For civil engineering structures and infrastructure, the fuel load is calculated as a fire load energy density (FLED), which is the sum of all the energy available for release when the combustible materials are burned, divided by the total floor area of the compartment, expressed in MJ/m^2. The available energy content can be distinguished into permanent, variable, protected and unprotected loads. For multi-story buildings, travelling fires are assumed as realistic fire scenarios. Each material is characterized by the heat of combustion which, for example, is 17–

20 MJ/kg for wood. Estimates can be given for different structure types; for example, for car parking buildings the FLED is 200-400 MJ/m^2.

In recent years, high-rise residential building fires are drawing more and more concern. In some residential buildings, large amounts of combustibles are stored in units of small area, with a mean fire load from 278 MJ/m^2 to 852 MJ/m^2. In a Canadian project on characterization of fires in multi-suite residential dwellings, a survey revealed the average fire load densities to be 807 MJ/m^2 for kitchens, 393 MJ/m^2 for dining rooms, 288 MJ/m^2 for basement living rooms, 534 MJ/m^2 for primary bedrooms, and 594 MJ/m^2 for secondary bedrooms. Another survey was done in Hong Kong where eight old high-rise residential buildings were investigated. Due to the small average living area, the fire load density was very high, 1135-1400 MJ/m^2. So, fuel load varies depending on building types and average size of apartments in different cities and countries.

Modern high-rise buildings can include also highly combustible material, as documented by recent large fires in the United Arab Emirates (UEA) cities of Sharjah and Dubai (e.g., the 35-story Tamweel Tower blaze in Dubai, 2013, and the 63-story Address Downtown Hotel in Dubai, 2016). Experts in the UAE have estimated that 70% of the high-rise buildings in the area have panel facade cladding made of a combustible thermoplastic core held between two sheets of aluminum.

Thus, estimation of the fuel load in residential buildings includes determination of the FLED based on the structural material used, type of the building, and size of living and other activity areas. Several large metropolitan areas in the nine countries with nuclear weapons will be selected, the information on amount of each building type (residential and commercial such as apartments, offices, colleges, libraries, department stores and warehouses) will be collected from aerial imagery, U.S. Census Data, construction management databases, city and county databases, and related literature. The fire load energy density will be combined with the statistics of building inventory to estimate the fuel loads of the selected cities.

The U.S. has more than 4,000,000 km of asphalt-paved roads and highways. The U.S. demand for asphalt is forecast to increase 3.3% annually to 26,800,000 tons in 2019. Asphalt does not burn from ordinary fires, but a nuclear blast could ignite it. The autoignition temperature of asphalt is 480°C. But the boiling point can be 315°C. The U.S. has about 3,500 asphalt plants, at least one in every congressional district. Each year, these plants produce a total of about 400 million tons of asphalt pavement material alone. The information on asphalt highways and bridge decks will be collected from the U.S. highway administration and state departments of transportation. The information on asphalt roadway will be collected from city and county agencies. Prof. Yunping Xi is the PI for the Colorado Local Technical Assistance Program (C-LTAP) located at the University of Colorado, Boulder, which is a long-term project of about 20 years (started from 1998). C-LTAP is one of the 50 LTAP centers located in each state in the U.S. We will collect fuel load information related to transportation infrastructure through our LTAP network.

The large number of garbage disposal sites around major metropolitan areas of the world is an additional source of fuel loading. Burning garbage produces large amounts of smoke, which can be divided into two main parts: inorganic fumes and organic soot. Inorganic fumes mainly come from solid waste ash, and organic soot is mainly due to the formation of carbon particles. Burning chlorine-containing compounds in waste, like plastic and kitchen waste generates acid-containing smoke. Moreover, the various types of metal elements in the waste incineration process exist as fine particles. A lot of heavy metals will be attached to the particles and form toxic smog. These heavy metals are mainly from waste batteries, fluorescent tubes, heavy metal-containing coatings, and paint.

The large garbage disposal sites around major metropolitan areas, their capacities, disposal compositions, and growth rate will be surveyed from city and county information systems and recorded in a database. A special solid waste will also be considered: fire from waste tires. In the U.S., every person generates a waste tire per year on average. There are billions of cumulative waste tires in various disposal and recycling sites. Tire fires are very difficult to extinguish and produce a lot of smoke, a dark and thick smoke that contains cyanide, carbon monoxide, sulfur dioxide, and products of butadiene and styrene.

Once the fuel loading is determined, we need to find the area that is burned. There are many studies of the area that nuclear weapons destroy by blast damage, and the area over which the thermal pulse can ignite fires. The August 6, 1945 bombing of Hiroshima with a 15-kiloton atomic bomb started a fire that incinerated an area of 13 km^2. Three days later, the fire ignited by the 20-kiloton bomb dropped on Nagasaki covered a smaller area, as the surrounding mountains prevented the flash and blast from affecting a larger region. Other examples of city fires, in San Francisco in 1906 after an earthquake and in Dresden, Hamburg, Darmstadt, Tokyo, and a number of smaller cities, started with "conventional" weapons in World War II, teach us that cities burn, but may not serve as good models for modern cities ignited by much larger weapons in the current nuclear arsenals. Current arsenals include 100- and 500-kiloton weapons, which would produce much larger fires and smoke generation. In addition, the resulting fire storms, which might propagate through a larger area than initially ignited, would depend on the weather and winds at the time of the fires.

To accurately calculate the amount of fuel burned, we propose to model fire propagation in several possible target cities as they exist today and as they will exist 20 years in the future. The only calculations of city fires done so far are of portions of cities with undamaged buildings for fire-fighting applications, such as *Lee and Davidson* [2010a, b]. There have been many model simulations of forest fires [see *Li and Lawrence*, 2016, and references therein].

Here we propose to model fires in cities initiated by nuclear blasts, and the subsequent fire spread and atmospheric emission of aerosols. This work will be done, in collaboration with the Principal Investigators, by Prof. Julie Lundquist (http://atoc.colorado.edu/~jlundqui/cv.html) and her students at the University of Colorado. Professor Lundquist is an expert on urban meteorology and the use of the Weather Research and Forecasting model (WRF) [*Skamarock et al.*, 2008] for small scale flows. WRF is the main weather forecasting model in the U.S. and is used by a large number of researchers around the world. It was built by the National Center for Atmospheric Research (NCAR) in Boulder. There are several specialized versions of WRF. For instance, WRF-SFIRE (http://www.openwfm.org/wiki/WRF-SFIRE_user_ guide), is used for wildland fires, which often occur in complex terrain. It couples WRF with a fire spread model. WRF will be run at a resolution of tens of meters, with surface energy and mass fluxes imposed based on fuel loadings from the above assessments, and initial fire areas based on the size and location of nuclear blasts from the scenarios that will be developed.

We propose a sequence of increasing complex simulations. First we will assume that blast has converted a city to ruble. We will then use the existing wildland fire version of WRF assuming an appropriate roughness for downed buildings, and the fuel loads we have determined previously. The goal will be to understand how terrain and surface roughness might impact the fire behavior. For example, is the fire impacted by buildings that are not knocked down by the blast? Such buildings can create violent updrafts. Would fire behave different in a hilly city, such as San Francisco, than in a flat city such as Manhattan? Would fire spread differently in a humid windy place like San Francisco, or a dry, still place like Phoenix?

We will next simulate the interactions between adjacent fires, either set within the footprint of one weapon, or set by multiple weapons. The goal is to understand how the fires merge. Will they repel each other and prevent the fire from spreading, or will they merge and burn fuels outside the footprint of the weapons explosion?

Our next goal will be to understand how fires might spread in areas in which buildings have not been converted to rubble. In this case we will need to couple WRF with an urban fire model such as that discussed by *Lee and Davidson* [2010a, b]. We will initially simulate an urban fire that has been relatively well observed, such as the Oakland Hills firestorm of 1991, which destroyed 2,483 single-family homes and 437 apartment and condominium units. We will then further investigate the merging and spread of fires from the rubble zone of a blast into undamaged urban and suburban areas.

Our final step in this area is to understand where the smoke from the fires ends up. Some may be rained out by pyrocumulonimbus. Some may be released into the boundary layer where it will have a lifetime in the atmosphere of only a few days. Much of the smoke is thought to end up in the upper troposphere, or the stratosphere. This smoke will remain in the atmosphere for years or even decades based on current knowledge. We plan to use modern models to better understand the distribution of the smoke above the fires. *Toon et al.* [2007b] reviewed our knowledge in this area based upon older models and observations. We will try two new approaches to this problem. First, the WRF model will tell us how high the hot plumes from the fires will rise, and how precipitation will develop. Previous studies from the 1980s with relatively simple models indicate that fires more than about 5 km in diameter will inject material directly into the stratosphere. There are a large number of cloud models that can be used in WRF. For this problem we need a model in which the cloud properties respond to the large number of smoke particles, and then transport the smoke particles inside cloud droplets and outside cloud droplets. It is expected that large numbers of smoke particles will over-seed pyrocumulonimbus and greatly diminish any precipitation. Without much precipitation most of the smoke will be released to the atmosphere. We will review the WRF models for clouds to determine if any of them are capable of properly doing this problem. If so we will use these codes in the studies of urban fires. However, we also will adapt a cloud model to WRF from a Large Eddy Simulation model named DHARMA, which was built by NASA. DHARMA is designed to do highly detailed studies of clouds and their interactions with aerosols. This new model will use the WRF dynamics, but replace its cloud physics. Dr. Eric Jensen, will perform these studies. Dr. Jensen is a leading expert on cloud physics and the author of more than 70 papers in the peer reviewed literature. He has already performed simulations of the interactions of cumulus clouds with aerosols that are suitable for studying pyro-convective clouds using DHARMA [e.g., *Jensen and Ackerman*, 2006]. This study will start by simulating a few fires that have been relatively well observed. For instance, the Chisholm fire in Alberta, Canada of 2001, was observed to put about the same amount of smoke into the stratosphere as expected from one Hiroshima-sized firestorm [*Fromm et al.*, 2008]. In a recent heavily-instrumented aircraft field program two cumulus clouds, one filled with smoke and one with no smoke were observed next to each other [*Barth et al.*, 2015]. After testing the code we will investigate where smoke ends up over the course of a fire. During the intense phase of the fire it is expected the smoke will be lofted to high altitude, but some may descend in downdrafts. During the smoldering aftermath of the fire, smoke is likely carried only into the low level boundary layer.

The products of these studies will include improved estimates of fuel loading for urban areas. Currently there are few data on fuel loads in suburban and urban areas, even in developed countries. Fuel loads, such as from trees and vegetation near buildings, is often critical in starting urban fires, such as the Oakland Firestorm of 1991. We will not only study U.S. cities, but also those in Europe, Russia, China, Korea, India, Pakistan, and the Middle East. In addition, once we have determined the amount of fuel and the areas burned from the fire spread models we can determine the amount of fuel burned. There have already been a number of experimental and laboratory studies of the amount of smoke generated from burning various fuels [see review in *Toon et al.*, 2007b].

The product of these studies will not only be useful for nuclear winter studies, but also for investigating and fighting fires which move from wildlands to urban areas, and fires following disasters such as large earthquakes. In addition, current fire models have not coupled weather models, such as WRF, with urban fire spread models. Such coupled models will benefit disaster preparedness studies, and firefighting studies.

C. After lofting how do soot particles get transported and modified by the atmosphere? Once a fire injects soot into the atmosphere, the soot will be affected by sunlight and winds, and will interact with itself and other chemicals in the atmosphere, which will affect its distribution and ability to absorb sunlight. So far, we have estimated that a certain fraction of the potential fuel in cities will end up, after scavenging by precipitation, as pure soot particles in the upper troposphere. The troposphere is the 10-17 km thick lowest layer of the atmosphere where we live; above it is the stratosphere. We have placed the soot into climate models and allowed them to interact with the soot by further rainout, by heating and lofting into the stratosphere, where there is no rain to scavenge it, and by winds blowing it around the world. We have assumed that the particles are pure soot (black carbon), and that they do not grow, do not get coated with other chemicals, and do not react with other chemicals in the atmosphere, such as ozone. The climate response, including the soot lifetime and its effect on sunlight, depends on these assumptions, so we propose to model these processes with a state-of-the-art aerosol and climate model from NCAR, WACCM-CARMA (the Whole Atmosphere Community Climate Model-Community Aerosol and Radiation Model for Atmospheres). This work will be done by Dr. Charles Bardeen and Dr. Mike Mills at NCAR working with a Ph.D. graduate student. We will start with initial soot loadings based on previous work, and then modify the results based on the results of parts A and B. WACCM will respond to the initial injection of gases and aerosols from city fires, and calculate the subsequent transport, removal, and interaction of the particles with clouds, incoming sunlight and climate. Dr. Bardeen and Dr. Mills have both previously worked on nuclear winter simulations using earlier versions of WACCM [e.g., *Mills et al.*, 2014].

In the previous climate simulations with the NASA Goddard Institute for Space Studies (GISS) climate model [*Robock et al.*, 2007a, b], the aerosol module [*Koch et al.*, 2006] accounted for black carbon particles. We assigned an effective radius of 0.1 μm to the soot particles, a standard value based on observations. At visible wavelengths, we assigned the following optical properties to the black carbon particles: mass extinction coefficient of 5.5 m^2/g, single scattering albedo of 0.64, and mass absorption coefficient of 2.0 m^2/g. These are typical of a mixture of black soot, smoke, and dust that would be injected into the atmosphere using the baseline scenario of *Turco et al.* [1983]. However, emissions from fires may contain particulate organic matter as well as pure black carbon [*Pausata et al.*, 2016], and the black carbon soot particles may grow as fractals over time and may become coated with other materials. This can affect their lifetime, their radiative interactions, their impacts on clouds, and their chemical interactions that affect ozone in the stratosphere. We will address these potential differences in the climate response to smoke from nuclear-ignited fires by the use of CARMA and new fractal soot models [*Wolf and Toon*, 2010]. These fractal soot models include fractal microphysics, as well as fractal optics. For example, fluffy conglomerations of soot particles fall more slowly than spherical particles. The optics of fractals is a combination of scattering by the small components of the soot conglomerations and the fluffy conglomeration itself. While, fortunately, we have no modern examples of city fires to use as observations to evaluate our models, there have been extensive forest fires [e.g., *Fromm et al.*, 2010; *Siddaway and Petelina*, 2011] that pumped soot into the stratosphere that we will simulate as a test of our models.

D. What would be the climate response to a variety of nuclear conflict scenarios? Since WACCM is an excellent climate model, and we have used it in the past, we will conduct simulations with it of the new scenarios developed in the previous steps. In the past, three different climate models were used for the 5 Tg of soot scenario (regional nuclear war between India and Pakistan), and while the results differed a little, they agreed on the basic climate response, validating each of the models, including WACCM, and giving confidence that the results do not depend on a particular climate model. (To continue this validation, we will make the new scenarios considered here and the detailed simulations of smoke emissions available for the use of other climate modeling groups who would like to repeat the simulations, and we will encourage others to participate.) This work will be done by a graduate student at Rutgers in collaboration with the Colorado graduate student working in part C, to allow for the consideration of a number of different scenarios.

One of the advantages of WACCM is that we will run it with its sophisticated ocean biogeochemical model turned on, which will simulate the impact of nuclear war on food availability from the ocean. *Mills et al.* [2014] found long-lasting impacts on the temperature of the upper ocean layers for the 5 Tg scenario, but did not explore how this would affect the oceanic food chain, including impacts on ocean salinity. Thus the output from our simulations will allow the analysis of global food availability from oceanic as well as terrestrial sources.

While nuclear winter has few close parallels in nature, there have been suggestions by Nobel Prize winner Paul Crutzen that geoengineering, used to offset greenhouse warming, could be done with soot [*Crutzen*, 2006]. However, nuclear winter simulations by *Mills et al.* [2008] and geoengineering simulations by *Kravitz et al.* [2012] showed that adding soot to the stratosphere could cause catastrophic damage to the ozone layer. *Toon et al.* [2016] show that the amount of soot found in geologic strata at the time of the extinction of the dinosaurs 66.1 million years ago, is about 100 times greater than that likely to be produced in a full scale nuclear war. In fact it requires that the entire biomass at the land surface, probably including the dinosaurs, was incinerated. Climate simulations [*Bardeen, Garcia, and Toon*, in preparation, 2017], show that this soot would have lowered global temperatures to about the same level as those found in nuclear winter simulations. However, for the extinction case, light levels drop so low that plankton would not be able to photosynthesize, which is probably the cause of the extinctions in the oceans that occurred when the dinosaurs died. Also the ocean surface became quite cold. These parallels between one of the most massive global extinction events in Earth history, and the aftermath of a nuclear conflict need to be better understood.

E. How would agricultural production, water resources, and the ocean biosphere change in response to the climatic disruption and enhanced ultraviolet radiation from nuclear war? We have so far only evaluated one nuclear war scenario (the 5 Tg regional nuclear war) looking at two crops in the U.S. (soy and corn) using only one agricultural model with the output from one climate model [*Özdoğan et al.*, 2013], and three crops in China (rice, wheat, and corn) using one different crop model with output from three climate models for the same 5 Tg of soot scenario [*Xia and Robock*, 2013; *Xia et al.*, 2015]. For these simulations, we used incident solar radiation, temperature, and precipitation to drive the crop models. However, changes of agricultural productivity depend on the crop model used, as well as potential adaptations, including different seeds or crops, and different fertilizer and irrigation. Furthermore, potential changes in ozone at the surface and ultraviolet radiation will affect different crops differently, and although we have looked at major grains in two major producing countries, interconnected agricultural markets mean that impacts must be evaluated globally to characterize the impacts on food and nutrition security the world over. Changing water resources will further impact agriculture and livestock, as well as having immediate consequences for human consumption. Finally, the environmental and economic impacts on the oceans, particularly fisheries, have never been studied.

This work will be conducted in collaboration with the Agricultural Model Intercomparison and Improvement Project (AgMIP, http://www.agmip.org/), a major international collaborative effort to improve the state of agricultural simulation and to understand climate impacts on the agricultural sector from farm to global scales. In collaboration with Lili Xia (Rutgers) and Joshua Elliott (University of Chicago) we recently conducted preliminary simulations with the output of the 5 Tg nuclear war scenario to investigate the global distribution of impacts on several different crops with two global crop models, Community Land Model – Crop [CLM-Crop, *Bilionis et al.*, 2015] from NCAR and the Decision Support System for Agrotechnology Transfer [DSSAT, *Jones et al.*, 2003] run globally as part of the parallel System for Integrating Impacts Models and Sectors [pSIMS, *Elliott et al.*, 2014]. This effort clearly demonstrated the value of this approach. The next step is to develop the necessary input data and modeling protocols to investigate all the major crops with the 10-20 different gridded crop models participating in the AgMIP Global Gridded Crop Model Intercomparison [GGCMI, *Elliott et al.*, 2015] project. Evaluations of the models are now proceeding using observations from around the world, with various experiments planned or underway to look at the impacts on crops of different climate change scenarios. These will be extended to include scenarios of nuclear war and evaluate farmer adaptation options by modifying planting and harvesting dates, changing irrigation and fertilization, changing varieties of seeds, changing crops, and even moving farming to other locations with a better climate, all subject to constraints of the availability of resources, including changing water resources, soil characteristics and farming land.

Working with Joshua Elliott (University of Chicago), we will hire a full-time postdoctoral crop modeler at the University of Chicago and a graduate student at Rutgers to conduct trial runs with CLM-Crop and DSSAT with the output we now have for the 5 Tg nuclear war scenario, and publish those results. The researchers will also use new versions of CLM-Crop, now under development, that include for the first time the impacts of changing ozone and UV on crops, which will be generated by the WACCM climate simulations. These climate scenarios will also be prepared for use, along with various other required inputs and detailed modeling protocols, by the full set of AgMIP GGCMI models. Results will be updated and improved as new climate model results and new capabilities from the crop models become available.

Working with Cheryl Harrison (NCAR/University of Colorado) we will also study the impacts of nuclear war-induced climate changes on the ocean. This has never been done before. Not only will the temperature and sunlight affect the ocean, but changes of precipitation over the ocean, and precipitation over land, which changes runoff into the ocean, also affect ocean salinity. In addition, changes in atmospheric winds and ocean currents will change the distribution of temperature and salinity, including the flow of nutrients from the deep ocean. All these changes will affect microorganisms, the oceanic food chain, and the supply of food from the ocean.

The WACCM climate model we will use includes ocean biogeochemistry. We will then apply those changes to models of fisheries. Fishery stocks are dependent on the timing, magnitude, rate, and spatial distributions of primary (phytoplankton) and secondary (zooplankton) production in the ocean, as well as temperature, and for some species oxygen levels and acidification [e.g., *Deutsch et al.*, 2015; *Orr et al.*, 2005]. While the ocean ecosystem component of WACCM was designed to model carbon cycling over long time scales [*Doney et al.*, 2009; *Long et al.*, 2013; *Moore et al.*, 2013], its output will be used to drive off-line fisheries models that have been developed for use with remote sensing or ocean model output data. Models such as the Spatial Ecosystem and Population Dynamics Model [SEAPODM; *Lehodey et al.*, 2008, 2010] have been used with great success to predict important fisheries such as tuna, and extended to model endangered species such as loggerhead turtles [*Abecassis et al.*, 2013]. SEAPODM uses the base of the food chain to simulate the mid-trophic levels (e.g., small fish) that the larger, commercially important fish rely on for forage. This methodology can be applied to look at potential fisheries output in commercially important areas, for coastal communities that depend on the sea for food, as well as to assess the potential impacts to endangered marine animals such as sea turtles and whales.

More immediately, the Biogeochemical Elemental Cycling model diagnostic package, developed at NCAR for model development assessment, will be used to look at physical and biogeochemical effects such as mixed layer depths, Atlantic meridional overturning circulation (indicating the strength of the global thermohaline conveyer belt), surface and interior temperatures, net primary production, net ecosystem community carbon biomass, oxygen, and how these compare with current ocean observations. This will give us a quick snapshot of all of the processes we know are important for ocean climate interactions, and how they are impacted by various nuclear war scenarios.

F. How would the availability of food and water in each nation, including the United States, change as global markets and distribution systems react? As crop production changes, world food trade will be impacted. Five years ago, faced with a heat wave and drought, Russia stopped exporting wheat, and the price of food doubled in the Middle East, prompting the Arab Spring revolts. Following even a "small" nuclear war, as food production fell, would nations hoard food or simply increase the price to make a profit? Using economic models of world food trade, driven by the changes in food production in part E, we will model the changes in food prices in different nations around the world for different scenarios, ranging from continued free trade with relief efforts in regions with famine, to complete hoarding. This will then allow us to predict the human impact of the different scenarios. This work will be done by a graduate student, in collaboration with Profs. Gal Hochman and Alan Robock at Rutgers.

Humanity relies on physical resources and natural systems for food, energy, and water (FEW), the demand for which is predicted to increase significantly in the coming decades because of population and economic growth. A nuclear war has the potential to adversely affect population and economic growth, through destruction and changes of temperature, precipitation, and sunlight. Such changes significantly impact agriculture, resulting in long-run ramifications to nutritional intake and immigration flows.

We propose to assess the inter-related impacts of nuclear war and socioeconomic dynamics on the FEW systems. War brings destruction, and nuclear war leads to climate change. The magnitude of these effects is determined by the size of the conflict (e.g., local, regional, or global). The destruction of the existing agricultural system offers an opportunity to rebuild a new system that will better accommodate the post-war era. To this end, the Marshall Plan rebuilt Europe after the end of World War II and led to decades of prosperity in Western Europe. This proposal will investigate the implications and opportunities destruction may create, and develop a variety of potential responses to the changes in agricultural markets. This part of the proposal will build on the seminal work of *Johansen* [1972], which was used by *Hochman and Zilberman* [2016] to better understand how uncertainty regarding the outcome of future elections affects the design of environmental policy.

We will use coupled climate, biophysical, economic, and nutrition models to quantify the nuclear war's long-term effects on agricultural systems, as described above, and investigate the food-mediated implications for the distribution of wealth and nutrition. We will employ a systems approach and develop an integrated systematical model that stresses the interactive nature and feedback effects among physical and economic factors. Changes in crop production affect the world food trade system, where the direction and extent of the climatic effects of the nuclear war varies across the regions and the scope of the nuclear attack. Impact assessment studies done with integrated modeling tools are driven by the changed climate affecting biophysical crop models that then alter socioeconomic activity [*Nelson et al, 2014*; *Robinson et al.*, 2014; *Schmitz et al.*, 2014; *Valin et al.*, 2014; *Lampe et al.*, 2014; *Muller and Robertson*, 2014; *Lotze-Campen et al.*, 2014]. Building upon this literature, we will use an integrated suite of environmental and economic models to investigate the long-run implications of a nuclear war. The proposed suite will be used to identify the mechanisms through which the climate change following nuclear war leads to wealth transfer, alters food insecurity, impacts nutritional intake, and may result in migration of populations from failing nations whose agricultural sectors are collapsing. The climate and biophysical models are discussed above. Here, we focus on the economic and nutritional models.

The economic model: The economic model is a multi-sector recursive dynamic computable general equilibrium model, which will be used to better understand how the global food system responds to the various scenarios. The economic model will be used to show how the world food trade system will be affected by nuclear war from the different scenarios. That is, the change in yield calculated in the crop models will affect agriculture productivity in the economic model that will simulate global economic outcomes under the various scenarios up to 2050. Changes in yields will affect the price of food by its local impacts on production and its effects on the world food trade system, which will influence markets, alter water demand, and dramatically change the global food supply chain. Climatic change may also lead to geographical/spatial changes in crop varieties, and stress local agricultural systems thus leading to migration across countries.

To introduce the potential for net migration between countries, the current project will focus on labor productivity in the agriculture sector. Climatic change may lead to a sufficiently large decline in labor productivity in countries directly impacted by the nuclear winter, hence resulting in a decline of wages and the triggering of migration to neighboring countries. We will test different parameterization of migration, which will be developed using existing literature [e.g., *Massey*, 1988, 1990; *Zimmerman*, 1995; *Walmsley et al.*, 2007; *Martin*, 2009]. That is, previous patterns of rural outmigration driven by wage differentials will be used to calibrate the model.

We will also assess whether reasonable parameterizations of FEW effects on migration result in significant population flows. The empirical literature identifies several pathways for climate to influence migration [*Gray*, 2009; *Drabo and Mbaye*, 2011; *Black et al.*, 2011; *McLeman*, 2013; *Bohra-Mishra et al.*, 2014; *Kleemans*, 2014]. Adverse climatic changes can spur emigration from a country, while increased precipitation and higher crop yield will increase immigration to a country [*Barrios et al.*, 2006]. Econometric analyses indicate that a 1% decrease in yields in the Corn Belt results in a ~0.2% net reduction in population through migration [*Feng et al.*, 2012]. In Mexico, a 10% decrease in crop yields results in a ~2% increase in emigration from Mexico to the United States [*Feng et al.*, 2010]. In this project, we will parameterize labor's incentives to migrate (e.g., wage differentials, destruction, radiation).

The nutritional model: Because, when investigating the effect of nuclear war, we aspire to go beyond the volumetric consumption, a nutritional model will be introduced. The approach taken follows that used by *Chen and Ravallion* [2010] and builds on two distinct models, one "macro" and one "micro" in scope. The "macro" economic model generates economy-wide impacts, while the "micro" nutrition model takes those economy-wide predictions for variables such as prices and quantities and models the impact on the urban and rural poor's food insecurity, nutritional intake, wealth transfer, and immigration. The "micro" model will utilize World Bank household survey data collected in 28 developing countries [*Ivanic and Martin*, 2008; *Ivanic et al.*, 2012].

The economic model is used to generate price and wealth impacts of nuclear war. The outcome of the economic model is then passed to the nutritional model. This approach allows the analysis to focus on the poor, without worrying about reconciling predictions from the nutritional model with those of the economic model – that is, this approach does not generate inconsistency among the models. The advantage from this specification is greater flexibility; since the aggregation and regularity conditions that constrain the economic model are not inherited in the nutritional model, the analysis can focus on rural versus urban poor nutritional intake in addition to the volumetric availability of food. While using household survey data, the model will also allow the disaggregation of the rural poor to the rural farmers and others.

In developing a new metric to measure food security, the effects on the rural poor farmers will be separated from those on the non-farmer poor (seasonal labor and service providers), thus capturing both the direct price effects and the indirect price effects via income changes arising from climate change. Food price increases affect rural communities differently than urban communities, as the 2012 drought in the Midwest U.S. suggests. While the drought caused corn output to fall by 25%, prices increased by 50%, resulting in an aggregate increase in national cash receipts in the agricultural sector. Furthermore, because the effect on yield is not uniform, the magnitude of the income effect will vary across regions and depend on the sensitivity of wages to changes in prices. The nutritional model will measure these variations, and assuming dietary differences across regions as documented in Food and Agriculture Organization of the United Nations [*WHO/FAO*, 2003].

In recent decades we have observed a "nutritional transition" that contributes to the causal factors underlying non-communicable diseases [*WHO/FAO*, 2003]. Nuclear war will affect this nutritional transition through its altering of climate and thus crop yields around the world unevenly, resulting in some countries facing adverse effects with serious dietary ramifications. We will test the hypotheses that the effect of nuclear war on dietary patterns and nutrition intake will be substantial and that these effects will differ significantly between low- and high-income populations, as well as between the urban and rural poor.

To summarize, the aforementioned suite of models will be used to investigate a variety of potential responses to the changes in agricultural markets, including behavioral changes such as migration, and policy changes such as trade restrictions and inventory management programs. The proposed suite of models will be used to identify the mechanisms through which nuclear war leads to wealth transfer, alters food insecurity, impacts nutritional intake, and may result in migration of populations from failing nations/regions whose agricultural sectors are collapsing.

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Facilities

Because of our previous research experience running WRF and WACCM on the University of Colorado supercomputers [https://rc.colorado.edu/resources/compute/janus; https://www.rc.colorado.edu/resources/compute/summit], we will use them. These machines have about 1500 nodes when fully developed, and on the new Summit machine each node has 40 cores. In the initial development phase of Summit, starting in February 2017, it will have only 380 nodes. There are priority assignments to run on these machines based in part on how intensive the computations are, but the machine is free for University of Colorado researchers and their affiliates. Our calculations are typically run on about 10 nodes, and require long run times. To ensure that we have high priority access to the computer at all times, we propose to purchase 15 compute nodes. WACCM is typically run at 1.9°x 2.5°, with 67 vertical levels extending up to about 150 km altitude. WACCM typically uses 360 cores. About 1.4 years can be simulated per day, so that a one-year of simulation uses 6500 core hours. Usually our runs cover 15 years until the soot has cleared and the climate has returned to near normal. WRF productivity depends on the resolution, nesting, and ultimately the total number of grid points and the length of the runs.

Management

This will be a three-year project. This project will be co-directed by Alan Robock and Brian Toon. The work will be done in collaboration with Prof. Gal Hochman (Rutgers University); Dr. Joshua Elliott (University of Chicago); Dr. Michael Mills (National Center for Atmospheric Research); Profs. Yunping Xi, Nicole Lovenduski, and Julie Lundquist, and Drs. Charles Bardeen and Cheryl Harrison (University of Colorado); one postdoc; and eight graduate students.