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VIEWPOINT

WHAT ARE THE ODDS? Assessing the Probability of a Nuclear War

Carl Lundgren

Nuclear optimists and pessimists disagree on whether the odds of nuclear war are low or high. This viewpoint assesses the odds of nuclear war over the past sixty-six years, exploring three pathways to nuclear war: an international crisis leading directly to nuclear war, an accident or misperception leading to nuclear escalation or nuclear retaliation against an imaginary attack, and a general conventional war leading to nuclear war. The assessment is based on the application of Bayes's theorem and other statistical reasoning and finds that the expected probability of nuclear war during this historical period was greater than 50 percent. This level of risk is unacceptably high. It is therefore urgent that effective measures be taken to substantially reduce the risk of nuclear war.

KEYWORDS: Nuclear war; Cold War; nuclear weapons

What are the odds of nuclear war? There has long been a sharp difference of opinion on this question. Nuclear optimists posit low odds for nuclear war, whereas nuclear pessimists posit high odds for nuclear war. Indeed, one book presents a ''debate'' between nuclear optimism and nuclear pessimism.[1] In that book, political scientists Kenneth Waltz and Scott Sagan debate whether the spread of nuclear weapons to new nations is likely to be good or bad overall. This viewpoint instead focuses on the question of whether nuclear weapons possession by the major nuclear powers is good or bad overall. Did we survive the Cold War because deterrence reduced the odds of war to a very low level? Or did we survive mainly because of good luck? Is nuclear weaponry our friend or our enemy?

This viewpoint explores three potential pathways to nuclear war and assesses the odds along each: an international crisis leading directly to nuclear war; an accident or misperception leading to nuclear escalation or nuclear retaliation against a nonexistent attack; and a general conventional war leading to nuclear war. These three routes do not encompass all possible routes to nuclear war. Pathways not considered include: an ''insane'' (or malevolent) president or military leader starting a nuclear war; a nuclear state deciding to launch a surprise nuclear attack during non-crisis peacetime; or a terrorist, criminal, or other unauthorized person exploding or launching a nuclear weapon.

Because there has not yet been a nuclear war, data directly bearing on its probability are not abundant. Classical statistical methods for ascertaining probabilities may be adequate when large amounts of data are involved, but are woefully inadequate for

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estimates based on limited data. This viewpoint instead uses Bayesian statistical reasoning, based, *inter alia*, on Bayes's Theorem, an especially applicable mathematical method of calculating probabilities where only limited data are available and assured knowledge is not possible, but important conclusions or inferences must still be drawn in order to make choices or to set policy. Decidedly different nuclear policy choices follow from nuclear optimism or nuclear pessimism, but assured knowledge is not possible due to conflicting hypotheses and limited data. Hence, the application of Bayes's Theorem to sort through conflicting claims could be a useful exercise, either to clarify thinking or to provide useful inferences.

This viewpoint applies Bayesian and other statistical reasoning to limited evidence to assess the odds of nuclear war, based on a set of reasonable assumptions (called prior probabilities), along with any relevant data, to derive a conclusion (called posterior probabilities) about the likely probability of nuclear war developing from each of the three pathways. The combined probability of nuclear war from the three pathways is estimated to be quite high. Consideration of uncertainty and sensitivity analysis does not reverse this high estimate.

Brief Explanation of the Bayesian Method

Bayes's Theorem, or Bayes's Rule, calculates probabilities, given an observation of evidence, that various hypotheses might be true.[2] For example, suppose a large urn contains a very large number of balls, both black and red, in unknown proportions. There are many possible hypotheses concerning the probability of drawing a red ball, e.g., 5, 20, 50, 80, or 95 percent.

An initial belief about the probabilities of various hypotheses is called a *prior probability distribution*. It states what we believe is likely to be true before we have seen the evidence. This prior distribution can be either objective (based on known facts) or subjective. For example, if there are five urns and one urn is selected at random, the objective probability is one-in-five that any one urn is chosen. If the probability cannot be objectively known, then it is subjective. Subjective probabilities are likely to differ among reasonable individuals. From a prior perspective, if balls are drawn at random, the prior probability that the first ball drawn would be black can be computed according to the ordinary laws of probability.

Now suppose we draw one ball from the urn completely at random. Suppose this ball is black. This constitutes evidence upon which Bayes's theorem can operate. The evidence is too small to learn anything for certain, but we can still make some reasonable inferences based on the evidence. Intuitively, if one randomly drawn ball is black, we can infer that the urn most likely contains more black balls than red balls. Bayes's theorem allows us to express this intuition quantitatively. Given this evidence of one black ball, we can apply Bayes's theorem to the prior probabilities in order to compute posterior probabilities for each hypothesis. This revised set of probabilities that various hypotheses are true is called a *posterior probability distribution*.

Even when the evidence is skimpy (one ball was black), Bayes's theorem estimates new probabilities for hypotheses based on a strictly logical inference from evidence. The prior probability is the best estimate before the evidence is observed. The posterior probability is the best estimate after the evidence is observed.

Applying Bayes's Theorem

In this viewpoint, Bayes's theorem is applied to four different parameters that impact the probability of nuclear war. Three of the parameters are probabilities, and the fourth is a percentage that can be treated as if it were a probability. These four parameters are assigned prior probability distributions, within which each possible probability that the parameter might take on is itself assigned an initial probability. Evidence pertaining to these four parameters is then evaluated in accordance with Bayes's theorem to determine posterior probability distributions. These posterior probability distributions (updated sets of probabilities about probabilities) are summed up, along with other modeling assumptions, to determine an estimate of the probability of nuclear war.

Bayesian statisticians generally argue that when nothing is known about a particular parameter, it is normally appropriate to assign a Jeffreys's prior distribution to that parameter. When a parameter is a probability, the Jeffreys's prior is a beta distribution with parameters $\alpha = \beta = 0.5$. This prior assigns somewhat more weight to probabilities that are close to either 0 percent or 100 percent, and somewhat less weight to probabilities that are close to 50 percent.

This viewpoint follows the convention of using the Jeffreys's prior when nothing is assumed about the parameter in question. To the extent that there is prior knowledge about the likely distribution of the parameter, this analysis augments the Jeffreys's prior by adding "observations" to the beta distribution to reflect the prior knowledge. These "observations" are a reflection of the prior knowledge about the parameter, and could consist of either actual observations about related types of events or other sources of belief about the parameter. Observations are added to the beta distribution, by adding 1 to α for each positive observation and adding 1 to β for each negative observation. The beta distribution assigns probabilities to each possible probability. When all these possible probabilities are summed up, the summary probability from the beta distribution is $\alpha/(\alpha + \beta)$.

Each of the three pathways is modeled such that there could be a trigger event that leads to nuclear war. The probability is estimated that the trigger event would occur, in which case an additional probability is conjectured that the trigger event would lead to nuclear war. For the sixty-six years under consideration, we observe the evidence that no nuclear war has occurred. We also observe whether any trigger events that could lead to nuclear war have occurred. Based on the various pieces of evidence and assumptions as described below, the probability of nuclear war from each pathway is estimated.

Pathway 1: International Crisis Results in Nuclear War

During the Cuban Missile Crisis (CMC), President John F. Kennedy is reported to have estimated the chances of nuclear war as approximately one in three or one in two.[3] His national security advisor, McGeorge Bundy, is reported to have estimated the chance as 1 percent.[4] Between 1 percent and 50 percent is a substantial gap that echoes the disagreement between nuclear optimists and nuclear pessimists. One fact we know is that we survived the crisis without a nuclear war. How much influence should this fact have on our estimate of the nuclear war risk?

For the prior, suppose we give equal weight to Kennedy's and Bundy's opinion. Kennedy predicted odds of nuclear war between one-third and one-half; the midpoint of this range is 41.7 percent. The midpoint between 1 percent and 41.7 percent is 21.3 percent.

Suppose for a nuclear war to occur under this pathway, there must first be a major military provocation, such as a US invasion or attack on Cuba, a Soviet invasion or attack on Berlin, or similar-sized military operation elsewhere. This would be the trigger event. If this trigger event occurred, suppose that there would be a 50 percent chance of nuclear war. Under these assumptions, a prior probability of 21.3 percent that the CMC would result in nuclear war requires a prior probability of 42.7 percent that the trigger event would occur. This prior probability corresponds to a beta distribution with $\alpha = 0.672$ and $\beta = 0.5$.

We then observe that there was no major military provocation during the CMC and no nuclear war. Given this evidence, the estimated probability that the CMC would result in deliberate nuclear war falls from the prior of 21.3 percent to the posterior of 11.5 percent.[5]

We further know that there were multiple international crises during the Cold War. Some of the other crises also carried risk of nuclear war. The CMC was unique only in that it brought us closest to nuclear war. Suppose these other crises, in total, carried the same nuclear risk as one CMC, so that the total risk of nuclear war from multiple international crises was equivalent in risk terms to two CMCs. Given this additional evidence, the posterior probability of deliberate nuclear war from one CMC risk falls further to 7.5 percent. The posterior probability of deliberate nuclear war from two CMC risks was 14.3 percent.

Alternatively, the CMC could be viewed as a series of minor military provocations, such as the quarantine or blockade of Soviet ships, the shooting down of a U-2, and US efforts to force a Soviet submarine to the surface. Many of these minor provocations had a small (but not negligible) risk of escalation to nuclear war. If the prior probability of nuclear war from the combined effect of these many minor provocations during one CMC was 21.3 percent, then the posterior probability of deliberate nuclear war from two CMC risks was 19.7 percent.

Pathway 2: Nuclear Mishap Results in Nuclear War

Fifteen years ago, noted radiologist and nuclear abolitionist Dr. Alan Phillips assembled a list of twenty mishaps that might have started a nuclear war by accident or false alarm.[6] Phillips indicates that his selection represents only a fraction of the mishaps on the US side. He reasons that there were likely about as many on the more secretive Soviet side, for a total of forty mishaps. Phillips speculates that the chances of nuclear war from each of these mishaps could have been 1 percent, or even as high as 10 percent.

A further analysis indicates that Phillips's list contains four non-crisis mishaps, sixteen crisis mishaps, and four potential launch-on-warning (LOW) mishaps. After Phillips prepared his list, two additional LOW mishaps came to light from the Soviet side. Each of these incidents could have produced a nuclear war, but only if the mishap is first mistaken for enemy military action. Hence, the trigger for nuclear war along this pathway is a mistake that continues uncorrected until a decision is made whether to retaliate.

If a mishap were mistaken for enemy attack, the probability that the mistake would lead to nuclear war varies, depending on the circumstances of the mishap. For the non-LOW mishaps, I set the probability that a mistake leads to nuclear war at 30 percent for crisis mishaps and 10 percent for non-crisis mishaps. The six known LOW mishaps present a range of circumstances. For the LOW mishaps, I initially set the probabilities of a mistake leading to nuclear war between 20 and 80 percent, depending on type of circumstance. I later adjust these estimates to reflect that a small percentage of mishaps do not get reported to higher authority.

On the US side, in 1979, (according to press accounts) a nuclear launch computer exercise tape misled analysts into "seeing" the onslaught of a massive Soviet missile attack.[7] If this mistake had not been treated as a false alarm, I estimate 80 percent probability of nuclear war. Twice in 1980, a faulty computer chip caused erroneous displays of numbers of inbound missiles to be detected at the North American Aerospace Defense Command, triggering a routine albeit short-lived alert response by the Strategic Air Command.[8] If either mishap had been mistaken for enemy attack, I estimate 60 percent probability of nuclear war for the first incident and 40 percent for the second incident. In 1995, Russian President Boris Yeltsin was presented with the briefcase containing the codes to launch a nuclear attack in response to the detection of a single missile—a scientific rocket launched from Norway mistakenly identified as a US submarine launched ballistic missile.[9] I estimate a 20 percent chance of nuclear war, if the mistake had continued into the time for decision.

Another circumstance, not on Phillips's list, was the Soviet leadership's seemingly paranoid misinterpretation of the North Atlantic Treaty Organization's (NATO) 1983 Able Archer high-level military command post exercise as possible cover for a US first strike on the Soviet Union.[10] Because of the extended time period of the exercise (eleven days) and the lowered standard for evidence when attack is feared, I estimate three LOW mishaps. If any of the mishaps had been mistaken for enemy attack, I estimate an 80 percent chance of nuclear war.

Yet another mishap, also not on Phillips's list, involved an apparent attack with five missiles by the United States against the Soviet Union on September 26, 1983.[11] On that day, Stanislav Petrov, a forty-four year old lieutenant colonel in charge of a secret early warning bunker south of Moscow, reported to his superiors—in violation of standard Soviet procedures—that the apparent missile attack was a false alarm, even though he had no hard evidence to prove this. Five missiles could have carried fifty warheads, and Petrov could not have known whether additional missiles might be launched. Soviet authorities later determined that the false alarm was due to an optical illusion caused by satellite sensors being spoofed by the sun. If Petrov had not declared the alarm as false to higher authorities, I estimate a 40 percent chance of nuclear war.

The Petrov incident creates ambiguity of interpretation. Under one interpretation, Petrov was simply doing his job, correctly reporting an alarm as false. Under another interpretation, Petrov did his job improperly (perhaps heroically), because he had no technical reason for calling the alarm false and should have treated it as a real alert. In an interview years later, Petrov only gave general reasons for his instinctual decision—the satellite early warning system had only been in operation for several months; it was illogical for the United States to attack the Soviet Union with just five missiles. "I had a funny feeling in my gut," he told a reporter. "I didn't want to make a mistake."[12] Under a worst interpretation, Petrov usurped the prerogative of higher authority to decide whether to retaliate against perceived attack.

For modeling purposes, I interpret the Petrov mishap as a genuine mistake by the Soviet command structure, which had set in place error-prone technology and procedures; however, the erroneous alarm was (mis-)reported to higher authorities as a false alarm, contrary to what was expected. Accordingly, for all non-crisis LOW incidents, I reduce my initial estimates of nuclear war probability, in the event of continuing mistake, to reflect the fact that not all missile alarms are reported to the highest authority. For the 1979 computer tape incident and the 1983 Able Archer exercise, I reduce the probability from 80 percent to 76 percent. For the first 1980 computer chip incident, I reduce the probability from 60 percent to 51 percent. For the second 1980 incident and for the Petrov incident, I reduce the probability from 40 percent to 30 percent. For the 1995 single missile incident, I reduce the probability from 20 percent to 13 percent.

The relative risk that a mishap might be mistaken for enemy action varies, depending on the circumstances of the mishap. I set the relative risk of a mistake at one for non-LOW mishaps that occur during an international crisis, at one-half for non-LOW mishaps that do not occur during crisis, and at five for LOW mishaps. LOW mishaps are more likely to lead to mistakes because there is very little time (fifteen minutes or less) for national leaders to determine whether a sensory reading of enemy missile attack is real or not before procedures call for launching a retaliatory response (to avoid having forces destroyed on the ground and/or command and control networks disrupted or destroyed).

I now quantify the units of relative mishap risk. The six LOW events combined had relative mishap risk of forty (eight LOW mishap risks times five). I estimate forty crisis mishaps (ten for each side per CMC for two CMC-equivalent risks) for a total of forty relative risk units. I estimate an equal number of non-crisis mishaps (at one-half relative risk each) for an additional twenty relative risk units. This totals 100 units of relative risk that a mishap might be mistaken for enemy action. During this sixty-six-year period, only one mishap is known to have been mistaken for enemy action.

Because not every mishap mistake results in nuclear war, these 100 units of relative mishap risk sum to only 35.4 units of relative nuclear war risk. The forty crisis mishap risks had twelve relative risk units of nuclear war (because a mistake had only 30 percent chance of escalating to nuclear war). The twenty relative units of non-crisis mishap risks had only two relative risk units of nuclear war (because a mistake had only 10 percent chance of nuclear war). The six LOW events had relative mishap risk of forty, but only 21.4 relative risk units for nuclear war.

Before observing the data, I start with a prior that each unit of relative mishap risk has 10 percent chance of being mistaken for enemy action (beta distribution with $\alpha = 0.5$, $\beta = 4.5$). After observing only one mistake from 100 units of mishap risk, the posterior probability that one mishap risk results in a mistaken belief of enemy action is 1.4 percent ($\alpha = 1.5$, $\beta = 103.5$). If we combine this information with other parts of the model and exclude the 1995 incident, the posterior probability of nuclear war from mishap risk during the Cold War was 34.9 percent.

By far the most influential observation within the model is the Petrov incident. If this incident had not occurred, the posterior probability that one mishap risk results in a mistaken belief of enemy action would have been only 0.5 percent ($\alpha = 0.5$, $\beta = 99.5$). When the model is re-estimated without this incident, the posterior probability of nuclear war from mishap risk during the Cold War is only 14.6 percent.

The second most influential observation within the model is the Able Archer military exercise. If we assume no paranoid Soviet interpretation of this exercise, the posterior probability that one mishap risk results in a mistaken belief of enemy action would be slightly higher at 1.7 percent ($\alpha = 1.5$, $\beta = 88.5$). When the model is re-estimated without this incident, the posterior probability of nuclear war from mishap risk during the Cold War is 33.2 percent.

Combined Estimates for Pathways 1 and 2 to Nuclear War

Before combining estimates of risk, I define two methods for measuring risk. The first method estimates incurred risk. Incurred risk measures risk based on the actual number of events that could result in nuclear war, e.g. two crisis risks and ninety-five relative units of mishap risk during the Cold War. The previously computed incurred risks of nuclear war were 14.3 percent from the crisis risk and 34.9 percent from the mishap risk. Accordingly, the combined incurred risk of nuclear war during the forty-four years of Cold War was 44.3 percent. This is equivalent to a 1.3 percent chance per year during the Cold War, or an average frequency of one nuclear war per seventy-six years. Because the evidence of no nuclear war (so far) was fully factored into the Bayesian estimates, these calculated odds fully account for this oft-cited observation.

The second method estimates expected risk. Expected risk measures risk based on the expected number of events that could result in nuclear war, e.g. two crisis risks and ninety-five units of relative mishap risk, taking into account that random chance could have provided a higher or lower number of these events than the actual number. If we assume the expected frequencies of these risks is the same as the observed frequencies, then we expect to see, on average, 0.045 crisis risks and 2.16 units of relative mishap risk per year. Accumulating this expected risk over forty-four years, the expected probability of nuclear war from significant military provocations during crises was 13.4 percent, which is close to the incurred risk of 14.3 percent.

However, the expected mishap risk was significantly higher than the incurred mishap risk, because each crisis has mishap risk, each of which increased dramatically during the latter years of the Cold War, thanks to pressure to move toward a LOW posture. In addition, if a crisis had occurred during this LOW period, the presence of LOW mishap risk would have increased the probability of nuclear war during crisis.

The last Cold War crisis (the Yom Kippur War) occurred in 1973 and the first known LOW mishap occurred in 1979. For purposes of estimation, I assume the LOW period began in 1976, midway between these events. The non-crisis non-LOW nuclear war risk was 0.06 relative risk units per year during the thirty-one-year period 1945–76. The non-crisis LOW nuclear war risk was 1.60 relative risk units per year during the thirteen-year period 1976–89.

A crisis with one CMC risk is assumed to have twenty relative units of mishap risk (ten mishaps for each side) during the non-LOW period. If any mishap is mistaken for enemy action, I assumed a 30 percent chance of escalation to nuclear war. There are accordingly six relative risk units for nuclear war by mishap from one CMC-like crisis during the non-LOW period. Because the CMC occurred during the non-LOW period, the estimated probability of nuclear war during this crisis was 14.1 percent, of which 7.2 percent came from mishap risk and 7.5 percent came from risk of significant military provocation.

The severe pressure to launch on warning would have been especially acute during crisis. If a crisis with one CMC risk occurred during the LOW period, I assume the same number of mishap events, of which fourteen are ordinary mishaps and six are false warnings of missile attack. If any ordinary mishap is mistaken for enemy attack, I assumed a 50 percent chance of escalation to nuclear war. The fourteen ordinary mishaps have fourteen relative risk units for mistake and seven relative risk units for nuclear war. If a false warning of missile attack is mistaken for a real attack, I assumed an 80 percent chance of nuclear war. The six false alarms have thirty relative risk units for mistake and twenty-four relative risk units for nuclear war. Accordingly, there would be thirty-one relative risk units for nuclear war by mishap from one CMC-like crisis during the LOW period. If a CMC-like crisis had occurred during the LOW period, the estimated probability of nuclear war would be 36.9 percent, of which 31.9 percent would come from mishap risk and 7.5 percent from risk of significant military provocation. Fortunately, no Cold War crisis occurred during the LOW period.

If we assume an average of 0.045 crisis risks per year, then the expected crisis mishap risk of nuclear war was 0.27 relative risk units per year during the non-LOW period and 1.41 relative risk units per year during the LOW period. Combining together thirty-one non-LOW years and thirteen LOW years along with other information in the model, the expected mishap risk of nuclear war was 44.1 percent. If the whole Cold War had been forty-four non-LOW years, the expected mishap risk would have been 18.0 percent. If the whole Cold War had been forty-four LOW years, the expected mishap risk would have been 70.7 percent.

In the 1980s, researchers became increasingly concerned about the risk of accidental nuclear war. Michael Wallace, a political science professor at University of British Columbia, Brian Crissey, a computing science professor at Linfield College, and Linn Sennott, a mathematics professor at Illinois State University, utilized 1978–83 data on US false alarms to estimate an approximately 50 percent chance of inadvertent nuclear war during a thirty-day crisis.[13] Sennott utilized similar (1977–84) data to estimate a non-crisis risk of inadvertent nuclear war at about double the rate I estimate.[14] These studies used quite different data and methods to estimate somewhat higher probabilities for nuclear war by mistake. More recently, A.M. Barrett, Seth D. Baum, and K.R. Hostetler have analyzed the 1978–83 data using additional methods, but with no significant change in conclusions.[15]

Pathway 3: Conventional War Results in Nuclear War

Nuclear states use the implicit—or sometimes explicit—threat of nuclear weapons to deter conventional war. During the Cold War, NATO relied on nuclear threats to deter a conventional force invasion of Western Europe by the Soviet Union. Israel and Pakistan similarly credit their nuclear weapons possession with deterring conventional attacks or invasions. Nuclear optimists claim that nuclear weapons have virtually abolished major conventional war between nuclear powers, citing the absence of a third world war in the sixty-six years since the early twentieth century's two global wars. Before jumping to this particular conclusion, it is worth considering the historical frequency of major wars involving multiple great powers before 1945.

Rutgers University political theorist Jack S. Levy has compiled a data set which shows nine general wars involving two-thirds of the great powers during the period 1495–1945.[16] This indicates a 2.6 percent chance of a general war starting in each year that began without a general war being in progress (343 years during the 450 year period). If we subdivide Levy's indicated period into three parts of about 150 years each, this frequency of starting a general war varies from 0.8 percent to 6.0 percent per non-war year.

The most recent period containing two world wars is ambiguous, depending on when we start the measurement; the longer period, 1815–1945, saw two general wars start in 120 years that began without general war, but the shorter period, 1895–1945, saw two general wars start in 40 years that began without general war. This is a general war frequency between 1.7 and 5.0 percent per non-war year. Whether the modern industrial period, absent nuclear weapons, should be regarded as a period of frequent or infrequent general war is statistically unknowable, given the small sample size of only two general wars. For purposes of estimation, I set the prior for the frequency of general war, absent nuclear weapons, at 2.5 percent per non-war year (beta distribution with $\alpha = 2$, $\beta = 78$). This is based on the frequency of general war during the intermediate period, 1855–1945, which saw two general wars start in 80 years that began without general war.

One can hypothesize various levels of deterrent effect that the presence of nuclear weapons might have on the probability of general conventional war. If the deterrent effect is strong, significantly fewer general conventional wars can be expected to occur. If the deterrent effect is weak, slightly fewer general conventional wars can be expected to occur. Both views are common. Does the evidence of sixty-six years without a general conventional war provide enough evidence to decide which view is correct?

From a classical statistical perspective, the question is impossible to answer, because sixty-six years without a general conventional war is consistent (at the 5 percent level) with a probability per year for general conventional war of anywhere between 0.0 and 4.4 percent. Let's therefore model the question from a Bayesian statistical perspective. Suppose we assume that nuclear threats have some ability to deter general conventional war, but assume nothing further about the extent of this deterrent effect. Define the deterrent effect as the percentage of general conventional wars that do not occur because of nuclear threats, compared to the number of general conventional wars that would occur without such threats. This percentage can be treated as a probability and given a Jeffreys's prior (beta distribution with $\alpha = 0.5$, $\beta = 0.5$).

For this pathway, a general conventional war is the trigger event that might lead to nuclear war. Suppose that a general conventional war (e.g., a Soviet invasion of Western Europe) would result in nuclear war 65 percent of the time. A pessimistic Soviet leader might see the odds as higher and be deterred. A sufficiently optimistic Soviet leader might see the odds as significantly lower and see an invasion as a risk worth taking.

Under these assumptions, the expected posterior probability that a general conventional war would have occurred during the past sixty-six years was 26.2 percent. The expected posterior probability that a nuclear war would have resulted from a general conventional war was 19.2 percent. The expected deterrent effect of nuclear threats against general conventional wars rose from a prior of 50 percent to a posterior of 64.8 percent. This calculation attributes the whole cause for unobserved general war since 1945 to nuclear deterrence. If other factors also contributed to the post-1945 decline in general war probability (assuming the decline is real), then the impact from nuclear deterrence is overestimated.

For purposes of allocating this sixty-six-year risk of general conventional war, I assume that the total risk occurred solely within the forty-four-year period of the Cold War, and none of this risk occurred during the subsequent twenty-two years. That is, the per-year risk during the Cold War was 1.5 times a "normal" risk of general conventional war, and then dropped to zero.

Combined Estimates for All Three Pathways to Nuclear War

Incurred risk measures risk based on the actual number of events that could result in nuclear war, e.g. two crisis risks, ninety-five relative risk units of mishap risk, and no general conventional war. As reported above, the posterior combined incurred risk of nuclear war during the Cold War was 44.3 percent.

Expected risk measures risk based on the expected number of events, e.g. two crisis risks, various non-LOW and LOW mishap risks, and a significant chance for general conventional war, where the counts of events could have been higher or lower than the actual number. The posterior combined expected risk of nuclear war during the Cold War was 60.9 percent. This is equivalent to a 2.1 percent chance per year, or an average frequency of one nuclear war per forty-seven years.

During most of the Cold War, the prospect of nuclear winter was an unknown risk. Nuclear winter would be caused by smoke and soot generated from nuclear explosions that loft high into the atmosphere and block sunlight, resulting in a significant climatic drop in temperatures. This sharp drop in temperatures would severely depress agricultural food production, leading to global famine. 1980s research suggested this effect would last a year or two, but more recent research suggests the effect would last ten years or more.[17] Averaging the world populations in the high-risk years of 1962 and 1983 gives an average Cold War population at risk of 3.9 billion.[18] If a nuclear war plus nuclear winter would have killed 80 percent of the world's population, the expected fatality risk from the Cold War was 1.9 billion people (3.9 billion $\times$ 0.80 $\times$ 0.609).

The first sixty-six years of the nuclear age produced a 61 percent chance of a nuclear war; they also produced a 7 percent chance of a general conventional war that would not result in nuclear war. In the event that nuclear weapons had never been invented, we would expect to see an average of 1.34 conventional world wars and no nuclear wars. In exchange for averting 1.26 (1.34–0.07) conventional general wars, the world risked 0.61 nuclear wars. This is a ratio of 2.1 conventional world wars averted for each nuclear war produced. Since a nuclear war could easily be more than five times as destructive as a general conventional war, this is a bad tradeoff. If nuclear war results in nuclear winter, a nuclear war could easily be more than fifty times as destructive as a conventional world war.

World War II, history's deadliest hot war, caused 60 million deaths. Even in the absence of a general hot war, the Cold War was exceedingly dangerous. Counting only the incurred risk from crises and mishaps, the probability of nuclear war was 44.3 percent. If a nuclear war would have caused 300 million deaths, the expected fatality risk from the Cold War was 133 million people (300 million x 0.443). If a nuclear war plus nuclear winter would have caused 3 billion deaths, the expected fatality risk from the Cold War was 1.33 billion people (3 billion x 0.443). In expected fatality terms, the Cold War was easily the deadliest war in human history.

Before 1989, it was not generally predicted that the Cold War would soon end. That it did end in 1989 came as a complete surprise to nearly everyone. One can easily imagine that the Cold War could have continued another twenty-two years. For purposes of estimating the additional risk of an extended Cold War, I assume that peacetime learning reduced the LOW mishap risk to zero during non-crisis periods of the additional twenty-two years. If the Cold War had continued, an additional expected risk of nuclear war of 44.0 percent would have been added onto the incurred risk of 44.3 percent for a total risk of nuclear war of 68.8 percent. Alternatively, the additional twenty-two years of Cold War would have raised the expected probability of nuclear war from 60.9 percent to 74.4 percent. These significantly higher estimates for an extended Cold War are due to the substantially higher risk of nuclear war under conditions of launch-on-warning.

Uncertainty Analysis

Classical statistical analysis often provides confidence intervals around estimated parameters. Bayesian analysis constructs credible intervals, using somewhat different procedures and the interpretation is also different. For four different probability parameters, this viewpoint started with a prior distribution, utilized the available evidence, and derived a posterior distribution. I show below the means, the medians, and the 95 percent credible intervals of these posterior distributions.

The incurred risk of nuclear war from significant military provocation during crises had a mean of 14.3 percent, a median of 8.7 percent, and a 95 percent credible interval of 0.018 to 53.7 percent. The expected risk of nuclear war from significant military provocation during crises had a mean of 13.4 percent, a median of 8.5 percent, and a 95-percent credible interval of 0.018 to 47.5 percent.

The incurred mishap risk of nuclear war during forty-four years of Cold War had a mean of 34.9 percent, a median of 32.5 percent, and a 95 percent credible interval of 3.5 to 78.3 percent. The expected mishap risk of nuclear war during forty-four years of Cold War had a mean of 44.1 percent, a median of 42.8 percent, and a 95-percent credible interval of 5.0 to 88.7 percent.

The expected risk of a general conventional war resulting in nuclear war during sixty-six years of the nuclear age had a mean of 19.4 percent, a median of 13.1 percent, and a 95 percent credible interval of 0.035 to 66.6 percent. The estimated deterrent effect of nuclear weapons in preventing general conventional wars has a mean of 64.8 percent, a median of 76.1 percent, and a 95 percent credible interval of 0.50 to 99.94 percent.

The above 95 percent credible intervals provide a fairly wide range of possible probabilities. These wide ranges tell us that it may be possible for further evidence or sound reasoning to alter the conclusions. These ranges are not, however, a license to choose whatever beliefs one wishes on these matters. For example, if the temperature tomorrow is predicted to be 70°F, with a 95 percent credible interval of 60°F to 80°F, we are not free to assume that the temperature will be either 60°F or 80°F, depending on which temperature we like better. Similarly, unless additional evidence can be found to demonstrate a different set of probabilities, the mean probability (not the median or a range) is the best probability estimate for the evidence and models in this viewpoint.

Another way to analyze uncertainty about the probability estimates is to test the sensitivity of the model to changes in assumptions. Various assumptions, described in this viewpoint, were utilized to obtain the probability estimates. If the assumptions and calculations are correct, the results are correct. Suppose one or more assumptions might be incorrect—how would the model results change?

The incurred risk of nuclear war was 44.3 percent from two pathways (crises and mishaps). Estimates from these two pathways depend on seven basic factors that were applied to the model. I varied each factor to be half or double their baseline values. I then classified the results of these alternatives as "optimistic" or "pessimistic," depending on whether they reduced or increased the estimated probability of nuclear war. When all seven factors are set to the optimistic variations, the probability estimate becomes 7.3 percent. When all seven factors are set to the pessimistic variations, the probability estimate becomes 91.2 percent.

The expected risk of nuclear war was 60.9 percent from three pathways (crises, mishaps, and general conventional war). Estimates from these three pathways depend on ten basic factors that were entered into to the model. When all ten factors are set to optimistic variations, the probability estimate becomes 16.4 percent. When all ten factors are set to pessimistic variations, the probability estimate becomes 94.7 percent.

Again, these ranges are not a license to believe whatever one wishes on these matters. They are simply a spur for further research to obtain more evidence, data, or analyses that could refine these numbers. The pathways to accidental nuclear war can be analyzed more carefully through engineering and process analyses, such as is often applied to safety analyses of nuclear power plants and other complex systems. Analyses of the pathways through conventional war or international crises require further research in the behavioral and social sciences. Future refinements of these estimates could just as easily be more pessimistic as more optimistic. In the absence of such further knowledge and sound reasons for arguing otherwise, there is no reason to suppose these estimates of risk are grossly incorrect.

Fighting the Cold War with nuclear armaments and nuclear threats was a perilous wager. The probability of a failure resulting in nuclear war exceeded the probability of making an incorrect call while flipping a coin. The world must find a way to unwind this desperate gamble. It is vital that all practical measures be considered and effective measures taken to reduce or eliminate the continuing unacceptable risk of nuclear war.

DISCLAIMER

The views expressed in this article are solely those of the author and do not represent those of any US government agency.

NOTES

1. Scott D. Sagan and Kenneth N. Waltz, *The Spread of Nuclear Weapons: A Debate Renewed* (New York: W. W. Norton & Company, 2nd ed., 2003).
2. Bayes's Theorem is a well-known mathematical or statistical method that is explained on the Internet and in textbooks. Two simplified explanations include Mario F. Triola, "Bayes's Theorem," undated, last modified January 26, 2008, <faculty.washington.edu/tamer/BayesTheorem.pdf>, and Eliezer S. Yudkowsky, "An Intuitive Explanation of Bayes's Theorem," 2003, <yudkowsky.net/rational/bayes>.
3. Kennedy estimated odds "somewhere between one-in-three and even." Martin E. Hellman, "Risk Analysis of Nuclear Deterrence," *Bent of Tau Beta, Pi* 99 (Spring 2008), p. 21, note 14. Kennedy estimated different chances on different days in the crisis.
4. Ibid.
5. Most of the formulas and intermediary calculations are not shown in this viewpoint. These are available in spreadsheet form from the author that verify all the numbers reported in this viewpoint.
6. Alan F. Phillips, "20 Mishaps that Might Have Started Accidental Nuclear War," Nuclear Age Peace Foundation, January 1998, <www.wagingpeace.org/articles/1998/01/00_phillips_20-mishaps.php>.
7. Phillips, "20 Mishaps;" William Burr, ed., "The 3 A.M. Phone Call: False Warnings of Soviet Missile Attacks during 1979–80 Led to Alert Actions for U.S. Strategic Forces," George Washington University, National Security Archive, posted March 1, 2012, <www.gwu.edu/~nsarchiv/nukevault/ebb371/>; Scott Sagan, *The Limits of Safety: Organizations, Accidents, and Nuclear Weapons* (Princeton: Princeton University Press, 1993), pp. 228–29, 238. According to Sagan, the mistake was not operator error vis-à-vis a misplaced computer tape. Rather, during software development for an upgraded computer system, "software test information, a simulation of a major Soviet missile attack, was *inexplicably* transferred onto the regular warning display at Cheyenne Mountain and simultaneously sent to SAC

(Strategic Air Command), the Pentagon, and Fort Ritchie." (Emphasis in original, footnote omitted), Sagan, p. 238.

8. Phillips, "20 Mishaps;" Burr, "3 A.M. Phone Call;" Sagan, *Limits of Safety*, pp. 232, 244–46.

9. Phillips, "20 Mishaps;" "Russian Roulette: A Close Call? The Norwegian Rocket Incident," *PBS Frontline*, February 1999, <www.pbs.org/wgbh/pages/frontline/shows/russia/closecall/>; David Hoffman, "Shattered Shield: Cold-War Doctrines Refuse to Die," *Washington Post*, March 15, 1998, p. A1, <www.washingtonpost.com/wp-srv-inatl/longterm/coldwar/shatterfull031598.htm>.

10. Benjamin B. Fischer, "A Cold War Conundrum: The 1983 Soviet War Scare," 1997, <www.cia.gov/llibrary/center-for-the-study-of-intelligence/csi-publications/books-and-monographs/a-cold-war-conundrum/source.htm>; Dmitry (Dima) Adamsky, "The 1983 Nuclear Crisis—Lessons for Deterrence Theory and Practice," *Journal of Strategic Studies* 36 (February 2013) pp. 4–41, <dx.doi.org/10.1080/01402390.2012.732015>; Nathan Bennett Jones, "One Misstep Could Trigger a Great War: Operation RYAN, Able Archer 83, and the 1983 War Scare," M.A. thesis, George Washington University, May 17, 2009; Douglas Birch, "The USSR and US Came Closer to Nuclear War Than We Thought," *Atlantic*, May 28, 2013, <www.theatlantic.com/international/archive/2013/05/the-ussr-and-us-came-closer-to-nuclear-war-than-we-thought/276290/>.

11. David E. Hoffman, *The Dead Hand: The Untold Story of the Cold War Arms Race and Its Dangerous Legacy* (New York: Doubleday, 2009) pp. 6–11. The website, <www.brightstarsound.com>, contains various links dedicated to Stanislav Petrov and his 1983 decision.

12. David Hoffman, "'I Had a Funny Feeling in My Gut,'" *Washington Post*, February 10, 1999, p. A19, <http://www.washingtonpost.com/wp-srv/inatl/longterm/coldwar/shatter021099b.htm>.

13. Michael D. Wallace, Brian L. Crissey, and Linn I. Sennott, "Accidental Nuclear War: A Risk Assessment," *Journal of Peace Research* 23 (March 1986), pp. 9–27.

14. Linn I. Sennott, "Overlapping False Alarms: Reason for Concern?" in Anatolii Gromyko and Martin E. Hellman, eds, *Breakthrough: Emerging New Thinking* (New York: Walker, 1988) pp. 39–44.

15. A.M. Barrett, Seth D. Baum, and K.R. Hostetler, "Analyzing and Reducing the Risks of Inadvertent Nuclear War Between the United States and Russia," *Science & Global Security*, forthcoming.

16. Jack S. Levy, *War in the Modern Great Power System, 1495–1975* (Lexington, KY: University Press of Kentucky, 1983), p. 75.

17. Recent research and summaries on nuclear winter include: Alan Robock and Owen Brian Toon, "Self-assured destruction: The climate impacts of nuclear war," *Bulletin of Atomic Scientists* 68, September 2012, pp. 66–74 <climate.envsci.rutgers.edu/pdf/RobockToonSAD.pdf>; Alan Robock, "Climatic Consequences of Nuclear Conflict," PowerPoint Presentation to U Congressional briefings, June 12, 2008, <climate.envsci.rutgers.edu/nuclear/RegionalNuclearConsequences20AAAS.ppt>; Alan Robock and Owen Brian Toon, "Climatic Effects of Nuclear Conflict," June 12, 2008, <climate.envsci.rutgers.edu/nuclear/RobockToonSummary.pdf>; Alan Robock, Luke Oman, and Georgiy L. Stenchikov, "Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences," *Journal of Geophysical Research: Atmospheres* 112, July 2007, p. 107, <doi:10.1029/2006JD008235>; Owen B. Toon, Alan Robock, and Richard P. Turco, "The Environmental Consequences of Nuclear War," *Physics Today*, December 2008, pp. 37-42, <www.envsci.rutgers.edu/~gera/nwinter/nw6accepted.pdf>.

18. World population was 3.1 billion in 1962 and 4.7 billion in 1983. Wikipedia, "World population," downloaded April 30, 2013, <en.wikipedia.org/wiki/World_population>.